DOT/FAA/AR-08/27

Air Traffic Organization
Operations Planning
Office of Aviation Research
and Development
Washington, DC 20591

# Advanced Guidance and Control—Operational and Safety Benefits

June 2008

Final Report

This document is available to the U.S. public
through the National Technical Information
Service (NTIS), Springfield, Virginia 22161.

U.S. Department of Transportation
**Federal Aviation Administration**

## NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the objective of this report. This document does not constitute FAA certification policy. Consult your local FAA aircraft certification office as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No.<br>DOT/FAA/AR-08/27 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>ADVANCED GUIDANCE AND CONTROL—OPERATIONAL AND SAFETY BENEFITS | | 5. Report Date<br>June 2008 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>Mohamed Eladl[1], Khaled Eltohamy[1], Bryan Hill[1], Thomas Horne[2], Boris Krasnovskiy[1], Ken Leiphon[1], and Susan Taylor[2] | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>[1] Honeywell International<br>Phoenix, Arizona 85027<br>[2] Gulfstream Aerospace Corporation<br>Savannah, Georgia 31407 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No.<br>DTFACT-03-Y-90018 Amendment 0004 |
| 12. Sponsoring Agency Name and Address<br>U.S. Department of Transportation<br>Federal Aviation Administration<br>Air Traffic Organization Operations Planning<br>Office of Aviation Research and Development<br>Washington, DC 20591 | | 13. Type of Report and Period Covered |
| | | 14. Sponsoring Agency Code<br>AIR-120 |

15. Supplementary Notes

The Federal Aviation Administration (FAA) Airport and Aircraft Safety R&D Division COTR was Charles Kilgore. The Aerospace Vehicle Systems Institute, Texas Engineering Experiment Station, Texas A&M University, College Station 77843 was the cooperative organization bringing together the Project Management Committee (FAA, Honeywell International, Gulfstream, and Smiths Aerospace) that funded this research.

16. Abstract

This project originally titled "Assessment of Operational and Safety Benefits of Functionally Integrated Flight Guidance and Control" was retitled "Advanced Guidance and Control—Operational and Safety Benefits" with the funding participants in mind (FAA, Honeywell, Gulfstream, and Smiths Aerospace) and with the goal of emphasizing the benefits that would accrue to these participants (government and industry). The project launched with multiple objectives, one of which included evaluating the suitability and effectiveness of this technology compared to a more traditional control scheme. Of particular interest was the ease of reuse and the associated performance achievable with the generic design when applied to an actual production program.

The generic Total Energy Control System (TECS) outer loop design was evaluated for reuse and robustness without customizing the TECS outer loop design to achieve optimum performance. Instead, a test of the TECS was chosen in which the outer loop design of a traditional autoflight system was replaced with the TECS outer loop design. Very few adjustments were made to the Federal Aviation Administration-provided generic TECS outer loop design. No modifications were made for compatibility of the inner loop and outer loop designs for the hybrid system. The only modifications involved aligning the operational philosophies of the two control approaches so that a tangible performance comparison could be performed.

A series of flight scenarios were run to compare the performance of the hybrid TECS/traditional design with the customized traditional design. Of particular interest was the relative performance of the two systems. Since the traditional system was tuned to yield a desired performance, a good response match of the TECS hybrid system would indicate good viability for reuse. The absolute performance of the systems was deemed less meaningful because many other factors independent of the control approach, such as simulation model fidelity, adversely influenced the absolute performance. Significantly improved TECS performance, over and above what is presented in this report, would likely be achieved by tuning the TECS.

| | | | |
|---|---|---|---|
| 17. Key Words<br>TECS, Outer loop, Inner loop, Autoflight | | 18. Distribution Statement<br>This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. | |
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>68 | 22. Price |

**Form DOT F 1700.7** (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors would like to thank the Project Management Committee (PMC) for their participation contributing to the success of this Aerospace Vehicle Systems Institute Authority for Expenditure #47 Project. The PMC met regularly, on a bi-weekly basis for more than a year, to coordinate the execution of this project. The PMC participation and cooperative effort proved to be very productive and beneficial to this project.

The PMC for this project was as follows:

| Participating Company | PMC Representative | PMC Alternate |
|---|---|---|
| FAA | Tony Lambregts<br>Federal Aviation Administration<br>Advanced Control Systems | Charles W. Kilgore, II<br>Federal Aviation Administration<br><br>Barbara Lingberg<br>Federal Aviation Administration |
| Honeywell | Ken Leiphon<br>Honeywell Flight Controls<br>Department Manager | Eric Christianson<br>Honeywell Flight Controls<br>Department Manager<br><br>Bryan Hill<br>Flight Controls Technical Lead |
| Gulfstream | Bill Whitton<br>Gulfstream Aerospace | Thomas C. Horne<br>Senior Experimental Test Pilot<br><br>Susan A. Taylor<br>Technical Specialist,<br>Human Factors |
| Smiths | Mike Feldmann<br>Engineering Manager<br>Smiths Aerospace Electronic Systems | Gerry Vossler |
| AVSI | Reza Langari | Don Ward |

In addition, the authors would like to acknowledge the overall contributions of both Tony Lambregts and Charles Kilgore of the Federal Aviation Administration for their contributions to this report. Special thanks to Tony Lambregts for his extensive technical contributions to this project and for the considerable content provided in various areas of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AC | Advisory Circular |
| AFE | Authority for Expenditure |
| ALT HOLD | Altitude hold |
| ALT ACQ | Altitude acquire |
| AP | Autopilot |
| ARAC | Aviation Rulemaking Advisory Committee |
| AT | Autothrottle |
| ATC | Air traffic control |
| AVSI | Aerospace Vehicle Systems Institute |
| CDU | Control and display unit |
| DARPA | Defense Advanced Research Projects Agency |
| FAA | Federal Aviation Administration |
| FBW | Fly-by-wire |
| FD | Flight director |
| FG | Flight guidance |
| FG&C | Flight guidance and control |
| FLCH | Flight level change |
| FMA | Flight mode annunciator |
| FMC | Flight management control |
| FMS | Flight management system |
| FPA | Flight path angle |
| GA | Go around |
| GAC | Gulfstream Aerospace Corporation |
| GCP | Guidance and control panel |
| GP | Guidance panel |
| GS | Glide slope |
| GUI | Graphical user interface |
| HUD | Head-up display |
| IAS | Indicated airspeed |
| KIAS | Knots indicated airspeed |
| LNAV | Lateral navigation |
| M | Mach |
| MIMO | Multi-input/multi-output |
| MMO | Maximum Mach operation |
| NASA | National Aeronautics and Space Administration |
| OVR | Override |
| PC | Personal computer |
| PFD | Primary flight display |
| PMC | Project Management Committee |
| TD | Trust director |
| TCS | Touch control steering |
| TECS | Total Energy Control System |
| THCS | Total Heading Control System |

| | |
|---|---|
| UAV | Unmanned aerial vehicle |
| VAR | Variable |
| $V_{max}$ | Maximum velocity |
| $V_{min}$ | Minimum velocity |
| VMO | Maximum operating speed |
| VNAV | Vertical navigation |

# EXECUTIVE SUMMARY

This project launched with multiple objectives, one of which included evaluating the suitability and effectiveness of this technology compared to a more traditional control scheme. Of particular interest was the ease of reuse and the associated performance achievable with the generic design when applied to an actual production program.

This project officially launched on September 24, 2004, with the first Project Management Committee (PMC) telecon, which included all the project participants. Project participants included representatives from the Federal Aviation Administration (FAA), Aerospace Vehicle Systems Institute (AVSI), Smiths Aerospace, Gulfstream, and Honeywell. PMC telecons were conducted on a biweekly basis throughout the project duration of September 24, 2004 through December 14. 2005.

The first and only face-to-face PMC meeting was held in Phoenix, AZ, November 8-9, 2004. The objective of this meeting was to draft the Project Plan that would chart the course for this project. The agenda for the meeting focused on technology discussions, simulator demonstration, and associated patent discussions leading to the drafting of the Project Plan. The Project Plan was distributed to all PMC members and reached final approval on December 1, 2004. The approved Project Plan included Project Objectives, Deliverables, and Measures of Success.

It is important to note that, since the focus of this project was to evaluate the reuse and robustness of the generic Total Energy Control System (TECS) outer loop design, no attempts were made to customize the TECS outer loop design to achieve optimum performance. Instead, a test of TECS was chosen for the evaluation in which the outer loop design of a traditional autoflight system was replaced with the TECS outer loop design. Very few adjustments were made to the FAA-provided generic TECS outer loop design, and no modifications were made for compatibility of the inner and outer loop designs for the hybrid system. The only modifications involved aligning the operational philosophies of the two control approaches so that a tangible performance comparison could be performed.

A series of flight scenarios were run to compare the performance of the hybrid TECS and traditional design with the customized traditional design. Of particular interest was the relative performance of the two systems. Since the traditional system was tuned to yield a desired performance, generally correct responses and behavior of the hybrid TECS would indicate good viability of the concept. The absolute performance of the systems was deemed less meaningful, because many other factors independent of the control approach adversely influenced the absolute performance. Significantly improved TECS performance, over and above what is presented in this report, would likely be achieved by tuning the TECS.

## 1. INTRODUCTION.

### 1.1 MEASURES OF SUCCESS.

To provide guidelines to ensure a successful outcome of this project, the Project Management Committee (PMC) established the following criteria for meeting the project objectives:

- Successful implementation of Total Energy Control System/Total Heading Control System (TECS/THCS) simulation
- Quantifiable performance standards defined and supported by results of TECS/THCS evaluations
- Objective pilot evaluation of operational suitability of the modes included in the project
- Evaluation of the reusability, standardization, and relative effort needed for TECS/THCS implementation compared to a traditional system development

### 1.2 SUCCESSFUL IMPLEMENTATION.

The Federal Aviation Administration (FAA)-provided outer loop TECS design was implemented, in its original form, in the real-time software of an Autoflight System on a Honeywell simulator used for a production program. The following adaptations to the overall simulink models, provided by the FAA to integrate with the existing real-time software, included:

- Partitioning of the algorithm for execution of the various parts at different frame rates
- Use of elevator inner loop control from an existing production program without customization for TECS
- Use of complementary filters from an existing production program
- Use of a Mach (M) control mode and Mode Logic from an existing production program

The objective of the project was to evaluate the effectiveness of the generic design. No design alterations were made to adapt the generic TECS outer loops, to the inner loops from an existing production program, to the target airplane/TECS combination, or to achieve any performance objective.

This evaluation focused on the reusability and portability of TECS control. The inner loops of an existing autoflight system were used for the evaluation. The TECS implementation integrated well, demonstrating good portability and compatibility with the existing inner loop design even though these inner loops were not designed for TECS. The TECS implementation was completed on schedule in preparation for the first pilot evaluation.

Per the Project Plan, THCS was not implemented in real-time software. Instead, the THCS evaluation was performed on the generic TECS/THCS simulation provided by the FAA.

## 1.3 QUANTIFIABLE PERFORMANCE.

Performance was evaluated via analysis of data obtained from the pilot in-the-loop simulation evaluations. Performance of the hybrid system, consisting of the generic TECS outer loop design combined with the inner loop design from an existing production program, was obtained and is detailed in section 5.

## 1.4 OBJECTIVE OF PILOT EVALUATION.

To achieve an objective pilot evaluation of operational suitability and the potentially achievable performance for the TECS/THCS technology, a combination of flight test pilots and line pilots were used over the course of this project. Flight test cards were prepared, representing specific flight scenarios. These specific scenarios were chosen based on the known challenges inherent in the required autoflight maneuvers. The flight test cards were assessed by multiple pilots over three separate evaluations as follows:

- Pilot Evaluation 1—Pilot evaluation was performed on April 26-27, 2005 on the TECS at the Honeywell simulator in Phoenix, Arizona by the Gulfstream Aerospace Corporation (GAC) team. The FAA was in attendance to support the evaluation.

- Pilot Evaluation 2—This pilot evaluation was performed on July 11-12, 2005 by the Gulfstream team on the TECS at the Honeywell simulator in Phoenix, Arizona. The FAA and an Aerospace Vehicle Systems Institute (AVSI) pilot were in attendance to support the evaluation.

- Pilot Evaluation 3—This pilot evaluation was performed at GAC on August 23-24, 2005 in Savannah, Georgia, by the GAC team, which included both flight test and line pilots. This evaluation used a laptop real-time TECS/THCS Demo System simulation with a more primitive interactive virtual Flight Guidance panel and primary flight display (PFD) projected on a laptop display. This evaluation focused on a simulator evaluation of both THCS and TECS operation and control. Pilot evaluation feedback was obtained via a comprehensive questionnaire following the simulator sessions with the cross-functional group. The FAA was in attendance to support the evaluation.

## 1.5 EVALUATION OF REUSABILITY AND REAPPLICABILITY.

To evaluate the reusability, standardization, and relative effort needed for TECS implementation, an analysis was performed comparing code size and performance of the TECS design with the more traditional designs. The results of the analysis indicated that TECS technology can yield equivalent or better performance with a code size estimated to be significantly less than the traditional system. Assuming that code size is a good indicator of relative effort for implementation complexity and reapplication, TECS would appear to offer significant cost and time savings over traditional approaches. Although reusability could not be directly assessed, as this project entailed a one-time application of the TECS outer loop, a high degree of reusability would be expected from the TECS outer loop design when interfaced with a compatible inner loop design customized for a specific aircraft application.

The above success criteria were used as guidance by the project monitors throughout the execution of this project. The project monitors determined that this project's objectives have been successfully met in yielding the conclusions of this project.

## 2. PROJECT PLAN OBJECTIVES.

This project is Phase 1/Year 1 of a multiphase and multiyear project. Its intention is to clear obstacles to the introduction and certification of advanced, functionally integrated Flight Guidance and Control (FG&C) systems in commercial airplanes. The TECS and THCS are examples of advanced functionally integrated FG&C algorithms available to this project.

The Phase 1/Year 1 objectives included:

1. Achieve TECS/THCS technology familiarization.

2. Establish performance standards for TECS/THCS outer loop control using existing inner loop designs for a traditional aircraft application. Assess the benefits in terms of performance enhancements and operational human factors (guidance panel (GP) considerations) associated with the multivariable control of speed and flight path during various segments of the flight envelope (i.e., cruise, nonprecision approach, and go around (GA)).

3. Evaluate the linear multivariable control for single- or dual-command inputs (speed and flight path angle (FPA)) during fully coupled operation with and without turbulence.

4. Evaluate the effectiveness of TECS/THCS as applied to envelope protection (assess performance for emergency descent).

5. Evaluate the TECS/THCS automatic flight path and speed control modes with autothrottle (AT) off (simulation only).

6. Develop the objectives and tasks needed to validate/flight test a TECS/THCS.

## 3. BACKGROUND.

### 3.1 FLIGHT GUIDANCE AND CONTROL SYSTEMS HISTORY AND THE EVOLUTION OF TECS/THCS.

Much has been written in the popular aviation press and by human factors specialists about flight deck automation deficiencies. Some believe that flight deck automation has gone too far. Others believe that flight deck automation problems are due to poorly designed man-machine interfaces. However, there is no doubt that automation clearly has been one of the pillars of aviation safety and productivity improvements. While the interfaces between the flight crew and the automatic systems are far from ideal, it would be unrealistic to expect that operational effectiveness and safety issues with an automatic FG&C system can be resolved by addressing the symptoms at the man-machine interface level only. The situation is far more complex. The current state of the art in automatic flight guidance and control is the result of more than 75 years of piecemeal evolution, mainly by a process of minimal change/minimal cost addition of more functions with each generation of airplane design. As a result of this historic evolutionary process, highly capable automatic flight guidance and control systems have evolved. Unfortunately, these systems have become exceedingly complex from the point of view of design, maintenance, and operation by the flight crew. This design tradition has resulted in too many modes and submodes, functional overlap, and inconsistencies of operation between modes, resulting in flight crew mode confusion, errors, and general difficulties in understanding automatic FG&C systems and maintaining situation awareness. Nevertheless, airlines and flight crews have come to regard many flight guidance and control functions as mission critical, although most functions were designed and certified under the rules for noncritical systems. Such noncritical systems were originally intended only to assist flight crews, and the responsibility for their correct and safe operation remains with the crew. Today, flight crews expect modern FG&C systems to operate correctly and with functional integrity in all flight conditions and to provide proper flight crew alerting in case of failure or unsafe operating conditions.

Many reported deficiencies have been known for decades. Their root cause lies in the historic/traditional design concepts that have been propagated through many design generations, without establishing a new, cleaned-up design baseline, using updated technologies and design integration techniques. In the early days, designs were constrained by limited design knowledge, relatively primitive technologies, and economic factors. Today, most earlier hardware technology constraints of analog electronics and mechanical instruments have been eliminated by the introduction of digital processing and electronic flight instrument technologies. Also, the knowledge for designing simpler, better-integrated FG&C systems and man-machine interfaces has been available for decades. Unfortunately, the early design practices are deeply entrenched in the industry and a paradigm shift in the FG&C design approach away from the minimum change/minimum cost approach has been difficult to sell. As a result, current systems are unnecessarily complex, very costly to develop and own, and still do not provide all desired safety and operational features. A more comprehensive discussion on this subject can be found in reference 1. Many of these automation safety concerns are documented in reference 2. Thus, the deficiencies in operational effectiveness, safety, and performance associated with the current generation FG&C systems are well known.

This situation has led to a number of incidents and accidents involving flight deck automation. Many of these incidents and accidents involve situations where pilots have difficulty understanding how the system operates and how to properly and timely interact with this system to assure their safe operation. Flight crew mode confusion, operations' errors of commission or omission, and unwarranted trust that these systems will inherently operate safely have led to a surprisingly frequent occurrence of loss of control (e.g., stalls, badly out of trim disconnects), some with catastrophic consequences. As a result of the safety issues, the Aviation Rulemaking Advisory Committee (ARAC) commissioned a group consisting of cognizant personnel from the FAA, the Joint Aviation Authorities, and the industry to rewrite the basic automatic flight guidance and control certification safety regulations Title 14 Code of Federal Regulations 25.1329/1335 and Advisory Circular (AC) 25.1329. This ARAC group has finished its work and a Notice of Proposed Rule Making for adoption of the updated certification requirements and guidance is in process. These updated certification requirements are expected to precipitate relatively far reaching changes in future automatic flight guidance and control system design, including the application of multivariable control technology, a much higher degree of function sophistication and integration, flight and performance envelope protection features, and a re-assessment of the design criticality of certain functions.

In the mid 1970s, as an outgrowth of the cancelled Supersonic Transport program, The Boeing Company delivered an advanced (for that time) FG&C system to National Aeronautics and Space Administration (NASA) Langley under the Terminal Configured Vehicle program. It included the first prototype digital flight control computers, digital cathode-ray tube primary flight and navigation displays, and a prototype flight management computer (FMC). This NASA program contributed much to the evolution of the current, modern automated flight deck, but also to its complexity, as the new operational capabilities were added onto an existing FG&C architecture. For example, the FMC not only incorporated new automatic navigation capabilities, but also a new batch of automatic control modes for controlling the airplane on waypoint-defined flight paths in the horizontal plane (lateral navigation [LNAV]), the vertical plane (vertical navigation [VNAV]) and airspeed control. It introduced a new keyboard-based control and display unit (CDU) that functions more like a general office machine than a traditional interface with dedicated function knobs and numerical readouts of reference targets. Although the new FMC and CDU provided many new capabilities, the complexities of how to operate the variety of system interfaces (the need to remember the correct syntax for programming and executing a desired automated maneuvering sequence) made the flight crew's job much more challenging. Pilots experienced difficulties in managing and understanding the operation of each subsystem. By the late 1970s, the NASA terminal area operations research, using this system, had clearly revealed a number of operational, control performance, and safety deficiencies. Much time and money was spent during this program in attempts to make the systems operationally acceptable and to improve the basic interaction of the control laws. It was concluded that this control law architecture, with its multitude of historically evolved overlapping single-input/single-output control modes and complex mode logic, would never provide the desired user-friendly system operation and optimal performance. As a result, a NASA program was undertaken, starting in 1979 and continuing through most of 1985, to develop a more effectively integrated FG&C system. The objectives of this program included:

- Develop a generalized reusable multi-input/multi-output (MIMO) control algorithm and system functional architecture that accommodates all needed modes for automatic and augmented airplane control operations

- Eliminate functional overlap between modes and provide operational performance consistency for all modes and flight conditions

- Provide decoupled vertical flight path and speed command responses by proper coordination of thrust and elevator control

- Provide flight envelope protection that covers all flight modes

- Provide operational effectiveness to the flight crew by simplifying the mode logic and man-machine interfaces

- Reduce overall system complexity; eliminate hardware subsystems (e.g., AT, flight management system (FMS) control laws, yaw damper, thrust asymmetry compensator) where possible, reduce software.

The Phase 1 of this research, carried out by Boeing, addressed the functional integration of all automatic and augmented manual control modes for airplane control in the vertical plane. This research resulted in the TECS. NASA and Boeing invested more than $5 million in the development and flight demonstrations of the TECS FG&C concept. Phase 2 of the research, which addressed the functional integration of all automatic lateral-directional control, was also carried out by Boeing as part of the Condor Unmanned Aerial Vehicle (UAV) High-Altitude, Long Endurance Technology Demonstration program (1983-1990), funded jointly by Defense Advanced Research Projects Agency (DARPA) and Boeing. It resulted in the THCS. In all, NASA, DARPA, and Boeing invested more than $20 million in the TECS/THCS FG&C system development. Both TECS and THCS were used in the Condor flight demonstration program.

The following TECS/THCS concepts were developed to satisfy the above functional, performance, and economic requirements.

- A minimum set of operationally required and preferred modes was defined.

- Generalized MIMO flight guidance and control strategies were identified for airplane control in the vertical and horizontal planes, and the corresponding functionally integrated systems architectures were developed.

## 3.2 THE TECS GENERAL DESIGN CONCEPT.

The TECS was developed for airplane control in the vertical plane. This concept uses an energy-based control strategy to realize all needed mode functions. The general TECS architecture is shown in figure 1.

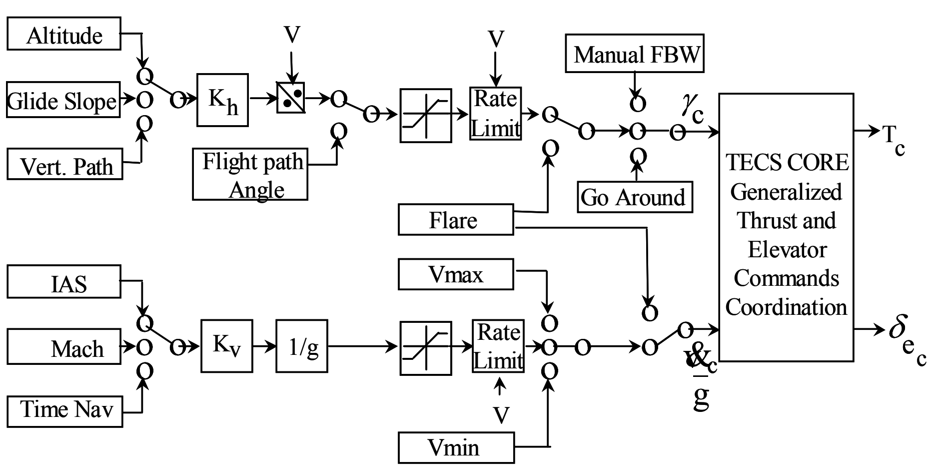



Figure 1. Generalized Mode Architecture for TECS

Thrust is used to control the airplane's total energy requirement based on flight path and speed targets. The elevator is used to control the channeling of energy to flight path or speed, or between flight path and speed. For any vertical path mode, the command and feedbacks are normalized into an FPA command (γc), which is the vertical flight path-related component of the airplane's specific energy rate. Likewise, for any speed mode the command and feedbacks are normalized into a dimensionless longitudinal acceleration command ( $\dot{V}/g$ ), which is the airspeed-related component of the airplane's specific energy rate. These commands are input to the TECS core algorithm, where the sum of the FPA error and normalized longitudinal acceleration error signals are formed to develop the net thrust command, and the difference of FPA error and normalized longitudinal acceleration error signals are formed to develop the elevator command. The total energy control strategy provides simultaneous coordinated elevator and thrust commands to achieve energy efficient, pilot-like control with decoupled command responses. Here, decoupled control means that the airplane will only respond as intended to a control command, without causing significant unintended responses in the other command state variable. The result is a generalized reusable design, applicable to all conventional airplanes, which supports all needed automatic and augmented manual control mode functions and provides performance consistency between modes.

The total net thrust command is scaled in proportion to the actual airplane weight. The energy distribution control dynamics and total energy control dynamics are designed to be identical. This is a prerequisite for assuring that the delta energy produced in case of a single flight path or speed command goes entirely toward satisfying the new command and does not spill over onto the variable with an associated constant command. This is the mechanism for providing very simple and effective control command response decoupling. Simultaneous flight path and speed commands with opposing energy demands are executed by first exchanging energy to the extent possible using elevator control only, before commanding a thrust change to satisfy the final total energy demand. Thus, maneuvers are always executed in the most energy efficient way possible, while also eliminating undesirable engine control activity. The TECS energy control concept makes the flight path and speed control modes fully generic/reusable, yielding the same performance in any airplane application.

Only the thrust and elevator control inner loops need to be adapted to the specific airplane application to match the thrust and FPA/longitudinal acceleration control dynamics.

An FPA rate command/FPA hold augmented, manual-control algorithm is also provided and is seamlessly integrated with the TECS core algorithm by developing an FPA command based on the pilot's stick input, along with appropriate feed forward commands to shape the control responses for the desired handling qualities.

Envelope protection strategies are implemented as part of the TECS core algorithm to provide protection against excessive angle of attack, underspeed, overspeed, and normal load factor, appropriate for each mode. These features are implemented seamlessly as part of the basic modes. For the automatic modes, normal load factor control is implemented as an integral part of energy management control.

Extensive pilot-in-the-loop simulator development and final evaluations were conducted for more than 5 years. Approximately 25 pilots from Boeing and NASA took part in its development and evaluation. The TECS program culminated in a very successful flight test evaluation and demonstration program in mid 1985, on the NASA B-737 airplane, covering all the integrated automatic flight path and speed mode operations, as well as the augmented manual (fly-by-wire [FBW]) control mode and all envelope protection functions. The system performed so well, no design changes or system retuning were needed during the flight test program. The amount of software needed to implement all the TECS functions was less than 40% of the amount of software for the B-757 longitudinal control mode, even though the B-757 did not feature full envelope protection. The TECS concept was used on the Condor UAV program because its generic, reusable design is ideally suited for low-budget, low-development effort applications. It was also chosen because the risk of loosing the airplane during a flight test due to an immature flight control system was considered substantially less than for a more traditional flight control system. All the mode functionality and mode logic was considered highly mature, and its generic software could be reused directly without significant specific development for the Condor UAV. The TECS application risk, due to differences between the airplane model used for designing the system and the actual airplane dynamics, is only confined to the inner loops. This was considered more manageable than when airplane dependencies appear throughout the design, as is the case in a more traditional design.

## 3.3 THE THCS GENERAL DESIGN CONCEPT.

Because of the success with TECS, it was decided to develop a functionally integrated lateral-directional control for the Condor UAV. The THCS uses a MIMO control strategy that is completely analogous to TECS. The general THCS architecture is shown in figure 2.

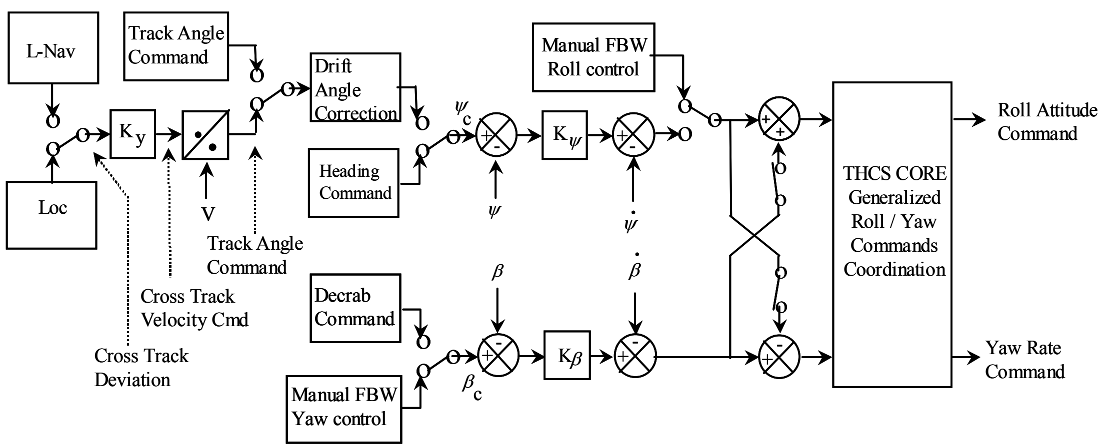



Figure 2. Generalized Mode Architecture for THCS

In this THCS concept, the horizontal flight path control error of any outer-loop mode is normalized into heading error, and a sideslip error is also developed. For normal operations, the sideslip command is zero. Nonzero sideslip commands are used for crosswind landing/decrab and as a result of rudder pedal inputs, in the augmented manual control mode. The normalized heading and sideslip angular errors are input to a core lateral-directional control algorithm, where the roll command is computed to null the sum of heading and sideslip errors and a yaw rate command is computed to null the difference between heading and sideslip errors. The THCS core algorithm provides simultaneous coordinated aileron and rudder commands to achieve a smooth, well-damped heading control response with near-perfect turn coordination (insignificant sideslip). It also provides inherent yaw damping, turn coordination, engine out yaw control, and automatic roll and yaw trim without the need for separate and dedicated sensors and control and mode logic software. Thus, the THCS concept supports all needed automatic and augmented manual control mode functions.

All outer loop mode and core roll and yaw rate command coordination functions, as well as the mode logic, are fully generalized and can be used directly on any conventional airplane. Only the roll and yaw inner loops need to be adapted to the specific airplane characteristics to produce properly coordinated roll and yaw dynamics.

### 3.4 APPLICATION OF TECS/THCS ON TRANSPORT AND GENERAL AVIATION AIRPLANES.

Recently, there has been renewed focus on automatic FG&C safety, and new design safety regulations will soon take effect. These new regulations will include requirements for envelope protection, improved man-machine interfaces, and operations concepts, as discussed above. It may be possible to implement most of the new design requirements in the existing FG&C system architectures, but the result will be still greater design complexity without making progress in system modernization and cost reduction of future designs. Development and ownership costs of overly complex, custom-designed FG&C systems will no longer be competitive when compared to generic reusable and functionally integrated designs such as TECS/THCS.

The TECS/THCS strategy worked well for the Condor UAV program: the design performed as intended. It did not need any further development and greatly enhanced the flight safety for the failures encountered. TECS/THCS provided fully automatic control from its first takeoff through its last landing and successfully managed a number of serious failure conditions, including two engine-out automatic landings and an inadvertent in-flight, full reverse thrust condition while operating close to stall speed.

Clearly, application of the generalized, reusable TECS/THCS algorithms will reduce FG&C system development, validation, and flight-testing efforts because all desired modes share major functional (possibly precertified) components. These concepts also provide for simple, effective operational envelope protection and simpler, more flight crew friendly man-machine interfaces. The approach eliminates traditional separate subsystems providing AT, yaw damper, turn coordination, and thrust asymmetry compensation functions. Instead, these functions are integrally and generically provided by the multiaxes TECS and THCS control algorithms. Thus, TECS and THCS hold the potential for providing simpler, safer, and less costly FG&C systems. TECS and THCS have very successfully gone through the final stages of a technology readiness demonstration, including flight testing, and have been shown to successfully address virtually all known FG&C automation issues that have recently been highlighted in aviation journals and FAA reports.

Thus, advanced guidance and control technologies that promise safer, more capable, and more effective FG&C designs exist and have been adequately demonstrated in piloted simulations and flight tests, but these technologies still have not found their way into U.S.-certified transport and general aviation airplanes. It is clear that availability of the technologies is not enough to assure their application. Application of these technologies has been impeded by industry concerns about the perceived risks and uncertainties associated with a design changeover to the new integrated FG&C system, including:

- The operational suitability and performance
- Flight crew system acceptance
- Flight crew training needs
- Effort required for comprehensive FG&C redesign and changeover
- Certification issues and efforts required to resolve the issues
- Safety and cost benefit

The potential payoffs include a simpler, better-integrated, generic design that can be reused on many future airplane programs with little additional development. This should translate into significant reductions in future FG&C systems costs. Therefore, this project has been structured to help overcome the impediments for introducing more advanced functionally integrated FG&C systems in transport and general aviation airplanes. Eight tasks have been identified to complete the overall project. Phase 1 of this project includes the following two tasks:

- Assess the merits, suitability and operational effectiveness of advanced functionally integrated FG&C technology (i.e., TECS and THCS) and establishes minimum performance standards. The work performed under this task is documented in this report (Year 1).

- Document safety, operational and certification requirements, and objectives for future FG&C systems. This task is scheduled to be performed in Year 2.

Six additional tasks have been defined to assess the operational suitability and safety improvements afforded by the already developed advanced FG&C systems, and to provide overall assessment of the technical and economic design readiness for introduction and certification on future transport aircraft. For these remaining tasks, funding will be sought under the NASA/FAA Aviation Safety Program, Phase II (identified herein as Phase 2), was due to start in FY06, with execution possibly under an AVSI umbrella, however it did not start.

Although the intent of the project is to eliminate impediments to the application of any advanced functionally integrated FG&C systems that will enhance operation safety and effectiveness of automatic airplane guidance and control, practically speaking, the only fully developed candidate system for this project was the TECS/THCS system. The FAA chief scientist and technical advisor for advanced control has implemented a full-function, full-flight envelope TECS/THCS simulation demonstration system in Mathworks™ Matlab® and Simulink® software and made a version with somewhat reduced functionality available for this project. This TECS/THCS software algorithm included the following functionality:

- Equivalent airspeed control mode

- FPA/GA control mode

- Altitude control mode, including altitude acquire (ALT ACQ) and altitude hold (ALT HOLD) functions

- Glide slope control mode

- Heading control mode

- Track angle control mode

- Localizer control mode

- Simplified augmented manual FPA rate command, and hold and roll rate command, and hold control modes

- Minimum velocity ($V_{min}$) and maximum velocity ($V_{max}$)protection function

- Normal load factor limiting function

- All associated mode logic

The software algorithms provided did not include the following functionality, which is part of the full TECS/THCS system definition:

- LNAV and VNAV modes
- Mach mode
- Speed profile (four-dimensional time navigation) mode
- Automatic landing flare mode
- Advanced augmented manual control mode features

## 4. EVALUATION SYSTEM DESCRIPTION FOR TECS.

This section provides a description of the system implemented by Honeywell to allow evaluation of the TECS outer loop control system. The system was implemented by Honeywell and jointly evaluated by Honeywell, Gulfstream, and the FAA. The system provides a robust user-friendly environment for evaluation of TECS outer loop control system.

### 4.1 EVALUATION SYSTEM ARCHITECTURE FOR TECS.

One of the goals of the Authority for Expenditure (AFE) #47 Project was to evaluate the performance of the generic TECS algorithm outer loop control system using an unmodified traditional inner loop from an existing airplane autopilot (AP) application. To accomplish the evaluation, within the constraints of the AFE #47 Project, Honeywell used existing components based on displays and control systems for a certified airplane. Previously existing technology used in the TECS evaluation system included:

- Certified flight instrument display software
- Certified flight control software
- Airplane simulation software
- Flight test data recording system software
- Cockpit simulation and control software and hardware

- Traditional FG&C panel (simulated)

The use of these production components was considered less than ideal for evaluating the maximum operational and performance capabilities of TECS, including pilot interactions needed to carry out flight maneuvers to gain insight into the novel TECS operations and logic. However, this approach was adopted to provide a possibility to evaluate the generic TECS implementation in-flight test on the target airplane without further inner loop development, if the TECS performance in simulation was found to be satisfactory.

A simulation of the traditional certified FG&C panel was provisionally modified to provide TECS mode activation and command setting capability. An existing light on this panel was modified to provide indication of the control priority used by TECS when thrust reached a thrust limit. TECS uses a light with the acronym VAR (variable) in either the speed control section or the flight control section of the TECS FG&C panel to indicate which mode control is temporarily suspended when thrust is at a limit.

A personal computer (PC)-based platform was used to host the different components whether they were portions of airborne hardware or laboratory systems. The PC-based platform permitted rapid integration of the existing technology with the TECS software implemented jointly with Gulfstream and the FAA for the purpose of this evaluation. Figure 3 illustrates the evaluation system design.

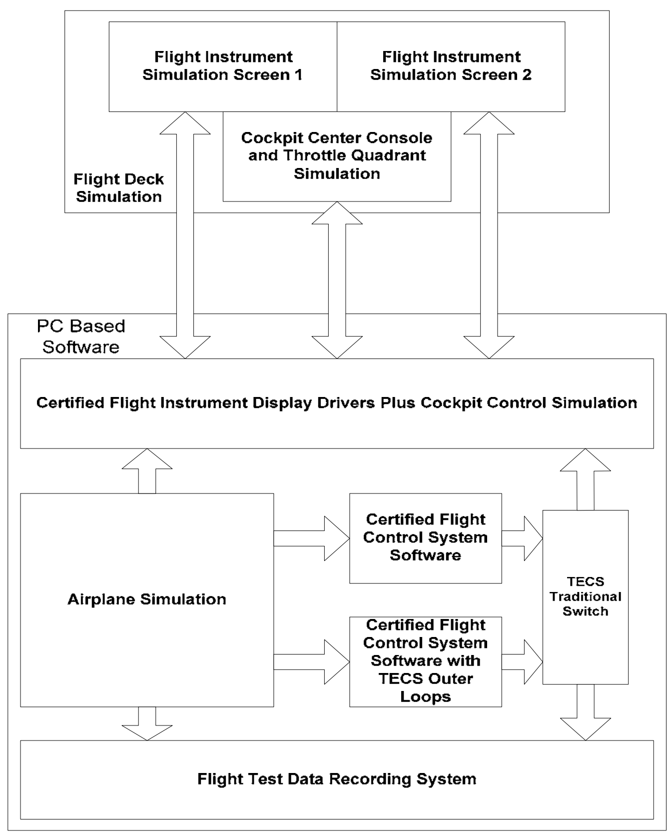



Figure 3. Evaluation System Structure for TECS

4.1.1 The TECS Evaluation System Hardware.

The hardware used to host the functions shown in figure 3 consisted of:

- Pilot's control yoke and pedals
- Three flat panel display screens
- Two high-performance PCs connected by a local area network

4.1.2 The TECS Evaluation System Capability.

The evaluation system provided the following capabilities:

- Real-time simulation of the airplane
- Real-time update of flight deck displays
- Real-time update of throttle position graphical user interface (GUI)
- Real-time update of glareshield control panel GUI
- Real-time operation of the certified flight display system software
- Real-time operation of the certified flight control system software
- Real-time operation of the TECS evaluation software package
- Real-time operation of the flight test data recording software

4.1.3 Functions Implemented to Support TECS Evaluation System.

The following functionality was implemented for the purpose of evaluating the TECS technology:

- TECS core
- TECS airspeed control
- TECS envelope protection
- TECS cross-coupling priority logic (speed-on-pitch versus flight path-on-pitch)
- TECS glide slope (GS) control
- TECS FPA/GA modes
- TECS vertical mode logic
- TECS vs certified traditional system selection switch
- Traditional flight guidance (FG) mode panel, modified to provide TECS mode control
- Provisional override (OVR)/VAR lights implemented on the guidance and control panel (GCP) of the traditional AP system.

- Integration with existing engines, AT inner loops, AP inner loops, and mode annunciation logic

- Integration with existing airplane simulation environment

4.1.4 The TECS Functions Implemented for the TECS Evaluation System.

The TECS functionality as delivered by the FAA consisted of an airplane model with engines, the TECS outer loop functions, and the inner loop functions. Honeywell extracted the outer loop portions and part of the TECS core of the FAA TECS implementation and integrated it with certified inner loops and input/output software to yield the TECS hybrid evaluation system. Figure 3-2 illustrates which functions from the top level of the TECS model were extracted and implemented.

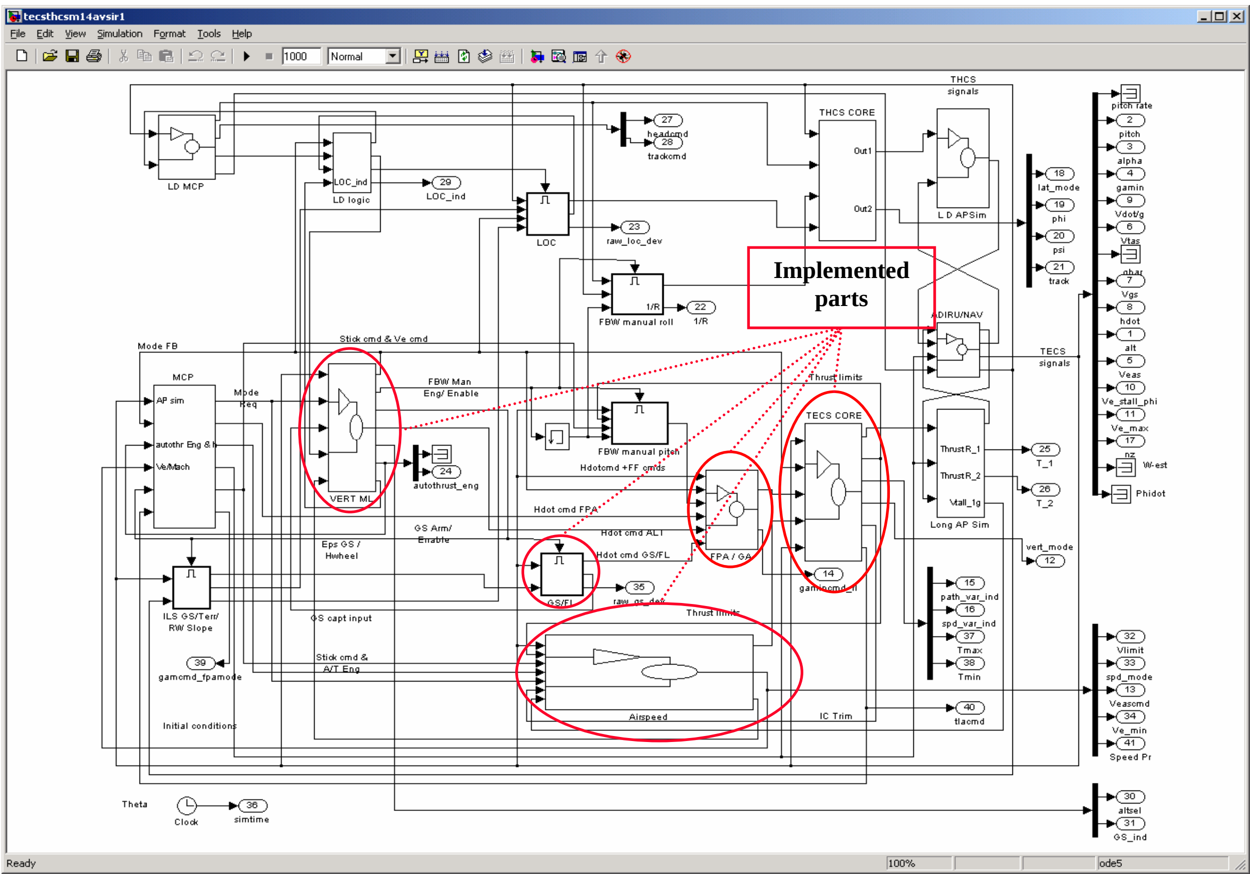



Figure 4. The TECS Functions Implemented

5. EVALUATION SUMMARY.

Three evaluations were performed on TECS, THCS, and the GP. The first evaluation looked at TECS and how it was incorporated onto the Honeywell simulator. A series of traditional outer loop evaluation tests were performed. During this evaluation, back-to-back comparisons were made between the traditional and TECS AP/AT systems. Manual flight was not investigated because it was not implemented in the TECS model used for the evaluation. As a result of this evaluation, several issues with the implementation of TECS were discovered and fixed for the second evaluation, and the test cards were modified as required.

The second evaluation was also performed on the Honeywell simulator, and the modified test cards from the first evaluation were used. In addition to comparisons between the traditional and TECS autoflight systems, data were recorded for posttest analysis. This was both a qualitative and quantitative evaluation looking at performance differences between the autoflight systems via time history data. There were still issues with the TECS implementation in the areas of maximum Mach operation/maximum operating speed (MMO/VMO) descents and GAs for two-engine and single-engine scenarios. As a result, Honeywell corrected the implementation and re-accomplished these cards at a later date. The original objective of the project was to run the flight test cases with and without turbulence. However, due to the inability to reproduce consistent turbulence profiles, comparison between the traditional and the TECS implementations was not possible with turbulence. Therefore, it was determined that the flight cases should be conducted under calm air conditions. In addition, this choice of flight conditions simplified the data analysis and the identification of the achieved performance characteristics of the TECS system. Although turbulence testing was not conducted, the speed complementary filter, provided as part of the TECS algorithm, was replaced by Honeywell-designed filters used in the traditional certified system. In addition, a vertical speed and altitude complementary filter was added. The intent was to use the same filters in TECS as in the traditional design, so that relative performance differences attributable to control strategy differences could be evaluated.

The third evaluation was conducted at Gulfstream and consisted of a laptop evaluation of the THCS as well as the TECS/THCS Demo System GP. This qualitative evaluation was performed with more of a cross section of flight test and operational Gulfstream pilots.

An attempt was made to evaluate the manual thrust control with coupled AP. However, due to limitations of the simulated GUI throttle levers, the pilot was not able to control thrust in a reasonable fashion. It was determined that an actual throttle quadrant would be required to perform the evaluation, and therefore, it was deferred to the flight test phase of this program.

## 5.1 EVALUATIONS PERFORMED.

### 5.1.1 Pilot Evaluation 1.

The purpose of pilot evaluation 1 was to

- evaluate the correctness of the TECS implementation.
- make a general assessment of the TECS performance relative to the traditional AP design.
- provide the first opportunity for a “pilot-in-the-loop” evaluation of the control laws and responses.
- determine what fixes would be needed for the second evaluation.

5.1.1.1 Test Scenarios.

During this evaluation, Honeywell provided an overview briefing of the simulations that were implemented and the implementation issues that still needed to be resolved. Honeywell also provided an explanation of the operational interface as well as information on what data would be recorded. Following this overview, the evaluation pilot became familiar with the implementation and performed a series of accelerations, decelerations, climbs, and descents with the traditional certified system and the TECS simulation. A few issues with implementation were resolved. A series of test points were accomplished, and comments as well as quantitative data were recorded. These initial test points were designed to highlight areas where traditional flight guidance systems have problems. The problems are generally found in areas where trades are required between AP and AT performance. Since TECS uses a generalized energy-based concept, one objective was to evaluate the performance in areas where energy trades are required. Performance was assessed first with the traditional flight guidance system simulation and then followed by a repeat with TECS. The following test points were accomplished:

- Several small and large climbs with decreasing speed targets
- Constant calibrated airspeed switching to constant Mach climb
- Baro steps (a 100-foot instantaneous offset in altitude) during ALT HOLD
- Level turns at 28 degrees angle of bank
- FPA climbs and descents
- MMO/VMO descents
- Traffic pattern descents and slowdowns for approach
- GS offsets
- GAs
- Level accelerations and decelerations
- FPA final approach with flight path offsets

5.1.1.2 Results.

Overall, both systems performed as expected. There were some issues that indicated some potential problems with TECS implementation. These issues were:

- Speed capture
    - Throttles were slow to respond to speed command
    - Engine response off idle was not matching real aircraft engine response
- Level flight
    - Throttle motion caused altitude deviation in ALT HOLD
    - GA g limit was incorrect

Some traditional design features, including touch control steering (TCS), flight director (FD), and trust director (TD), were not provided in TECS. As a result

- GS step offsets using TCS could not be conducted
  - GAC would like head-up display (HUD) cue displayed while flying TECS (prefer FPA symbol visible on the PFD)
  - GAC would provide manual thrust and flight director evaluation

Once these issues were understood, Honeywell corrected them for the second evaluation. TCS and HUD were not implemented.

The performance results from the first evaluation indicated that TECS met performance expectations and would provide improvements in performance in corner cases that were relative to the traditional AP. Thus, it would be worthwhile to evaluate TECS in-flight test to provide additional information as to its operational suitability. The resources available were not sufficient to accomplish this during Phase 1, Year 1. At this time, Honeywell decided to implement alternate filters for airspeed, longitudinal acceleration, and vertical speed to evaluate a flight worthy configuration.

5.1.2 Pilot Evaluation 2.

The purpose of pilot evaluation 2 was to

- check the fixes incorporated in the simulation as a result of discrepancies discovered in evaluation 1.
- approve the simulations as suitable for operational pilot evaluations.
- conduct the pilot-in-the-loop evaluations.
- record the performance data for this report.
- review the plan for the operational evaluation of the THCS laptop simulation and the TECS/THCS research guidance panel.

5.1.2.1 Test Scenarios.

Based on the results of the first evaluation, several implementation issues were identified that were corrected for evaluation 2. In addition, the data recording system was improved, and it was decided which parameters to record. Finally, the existing filter for true airspeed and longitudinal acceleration was removed and new Honeywell filters for airspeed and altitude rate were incorporated. These new filters improved the integrity of the evaluation by including gust and turbulence suppression filters that were deemed necessary for production software. The intent was to use the same new filters in TECS as in the traditional design so that relative performance differences attributable to control strategy differences could be evaluated.

The new filters were added to ensure the software evaluated was as close as possible to the expected final configuration software. At this point, it was decided to rerun all the evaluation 1 cards and use the results of evaluation 2 for the report. Honeywell also decided to move to their most recently certified production software, in the area of flight level change (FLCH) control laws, between evaluations 1 and 2.

The following scenarios were performed for both the traditional and TECS simulator model:

- Several small and large climbs with decreasing speed targets
- Constant calibrated airspeed to constant Mach climb
- Baro steps (a 100-foot instantaneous offset in altitude) during ALT HOLD
- Level turns at 28 degrees angle of bank
- FPA climbs and descents
- MMO/VMO descents
- Traffic pattern descents and slowdowns for approach
- GS deviation offsets (precision approach)
- GAs
- Level accelerations and decelerations
- FPA final approach with path offsets (nonprecision approach)
- Single engine GA
- GP evaluation

5.1.2.2 Results.

- FLCH Climb; Speed Dial Down in Dynamic Climb

  Pilot comments: This test card consisted of stabilizing at 250 KIAS at 5000' msl. The altitude preselector was dialed to 10,000' and flight level change (FLCH) or TECS Altitude Acquire was selected. When level at 10,000' the altitude pre-selector was dialed to 18,000', the speed target selected to 320 KIAS and another climb was selected. When level at 18,000', the altitude pre-selector was set at 24,000' and a climb started. At 20,000' during the climb the speed was dialed down to 220 KIAS.

  Overall The TECS simulation had slightly better speed control during execution of simultaneous climb and speed commands. During small climbs the traditional took 68% longer as there is an acceleration limit for small climbs to reduce the amount of throttle used for the maneuver, improving ride quality . Results are shown in Figure FC03.

  Engineering post analysis: Although, for the traditional design, the final segment of simultaneous altitude and speed capture time history is cut off, the raw data indicates 1 knot of speed undershoot. TECS handled the simultaneous speed and altitude capture without overshoots. There is a slight transition in both systems' pitch attitude response during the execution of the speed increase from 250 to 320 knots, at the time the throttles reach the forward limit. For the Traditional system this could be attributed to hitting limits present in the system. For the TECS, it is likely due to a mismatch of the thrust and elevator inner loops. Note: the term "Ride Quality" used throughout this report refers to manufacturer preferences regarding passenger comfort levels experienced for a given maneuver.

- 250 KIAS to M 0.7 Climb

  Pilot comments: This test card was for evaluating the changes when switching from CAS to a Mach schedule during a climb. No perceptible difference between the traditional and TECS systems were observed. Results are shown in Figure FC04.

  Engineering post analysis: The TECS and traditional time histories of airspeed show speed transients after the speed mode changes from IAS to Mach. There is also a large pitch Attitude transient at this transition. These transients are not characteristics of either algorithms and are attributed to CAS/MACH logic implementation limitation of the simulated environment resulting from the use of a simulated Guidance Panel which does not use certified software. Mach mode was not included as part of the original TECS models provided by the FAA and was incorporated by Honeywell to support desired flight card evaluations.

- Baro Steps

  Pilot comments: This test card consisted of stabilizing at M .85 at FL 450 in altitude hold and then instantaneously changing the altitude by +- 100 feet. Although either the traditional or TECS were totally acceptable in returning to the altitude hold altitude, the traditional slightly overshot the altitude. Results are shown in Figure FC05.

- Level Turns

  Pilot comments: This test card evaluated the smoothness in 90 degree heading changes as well as the speed and altitude hold performance during turning flight. TECS was slightly better than the traditional autopilot during the roll in and roll out with very little altitude loss on TECS. During the steady turning portion of the maneuver both systems had identical performance. The same traditional roll control system was used for both the TECS and traditional system evaluation. Results are shown in Figure FC06.

- Flight Path Angle Descent and Climb

  Pilot comments: This test card began at 45,000' and M 0.8. The altitude preselector was dialed to 43,000' and the speed target simultaneously increased to M 0.85. After leveling on conditions at 43,000' a climbing reversal to the initial conditions was accomplished. In both the descent and climb, a FPA of 2.5 degrees was used. TECS accomplished the descent and captured 43,000' in 70 seconds vice 110 seconds for the traditional. TECS had no overshoots in altitude acquisition, whereas the traditional overshot by 20 feet. TECS took 95 seconds versus 75 seconds for the traditional to climb. Results are shown in Figure FC07.

- MMO/VMO Descents

  Pilot comments: This test card began at 43,000’ and M 0.85 in the Altitude Hold and Mach mode. At this point a FLCH or altitude acquire maximum performance descent to 10,000’ was begun holding the airspeed at the upper operational limit. In this maneuver TECS took slightly longer. Results are shown in Figure FC08.

- Traffic Pattern Descents

  Pilot comments: This test card consisted of a series of slowing and descending maneuvers to get ready for approach. From an initial altitude of 4,000’and 250 KIAS, a FLCH or altitude acquire descent to 2,000’ while slowing to 220 KIAS as accomplished. After stabilizing at 2,000’ and 220 KIAS, the speed was dialed to 180 KIAS in level flight. In these maneuvers the TECS was programmed to obtain the airspeed first prior to any descent whereas the traditional was programmed to descend immediately at a low vertical speed while slowing the airplane to the speed target. The latter implementation was a spec requirement for the traditional system design to achieve operational suitability in the air traffic environment. TECS, as delivered, assumed a different operational philosophy. As a result of the TECS speed priority programming, TECS took 50% longer to descend. Results are shown in Figure FC09.

  Engineering post analysis: A simple change in the speed control authority number from 1 to .5 will change the control priory from a full speed priority to a 50%/50% shared control authority for simultaneous speed and flight path command execution.

- Glide Slope Offsets

  Pilot comments: This test card consisted of establishing final approach configuration and airspeed, intercepting an ILS three degree glide slope then instantaneously offsetting the airplane 1 dot below glide slope. In this test TECS had much better performance as it smoothly pulled up to level flight until approaching the glide path and then smoothly pushing over to minus three degrees re-capturing glide slope with no overshoots. The traditional pulled up to a three degree climb and overshot the glidepath several times before recapture. The time to recapture glidepath was identical for both, but the–ride quality was worse for the traditional. Results are shown in Figure FC10.

  Engineering post analysis: The results of this test indicate that the tests were conducted slightly different.

- Go Arounds

  Pilot Comments: At approximately 100 seconds on card 10, a Go Around was selected and the configuration kept in the approach configuration. Both the traditional and TECS had problems with this maneuver. The traditional throttle response was much faster than TECS (6 seconds vice 15 seconds) and the traditional also had a 12 degree pitch attitude target. Traditional overshot climbout speed by 17 Knots whereas TECS pulled higher to a 20 degree climb angle and only overshot by 7 Knots; however TECS took longer to initiate the climb. As a result of these results the implementation of TECS was questioned. The implementation was corrected and the test repeated. In this second test TECS throttle response still took around 12 seconds, the climb angle smoothly increased to 20 degrees and the speed overshoot was just over 5 knots. Results are shown in Figure FC10 and FC11.

Engineering post analysis: One of the goals of this flight card was to achieve max power throttle setting during the Go Around. The intent of FC 10 was to evaluate the basic Go Around maneuver without configuration changes, or flight path and speed command changes. Unfortunately, the tests FC 10 and FC11 were not run the same for both systems. In FC 10 the TECS Go Around maneuver was executed as planned. For the FC 10 Go Around with the traditional system, the altitude target was only 600 ft above the Go Around initiation altitude, causing the altitude capture to start shortly after the Go Around initiation. In the FC 10 TECS Go Around the altitude target was set much higher and the climb-out continued to the end of the test. The TECS Go Around was executed with a speed increase of 30 kt commanded ~7 seconds after the Go Around initiation. This resulted in a reduction of the climb rate during the acceleration by ~50 %. In the FC 11 traditional system test, the speed command was held constant but the speed temporarily increased by 5 kt. The original flight test card called out the speed target to be constant during the maneuver.

- Acceleration/Decelerations

Pilot comments: This card was begun at 2,000' and 250 KIAS in the cruise configuration. It consisted of speed changes and stabilization at 300, then 250, then 200 Knots. Once stable at 200 Knots the speed target was selected to 250 Knots and as the aircraft was beginning to arrive at 250 Knots the target was moved to 300 Knots. Then as the throttle started to move forward the target was lowered to 200 Knots. Overall TECS had a faster acceleration time as the traditional was limited to 1.5 Knots/sec for passenger ride comfort. As a result when the reversal was attempted, the traditional reversed airspeed faster than TECS and TECS overshot by 40 Knots in one case. TECS lost more altitude than the traditional; up to 20 feet. Results are shown in Figure FC12.

Engineering post analysis: Overall TECS had a faster acceleration time as it has no longitudinal acceleration limit implemented during operation with the throttle within the upper and lower limit, whereas the traditional design was limited for passenger ride comfort. As a result when the speed command was reversed in TECS at a point of high thrust and high acceleration, it took a relatively long time to establish a deceleration. As a result, after the speed command reversal the speed continued to increase another 40 knots before speed started to decrease. Here, the slow reversal from a high acceleration to a deceleration is due to the acceleration command rate limiter used in TECS for normal acceleration limiting when the throttles are at the limit and for energy management when the throttles are in mid-range. For the traditional system the airspeed increased only 15 knots after the command reversal, because of the limited acceleration.

- FPA Non-Precision Approach

  Pilot comments: This test card was a final approach configuration, final approach airspeed descent from 2,000' using the FPA mode with a three degree FPA command. After the airplane stabilized on approach the FPA target was varied +-1 degree above and below the three degree path. TECS performed better with less speed overshoots and less throttle activity than the traditional. Results are shown in Figure FC13.

  Engineering post analysis: The TECS again exhibits signs of a mismatch between the inner loop and outer loop, resulting in a higher than desired speed deviation due to the FPA decrease, as well as a throttle undershooting its steady state value. While this generic TECS response is acceptable, better performance would be achieved by tuning designing the inner loops to match up with the TECS outer loop system.

- Single Engine Go Around

  Pilot comments: In this maneuver, the speed target was set at 120 Knots and Go Around selected approximately 20 seconds after initiating the glide slope descent. Approximately 35 seconds after Go Around initiation the TECS speed target was dialed to 140 Knots, then again 30 seconds later dialed above 160 Knots. TECS performance resulted in a 4 knot excursion initially then settled nicely into trading climb angle for the increase in speed target. The time from Go Around to maximum climb angle was approximately 20 seconds for TECS.

  For the traditional aircraft the speed target was initially 120 Knots, then dialed up to 140 knots approximately 10 seconds later, then up to 150 Knots after 5 seconds. When Go Around was selected the traditional immediately started the climb and achieved maximum climb angle in 10 seconds. The traditional appeared to achieve approximately 6 degrees less climb angle than TECS, mainly because the speed deviated substantially above the target speed. The airspeed increased 18 knots above the 120 Knot target before the speed target was changed.

  Overall, either system's performance was acceptable. Both techniques were able to climb to 2000 ft in approximately the same time. Notable differences were that TECS tracked the speed closer and obtained a higher climb angle, whereas the traditional accelerated significantly above the initial speed target, while achieving its' climb angle sooner. Results are shown in Figure FC14.

  Engineering post analysis: The TECS system performed better than the traditional system, in spite of the mismatch between the TECS outer loops and the traditional system's inner loops. TECS time histories show a ~4 kt increase during the initial part of the Go Around, then settled back to the command before the first speed command increase occurred. TECS implementation problems are still evident. The initial response to the Go Around initiation was slower than ideal in throttle response and the speed would ideally not have increased by 4 knots. The problem appears to be associated with the low normal acceleration achieved during the initial pull-up, which should be .25 g, but reached only ~.1 g then declined until after about 10 seconds it increased to ~.15 g.

The throttle response also exhibits a temporary small reversal, as noted in other maneuvers. The time from Go Around to maximum climb angle was approximately 20 seconds for TECS. The TECS response was not fully satisfactory and better performance would be achieved with a better match of generic TECS outer loops and the inner loops. The Traditional system's 18 knot uncommanded speed increase is particularly undesirable in this regard. These performance anomalies are attributed, in part, to degraded simulation fidelity in this flight regime.

- Laptop Evaluation of THCS

  An evaluation of a laptop model of THCS was performed as a precursor to pilot evaluation 3. It was impractical to incorporate THCS on the Honeywell simulator within the scope of this task. THCS requires a fully available lateral/directional airplane simulation and primary control system. The one THCS feature of special interest that should be demonstrated for pilot evaluation 3 was the inherent automatic compensation for engine failures.

- Laptop Evaluation of GP

  An evaluation of the laptop model of the TECS GP was accomplished. This model had a lot of the features of present day GPs, but did not have Back Course, FMS, or microwave landing system features. The model was evaluated, and it was decided to demonstrate this during evaluation 3 to gain further feedback from other pilots.

5.1.3 Pilot Evaluation 3.

The purpose of pilot evaluation 3 was to

- present the TECS/THCS system to a group of test and demonstration pilots with typical Gulfstream flight conditions to evaluate and identify any human factors issues with TECS/THCS.
- assess whether the TECS/THCS modes and manual entries perform as intended, specifically instrument landing system, indicated airspeed (IAS), M, ALT ACQ, ALT HOLD, FPA, and GA.
- familiarize evaluators with mode panel features and entries for both longitudinal and lateral control.
- evaluate overall usability of mode control panel.
- assess whether all the TECS/THCS research GP annunciation lights VAR, $V_{min}$, $V_{max}$, and GA lights present meaningful, interpretable information to pilot.
- provide feedback on addition of air traffic control (ATC) datalink control through flight GP.

5.1.3.1 Test Scenarios.

Six pilots participated in the TECS/THCS evaluations, five test pilots and one demonstration pilot. Using a laptop research flight guidance panel projected on an overhead screen (see figure 5), the pilots evaluated the aircraft indications and response characteristics (via observing display activity) for a series of test points provided by GAC Flight Operations that simulated normal Gulfstream aircraft maneuvering in the ATC environment and typical piloting tasks. The pilots attended a 2-hour familiarization briefing with the TECS/THCS flight guidance concept prior to their evaluations. All pilot comments were recorded, and at the end of the session, each pilot rated the TECS/THCS flight guidance panel and functions on a series of attributes assessing its usability.

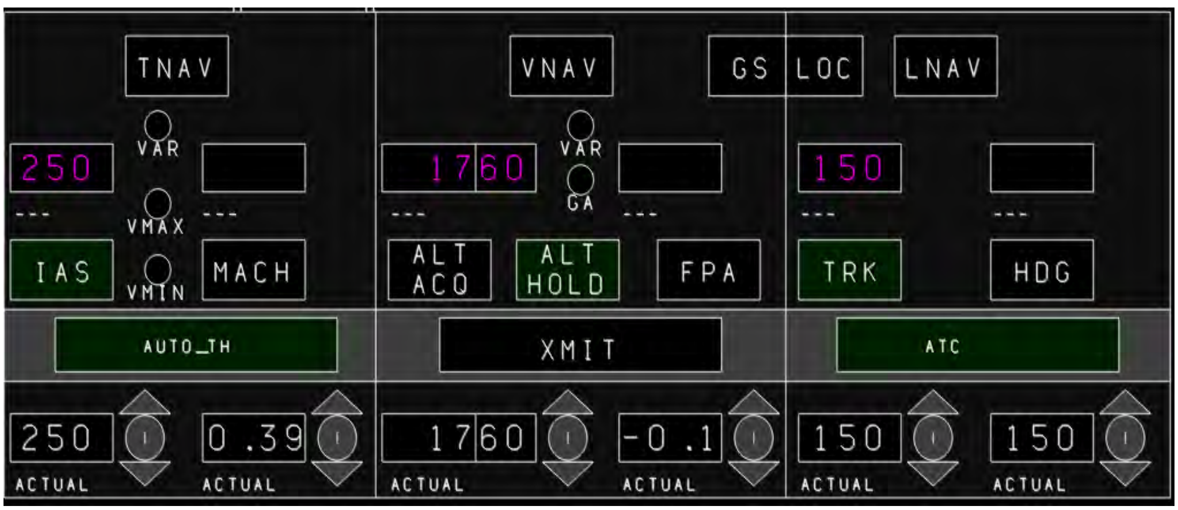



Figure 5. The TECS/THCS Flight Guidance Panel

5.1.3.2 Normal Operations.

The normal procedures evaluated included the tasks shown in table 1.

Table 1. Normal Operations Assessed

| Normal Operations | Subjective Data Collected |
|---|---|
| Speed Dial Down in Dynamic Climb<br>FL180, 320 IAS Manual<br>FL240<br>FL200, 220 IAS Manual | Pilot Comments/Guidance Panel Usability Assessment |
| Level Turns<br>Left and right 30 degrees for 90 degrees heading | Pilot Comments/Guidance Panel Usability Assessment |
| Traffic Pattern Descent | Pilot Comments/Guidance Panel Usability Assessment |
| Missed Approach/GA | Pilot Comments/Guidance Panel Usability Assessment |

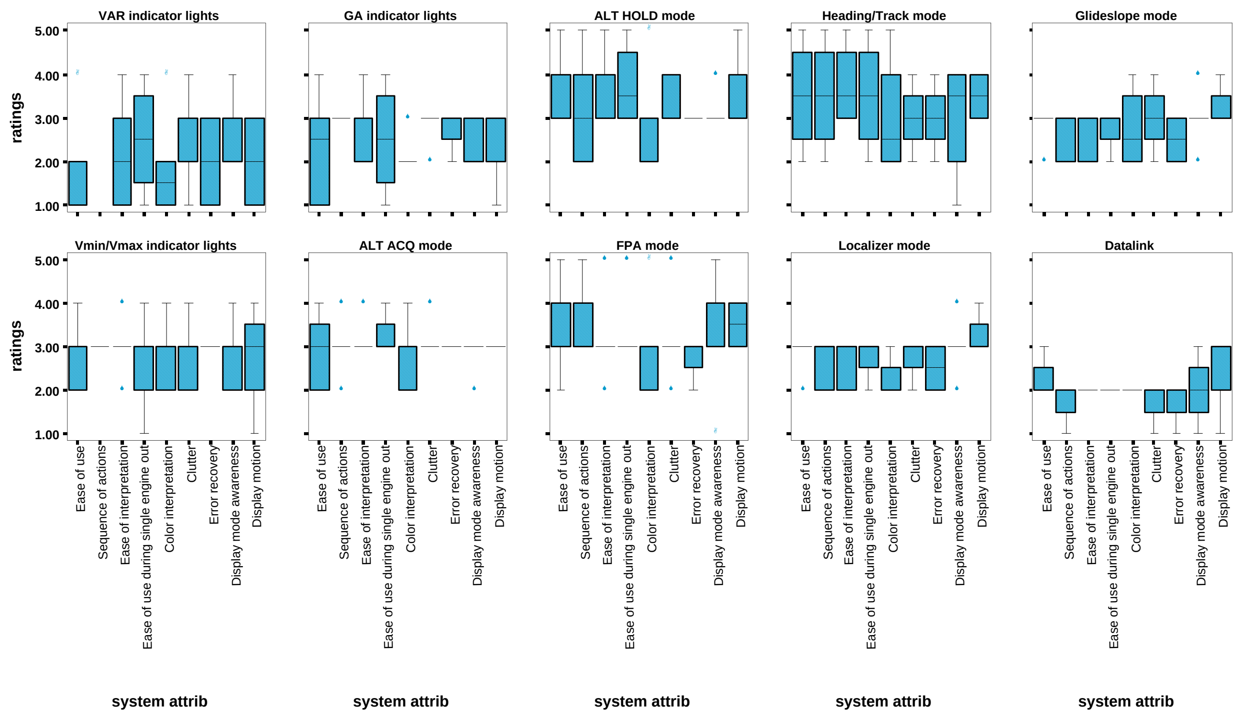
5.1.3.3 Abnormal Operations.

The abnormal modes evaluated included the tasks shown in table 2.

Table 2. Abnormal Operations Assessed

| Abnormal Operations | Subjective Data Collected |
|---|---|
| MMO/VMO Descents | Pilot Comments/Guidance Panel Usability Assessment |
| Envelope Protection $V_{max}/V_{min}$ | Pilot Comments/Guidance Panel Usability Assessment |
| GA/Single-Engine Fail | Pilot Comments/Guidance Panel Usability Assessment |

The features of the TECS/THCS flight guidance panel design were rated using a 5-point rating scale, which ranged from 1 = not adequate to 5 = excellent. The guidance panel features were rated for ease of use, sequence of actions, ease of interpretation, ease of use during single-engine out, color interpretation, clutter, error recovery, and display mode awareness, as shown in figure 6.




[1 = Not adequate, 5 = Excellent, (* O) = Outlier rating, (--) = Median rating]

Figure 6. Pilot Ratings on TECS/THCS Flight Guidance Panel and Display Indications

5.1.3.4 Results.

Pilot comments: Overall pilot subjective ratings indicated that several features of the TECS/THCS Demo System flight guidance system interface would require refinement to be acceptable in an operational application. The pilots rated the ALT HOLD, ALT ACQ, FPA, and Heading/Track mode indications favorably, which is not surprising because these modes were the most similar to the Gulfstream guidance panel. Pilot ratings were less favorable for Glide slope, GA, LOC, and VAR indications which were implemented quite differently from the Gulfstream guidance panel and illustrated the subtle differences of the TECS/THCS system. Color interpretation was rated lower for almost all of the features and this could be attributable to the use of the Boeing color logic, which is quite different from the Gulfstream color set. Sequence of actions was also rated lower for most of the features, even those features favored by the pilots, because of the added steps of working through the datalink interface to make flight guidance panel changes. Of significance was that error recovery was noted as a concern for all of the features except the two most familiar, ALT ACQ and ALT HOLD.

Because Gulfstream pilots tend to rely more on the mode annunciation panel at the top of the PFD, they were less inclined to use the indicator lights for GA, VAR, Vmax, or Vmin provided by the TECS flight guidance panel. The datalink interface was also rated less favorably by the pilots because this interface added more steps to affect normal, manual changes to the TECS/THCS flight guidance system. A datalink option discussed and preferred was displaying ATC messages on the smaller multi-function displays to provide the crew with a textual review prior to affecting the flight guidance system. Pilot comments obtained during the evaluation and added on the rating sheets follow the ratings graph below. Any rating below a 3 indicated that the feature being rated may need more design review for operational suitability. The lines in the graphs indicate median ratings for the pilot group.

Engineering post analysis: Although the simulated Guidance Panel provided a means of evaluating the TECS concepts, inherent limitations exist with this type of demonstration. In this case, the allowed pilot training time was limited and likely insufficient. In addition, using a virtual GP with primitive curser controls, instead of hardware rotary knobs and a research PFD was quite different from that which the pilots were accustomed. This likely introduced some subjectivity into the results. In many cases the pilot comments are at odds with the engineering understanding of the GP operation and system mode logic. Additional familiarization, with the TECS/THCS GP concepts and hands-on evaluation with a real GP might change these results. Also, two evaluations were performed simultaneously which likely provided confusion in both evaluations. Because the TECS mode transitions and data link were demonstrated concurrently, the pilots may have been uncertain as to which mode transitions were due to ATC and which were due to TECS mode transitions.

Pilot Comments

**General**

- I do not favor additional annunciators on the guidance panel.

- With proper mode display on the PFD, the independent indicator lights on the proposed mode control panel may be not only unnecessary, but also out of the primary field-of-view (defined as the area that can be readily focused upon without any head movement).

- When the flight guidance panel auto-transitioned to Mach (from KCAS) the speed tape on the PFD stayed in KCAS as primary.

- When deselecting AutoThrust, the target airspeed is no longer displayed.

- No flight director precludes easy hand-flying (only raw data).

- Don't like heading numbers on the horizon line.

- Heading numbers on horizon line – would prefer zeros behind them.

- Should be a bug on the heading to indicate target.

- Labels every other tick increases clutter.

- Pitch ladder must be centered, longer ticks.

- What can I turn off to get back to manual? (Engineering note: Press right elongated ATC bar.)

- Need some indication that controls are split (e.g., sideslip indicator). (Engineering note: Trapazoid Side slip indicator ( bottom part of bank angle pointer) on PFD was not hooked up.)

- Should move the controls to the current force positions being controlled so that the pilot gets an indication of the current force state of the system (Engineering note: Not per intended design.)

- VAR indicator lights

- Maybe training wasn't adequate – but the VAR lights are not intuitive and I was more confused than with our guidance panel – and ours has more modes!

- The "VAR" light for airspeed (AT) has little application for the pilot in its current implementation.

- The "VAR" should be utilized only if the target airspeed/Mach cannot be maintained (depends on priorities with VNAV and LNAV), which depends on system priority logic. (Engineering note: Per intended design.)

- The "VAR" light for altitude is only necessary once again, dependent only on the incapability of the system to maintain a desired rate or input, which depends on system priority logic. (Engineering note: Per intended design.)

- I don’t know what VAR lights mean – not intuitive to me; would need to work on understanding them.

- If VAR used, should be only in flight mode annunciator panel (PFD) because guidance panel is typically not in crosscheck.

- VAR symbol doesn’t need to be displayed (wouldn’t use amber color, misinterpreted).

- VAR in both guidance panel and PFD is not bad.

- VAR light makes it a little clearer that vertical is variable.

**ALT ACQ/ALT HOLD mode**

- As soon as it started leveling off, it should have switched modes – superior to ASEL – ALT HOLD is understood by everybody. (Engineering note: Not per intended design.)

- Objectionable that steady state, once reached, still has VAR there for ALT ACQ mode. (Engineering note: May have been a glitch, not per intended design.)

- Underneath “Auto Thrust”, put “MAX” and “IDLE” or just take it off when in between.

- You have to include logic for RVSM rules (for last 1000 ft., climb @ 1000 ft./min.).

- Same number of steps we currently use

**FPA mode**

- FPA mode will require training for pilots who have only used vertical speed. It will be like converting to metric system. You need some way to track localizer only without glide slope. This demonstration did not let me see enough to understand how to use FPA. I do not see how making a radical change on how we fly airplanes is really giving us any benefit over what we already have.

- The FPM does not necessarily overlay the FPA-predictor. Non precision approaches – could be a hole in logic because minimum descent altitude (MDA) uses guidance panel for low altitude targets. (Engineering note: Design spec issue)

- For case where manual portion of approach (<500 ft), then if hit TOGA, would want system to pull up FPM to clear. (Engineering note: Design spec issue)

- TECS/THCS requires extra button pushes to get to current Gulfstream APP mode

- Could maybe use FPA for current VS mode [along with INAV] “graphically” to get rate info by using predicted vertical speed arc. Loss of VS would be negative initially; mitigating factor would be INAV/VSD graphics. (Engineering note: Design spec issue)

- Guys are hard over on FPA; transition will be difficult. They want to know rate of climb. (Engineering note: Design spec issue)

- Would like to preselect FPA

**Vmin/Vmax/EDM simulation**

- Would use PFD indications as primary location, but like it in both places.

- Did a manual pushover. Methodology makes a lot of sense, never having flown a FBW aircraft.

- Would like to see a 10,000 ft. warning. (Engineering note: Design spec issue)

- A true EDM should require no pilot action. (Engineering note: Design spec issue)

- If during turn, pushing over to 0 g is unsafe; don't go less than .25 g – start with a .5 g push.

- Use 60 deg. bank to reduce vertical component of g out – turn 90 deg. to get off airway (turn to left).

- VAR/Vmax/Vmin/GA indicator lights are above nomenclature. Other switch capsules on panel have indicator lights below.

- Like energy management of bank/heading.

- Would not want to go to 0 g's or 30 degrees nose down unless accelerating (EDM simulation). (Engineering note: Design spec issue)

- Vmin = VAR light doesn't make sense to me

- GA mode/Single engine fail:

- I like the GA, single engine fail response – frees "brain cells".

- VAR/GA labels below lights should go elsewhere.

- GA mode should never stop at 500ft. (Note: GA should remain engaged to 1500' minimum for Part 25 aircraft.)

- Needs TOGA button implementation.

- If you wait for FPA to reach target and then engines catch up, you may be in trouble – need to get to acceleration limit quickly. (Engineering note: Design spec issue)

- In reality, autospeeds should be there; it is workable; understandable. (Engineering note: Design spec issue)

- Would be hard to select AP back on at this point in the Go Around. (Engineering note: Not per intended design)

5.1.4 Flight Test Cards.

Tables 3 through 5 describe the flight test cases that were executed during pilot evaluations 1 though 3. Some of the flight cases were modified to accommodate either the operational limitations of the demonstrator or to shorten the flight time leading to the actual flight maneuver under test.

Table 3. Pilot Evaluation 1 Test

| Test Description | Aircraft Configuration: Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| FLCH Climb; Speed Dial Down in Dynamic Climb | AR | | 5000 | 250 KIAS | Select Alt Preselect to 10000<br>Select FLCH<br>Note timeliness to capture altitude<br>Note pitch and flight path oscillations<br>Note altitude and/or speed overshoots/undershoots<br>Note passenger comfort<br>Select Alt Preselect to FL180<br>Select speed target to 320 IAS manual<br>Select FLCH<br>Repeat observations noted above<br>Select Alt Preselect to FL240<br>Select FLCH<br>At FL200, select speed target to 220 IAS Manual<br>Repeat observations noted above |
| 250 KIAS to M.7 Climb | UP | | FL240 | 220 IAS | Select Alt Preselect to FL450<br>Select speed target to 250 Manual<br>Select FLCH<br>When M .7 occurs, select Manual .7 M<br>Note pitch and flight path oscillations<br>Note accuracy tracking M/airspeed |
| Baro Steps | AR | | FL450 | M.85 | Dial altimeter setting up or down from 29.92 by 100'<br>Note timeliness to capture altitude<br>Note pitch and flight path oscillations<br>When ALT HOLD is captured, repeat first procedural instruction above, as necessary |
| Level Turns | | | | | Select high bank and do left and right 28 deg. turns for 90 deg.<br>Note pitch and flight path oscillations<br>Note altitude loss/gain<br>Note AT activity |
| FPA Descent | AR | | FL450 | M.8 | Select Alt Preselect to FL430<br>Select speed target to M.85 Manual<br>Select -2.5 deg. FPA descent<br>Select FPA<br>Note AT activity vs traditional |
| MMO/VMO Descents | AR | | FL430 | M.85 | Select Alt Preselect to 10000<br>Select speed target to M.885 Manual<br>Select FLCH<br>When M changes to IAS, dial speed target to 340 KIAS<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Assess envelope protection features |

Table 3. Pilot Evaluation 1 Test (Continued)

| Test Description | Aircraft Configuration | | | | Test Procedure |
|---|---|---|---|---|---|
| | Gear Flap | ACGW | Alt | Air Speed | |
| Traffic Pattern Descent | AR | | 9500 | 300 KIAS | Select Alt Preselect to 6500<br>Select speed target to 220 IAS Manual<br>Select FLCH<br>When altitude captures and speed is steady, select 180 IAS Manual<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Assess envelope protection features<br>Select Alt Preselect to 7000<br>Select speed target to 180 IAS Manual<br>Select FLCH<br>When altitude captures and speed is steady, select 150 IAS Manual<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Note presence/absence of AT overshoots |
| GS Offsets | 39 | | 2000 | Noted | Acquire glide slope using AP<br>Engage TCS and offset by 1 and 2 dots above and below GS<br>Allow system to enter GS track mode<br>Repeat offsets<br>Note smoothness of GS acquisition<br>Note pitch and flight path oscillations<br>Note timeliness to reacquire GS after offsets<br>Note timeliness to reacquire in track mode |
| GA | 39<br>Down | | 100 | Vref | Select Alt Preselect to 2000<br>Activate GA mode<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |

Table 3.  Pilot Evaluation 1 Test (Continued)

| Test Description | Aircraft Configuration | | | | Test Procedure |
|---|---|---|---|---|---|
| | Gear Flap | ACGW | Alt | Air Speed | |
| Accel/Decel | AR | | 2000 | 250 IAS | Select Alt Preselect to 3000<br>Select speed target to 300 IAS.  Stabilize<br>Select speed target to 250 IAS.  Stabilize<br>Select speed target to 200 IAS.  Stabilize<br>Select speed target to 250 IAS.  As airspeed approaches 250 and throttle begins to move back, select 300 IAS.  As throttle begins to move up, select 200 IAS.<br>Note timeliness to capture airspeed<br>Note interpretability and timeliness of override lights; verify acceptable logic presentation<br>Note acceptability of AT activity |
| Nonprecision Approach | 39 Down | | 2000 | AR | Engage TCS and offset by 1 and 2 dots above and below flight path<br>Note smoothness of flight path acquisition<br>Note pitch and flight path oscillations |
| GA, Single Engine | 20 Up | | 6000 | 140 IAS | Select Alt Preselect to 2000<br>Activate GA mode<br>Fail one engine<br>Speed up to flaps 20 speeds with positive climb<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |

AR = All retracted
AT = Autothrottle
ACGW = Aircraft gross weight

Table 4. Pilot Evaluation 2 Test

| Test Description | Aircraft Configuration: Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| ALT ACQ Climb; Speed Dial Down in Dynamic Climb<br><br>(Figure 7) | AR | | 5000 | 250 KIAS | Select Alt Preselect to 10000<br>Select ALT ACQ<br>Note timeliness to capture altitude<br>Note pitch and flight path oscillations<br>Note altitude and/or speed overshoots/undershoots<br>Note passenger comfort<br>After ALT HOLD appears, select Alt Preselect to FL180.<br>Select speed target to 320 IAS Manual<br>Select ALT ACQ<br>Repeat observations noted above<br>Select Alt Preselect to FL240<br>Note transition to M.7 on mode control panel<br>Note transition to M on flight mode annunciator on PFD<br>Select ALT ACQ<br>At FL240, select speed target to M.35<br>Note Vmin indication on mode control panel<br>Note Vmin indication on PFD |
| 250 KIAS to M.7 Climb<br><br>(Figure 8) | UP | | FL240 | 220 IAS | Select Alt Preselect to FL450<br>Select speed target to 250 Manual<br>Select ALT ACQ<br>When M .7 occurs, select Manual .7 M<br>Note pitch and flight path oscillations<br>Note accuracy tracking M/airspeed |
| Baro Steps<br><br>(Figure 9) | AR | | FL450 | M.85 | Dial altimeter setting up or down from 29.92 by 100’<br>Note timeliness to capture altitude<br>Note pitch and flight path oscillations<br>When ALT HOLD is captured repeat first procedural instruction above, as necessary |
| Level Turns<br><br>(Figure 10) | AR | | FL270 | M.7 | Select high bank and do left and right 28 deg. turns for 90 deg.<br>Note pitch and flight path oscillations<br>Note altitude loss/gain<br>Note AT activity<br>Note airspeed gain/loss |
| FPA Descent<br><br>(Figure 11) | AR | | FL270 | M.8 | Select Alt Preselect to FL430<br>Select speed target to M.85 Manual<br>Select -2.5 deg. FPA descent<br>Select FPA<br>Note AT activity vs traditional |

Table 4.  Pilot Evaluation 2 Test (Continued)

| Test Description | Aircraft Configuration<br>Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| MMO/VMO Descents<br><br>(Figure 12) | AR | | FL270 | M.85 | Select Alt Preselect to 10000<br>Select speed target to M.88 Manual<br>Select ALT ACQ<br>When M changes to IAS, dial speed target to 340 KIAS.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Assess envelope protection features |
| Traffic Pattern Descent<br><br>(Figure 13) | AR | | 9500 | 300 KIAS | Select Alt Preselect to 6500<br>Select speed target to 220 IAS Manual<br>Select ALT ACQ<br>When altitude captures and speed is steady, select 180 IAS Manual.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Assess envelope protection features<br>Select Alt Preselect to 7000<br>Select speed target to 180 IAS Manual<br>Select ALT ACQ<br>When altitude captures and speed is steady, select 150 IAS Manual.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Note presence/absence of AT overshoots |
| GS Offsets<br><br>(Figure 14) | 39 | | 2000 | Noted | Acquire GS using AP<br>Engage TCS and offset by 1 and 2 dots above and below GS<br>Allow system to enter GS track mode<br>Repeat offsets<br>Note smoothness of GS acquisition<br>Note pitch and flight path oscillations<br>Note timeliness to reacquire GS after offsets<br>Note timeliness to reacquire in track mode |
| GA<br><br>(Figures 14 and 15) | 39<br>Down | | 100 | Vref | Select Alt Preselect to 2000<br>Activate GA mode<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |

Table 4. Pilot Evaluation 2 Test (Continued)

| Test Description | Aircraft Configuration: Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| Accel/Decel<br><br>(Figure 16) | AR | | 2000 | 250 IAS | Select Alt Preselect to 3000<br>Select speed target to 300 IAS. Stabilize<br>Select speed target to 250 IAS. Stabilize<br>Select speed target to 200 IAS. Stabilize<br>Select speed target to 250 IAS. As airspeed approaches 250 and throttle begins to move back, select 300 IAS. As throttle begins to move up, select 200 IAS.<br>Note timeliness to capture airspeed<br>Note interpretability and timeliness of override lights; verify acceptable logic presentation<br>Note acceptability of AT activity |
| Nonprecision Approach<br><br>(Figure 17) | 39 Down | | 2000 | AR | Engage TCS and offset by 1 and 2 dots above and below flight path<br>Note smoothness of flight path acquisition<br>Note pitch and flight path oscillations |
| GA, Single Engine<br><br>(Figure 18) | 20 Up | | 6000 | 140 IAS | Select Alt Preselect to 2000<br>Activate GA mode<br>Fail one engine<br>Speed up to flaps 20 speeds with positive climb<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |

AR = All retracted
AT = Autothrottle
ACGW = Aircraft gross weight

Table 5. Pilot Evaluation 3 Test

| Test Description | Aircraft Configuration: Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| ALT ACQ Climb; Speed Dial Down in Dynamic Climb | AR | | 5000 | 250 KIAS | Select Alt Preselect to 10000<br>Select ALT ACQ<br>Note timeliness to capture altitude<br>Note pitch and flight path oscillations<br>Note altitude and/or speed overshoots/undershoots<br>Note passenger comfort<br>After ALT HOLD appears, select Alt Preselect to FL180.<br>Select speed target to 320 IAS Manual<br>Select ALT ACQ<br>Repeat observations noted above<br>Select Alt Preselect to FL240<br>Note transition to M.7 on mode control panel<br>Note transition to M on flight mode annunciator on PFD<br>Select ALT ACQ<br>At FL240, select speed target to M.35<br>Note Vmin indication on mode control panel<br>Note Vmin indication on PFD |
| Level Turns | AR | | FL270 | M.7 | Vert Mode: ALT HOLD<br>Select high bank and do left and right 28 deg. turns for 90 deg.<br>Note pitch and flight path oscillations<br>Note altitude loss/gain<br>Note AT activity<br>Note airspeed gain/loss |
| FPA Descent | AR | | FL270 | M.8 | Select Alt Preselect to FL430<br>Select speed target to M.85 Manual<br>Select -2.5 deg. FPA descent<br>Select FPA<br>Note AT activity vs traditional |
| MMO/VMO Descents | AR | | FL270 | M.85 | Select Alt Preselect to 10000<br>Select speed target to M.88 Manual<br>Select ALT ACQ<br>When M changes to IAS, dial speed target to 340 KIAS.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Assess envelope protection features |

Table 5. Pilot Evaluation 3 Test (Continued)

| Test Description | Aircraft Configuration<br>Gear Flap | ACGW | Alt | Air Speed | Test Procedure |
|---|---|---|---|---|---|
| Traffic Pattern Descent | AR | | 9500 | 300 KIAS | Select Alt Preselect to 6500<br>Select speed target to 220 IAS Manual<br>Set flaps to 5<br>Select ALT ACQ<br>When altitude captures and speed is steady, select 180 IAS Manual.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Note presence/absence of AT overshoots<br>Select Alt Preselect to 2500<br>Select speed target to 180 IAS Manual<br>Select ALT ACQ<br>When altitude captures and speed is steady, select 150 IAS.<br>Note accuracy tracking airspeed<br>Note pitch and flight path oscillations<br>Note presence/absence of AT overshoots<br>Set flaps to 15 |
| GA | 39 Down | | 100 | Vref | Select Alt Preselect to 2000<br>Activate GA mode<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |
| GA, Single Engine | 5 Up | | 2200 | 170 KIAS | Select Alt Preselect to 2000<br>Activate GA mode<br>Fail one engine<br>Speed up to flaps 20 speeds with positive climb<br>Allow system to perform GA and ALT ACQ<br>Note smooth, timely pull up to GA flight path<br>Note lack of overshoots onspeed/altitude capture<br>Note throttle movement to GA power and then level off (should be brisk throttle movement) |

AR = All retracted
AT = Autothrottle
ACGW = Aircraft gross weight

## 5.2 RECORDED DATA.

Figures 7 through 18 show the data from pilot evaluation 2.

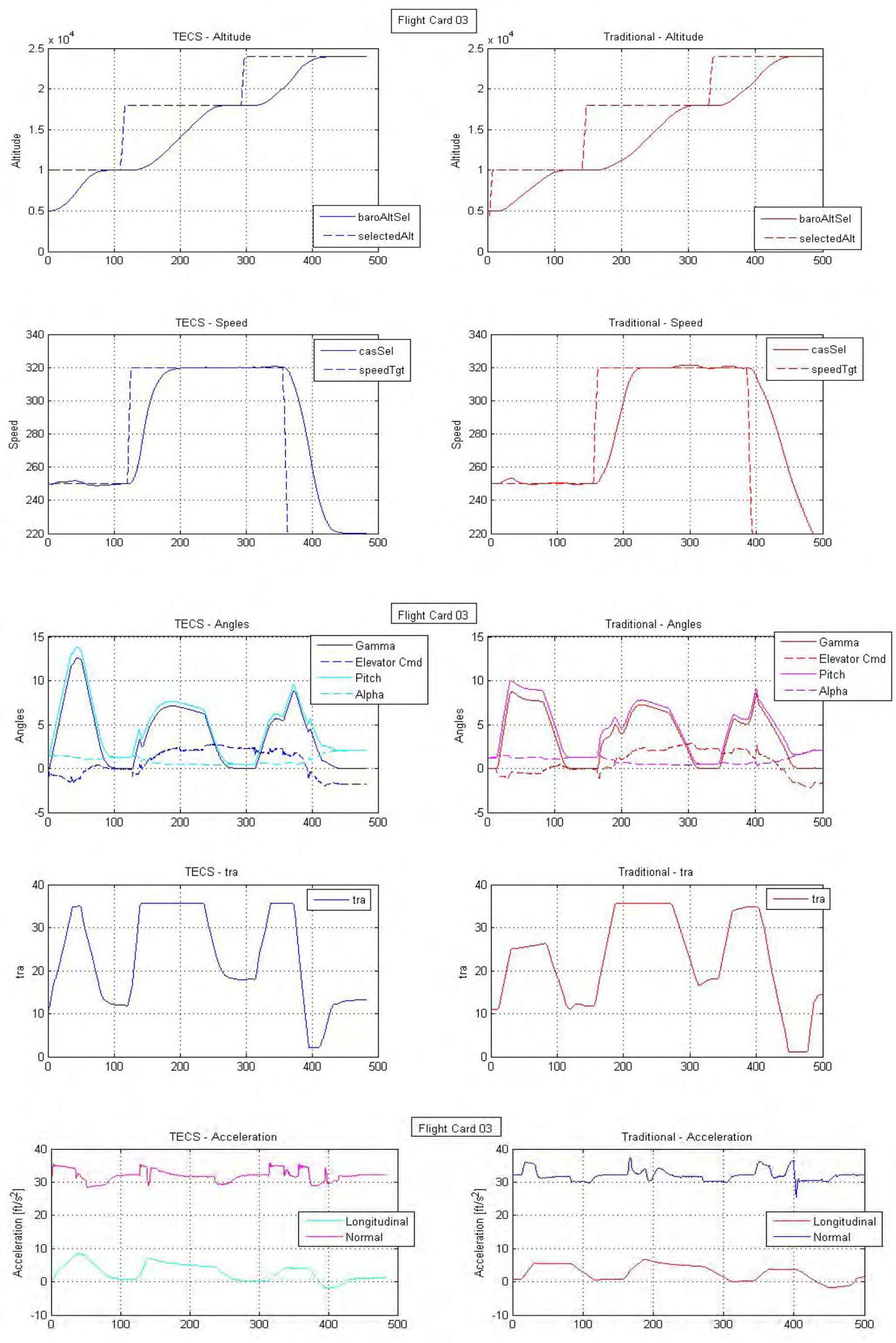



Figure 7. Flight Card Results 1—FC03

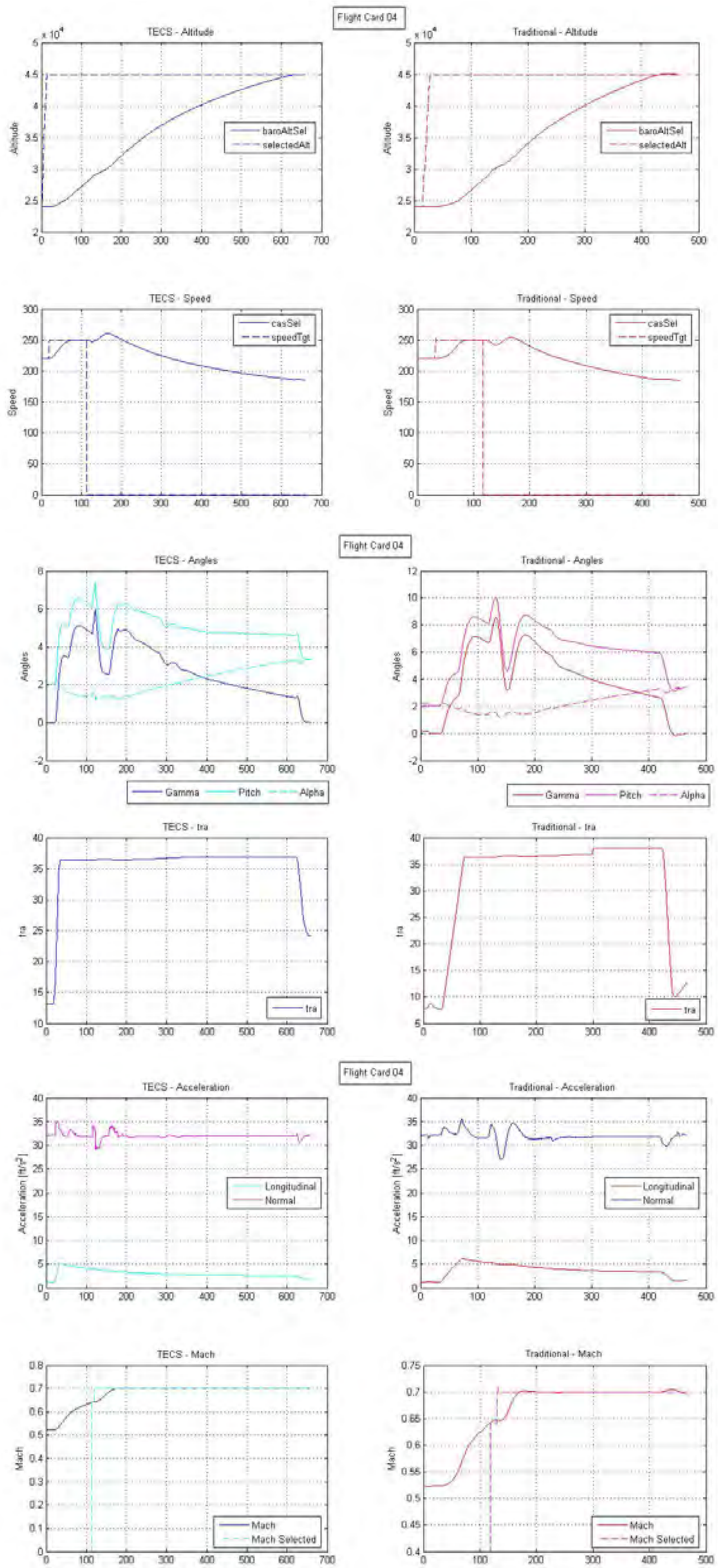



Figure 8. Flight Card Results 2—FC04

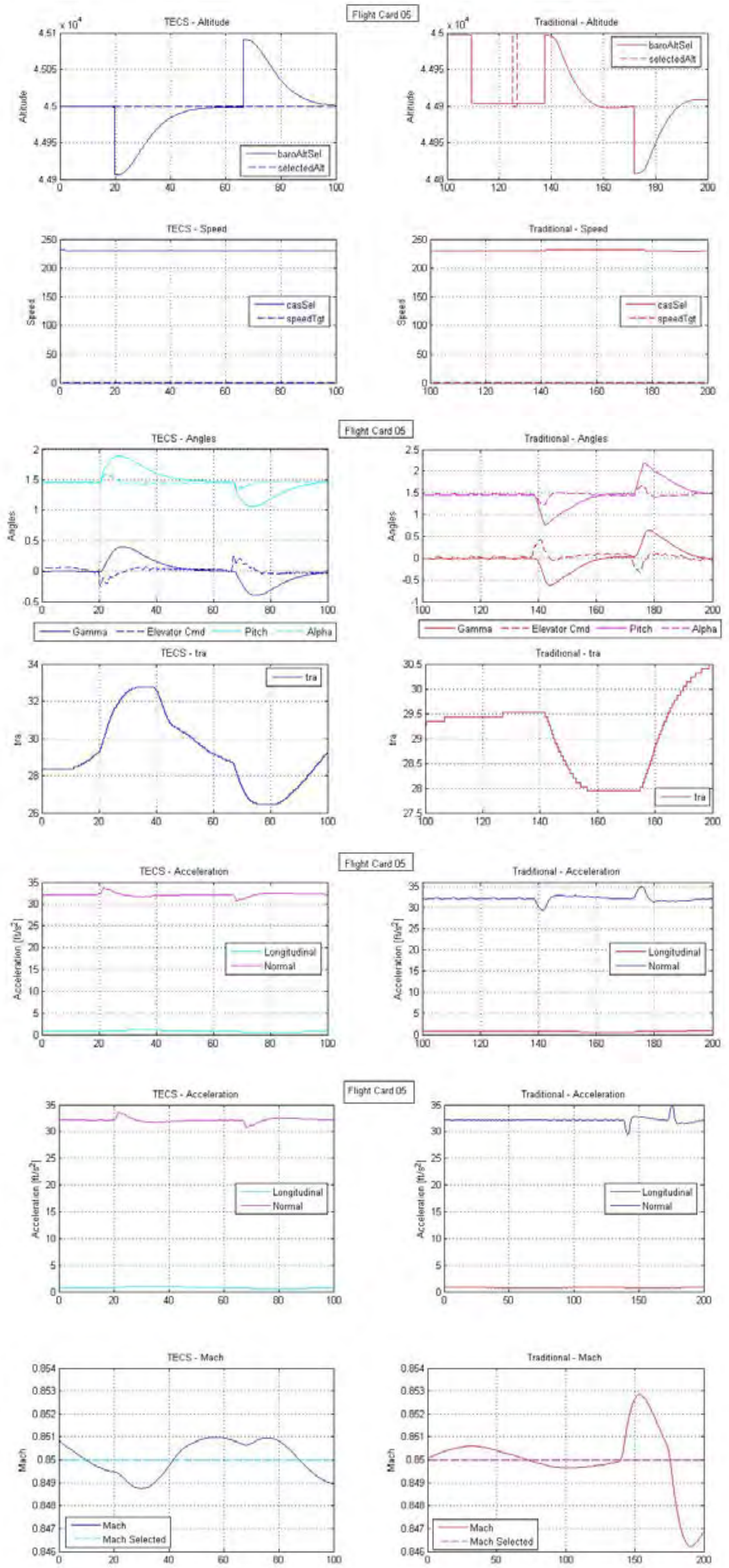



Figure 9. Flight Card Results 3—FC05

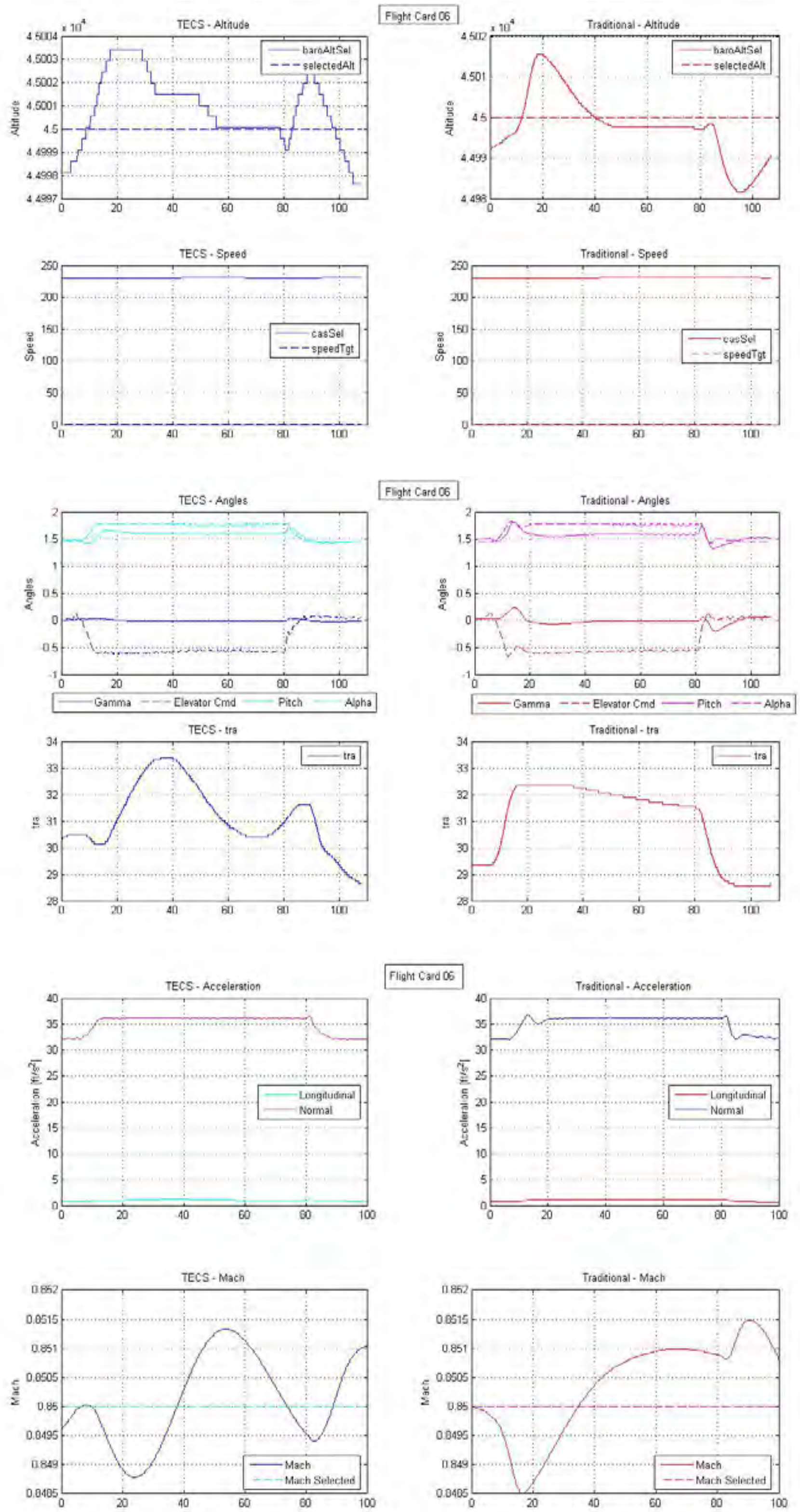



Figure 10. Flight Card Results 4—FC06

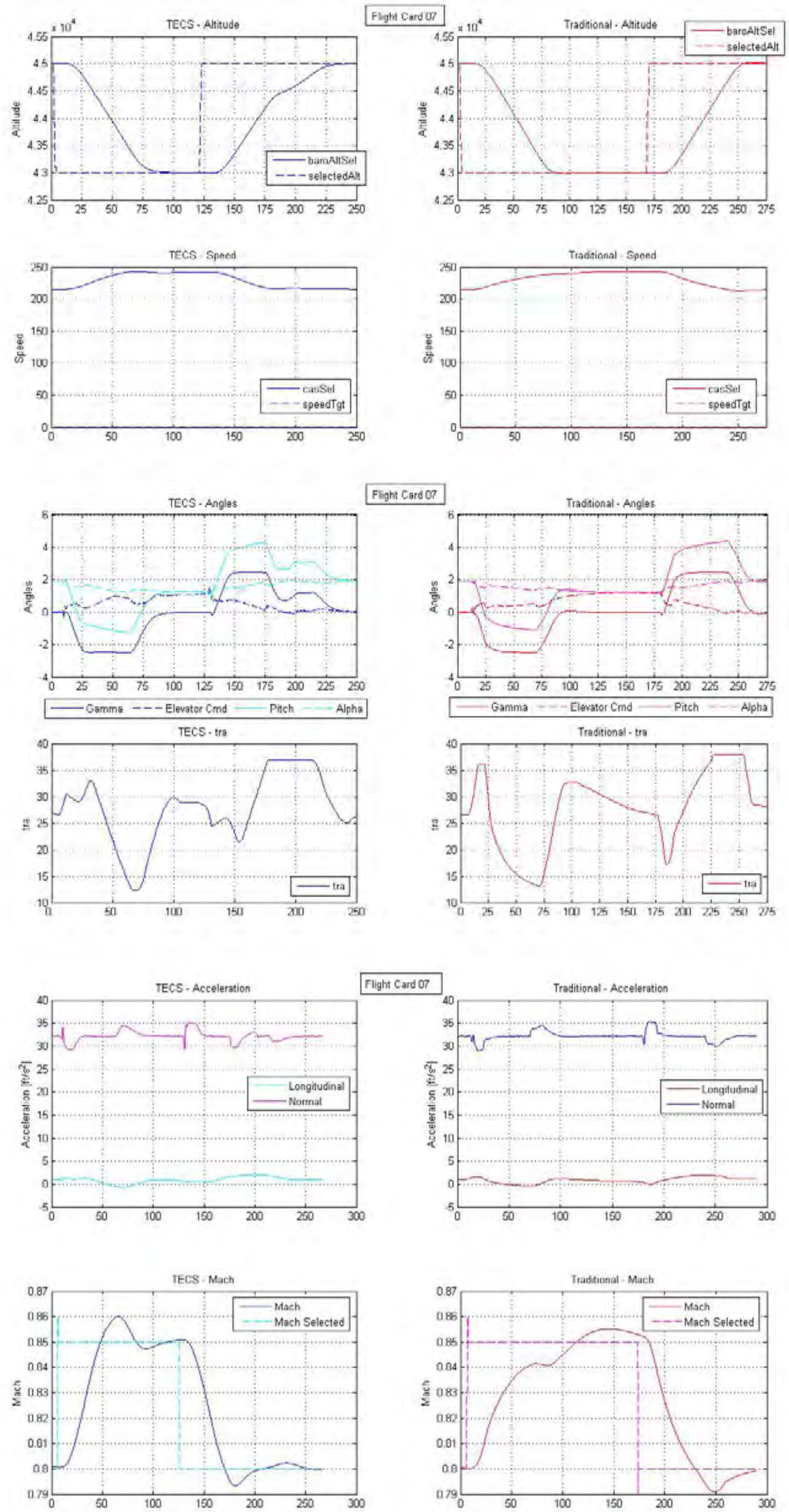



Figure 11. Flight Card Results 5—FC07

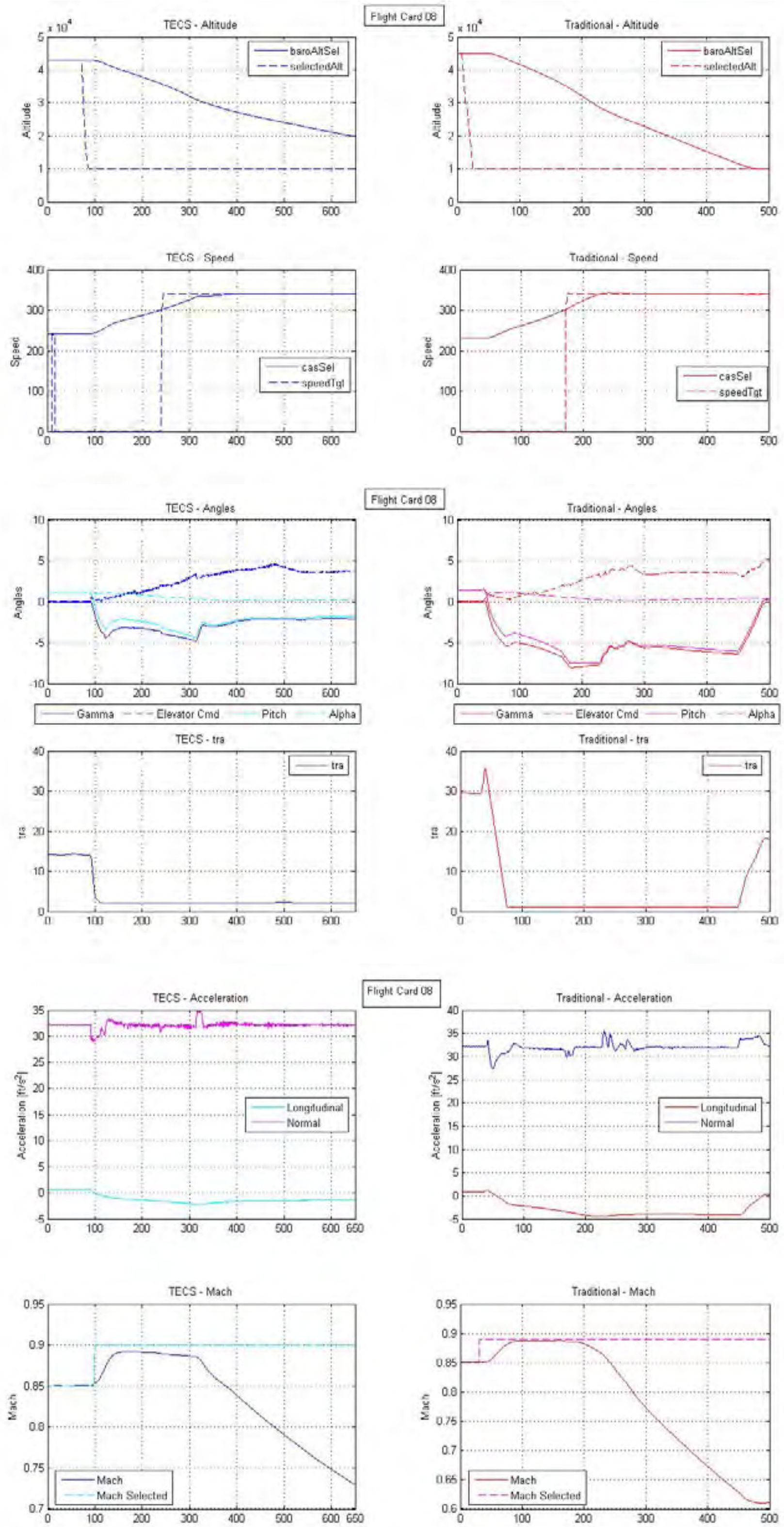



Figure 12. Flight Card Results 6—FC08

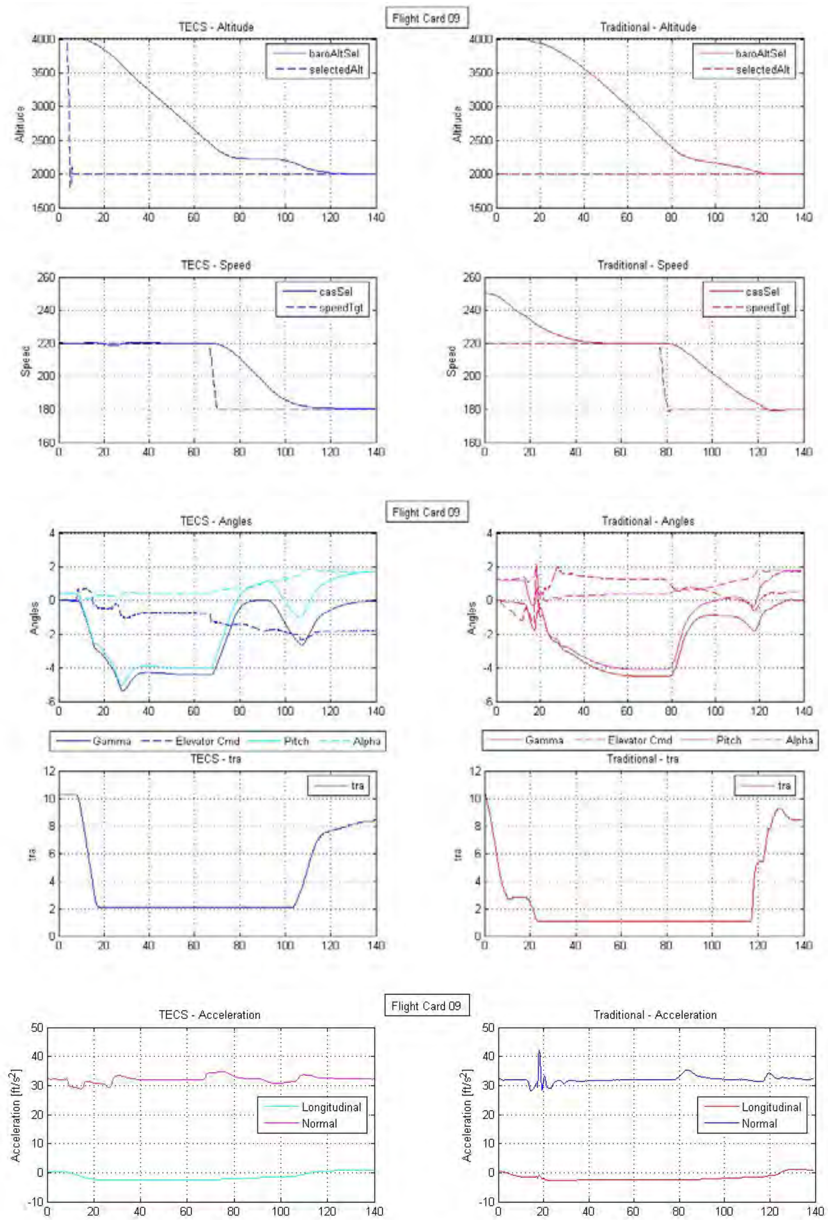



Figure 13. Flight Card Results 7—FC09

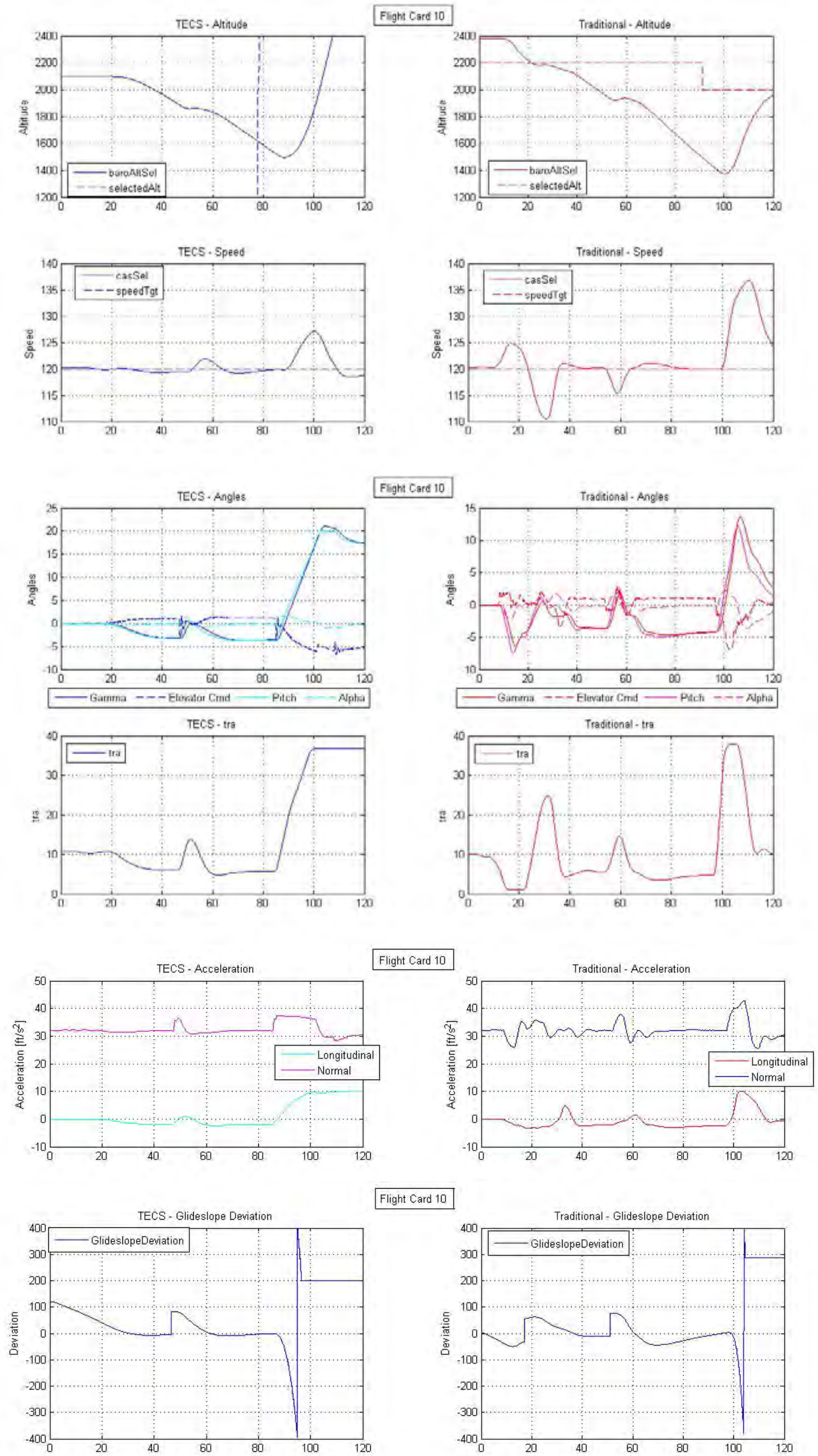



Figure 14. Flight Card Results 8—FC10

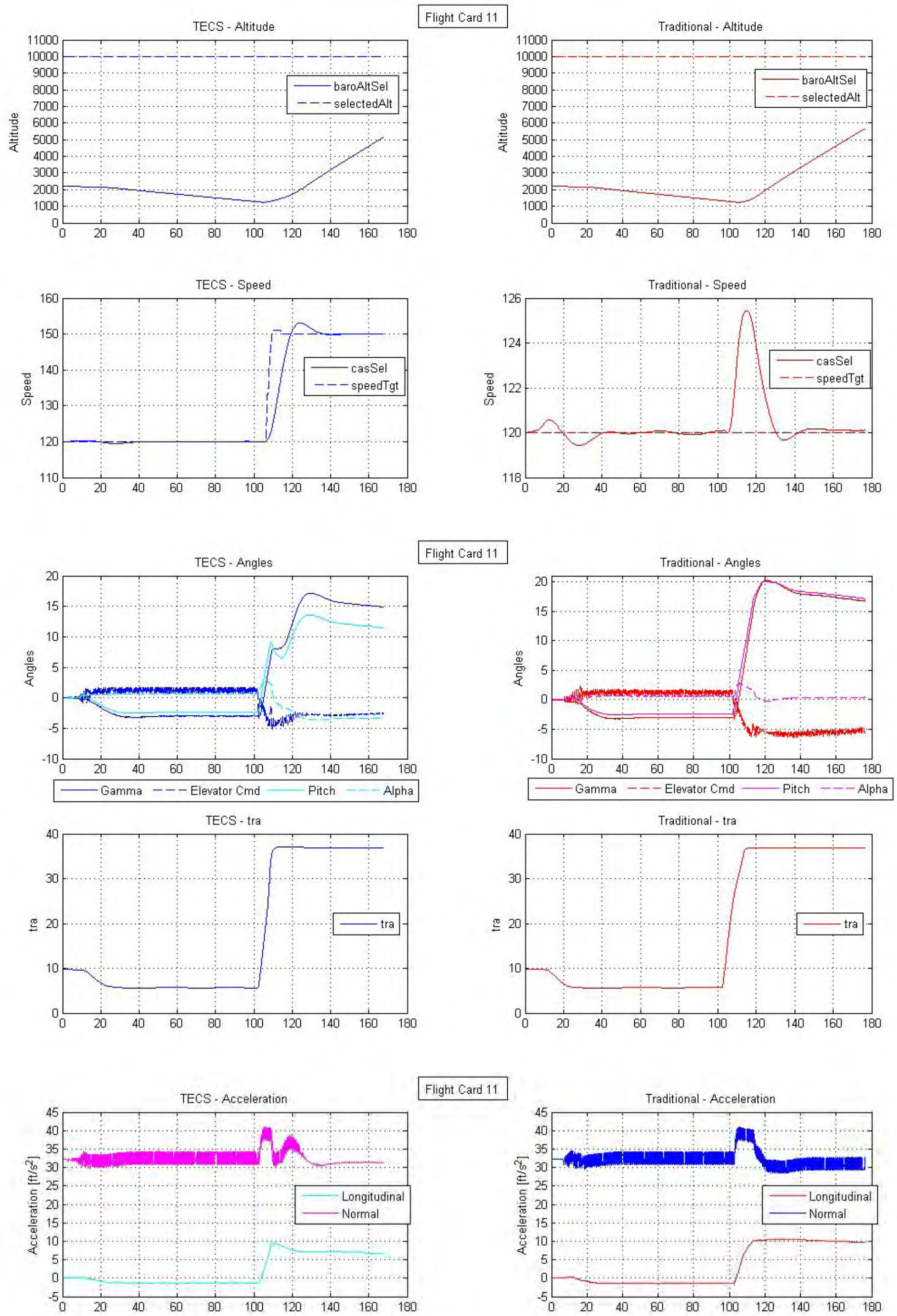



Figure 15. Flight Card Results 9—FC11

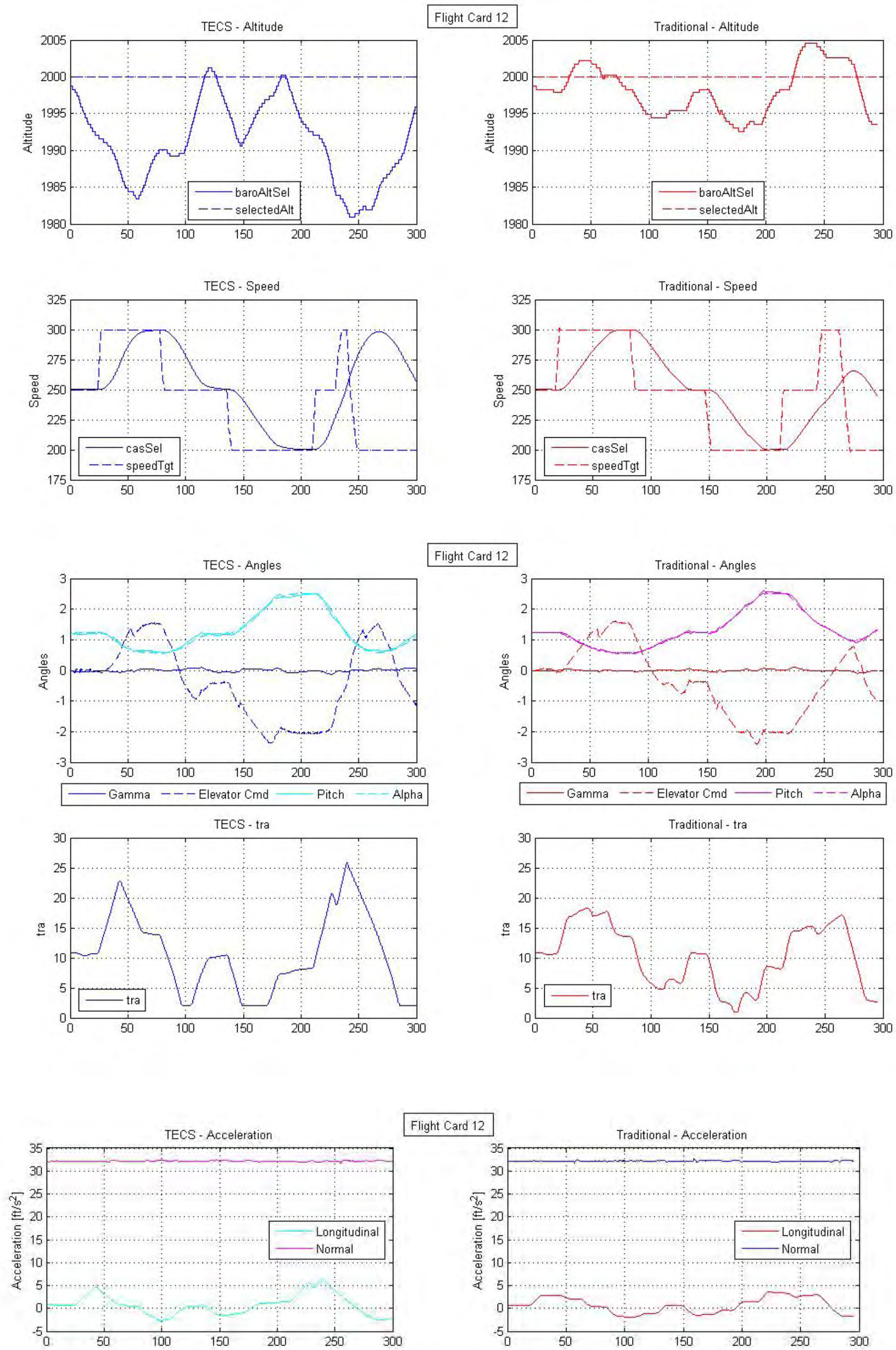



Figure 16. Flight Card Results 10—FC12

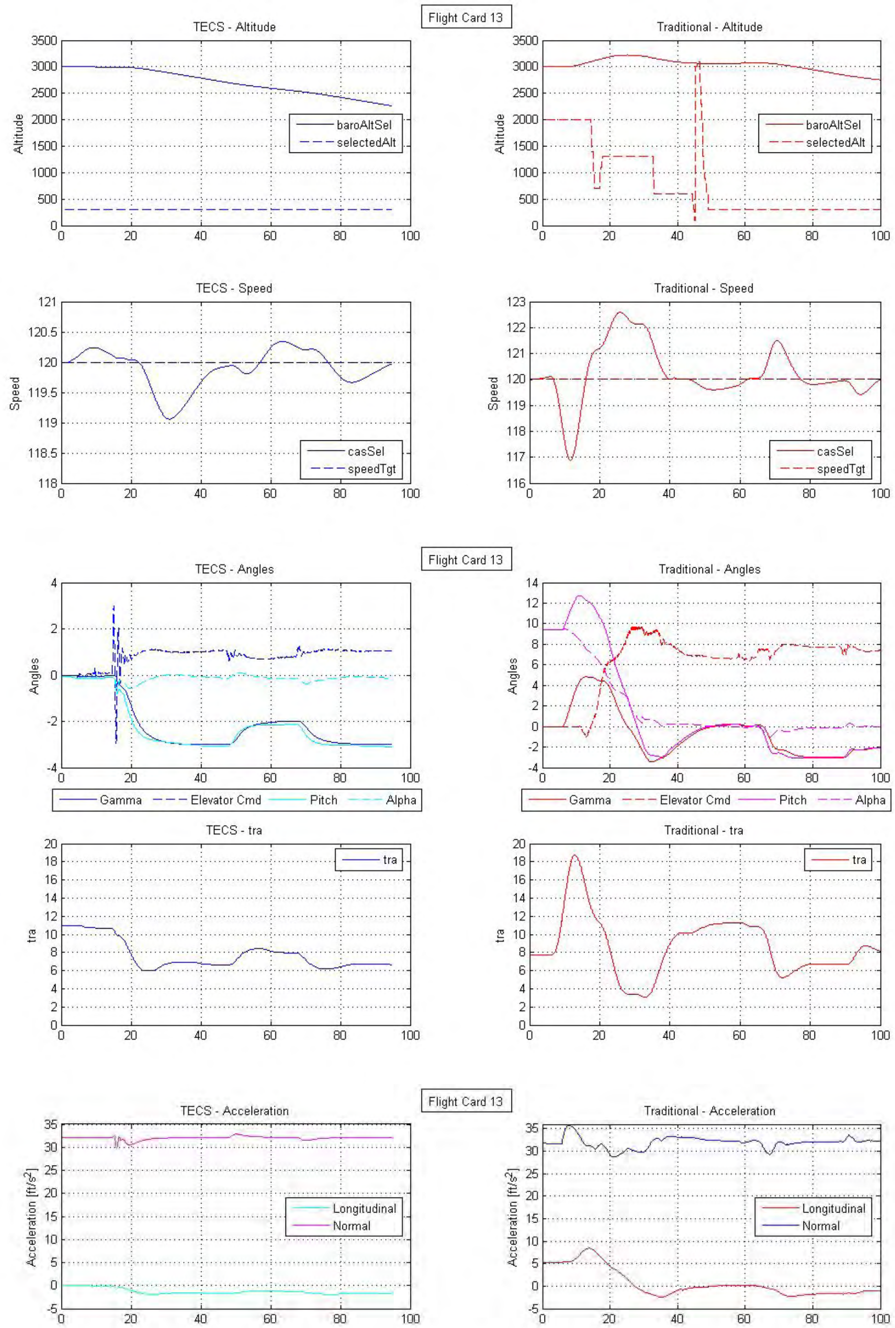



Figure 17. Flight Card Results 11—FC13

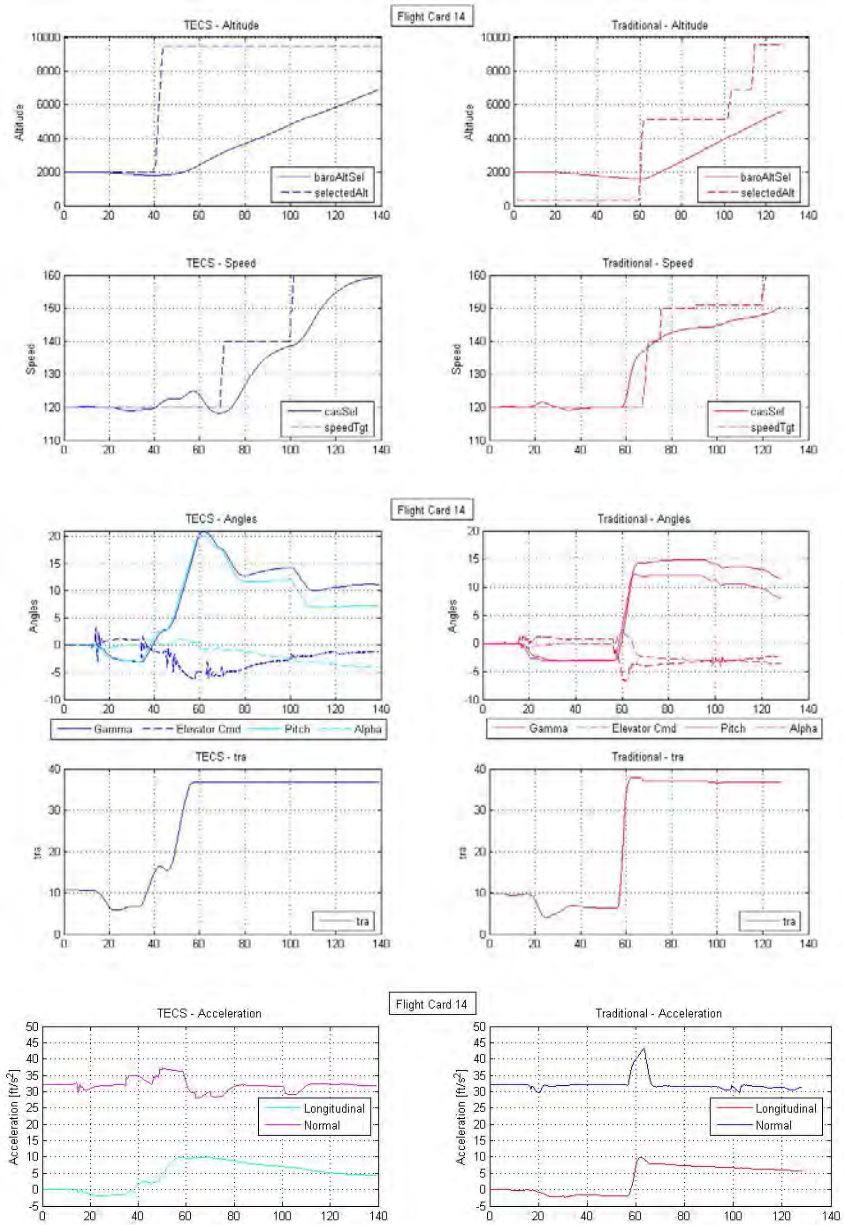



Figure 18. Flight Card Results 12—FC14

5.3 DATA ANALYSIS AND ACHIEVED PERFORMANCE.

Table 6 shows the results of the tests conducted during the second evaluation session in engineering design terms. These results have been used to establish a set of outer loop performance standards for TECS systems in which no or minimal customizations are made to the generic TECS outer loop control laws.

Table 6. Data Analysis and Achieved Performance

| Outer Loop Mode | Engineering Variable/Unit | Transient Response (Unit) | Steady State Tracking Error |
|---|---|---|---|
| ALT ACQ | Altitude (ft) | 0 | 0 |
| | Airspeed (knots) | 0.9 | 1.9 |
| | Normal Acceleration (ft/sec$^2$) | 3.69 | ±0.1 |
| ALT HOLD | Altitude (ft) | 0 | 0 |
| | M | 0 | ±0.01 |
| | Normal Acceleration (ft/sec$^2$) | 1.52 | ±0.02 |
| GA | Airspeed (knots) | 3.1 | 0 |
| | Normal Acceleration (ft/sec$^2$) | 8.86 | 0 |
| Flight Level Change | Airspeed (knots) | 0 | 0 |
| | M | 0 | -0.01 (Note1) |
| | Normal Acceleration (ft/sec$^2$) | 1 | ±0.15 |
| Flight Path Hold | FPA (degrees) | 0.003 | 0 |
| | Normal Acceleration (ft/sec$^2$) | 1 | ±0.01 |
| Nonprecision Approach | Normal Acceleration (ft/sec$^2$) | 2.42 | ±0.02 |
| Approach (CATII) | GS deviation (µA) | 9.29 | 0 |
| | Normal Acceleration (ft/sec$^2$) | 4.45 | ±0.01 |

µA = Micro amps
Note: The tracking error was 0.01 M below the target.

6. FLIGHT TEST PLAN.

The objective of the Phase 1, Year 1 Project Plan was for GAC to scope the plan for Advanced G&C TECS/THCS system hosting and flight testing.

A subset of the anticipated flight test cards, which would be performed as part of the flight test program, is identified in section 5.2. The overall scope of the comprehensive ground and flight tests was highly dependent on the aircraft selected for flight testing. When this objective was originally developed, the assumed platform was a Gulfstream aircraft. Due to resource constraints, GAC could not commit the platforms for this follow-on effort. Therefore, no attempt was made to scope the requirements for system hosting and flight testing.

## 7. SUMMARY.

### 7.1 PROJECT OBJECTIVES.

The first objective of the AFE #47 Research Project Advanced Flight Guidance and Control Systems was to provide the participating companies a familiarization with an example (TECS/THCS) of an advanced guidance and control system that uses a generalized functionally integrated MIMO control architecture.

The second objective of the AFE #47 was to determine if the TECS/THCS control concepts provided sufficient flight control performance to make it a candidate for future airplane fight control development programs.

The third objective was to evaluate the technical merits/deficiencies of the TECS/THCS advanced MIMO control algorithm technology and design features.

The fourth objective was to consider what other production and certification issues need to be addressed to be certain TECS/THCS is a viable technology.

The following sections discuss performance and known issues, including what might be required to develop a complete, functionally integrated TECS/THCS-based FG&C ready to deploy to the field.

### 7.2 THE TECS/THCS CONCEPTS EVALUATION RESULTS.

The TECS and THCS algorithms were provided for the AFE #47 Research Project only as an example of an advanced functionally integrated FG&C concept and technology to allow evaluation of the merits of the TECS concept and to make performance comparisons relative to a traditional design.

#### 7.2.1 Performance.

The following maneuver scenarios were evaluated:

- Altitude Acquire/ALT HOLD (Analogous to Flight Level Change and Altitude Hold mode of traditional system)
- FPA changes
- GS capture, and track

- GA
  - All engines operating
  - Engine out

Pilot Commentary: Generic TECS and the Traditional autoflight performance are very similar. Except for a few areas, where each seemed to have some advantages, either system appears to have adequate performance.

Engineering Commentary: For the most part, the generic TECS performed as well or better than the Traditional autoflight system, in spite of the not having matched inner loops. There were a few areas where TECS did not meet specific design requirements imposed on the Traditional system, e.g. TECS had different acceleration limits. The most obvious performance deficiencies noted in TECS may have been the result of implementation errors and mismatched inner loops. Tuning of the system would result in better thrust, attitude, and speed control. Deficiencies in the performance of the Go Around for both systems were not fully analyzed. The generic TECS implementation may have areas where the integration with the existing system caused unexpected consequences, and the mismatch between TECS and the existing inner loops is certainly impacting performance.

Pilot Commentary: Pitch attitude control, speed control, tracking during altitude, thrust, and speed changes, and acceleration during maneuvers were evaluated with the full TECS engaged.

Engineering Commentary: Time histories of airspeed, altitude, flight path angle, pitch attitude, thrust, elevator and normal acceleration were evaluated during maneuvers involving single and simultaneous commands of speed and flight path. Although problems were noted which may have been caused by the TECS implementation and the use of inner loops from an existing traditional system, the performance of the hybrid TECS compared favorably with that of the traditional system and in a number of situations, involving complex simultaneous flight path and speed maneuvers, surpassed that of the traditional system. With inner loops tuned specific to TECS, performance is expected to improve and may outperform traditional systems.

In conclusion, no performance risk is anticipated in the use of TECS on commercial and general aviation airplanes.

7.2.2 The TECS Control Algorithm Safety.

Engineering Commentary: The TECS system as implemented operated correctly and safely for all the scenarios evaluated. At no time was pilot override or assistance required to achieve the desired airplane control behavior and performance. No safety issues are anticipated in using TECS.

7.2.3 Control Simplification and Reusability.

Engineering Commentary: The evaluation demonstrated the ability of the generic TECS control system to be ported from one application to another with minimal change. No modifications were made to the TECS controls as delivered, and no scenarios were found where the mode structure or mode logic was found to be deficient in the control and guidance of the target airplane. As a result, implementation of an initial TECS system and reuse in a different application is anticipated to be much simpler and require much less custom tuning than with traditional systems.

7.2.4 The TECS/THCS Flight Guidance and Control Panel.

Engineering Commentary: The TECS pilot-in-the-loop simulator evaluations required the use of a simulated hardware flight guidance and control panel based on an existing system due to budget and time constraints. Basing the control panel on an existing system allowed the use of existing certified display and non-TECS flight control software. In order to evaluate a flight guidance and control panel designed specifically to support and enhance the TECS control philosophy, a separate session was held at Gulfstream. This evaluation was to specifically evaluate the TECS and THCS mode and flight guidance panel operations.

The evaluation was performed on a Laptop TECS/THCS Real-time simulation demo system that included an interactive virtual flight guidance panel specifically designed for TECS/THCS. The guidance panel together with a PFD was shown on the laptop display as well as on an LCD projection screen, so a number of pilots could observe the TECS/THCS operations simultaneously. The PFD included a Flight Mode Annunciator (FMA) panel specifically designed for TECS/THCS.

This evaluation was successful, but it showed that the proposed panel will require additional work and pilot feedback. The guidance panel simulation which was available also included provision for ATC Data Link. The inclusion of the data link provisions caused pilot confusion and deserved or undeserved criticism for the TECS/THCS guidance panel and FMA layout. Post analysis of the pilot's comments indicated that the data link provisions were not viewed separately from the TECS control mechanisms. Several of the comments lead to the conclusion that some of the pilots thought the data link provisions were a necessary portion of the TECS. The conclusion from this evaluation is that more flight guidance panel and FMA development and pilot evaluation without the data link provisions will be required.

7.3 ADDITIONAL TECS THCS SYSTEM EVALUATIONS NEEDED.

Engineering Commentary: Due to time and budget constraints, many aspects of the TECS THCS system were not evaluated. The TECS system performance was not evaluated in turbulence or windshear conditions, nor was the system evaluated for with autothrust disengaged. THCS was only evaluated using a laptop simulation without data analysis. The TECS and THCS algorithms include augmented manual control modes. However, the augmented manual control modes could not be evaluated. The Flight Guidance Panel and Flight Mode Annunciator designs did not meet pilot expectations.

In addition, these important TECS/THCS system aspects will need to be addressed to clear away remaining TECS/THCS conceptual issues and application risks and enable the adoption of this technology:

- Mutivariable control aspects,

- Non-normal operations with split axes control,
- Final sensor set and use, e.g. for pitch and roll/yaw inner loops and envelope protection functions,
- Hardware architecture design implications,
- Failure mode propagation into multiple control axes; common mode failures,
- In-flight assessment of system operational suitability and safety,
- TECS/THCS compatible Flight Director and Thrust Director for manual control operations.

7.4 HUMAN FACTORS/MODE SIMPLIFICATION.

Pilot Commentary: The laptop evaluation, while limited, yielded productive pilot feedback about the prototyped TECS/THCS flight guidance panel design and its proposed implementation. It is not surprising that the modes most similar to the Gulfstream flight guidance system (ALT ACQ, ALT HOLD, FPA, and Heading/Track) were rated more highly. For those modes with a different implementation operationally (GA, Mmo/Vmo descents, and LOC) the pilots had several recommendations on how to improve the system for operational use in an ATC environment. Overall pilots felt the datalink interface was cumbersome, with the added steps contributing to, rather than reducing, workload. As noted in earlier evaluations with the AVSI project pilot, the VAR lights did not provide relevant information to the crew, who were trained to rely on redundant information presented on the PFD flight mode annunciator panel at the top of the display. Once accustomed to the VAR lights, they reverted to previously trained habits of scanning the PFD for mode status. Additionally, the comment was made that adding indicator lights to the guidance panel put them out of the normal scan for pilot crosscheck. It could be that while useful to the designers to status the system, the indicator lights added complexity without providing a strong benefit to the crew. The VAR lights may need more evaluation with more operationally representative tasks and line pilots to assess the pros/cons of this aspect of the design.

Learned behavior, previous training, and common piloting practices within a fleet may, at times, outweigh purely performance-based or cost effective design of a flight guidance system. The usefulness of iterative usability evaluations with prototyping tools and pilot experts early in the conceptual design cannot be underestimated. For flight guidance systems, the interface takes a pivotal role in whether the design is assessed as acceptable or not by the crew. This evaluation provided early end user feedback on the proposed interface and was able to quickly identify several areas to consider for a production application of TECS/THCS.

Engineering Commentary: In this TECS/THCS Human Factors evaluation, the allowed pilot training time was limited and likely insufficient. In addition, using a virtual GP and the research PFD was quite different from that to which the pilots were accustomed. This introduced some subjectivity into the results. Additional familiarization, with the TECS/THCS concepts may change these results.

## 7.5 OPERATIONAL ASSESSMENT.

From these performance evaluations, the conclusions were:

1. Pilot Commentary: Generic TECS and the Traditional autoflight performance are very similar. Except for a few areas where each seemed to have some advantages either system appears to have adequate performance.

   Engineering post analysis: Deficiencies in the performance of single engine Go Around for both systems were not fully analyzed. Overall performance problems in this regime were, in part, likely the result of simulation model accuracy deficiencies in the evaluation system.

2. Pilot Commentary: The generic TECS implementation still has some areas where the integration with the existing system may not have been either correctly performed or may need to be adjusted for individual preferences.

   Engineering note: Agreed. Since the objective of this evaluation was to validate the robustness of the generic TECS design, minimal customizations were made to effect ride quality or control performance. Performance improvements are considered tuning issues that would need to be addressed in a production program.

3. Pilot Commentary: Path and glide slope offsets seem to be better performed using TECS.

4. Pilot Commentary: These results are based on simulator evaluations excluding turbulence or windshear. The inflight performance of TECS should be evaluated before conclusions can be reached about turbulence and windshear performance.

5. Pilot Commentary: Manual flight director and thrust modes are very important for Part 25 airplanes. These modes should be consistent with the Autoflight modes and allow the pilot to transition between autopilot/autothrottle and manual flight director and manual thrust modes with a minimum of confusion. Before any conclusions as to the desirability of one approach over the other are made it is essential that these manual modes also be evaluated.

6. Pilot Commentary: Since TECS uses flight path angle (FPA) as its core design philosophy additional work needs to be accomplished to train pilots, not accustomed to using FPA, and familiarize them with the FPA control concepts.

Engineering Commentary: Since this evaluation was limited to an assessment of the generic TECS outer loops connected to unmatched inner loops, the full capability of TECS was not explored. With a little more effort it is believed that discrepancies could be resolved and desired performance achieved. More work is to be done before final conclusions can be formed regarding the best overall performance achievable with TECS.

8. REFERENCES.

1. Lambregts, A.A., "Automatic Flight Controls: Concepts and Methods," Draft paper by FAA National Resource Specialist for Advanced Controls, January 1998.

2. Abbott, K., Slotte, S.M., and Stimson, D.K., "The Interfaces Between Flight Crews and Modern Flight Deck Systems," FAA report, June 1996.