Flight Deck Audio Displays: Striking the Right Tone in Future Designs

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The 2009 accident involving Air France Flight 447 illustrates the gap between visual and auditory display design and implementation in commercial aircraft. By examining the successful evolution of Enhanced Ground Proximity Warning System (EGPWS) and Traffic Alert and Collision Avoidance System (TCAS) to incorporate both audio and visual alerting and resolution guidance to flight crews, a contrast is drawn with similar aids available in advance of aircraft upset episodes. A universal approach for future design should incorporate harmonized video and audio displays providing optimized alerting and guidance along with the latest in simulator training designed to emphasize aircraft state awareness degradations before a loss of control incident emerges. By promoting continued dialogue among the aviation community, it is hoped that the existing gap among research, design, and operations may be narrowed, resulting in flight deck audio displays optimized to support effective pilot performance.

This paper explores issues of flight deck audio display design using the backdrop of the 2009 accident involving Air France Flight 447 to illustrate the continuing opportunities to refine and improve this important sensory aid for new generation commercial aircraft. Simpson (2007) laments on early audio display designs: “research literature is replete with examples from earlier times of arbitrary assignment of sounds to cockpit alerting meanings.” A recent study surveying the commercial pilot community on auditory alert characteristics indicates loud and persistent alerts may result in adverse unintended consequences, yet remain widespread in modern commercial aircraft design (Peryer, Noyes, Pleydell-Pearce & Lieven, 2005). Aside from cutting-edge military applications, these norms have become firmly established and are indicative of disconnect between the aviation human factors and manufacturer design engineer’s communities, ultimately contributing tragic links to the accident chain of many ill-fated flights. By promoting continued dialogue among the aviation community, it is hoped that the existing gaps among research, design, and operations may be narrowed, resulting in flight deck audio displays optimized to support effective pilot performance.

Air France 447

In the early morning hours of June 1, 2009, Air France Flight 447 began to experience a chain of events that quickly resulted in the Airbus A-330-203 entering a deep stall and rapid descent, crashing into the sea near the TASIL reporting point, in international waters of the Atlantic Ocean (BEA, 2011). The aircraft had been cruising at Flight Level 350 when it entered a cloud layer associated with nearby precipitation indicated by onboard radar and subsequently experienced inconsistency between measured airspeed indicators, most likely due to an obstruction of the pitot probes in an ice crystal environment (BEA). Consequently, the invalid airspeed displays resulted in an automatic disconnect of the autopilot along with the associated “cavalry charge” auditory cue (BEA). This disconnect alert was followed four seconds later by the “Stall Stall” audio warning in response to manually entered aft control inputs which caused the aircraft pitch to momentarily exceed the stall warning threshold limits for the given situation (BEA). This first stall warning was a short-lived transient cue that was triggered in advance of an actual stall situation. Later in the accident sequence, as the aircraft actually entered a deep stall condition, the “Stall Stall” audio speech warning and associated “cricket” tonal warning were heard on the Cockpit Voice Recorder (CVR) for a continuous period of 54 seconds (BEA).

Audio Display Design

Drivers

The need to offload the visual system of humans interacting with machines provided the initial stimulus for the development of audio systems to deliver warning messages (Cooper, 1977; DuRoss, 1978). Another advantage sound enjoys over vision is a typically faster processing time, a characteristic often resulting in sound being used effectively to transmit critical information (Petocz, Keller & Stevens, 2008). Unlike the visual system, in order to perceive audio signals, there is no requirement on the user to be positioned in a particular way to receive the signal

(Petocz, Keller & Stevens, 2008). Thus, responding to detected anomalies or system state changes in routing task monitoring may be ideal applications for audio display alerting systems.

Design Philosophy

The laboratory-to-development approach outlined by Patterson (1982) featured purpose-built auditory icons designed as attention getting sounds. Early lab test results were used to formulate a range of parameters based on pulse rate, pitch and dissonance as measured against the perceived urgency among the test subject (Simpson, 2007). Later experiments would compare alert systems where pilots received spoken alerts with preceding attention-getting sounds vs. the same spoken alerts with no attenson preceding the spoken alert (Simpson, 2007). Other researchers experimented by grouping auditory signals by speech, abstract sounds and auditory icons (i.e., environmental sounds with pre-existing associations) (Petocz, Keller & Stevens, 2008). This research established the importance of the association of the strength of the auditory sound with the psychoacoustic knowledge of the subject, the signal referent relationship (Petocz, Keller & Stevens, 2008).

Applied Audio Display – Classic Use Case

Eastern 401

Eastern Airlines Flight 401, operating a Lockheed L-1011 aircraft, crashed 18 miles from Miami, Florida while the flight crew attempted to ascertain whether the nose wheel was in the down and locked position for landing (NTSB, 1973). On the initial approach the crew did not observe an illuminated nose gear down light following the selection of the landing handle to the down position and asked Air Traffic Control (ATC) for vectors to go troubleshoot the situation away from the airport (NTSB). Although the primary cause of this accident was determined to be poor crew coordination, which was manifest by the fact that none of the flight crew was flying the aircraft or actively monitoring its performance, the author believes audio display design played a contributing role to the accident, which claimed 101 lives (NTSB).

Autopilot disconnect. When the Eastern L-1011 crew executed a missed approach because of the suspected nose gear malfunction, they proceeded to climb the aircraft to 2,000 feet, where upon the captain instructed the first officer who was the flying pilot to engage the autopilot (NTSB). Unbeknownst to the crew, the altitude hold feature of the autopilot was disengaged following a suspected control input by the captain as he turned around in his seat to conduct a conversation (NTSB). According to the NTSB report, the altitude disengage feature would not trigger an accompanying “CMD DISC” warning on the captain or first officer annunciator panel and there was no audio warning of an autopilot disengagement available.

Altitude alert. When the aircraft was assigned to maintain the altitude of 2,000 feet Mean Sea Level, that value was entered into the altitude alert window (NTSB). Following the undetected disengagement of the altitude hold feature of the autopilot, the aircraft began a subtle decent towards the ground which was not initially noticed amid the commotion on the flight deck. As the aircraft descended through 1,750 feet the altitude alert system produced an audio warning and the NTSB report noted “a half-second C-chord, which indicated deviation of +/- 250 feet from selected altitude sounded in the cockpit. No crewmember commented on the c-chord. No pitch change to correct for the loss of altitude was recorded.” Therefore, the audio warning was not processed or acted upon by any of the crewmembers in a manner that was recorded and analyzed.

Radar altimeter. The final example of an audio warning in the Eastern 401 accident was issued by the radar altimeter, which was still set for the initial approach sequence to Miami International. As the aircraft neared the ground, ATC noted the flight had departed 2,000 feet and asked the flight how things were going (NTSB). When the crew informed ATC that they wanted to return to the airport, the subsequent clearance triggered the crew to enter a new heading into the auto flight system, whereupon they quickly noted something was amiss with their altitude. Shortly after the captain exclaimed “Hey, what’s happening here” the first of six radio altimeter warning “Beeps” began followed by the sound of impact (NTSB). This audio warning was not designed for this type of situation and by the time this audio was perceived, it was too late to recover the aircraft.

Lessons Learned

While Eastern 401 may be viewed by some in the human factors field as a case study of dysfunctional Crew Resource Management (CRM), the author believes it equally seminal to those researchers studying audio display designs in early commercial jet aircraft. This accident demonstrates the importance of a balanced design approach to facilitate appropriate problem solving under stressful conditions utilizing proper alert intensity, duration and urgency conveyance. Many developments in audio display design have been the result of difficult lessons revealed by this and other related accident investigations.

Enhanced Ground Proximity Warning System (EGPWS)

In a summary of the evolution of terrain avoidance warning systems, Barry C. Breen (1995) of Allied Signal Electronics & Avionics Systems details that the leading cause of worldwide aviation fatalities into the 1990's comes from controlled flight into terrain (CFIT) accidents, where there was nothing remarkably wrong with the aircraft as was the case for Eastern Flight 401. Responding to the high rate of worldwide CFIT accidents, the Commercial Aviation Safety Team (CAST), a joint collaboration of the Federal Aviation Administration (FAA) and industry, successfully developed both technology and training safety enhancements (SEs) designed to mitigate this leading cause of accidents (Angers, 2009). The ground proximity warning system (GPWS) received enhancements including a digital terrain elevation database (DTED) and advanced look-ahead algorithms, which reduced false warnings and provided additional time to execute avoidance maneuvers (Breen). The results of this multi-faceted approach show a significant decline in worldwide CFIT accidents (Boeing Aircraft Company, 2011).

Although the EGPWS information is primarily displayed to the flight crew on the electronic flight information system (EFIS) in the form of the terrain avoidance display (TAD) that appears when the system is manually selected or when a look-ahead warning is triggered, an audio display is also associated with EGPWS. The audio warnings include voice-synthesized warnings such as "Terrain –Terrain" and "Pull-Up Pull-Up" interspersed between a "Whoop Whoop" generated tone (Breen, 1995). The most noteworthy concept of this approach is that the speech portion of the audio display contains two important aspects of interest for the flight crew. First, it informs them of the nature of the threat (terrain) and secondly, it provides them with a corrective action (pull-up). The implementation of EGPWS into the commercial airline fleet, combined with proper crew training, has largely eliminated CFIT accidents in the United States, as FAA's Deputy Associate Administrator for Aviation Safety Peggy Gilligan (2007) reported to Congress in 2007, the last CFIT accident in the U.S. occurred 29 years ago.

Traffic Alert and Collision Avoidance System (TCAS)

Another evolutionary safety enhancement encouraged by the CAST, is the traffic alert and collision avoidance system (TCAS) (Angers, 2009). TCAS is an airborne system developed by the FAA that operates independently from the ground-based Air Traffic Control (ATC) system and contains both visual and audio displays (Searight, 2010). Designed to increase cockpit awareness of proximate aircraft and to serve as a "last line of defense" for the prevention of mid-air collisions, the latest versions of TCAS include speech generated warning and guidance output similar to EGPWS (Searight, 2010). The evolution of TCAS has continued with the refinement of resolution advisories that include 3-D audio representation of the traffic conflict, depicted with reference an out-of the-cockpit view (Begault, Wenzel & Lathrop, 1997). An outgrowth of contemporary military systems designed to optimize flight deck control/display interfaces, the 3-D audio feature may soon make its way onto the commercial flight deck of the future (Taylor, et al., 2001).

Survey Says

Shock and Awe

Ask any commercial pilot, and you will be certain to get an opinion about the nature of audio alerting in transport category aircraft. When Peryer, Noyes, Pleydell-Pearce and Lieven (2005) conducted their survey, they noted the association between high intensity audio sounds and both undesirable physiological and psychological effects. Highest on the pilot survey of criticisms of auditory alerts is the unnecessarily extreme volume (Peryer, et al.). Their study also cited Aviation Safety Reporting System (ASRS) database reports declaring loud alerts as an adverse factor in flight safety, sometimes resulting in the immobilization of crews subjected to the startle factor of the alert (Peryer, et al.).

Make it Stop

Pilots interviewed for a study on approaches to improving auditory and visual alerting in aircraft expressed that certain audio alerts had durations that were inappropriately prolonged (Ulfvengren, Martensson & Singer, 2002). In some cases, the lack of ability to cancel the alert following acknowledgment was seen as contributing to perceptual and cognitive overload, undermining the ability of the pilot to understand and evaluate two keys for successful problem solving. Peryer, et al. (2005), citing previous work notes:

> The auditory modality is very sensitive to change, which makes it ideal for warning presentation; however, if the alert continues, attention, even at a rudimentary level, is still devoted to processing the auditory signal and is diverted away from processing task-related information (Banbury et al., 2001; Wickens & Hollands, 2000).

While these surveys were conducted with subjects who fly advanced-automation aircraft representing all of the major airframe manufacturers, it is noteworthy that pilot criticism of auditory alerting found throughout these surveys has not substantively changed over the last 20 years (Peryer, et al.). Patterson (1982) notes that design engineers have “flooded the flightdeck” with piercing sounds which are not only disliked, but more importantly disrupt thought and inhibit communication during critical events. This comes in spite of the dramatic gains to the visual displays on the same aircraft (Peryer, et al.).

Aircraft State Awareness

A Complex Problem

While much of this paper has discussed events involving aircraft avoidance of objects, EGPWS avoiding terrain and TCAS avoiding aircraft, a more confounding problem in flight deck design appears to be audio display of aircraft performance state related to in-flight upset incidents. It is significant that EGPWS and TCAS are fundamentally geo-spatial problems to solve, being less dependent on specific aircraft aerodynamic performance characteristics. Additionally, there is often more time to accurately predict and present alerts and solution guidance both visual and aural, for EGPWS and TCAS. Aircraft state awareness involves a considerably greater dynamic set of variables including meteorological aspects, which along with a specific airframe’s aerodynamic properties and operational differences may contribute to aircraft upset incidents like a high altitude stalls and ice induced roll upsets.

Don’t Get Upset

According to Sunjoo Advani, chairperson of the International Committee for Training in Extended Envelopes, organized by the Royal Aeronautical Society, when an aircraft is upset it is not only outside the normal flight envelope, but also in an agitated condition (Warwick, 2011). Pilots in these types of situations need to quickly and accurately correlate the stimuli presented, including aircraft generated audio alerts in order to affect a recovery. Aircraft behavior in an upset may seem more startling and perplexing to flight crews whose only previous exposure is likely to have been in a training simulator (Warwick, 2011). The audio displays associated with these events need to support and complement existing visual cues, not conflict and confound an already task-saturated flight crew.

Closing the Visual-Auditory Display Gap

Ulfvengren, Martensson and Singer (2002) describe each of the major design philosophies employed by aircraft manufacturers, in leading up to their discussion on improving aircraft audio designs. The “Sort and Guide” model they state, was inspired by the A320 model of alert logic prioritization in which immediate action items are presented one at a time, in priority order, with clear fault information presented along with guidance for recovery (Ulfvengren, Martensson & Singer, 2002). Examination of Figure 1 below will show the many auditory alerts generated by the A330 aircraft flown by Air France Flight 447 (A330 flight deck, 1999). It should be noted that with respect to aircraft state awareness, the synthetic voice alerts generated provide no direct guidance for recovery, unlike those previously described for EGPWS and TCAS alerts. Stanton and Edworthy (1999) suggest development of new audio designs should focus on the linkage between the sound and the potential for remedial action, referents should guide action required of the pilot. Air France Flight 447, and similar in-flight upset accidents, show a need for further research and development of audio displays to fully actualize the concept of ‘Sort and Guide”.

WARNING SIGNAL	CONDITION	DURATION	SILENCING
CONTINUOUS REPETITIVE CHIMIE	RED WARNINGS	PERMANENT	Depress* MASTER WARN lt
SINGLE CHIME	AMBER CAUTION	1/2 sec.	
CAVALRY CHARGE	A/P DISCONNECTION BY TAKE OVER pb	1.5 sec	Second push on TAKE OVER pb
	A/P DISCONNECTION DUE TO FAILURE	PERMANENT	Depress MASTER WARN lt or TAKE OVER pb
CLICK	LANDING CAPABILITY CHANGE	1/2 sec (3 pulses)	
CRICKET + "STALL" message (synthetic voice)	STALL	PERMANENT	NIL
INTERMITTENT BUZZER	SELCAL CALL	PERMANENT	Depress RESET key on ACP
BUZZER	CABIN CALL	3s	NIL
	EMER CABIN CALL	3s REPEATED 3 TIMES	NIL
	MECH CALL	As long as outside pb pressed	NIL
	ACARS CALL or ALERT	PERMANENT	Message reading on MCDU or Depress MASTER CAUT
C CHORD	ALTITUDE ALERT	1.5 sec or PERMANENT	new ALTITUDE selection or depress MASTER WARN pb
AUTO CALL OUT (synthetic voice)	HEIGHT ANNOUNCEMENT BELOW 400 FT	PERMANENT	NIL
GROUND PROXIMITY WARNING (synthetic voice)	UNSAFE TERRAIN IN CLEARANCE FORESEEN	PERMANENT	NIL
"WINDSHEAR" (synthetic voice)	WINDSHEAR	REPEATED 3 TIMES	NIL
"PRIORITY LEFT" "PRIORITY RIGHT" (synthetic voice)	A/PTAKE OVER pb	1 sec	NIL
"RETARD" (synthetic voice)	THRUST LEVER NOT IN IDLE POSITION FOR LANDING	PERMANENT	THRUST LEVER
TCAS (synthetic voice)	TRAFFIC OR POTENTIAL COLLISION	PERMANENT	NIL

Figure 1. A-330 Electronic instrument system – ECAM audible warning definitions. Synthetic voice provided guidance for EGPWS and TCAS highlighted in green.

Discussion

The tragedy of Air France Flight 447 should be a call to the aviation industry to evaluate how to best leverage the use of automation in concert with advanced upset training for pilots. A universal approach for future design should incorporate a combination of harmonized video and audio displays with the latest in simulator training. This would provide optimized alerting and guidance in a training environment designed to emphasize aircraft state awareness degradations before a loss of control incident emerges, resulting in aircraft control being continually maintained. Many challenges remain to be solved to enable audio display design to complement visual alerts, and not issue contradictory or confound information in an emerging upset scenario. With the near elimination of CFIT as the number one cause of accidents in the US, it is time to redouble our efforts and apply the lessons learned from CFIT to other areas of aviation safety. With solid research, development, validation and implementation, it is possible to have a similar reduction on the Loss of Control (LOC) accident rate as has been realized with Controlled Flight Into Terrain (CFIT) accidents. Striking the right tone in future audio display designs will help eliminate one link in the accident chain.

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