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The 787 Vertical Situation Display Human Factors Evaluation Enhancements to Flight Path Awareness

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A two-phased focused evaluation was run to validate the design implementation of the 787 Vertical Situation Display (VSD), using static and dynamic scenarios in a prototype flight deck. Pilot feedback and pilot questionnaire data were recorded and videotaped for analysis. The validation testing results suggest that overall an effective implementation has been designed. There was one area where issues were found that necessitated requirement changes. The mode transition logic (during takeoff) was redesigned and additional validation testing was conducted to ensure acceptability.

Introduction

One of the basic features of the Boeing 787 airplane is a Vertical Situation Display (VSD) located on the pilots' navigation displays in the flight deck. The VSD is a side view of the airplane's vertical path in space. Together with the lateral view of the airplane's flight path on the Navigation Display (ND), the displays will present pilots with a complete picture of the flight path and related external hazards. The 787 VSD incorporates new display features and is an evolution from the original VSD certified on the Boeing 737.

When a new feature is designed for a pilot display that requires a high level of integration with existing displays, more scrutiny is necessary than that which is required by either a stand-alone display or a display that is similar to one with significant in-service exposure. Within the Boeing flight deck Human Factors design process, these types of new features go through a focused evaluation process to validate the design. Focused evaluations are devised to address concerns, issues, and/or detailed design requirements of new flight deck equipment or functions early in the design/build schedule for an airplane or airplane modification program. This heightened scrutiny has recently been formalized in the certification of new flight deck features by the new European Aviation Safety Agency regulation (CS 25.1302) and its associated Acceptable Means of Compliance (AMC 25.1302) to provide guidance in the certification of new flight deck equipment. The Federal Aviation Administration is expected to adopt similar guidance in the near future.

This paper presents Boeing's 787 VSD design solution and provides two examples of the issues and design details that were assessed during our focused evaluation process to ensure that the pilots could safely, efficiently, and effectively get appropriate information from the VSD.

Background

The primary safety purpose of a VSD is to mitigate Controlled Flight Into Terrain (CFIT) and Approach and Landing Accidents (ALAs), as well as to provide a tool for pilot decision-making related to approach stabilization. The 787 VSD builds upon the Boeing 737 VSD (Jacobsen, Chen, and Wiedemann, 2000; Chen et al., 2000; Houck, Kelly and Wiedemann, 1986). Both the 737 and 787 VSDs provide a mode that depicts the vertical profile along the airplane's current track. To increase pilot awareness of VNAV performance (i.e., the airplane's vertical navigation performance calculated within the Flight Management Computer [FMC]), the 787 VSD has added a mode enabling a graphic representation of the vertical path along the (active) FMC route. This new Path mode gives the pilot a powerful tool to assess the intended FMC vertical profile and its relationship to the approaching terrain, current airplane altitude, selected altitude on the Mode Control Panel (MCP), and decision altitudes.

Without the Path mode VSD, pilots construct a mental picture from FMC VNAV information in conjunction with the graphical terrain depicted on the ND in order to anticipate what the airplane will be commanded to do given the programmed VNAV path. The 787 VSD Path mode will provide a graphical profile depiction of level offs, deceleration/acceleration segments, step climbs, top of climb, top of descent, altitude constraints and vertical targets (e.g., MCP altitude, radio altitude minimums, barometric pressure minimums). This graphical representation of the VNAV path provides an integrated view of all of this information, enabling quick interpretation by the pilot.

VSD Format

The VSD is located on the bottom third of the ND and depicts the following information: airplane current altitude, terrain features, basic navigation data, trend information concerning the airplane's vertical path and speed, as well as some pertinent vertical information, such as Selected Altitude and Minimum Descent Altitude.

There are two modes of the 787 VSD: Track mode and Path mode. The two modes are automatically selected depending upon the state of the airplane automation and the airplane relationship to the FMC route. When the airplane has been selected to fly a lateral path mode of the FMS/autopilot (lateral navigation "LNAV," localizer "LOC," final approach course "FAC," etc.) and is within the set criteria for allowable path deviation, the VSD Path mode is depicted. In all other cases, the VSD Track mode is depicted (e.g., Heading Select "HDG SEL," Heading Hold "HDG HOLD"). In both Track mode and Path mode, a pair of cyan dashed lines (i.e., a swath) is shown on the horizontal view of the Navigation Display that directly corresponds to the information depicted on the VSD. This cyan swath depicts the lateral area over which the VSD is showing terrain and associated waypoint altitude constraints.

In Track mode (see Figure 1), the VSD depicts the information along the airplane's track. The cyan swath aligns with the airplane track and not the FMC route. When the VSD is in Track mode, the LNAV waypoint altitude constraints, underlying terrain, MCP altitude, altitude minimums, and final approach path along the airplanes current track are depicted. In Path mode (see Figure 2), the VSD depicts the information along the FMC route. The cyan swath aligns with the FMC route. When in Path Mode, the terrain at the twelve o'clock position is not within the cyan swath and thus is not depicted on the VSD.

Figure 1. Track mode VSD

Figure 2. Path mode VSD

Project Approach

While validation of the VSD for the 787 occurred throughout an iterative design process, we performed a focused evaluation and validation toward the end of that process. Given that the Track mode VSD has been certified and is being used in service on the 737, the purpose of our evaluation was to validate the Path mode functionality on the VSD, with respect to the following: 1) the new functionality associated with the new Path mode, 2) the integration of the Path mode with the Track mode, and 3) the integration of the new dual-mode VSD into the new 787 flight deck.

We used an iterative process to identify the potential issues associated with the Path mode VSD. We started by bringing together the team that had been involved in the design and oversight of the original VSD, and with the development of the new Path mode, much of which had already been dynamically prototyped. Team member's expertise comprised Engineering, Human Factors and Flight Operations. First, we identified the areas where validation was required (e.g., the new symbology and dynamic behavior associated with the new symbology). Next, we created a matrix that identified the validation objectives and test questions were crafted to address each item requiring validation. Once the test questions were agreed upon, specific test scenarios were proposed for each question. The scenarios were prototyped and presented to the team for review, discussion, and refinement.

A two-phased evaluation was designed to address issues and concerns related to: 1) ND/VSD correlation, 2) Mode transition logic, 3) Holds, 4) Procedure turns, 5) Path depiction during climbs and level offs, 6) Lateral swath depiction, 7) Map range consistency, and 8) Route discontinuities. For the purposes of this paper, we will expound upon the first and second items (i.e. ND/VSD correlation and the takeoff mode transition logic).

In Phase 1, we used static scenarios to solicit early feedback from the pilots. During a static scenario, the pilot viewed static displays in the 787 rapid prototyping device. These scenarios were comparable to what you would expect to see if you took a snapshot of a paused or stopped simulator during a flight. Use of static scenarios was effective in assessing whether the pilots were able to successfully correlate information (e.g., symbology on the VSD to the ND) and whether there was any confusion resulting from the format design. In Phase 2, the scenarios were conducted in the same 787 rapid prototyping device, however during this portion of the testing, the pilots viewed the displays while flying the simulator on autopilot, utilizing the MCP to control the airplane. Questions that could not be addressed by the static scenarios, such as the mode transition logic, were addressed during the dynamic scenarios.

ND/VSD Correlation & Mode Transition Logic – Testable Questions

Given that the selection between Track and Path modes is automatic, it is essential that the pilots maintain an ability to correlate the information on the VSD and ND during all phases of flight. Also it is important that the transitions between Track and Path mode occur at the appropriate time, such that the information depicted is interpreted correctly. Depending upon the mode that the VSD is displaying (i.e. Track or Path), the information (e.g. terrain and waypoints) depicted will often differ. For example, when in Track mode, the VSD displays the information in front of the airplane, along the airplane's current heading. Thus, at the point at which the airplane's route changes heading (i.e., to a direction other than the current airplane heading), the waypoints and terrain along the route are no longer visible from the point where the route alters direction (See Figure 1).

The information displayed while in Path mode is different in that the information along the route programmed into the FMC and executed is depicted on the VSD regardless of whether the route is along the airplane's heading (See Figure 2).

The following are the testable ND/VSD Correlation & Mode Logic questions:

- What do the pilots understand from looking at the VSD and how do they correlate it to the ND map and computer display unit (CDU)? What information was used in making the determination?
- Does the VSD display what was expected?
- Did the point at which the VSD transitioned from Path mode to Track mode align with the pilot's expectations?
- Was there anything that appeared to be conflicting or confusing?

- Are there any potential certification or safety issues associated with the Path mode implementation?
- Were there any items that the pilots would prefer to see depicted differently?
- Is the mode transition logic understandable by the pilots?

The static scenarios focused on presenting the pilots with possible airplane configurations (e.g., LNAV and Path mode, HDG SEL and Track mode, Takeoff Go-Around[TOGA] without LNAV armed and Path mode) followed by an inquiry as to what information on the ND was being displayed on the VSD.

The dynamic scenarios focused on presenting the pilots with possible mode transitions (e.g., airplane in TOGA without LNAV armed during takeoff, Path mode displayed on the VSD until the 400' above ground level (AGL) transition to Track mode) and were followed by an inquiry as to the intuitiveness of the mode transition logic.

Methodology

Participants

In Phase 1, 14 air transport pilots participated in the validation. Eleven out of the 14 pilots had prior experience using the VSD. The pilots had Boeing Designated Engineering Representative (DER) flight test or Boeing Training pilot experience. Some of the pilots also had prior line flying experience with a major airline.

In Phase 2, 12 air transport pilots participated in the validation. Eleven pilots that participated in Phase 1 returned to participate in Phase 2. One additional pilot, who did not participate in Phase 1, participated in Phase 2. Ten of the 12 pilots had prior experience using the VSD in the 737.

Research Environment

Both phases of testing were conducted in the Rapid Prototyping Development System (RaPiDS). RaPiDS is a PC-based 787 dynamic flight deck simulator utilized as a flight deck engineering development tool. RaPiDS provided the needed interactivity and functionality to complete a thorough validation of the VSD.

In Phase 1, nine sets of static display pictures were depicted on their prospective display units: Primary Flight Display (PFD), Navigation Display (ND), Vertical Situation Display (VSD), Engine Indication and Crew Alerting System (EICAS) and Control Display Unit (CDU). Full-scale laminated pictures of the Mode Control Panel (MCP) displaying the appropriately illuminated buttons and settings were presented in the MCP location during each scenario. Additionally, the gear lever and flap lever were set to the correct position for each scenario. Directly after viewing each test scenario, the pilots answered a predefined set of questions and provided feedback.

In Phase 2, the pilots flew six scenarios. The displays, MCP, flaps and gear were operational during these flight scenarios.

Test Conduct

Pilots were brought in twice within a three month period to participate in the two phases of the test. A checklist was utilized to ensure that RaPiDS was configured in the same way for each pilot prior to each scenario. Upon arrival, a pilot experience questionnaire was filled out and a brief written summary explaining the purpose of the testing and what the pilots should expect was provided. Pilots then completed a self-paced Computer-Based Training (CBT) module on both modes of the VSD. After each scenario in the Phase 1 and Phase 2 testing, the pilots provided feedback by completing a questionnaire. Observations were recorded by the test administrator and videotaped (i.e., during completion of the CBT module and during completion of the Phase 1 and Phase 2 test scenarios). Additionally, the majority of pilots provided verbal feedback and commentary throughout the testing, which was also captured.

Phase 1. The pilots viewed nine static scenarios and provided feedback via a questionnaire. The test in its entirety took approximately two hours to complete. In this paper, we will describe four of the nine Phase 1 scenarios.

Phase 2. Phase 2 was primarily focused on validating: 1) the mode transition logic (i.e., during takeoff and during typical transitions between VSD modes) and 2) the display depictions during transitions (i.e., hold and climb depiction). The pilot who had not participated in Phase 1 completed the CBT training upon arrival. In Phase 2, the pilots flew six scenarios and provided feedback via the questionnaire. Test subjects served as the captain (pilot flying). One of the test administrators served as the first officer (pilot not flying). The test in its entirety took approximately 90 minutes to complete. In this paper, we will describe two of the six Phase 2 scenarios.

Results and Conclusion

Phase 1

Scenario 1: Pilots viewed a static display of a VSD in Path mode with LNAV/VNAV engaged. All of the pilots correctly correlated the VSD information to the ND. They all utilized the cyan swath to determine the mode, and nine pilots out of 14 also used the presence of the magenta route on the VSD to assist in correlating the ND and VSD.

Scenario 2: Pilots viewed a static display of a VSD in Track mode with LNAV/VNAV engaged and a cross track error that exceeded RNP. Typically, when LNAV/VNAV is engaged, the VSD would be in Path mode, however when cross track error exceeds RNP, the airplane will not fly the FMC route. Because the VSD depicts the route the airplane will fly, the VSD depicts Track mode in this case. Twelve out of 13 pilots accurately correlated the VSD information to the ND. Twelve out of 14 pilots indicated that they used the cyan swath and five pilots used the absence of the magenta vertical route depicted on the VSD to indicate the VSD was in Track mode.

Scenario 3: Pilots viewed a static display of an airplane in Track mode with HDG SEL engaged. All 14 pilots correctly correlated the VSD information to the ND. Thirteen pilots indicated that they used the cyan swath to make their determination. Ten pilots referenced the HDG SEL roll mode in making their determination and only six pilots indicated that they used the absence of the magenta vertical route depicted on the VSD as a cue to determine that they were in Track mode.

Scenario 4: Pilots viewed a static display of an airplane in Path mode with LNAV/VNAV engaged; the ND range set to 1280 nm and the VSD displaying 2560+ nm. All 14 pilots correctly correlated the VSD information to the ND. Thirteen pilots used the cyan swath to make the correlation. Five pilots used the magenta line on the VSD and three pilots relied on the fact that LNAV was the roll mode in making their determination.

Consistently, throughout Phase 1, the pilots were successfully able to correlate the information on the ND and the VSD. We noted that the cyan swath was the most powerful cue used in correlating the information on the two displays and the magenta vertical route depicted on the VSD was used as a secondary cue.

Phase 2

Scenario 5 and Scenario 6: During each of these two scenarios, the pilots flew the Gypsum 3 departure out of Eagle, Colorado. All pilots flew this scenario with and without the VSD displayed. During Scenario 5, the VSD was depicted and during Scenario 6 it was not depicted. Seven of the pilots flew it first with the VSD (Scenario 5) and five of the pilots flew it first without the VSD depicted (Scenario 6). During both of these scenarios, immediately after takeoff (i.e., at 400’ AGL), the airplane transitioned from TOGA to HDG HOLD and no longer followed the FMC path as was depicted on the ND and VSD prior to and during takeoff up to 400’ AGL. Simultaneously, at 400’ AGL as the airplane was encroaching upon hazardous terrain, the VSD automatically transitioned from Path mode to Track mode. This transition was caused by the absence of LNAV/VNAV being engaged prior to takeoff.

The feedback from all 12 pilots was consistent regardless of the order in which the scenarios were flown. The pilots indicated that they expected the airplane to follow the FMC route after takeoff. They indicated that they were surprised by the 400’ transition and that Path mode was depicted on the VSD, despite the fact that the airplane was not going to fly the path after takeoff. They indicated that the presence of the magenta vertical route on the VSD and the cyan swath on the ND prior to takeoff led them to expect that the airplane would follow the LNAV/VNAV route after takeoff. We also received feedback that when LNAV was not armed at takeoff, the VSD should have been in Track mode and that this implementation posed both a safety and certification risk. The VSD logic was overwhelmingly perceived as conflicting, confusing and/or concerning. Interestingly, one of the pilots that had just finished flying the scenario a second time commented that despite his prior exposure to this scenario, he still assumed that LNAV was armed because of the presence of the cyan swath aligning with the LNAV path on the ND.

We received strong, consistent feedback from the pilot group regarding the VSD implementation and transition logic after flying the Gypsum 3 departure out of Eagle, Colorado. The consensus, regardless of which order the pilots flew the scenarios, was that if the airplane wasn't going to fly the FMC route after takeoff, Path mode should not have been displayed. There was consensus that 400' AGL is not an appropriate time to transition between VSD modes (i.e., from Path to Track). Across the board, pilots agreed that there was a certification and safety risk associated with the current implementation. Hence, a design change was strongly recommended. Additionally, the importance of the cyan swath and the information that it conveyed was strongly emphasized by the pilots during these scenarios.

Based upon the feedback that we received, new logic addressing the certification and safety concerns was developed. In accordance with the direction received, the new logic ensured that the VSD remains in Track mode on the ground when the airplane is not going to fly the FMC route after takeoff. Additionally, there is no longer a trigger point at 400' AGL enabling the VSD to transition between modes. The VSD now consistently depicts the information within the swath along the route that the airplane is configured to fly. A follow-on test with dynamic scenarios was conducted to successfully validate the final design.

Summary

As stated, the purpose of this focused evaluation was to validate that there were not any certification and/or safety issues related to the VSD design implementation and that the VSD Path mode has been implemented in a way that provides the pilot with an improved awareness of the airplane's current position relative to the commanded vertical path. A two-phased effort was effective in conducting the evaluation. Scenarios presented in a static environment were valuable in ascertaining how well information was correlated between the VSD and the ND. Dynamic flight scenarios were instrumental in discovering issues with the mode transition logic. The validation testing (Phase 1, Phase 2, and follow-on testing) results suggest that an effective implementation has been designed. In the area where certification and/or safety concerns existed (i.e., the mode transition logic at takeoff), design changes were incorporated and re-tested.

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