IMPROVING PILOT UNDERSTANDING OF TCAS THROUGH THE TRAFFIC SITUATION DISPLAY

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William P. Cleveland

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IMPROVING PILOT UNDERSTANDING OF TCAS THROUGH THE TRAFFIC SITUATION DISPLAY

Approved by:

Professor Amy R. Pritchett, Advisor
Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology

Professor Karen M. Feigh
Daniel Guggenheim School of Aerospace Engineering
Georgia Institute of Technology

Dr. Wesley Olson
Lincoln Laboratories
Massachusetts Institute of Technology

Date Approved: 10 December 2012

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LIST OF SYMBOLS OR ABBREVIATIONS

ADS-B Automatic Dependent Surveillance-Broadcast.

ALIM Altitude LIMit (TCAS Variable).

ASRS Aviation Safety Reporting System.

ATC Air Traffic Control.

CDTI Cockpit Display of Traffic Information.

CPA Closest Point of Approach.

DFW Dallas Fort Worth (airport).

DMOD Distance MODification (TCAS Range Variable).

FAA Federal Aviation Administration.

HLA High Level Architecture.

MIT Massachusetts Institute of Technology.

MOPS Minimum Operational Performance Standards.

PFD Primary Flight Display.

RA Resolution Advisory.

RFS Reconfigurable Flight Simulator.

RRT Rapidly-Exploring Random Tree.

SME Subject Matter Expert.

TA Traffic Advisory.

TCAS Traffic alert and Collision Avoidance System.

TGF Target Generation Facility (Air Traffic Simulator Software).

TSD Traffic Situation Display.

VSD Vertical Situation Display.

WDA Work Domain Analysis.

ZTHR Z (altitude) THReshold (TCAS Variable).

SUMMARY

The goal of this thesis is to improve pilot understanding of the Traffic alert and Collision Avoidance System (TCAS) by changing the Traffic Situation Display (TSD). This is supported by two objectives.

The first objective is to create an integrated, realistic air traffic environment. This serves as an experimental platform for testing and evaluating future TCAS TSDs. The simulator environment includes a desktop flight simulator, background air traffic simulator, and intruder aircraft. The intruder aircraft uses seven dimensional waypoints to robustly follow trajectories and cause specific resolution advisories.

Second, the relative benefits of, and potential concerns with, new TCAS TSDs are explored using a structured, iterative design process with subject matter experts (SMEs). Incremental changes to the TSD were implemented into the simulator environment. SMEs evaluated the displays and potential points of confusion were identified.

Several display features are discussed and implemented for future evaluations. These include boundary lines of TCAS variables depicted on the TSD and on a vertical situation display, speed lines which vary with the TCAS estimate of time to closest point of approach, and a prediction of the safe altitude target during a resolution advisory.

Scenarios which may be confusing or misleading are discussed. These scenarios may be ameliorated or exacerbated by display features. This information is useful to guide both design and certification or operational approval and is a starting place for future TCAS experiments.

CHAPTER I

INTRODUCTION AND MOTIVATION

The Traffic alert and Collision Avoidance System (TCAS), a system currently installed on all commercial aircraft, is designed to prevent airplanes from colliding: it is the failsafe when both air traffic control (ATC) and flight crew otherwise fail to identify and avoid a potential conflict. TCAS first alerts the flight crew with a traffic advisory (TA), followed by a resolution advisory (RA) in the form of a commanded vertical avoidance maneuver (e.g. climb or descend) predicted to prevent a mid-air collision.

Compliance to TCAS, i.e. flight crew following the commanded vertical maneuver, has been less frequent than expected. For example, in the set of RAs observed by the FAA-MIT Lincoln Lab TOPA project over a six-month period, only 50-60% of aircraft achieved a climb or descent greater than 400fpm during climb/descent RAs commanding 1500fpm [1]. This is a generous definition of compliance which demonstrates that many pilots are not following TCAS guidance. While compliance is not a goal in-and-of itself, the lower than expected compliance rate is an indication that pilots are not interacting with TCAS in the manner assumed with its design.

With TCAS, pilot decisions include any combination of complying with the commanded RA maneuver, ignoring the advisory, avoiding the proximate traffic with some other maneuver, and contacting ATC about the event. These decisions are informed by a variety of sources including flight deck displays, views out the window, and ATC. Further, the way in which information is presented to the pilot, combined with the pilot's knowledge base by which they interpret this real-time information, may impact their decision making process.

The timing of TCAS advisories and the vertical avoidance maneuvers appear complex and hard to understand to the pilot due to the fact that TCAS is computing real-time decisions based on data which may not be observable to the pilot and may be noisy, and via calculations not apparent to the pilot. This thesis examines the extent to which the TCAS Traffic Situation Display (TSD) may currently contribute to this problem, and how its design my ameliorate or exacerbate it.

Pilots have reported at times not understanding TCAS. For example, pilot quotes in the ASRS database suggest confusion based on the TSD:

> "*It was very hard to see [the other aircraft's] altitude as it was all cluttered together [on the traffic situation display]*"[1] (ACN: 840426, 2009) [2].

> "*Descending into an airplane that is clearly descending? TCAS software clearly did not give appropriate guidance, nor did it self-correct when the initial guidance was so clearly wrong*"[1] (ACN: 854982, 2009) [2].

An example of a TCAS TSD, drawn inside a navigation display, is shown in Figure 1. The TCAS TSD emphasizes threats based on spatial proximity. Thus, pilots looking at the TSD can quickly learn about the range and bearing relative to another aircraft. As traffic becomes proximate (within 6 miles horizontally and 1200 feet vertically) the traffic is highlighted to emphasize spatial proximity. However, spatial proximity often does not correspond to how TCAS assesses the need for an advisory. The TCAS logic invisibly computes the closure rate of intruder aircraft, how close these aircraft are predicted to pass, and how long until Closest Point of Approach (CPA). These computations are compared to multiple alerting criteria, and thus TCAS may alert based on the computed time or computed position. In addition to alerting for the TA and RA, TCAS calculates an avoidance maneuver resolution

[1] Pilot report to the Aviation Safety Reporting System (ASRS), identified by report accession number and year. The ASRS database is a repository of safety information provided by pilots, controllers, and other aviation personnel.

Figure 1: Example of a Current TSD (copied from [3])

during an RA by comparing projected miss distances for multiple resolutions to select both maneuver sense (i.e., climb or descend) and then a maneuver strength sufficient to create adequate separation.

In addition, TCAS changes operational modes in ways that are not visible or obvious to the pilot. The TCAS alert thresholds change with altitude, such that TCAS will alert sooner (longer time until closest point of approach) at higher altitudes [4]. Alerts are suppressed low to the ground. Pilots who become accustomed to the thresholds at low altitudes where alerts are delayed may become confused as to the reason why they get an alert earlier at a higher altitude.

In conclusion, TCAS appears to be difficult for the pilot to understand. There can be a gap between what TCAS computes and what the pilot understands. The TSD can be viewed as a filter that can potentially present the most important information in a timely way that supports the pilots in making sense of the TCAS advisories, and thereby improve pilot interaction with and understanding of TCAS.

Therefore, the goal of this thesis is to improve pilot understanding of TCAS by changing the TSD. This is supported by two objectives. The first objective is to create an integrated, realistic air traffic environment. This serves as an experimental platform for prototyping and evaluating future TCAS TSDs. Second, the relative benefit of, and potential concerns with, new TCAS TSDs are explored using a structured, iterative design process and evaluated in consultation with subject matter experts (SMEs) for situations where the TSD may help or hinder pilot understanding of TCAS.

CHAPTER II

BACKGROUND

This chapter discusses the existing literature relevant to this thesis. The first section reviews the history of TCAS, how it operates, current guidance on the TSD, and some common modes in which TCAS is used. Portions of a literature review of TCAS completed by a larger study of TCAS under DTFAWA-10-C-00084 [5] are included with some modifications inline to relate the literature review to the specific focus of this thesis: the TSD and pilot understanding of TCAS. The second section discusses the literature on display design relevant to the TSD.

2.1 TCAS

TCAS has been under development since 1981 by the Federal Aviation Administration (FAA). Installation is currently required on all commercial turbine-powered transport aircraft with more than 30 passenger seats or MTOW above 33,000 pounds; other aircraft have also been installing it voluntarily [4, 6]. TCAS has undergone extensive testing throughout its development and operation [7, 8]. Its aural alerts and logic for triggering advisories have been monitored and updated several times since its inception. The most recent update is TCAS II version 7.1 [9]; fast-time simulations of this version have shown improved alerting logic which reduces the risk of mid-air collision and false alarms [9]. The purpose of this thesis is not to comment on how TCAS operates; instead, it will accept that TCAS has been validated and currently works as described.

Table 1 discusses what information TCAS uses and how it obtains this information. Note that TCAS uses a lot of data from a variety of sensors. Much of the data is noisy and must be filtered. TCAS assesses the threat posed by other aircraft using logic that is not visible to the pilot. Some of the data can be shown to the pilot (e.g. intruder location and altitude), but other data is internal and cannot be shown easily (e.g. intruder range rate, various thresholds, and projected time to closest point of approach). These internal computations are complex in that they cannot be consistently explained with simple heuristics.

Table 1: How TCAS Works (based on [5])

This section highlights those aspects of TCAS II functioning relevant to pilot interaction with TCAS, as taken from several sources [9, 10, 11]. For the purpose of collision avoidance and alerting, TCAS does a very good job of sensing range and estimating range-rate through time differencing. In contrast, altitude is broadcast by each aircraft, encoded in its transponder signal; for the purpose of collision avoidance, the altitude information is comparatively poor because it is discretized into increments of 25ft by the Mode S transponders on other aircraft equipped with TCAS II and 100ft by the Mode C transponders carried by all other aircraft in Class A, B, and C airspace. (In other classes of airspace, older, small aircraft may still only fly with Mode A transponders which do not report altitude or fly with no transponder.) Altitude rate is estimated by time differencing the already-poor, discretized altitude measures, adding further variability. A directional transponder antenna, composed of several small antenna elements around a center, is used to estimate bearing; however, this bearing data has a standard deviation of 5 degrees and peak error of 15 degrees, which is comparatively poor for collision avoidance calculations even with elaborate filtering [12]. TCAS updates its calculations once per second, and at each update it evaluates several criteria to see whether a TA or RA should be issued. First, it examines the range between the aircraft: if either (1) range is less than a specified minimum range using the distance modification (DMOD-TA and DMOD-RA) or (2) estimated time to closest point of approach (CPA), also known as tau, is less than a specified minimum time threshold (tau-TA and tau-RA), then it additionally checks for predicted vertical separation. Similar to the distance calculations, the assessment of vertical separation considers whether either (1) the current vertical separation is less than a specified minimum (the altitude "Z threshold" or ZTHR), or (2) the estimated time to reach co-altitude is less than a specified minimum time (tau-TA and tau-RA). In cases of maneuvering or accelerating aircraft, the estimates of tau and time to reach co-altitude can vary so quickly between 1.0 second updates that the TA may be replaced by an RA quickly or immediately.

In addition, TCAS changes its thresholds and behaves differently at varying altitudes, invisibly to the pilot. This adds an additional difficulty to predicting what TCAS will do: there is not a simple mnemonic to teach the pilot that would always be correct or consistent because the system is changing. TCAS only uses altitude to account for traffic sensitivity, and does not consider airspace or context in the way a pilot may expect it to. A complete definition of the sensitivity levels and layers is provided in [10].

2.2 Traffic Situation Display

The TCAS Minimum Operational Performance Standards (MOPS) describe the minimum for the pilot interface to have a unit certified as TCAS [10]. These include minimum requirements for the TSD as discussed in in Table 2.

The TCAS MOPS instruct that the purpose of the TSD is to: "a. Aid in the visual acquisition of traffic and differentiation of intruder threat levels. b. Provide situational awareness. c. Instill confidence in the displayed resolution advisories."[10]. However, air traffic geometries are complex to visualize and understand. For example, explaining a traffic event post facto requires a great deal of description of the event from various viewpoints. In contrast, pilots only have limited time to perceive information about traffic (while simultaneously focusing on other flight deck tasks) before making a decision to act. Therefore, it is crucial to provide only the most important information to the pilot. While the pilot may choose to evaluate the traffic situation in detail at low-tempo intervals, he does not have time to interpret complex displays or display features in the moments before an alert. Likewise, data from TCAS must be presented in a way that is succinct and easy to interpret. This is a challenge because TCAS is not simple or easy to explain.

Previous research has examined a variety of Cockpit Displays of Traffic Information (CDTI). Rantanen and Wickens summarize various human factors criteria

Table 2: Requirements for the Pilot Interface, Including the TSD (based on [5])

The TCAS MOPS [10] provides minimum requirements for the three parts of the pilot interface: an auditory interface, a TSD, and a visual display of an RA's commanded avoidance maneuver. The auditory interface plays recordings of verbal commands. When a TA is triggered, the auditory interface calls out "traffic, traffic." When an RA is triggered, the auditory interface calls out the aural command corresponding to the commanded avoidance maneuver. If the RA is strengthened or reversed, appropriate aural commands are then given too. Finally, once an RA is removed (completed), the auditory interface calls out "clear of conflict." The minimum specifications for the TSD stipulate a horizontal plan view of neighboring aircraft relative to the own aircraft. An aircraft generating "no alert" or an "advisory alert" is shown as cyan or white unfilled diamonds. The "advisory alert," also described as "proximate traffic," portrays traffic within 6 nautical miles horizontally and 1200 feet vertically, and is shown as a filled diamond of the same color [4]. Traffic generating a TA is shown as yellow or amber circle, and traffic generating an RA is shown as a red square [11]. Should the heading information be available with Automatic Dependent Surveillance-Broadcast (ADS-B) or Traffic Information Systems-Broadcast (TIS-B), surveillance information may be integrated into the display by instead using directional symbols. Relative altitude is shown adjacent to the symbol in the same color, in numerals describing altitude in hundreds of feet; if the traffic is above the own aircraft the numerals are placed above the traffic symbol, and if the traffic is below the own aircraft the numerals are placed below the traffic symbol. Altitude may be valued relative to the own aircraft or as the traffic's absolute altitude MSL, depending on implementation; on some units, this may be selectable by the pilot. Similarly, minimum requirements for visual display allow for a wide range of specific implementations. "Retrofit" implementations add a "TCAS display" to established flight decks, showing the vertical maneuver on a vertical speed ring circling the TSD. "Integrated" implementations (common in new aircraft), in which the TSD is integrated into the navigation display, also visually portray the avoidance maneuver on the primary flight display (PFD) as an exclusion zone displaying allowable aircraft pitch or vertical speed.

found to be useful for displays of traffic information, including lessons learned from TCAS/ASRS reports [13]. A recommendation for future CDTI which interact with traffic alerts, such as provided by TCAS, proposes the inclusion of the following features: visual functions (e.g. leader lines) automatically restored with the auditory alert (because pop-up information provides visual alerting), acknowledgment of the role of time versus space in the display, and increased focus on vertical representation of traffic [13]. The literature also discusses some things specific to CDTI without considering integration with alerting, such as challenges in pilot visualization of climbing/descending traffic (e.g. how a 2D co-planar display combined with a vertical situation display increases conflict understanding more than a 3D display due to the ambiguity of collapsing a 3D volume onto a 2D display) [13].

Other previous work from Ho & Burns proposed design changes to the symbology on the TCAS TSD as shown in Figure 2 [14]. The proposed display has four key features. First, a red circle shows the predicted collision location. The time until loss of separation, referred to as tau, is displayed in text below the intruder symbol. A circle of unspecified size indicates the protected volume around aircraft. Finally, each aircraft has a groundspeed vector of unspecified length showing heading and velocity. The details of how this display works (i.e. the criteria for these features) was not published. Additionally, their work domain analysis (WDA) "revealed additional information [...] such as traffic history trends, traffic path prediction, explicit display of time-to-contact, and closure rate envelopes [as] viable candidates for further TCAS display research" [14].

Using displays to explain complex ideas has worked well in other domains. For example, a study varying the representation of moves in a Tower of Hanoi game changed the cognitive task of solving the puzzle such that the puzzle was completed in less time and with less errors [15]. The study asserts that "different processes are activated by different representations" (e.g. external representations versus internal

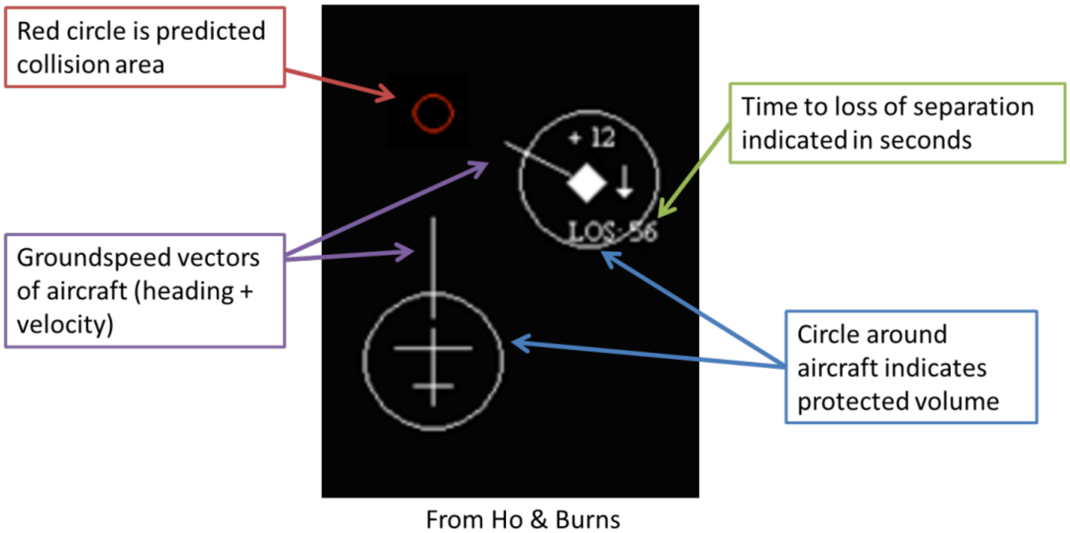


Figure 2: Traffic Situation Display Proposed by Ho & Burns [14]

representations). External objects (e.g. TCAS TSD) provide an external representation to a problem which can serve as a memory aid, provide raw information, anchor and structure cognitive behavior, or change the nature of a task.

For example, this principle was applied in the flight deck when a novel display was used to explain auto flight modes which use complex logic to automatically transition between modes, and to translate pilot commands of modes into accurate predictions of aircraft behavior. Specifically, a vertical situation display presented a vertical profile which revealed the current mode along with a prediction of when and where the auto flight mode would change modes. This novel display was found to explain the complex mode switching of auto flight systems successfully [16, 17].

The potential for the TSD to change behavior has also been found in a prior study of closely spaced parallel approaches which varied alert criteria and TSD features [18]. The study compared a baseline display, two different alerting criteria, and two alternate displays (where each display revealed one alerting criteria). When pilots were instructed to use their best judgment to avoid a traffic conflict, the combination of the display and alert criterion significantly impacted the results: an alert consonant with the display (i.e. the alert criteria matched the safe boundary displayed to the pilot) appeared to simplify the pilot's verification process. The study argues the need to build "alerting system awareness" into TSDs.

However, it is difficult to accurately motivate the same pilot behavior in flight simulator evaluations as the pilots would apply in real operations, and thus also difficult to test TSD designs. Of note, previous studies of the TCAS TSD and other CDTI have not incorporated a fully realistic air traffic environment. For example, a study at NASA Ames inspected the TCAS TSD in a part task simulator. However, pilots in this study were only looking at the TSD and did not have to balance a realistic workload [19, 20]. Another study of the TCAS TSD, which examined traffic symbology, incorporated a full motion simulator [21]. Background traffic was shown on the TSD as a distractor. However, air traffic communication was limited to only that necessary for the pilot and issued by the simulation instructor. The generated RA traffic was designed to produce specific RAs, but the actual RAs generated varied based on pilot maneuvering. Thus, these studies could not always control the full range of information sources, of which the TSD is one part, that may be available in the flight deck.

Finally, synthetic vision has been proposed and under developed since the late 1970s. The first FAA certified flight deck to use synthetic vision was the Gulfstream PlaneView in 2009. Several other glass cockpit systems have released synthetic vision systems since then (e.g. Garmin G1000). However, these displays currently do not depict traffic in any certified way. It is important that research is done on the good practices for displaying traffic on these displays. NASA has been heavily involved in research on synthetic vision, and is also working towards answering the questions regarding the display of traffic in their 3D CDTI research [22].

2.3 *Summary*

TCAS has been under development for over 30 years and has gone through many updates. Its use is required on commercial aircraft. TCAS uses altitude to change sensitivity levels with altitude without considering airspace or context (e.g. traffic routes) in the way a pilot may expect, and it relies on altitude information from transponders (broken into discrete 25 feet or 100 feet increments). TCAS uses time differencing to compute altitude rate and range rate which adds variability. To further complicate matters, TCAS separately considers horizontal and vertical information in evaluating alerts. For each intruder, once the estimated time to CPA is less than a specific threshold (horizontal and vertical tau), or range closer than a specific threshold (DMOD horizontally and ZTHR vertically), TCAS issues an advisory. The system operates with data that is noisy and cannot be shown easily to the pilot. Thus, simple heuristics cannot consistently explain how TCAS operates.

The TCAS MOPS give the specifications for the pilot interface including the TSD. The purpose of the TSD is to aid visual acquisition of traffic, to increase situational awareness, and to instill confidence in the resolution advisories. During a traffic encounter, there is limited time to display traffic information; presenting information clearly and succinctly is a challenge because TCAS is not simple to explain.

Previous research has been done on CDTI, TCAS TSDs, and other flight deck displays. This thesis incorporates the previous related research along with a new goal of improving pilot understanding of TCAS using the TSD. Another difficulty of TCAS TSD research which this thesis addresses is simulating the intruder aircraft displayed by the TSD.

CHAPTER III

OBJECTIVE 1: SIMULATOR SETUP

The first objective of this thesis is to create an integrated simulation of a realistic air traffic and flight deck environment to support prototyping and evaluation of TCAS components, including the TSD. In support of this thesis research and other research with the cooperative agreement under DTFAWA-10-C-00084, the Cognitive Engineering Center has prepared a simulator infrastructure. This section discusses the simulator infrastructure, along with a detailed discussion of a contribution by this thesis: guidance of the intruder aircraft to create a specified aircraft trajectory.

3.1 Simulator Interface

Simulating a complete air traffic environment, as perceived by a pilot, requires several components as shown in Figure 3. First, background nominal air traffic is provided by the FAA software "Target Generation Facility" (TGF) [23], which connects to the simulator infrastructure over the High Level Architecture (HLA). TGF replays data recorded from airport operations around the DFW airport and provides displays of the traffic environment, enabling an experimenter to play the role of an air traffic controller. Second, ATC communications have been studied and realistic transcripts of background and pilot commands have been established. Third, the "Reconfigurable Flight Simulator" (RFS) provides a desktop, fixed-based B747-400 simulator [24]. Fourth, a specific intruder aircraft is simulated to follow a trajectory which causes a desired traffic event, such as specific TCAS RAs. Finally, the TCAS logic as given in the TCAS MOPS [10] checks for a traffic event and issues a TA or RA. Traffic information is passed to the pilot's TSD, and an annunciator provides the aural TCAS messages.

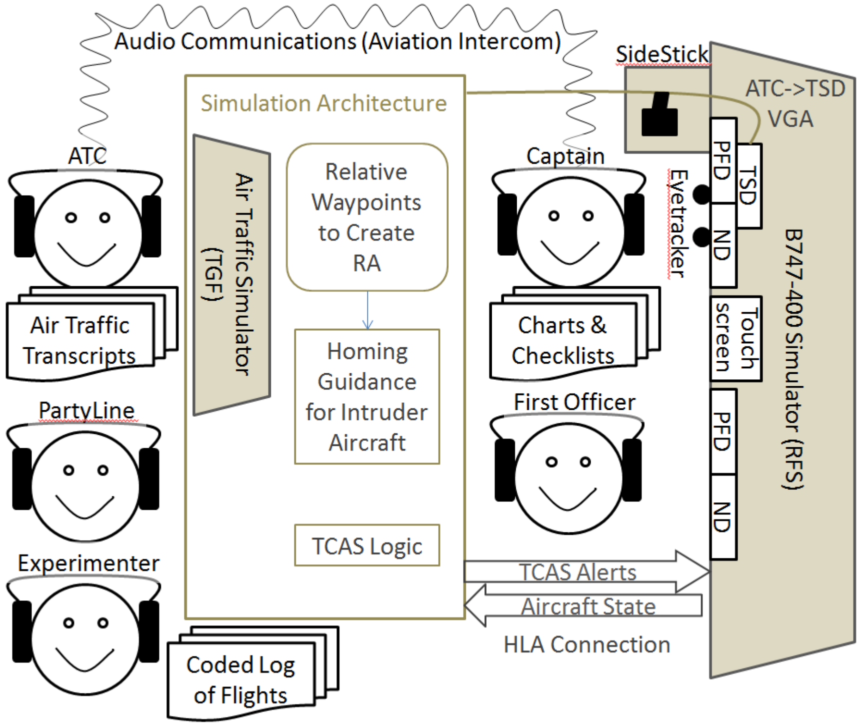


Figure 3: Overview of Simulator Setup (copied from [25])

The author was responsible for the system integration of all of these components, and worked with several other research assistants to collaboratively develop each of them. A launcher program starts each of these components for a single simulation run. The launcher is responsible for starting the simulation and handles the communication with each component. Messages about the location of each background aircraft are sent from TGF over HLA. RFS sends location of the ownship aircraft over HLA. The intruder aircraft get a copy of the ownship position information to update their guidance logic, which steers each intruder relative to the ownship. The simulation launcher also takes these aircraft location messages and forwards them to the TCAS logic every second. The outputs of TCAS are sent to the TSD, to an audio annunciator, and to RFS (for drawing any RAs onto the PFD). A TSD following the minimum specifications has been developed and is shown in Figure 4.

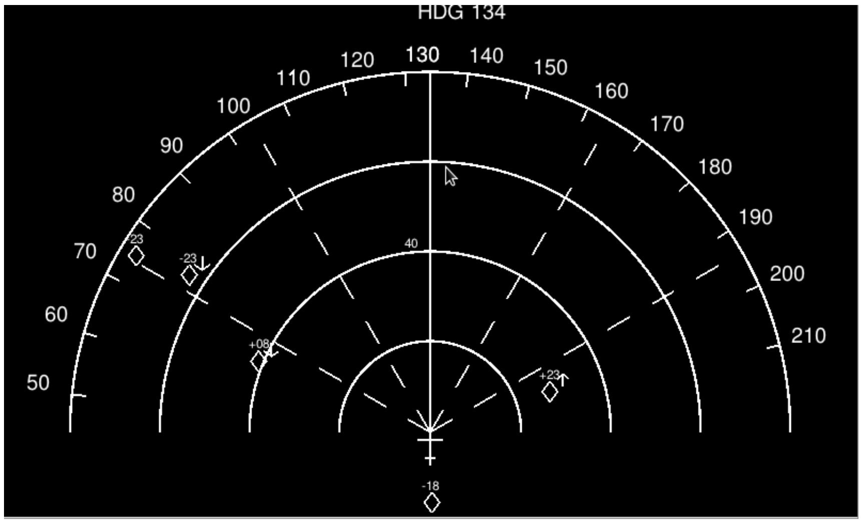


Figure 4: Implementation of the TSD Following the Minimum Specifications

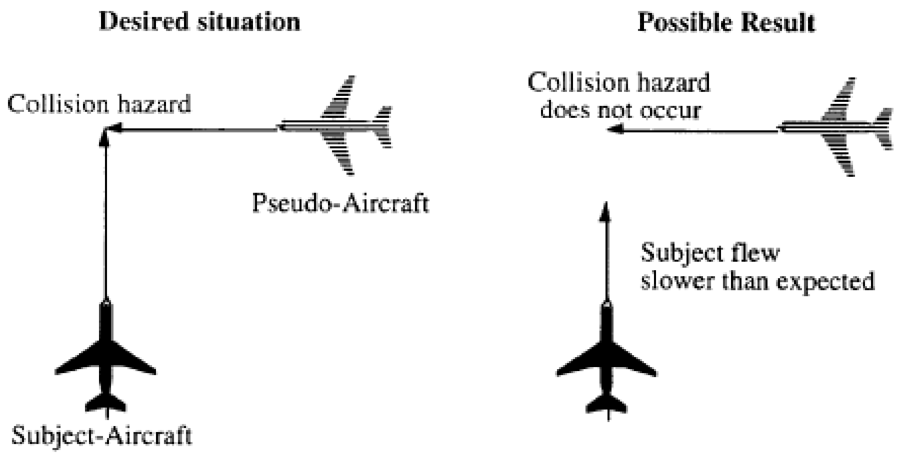


Figure 5: Comparison of Planned Collision Hazards (copied from [26])

3.2 Intruder Development

Generating traffic events, including specific RAs of interest, has been an issue in previous TCAS studies. If the pilot makes a small deviation in the flight simulator from the expected trajectory, a planned collision may not occur, as shown in Figure 5. For example, pilots can be given a specific clearance to descend or slow down at a specific time, but how they execute the clearance (e.g. "flight level change" versus "vertical speed" mode) can drastically change their trajectory.

Table 3: Aircraft States and Targets

State	Symbol	Units
Longitude	l	Degrees
Latitude	μ	Degrees
Altitude	z_{ft}	Feet
True Heading	ϕ	Degrees
Roll Angle	ψ	Degrees
Flight path angle	γ	Degrees
Airspeed	V_{KTS}	Knots

Target	Symbol	Units
Speed	V_T	kts
Heading	ψ_T	^{o}
Altitude	z_T	ft
Vertical Speed	VS_T	$^{\text{ft}}/_{s}$

To guarantee the pilot will experience a desired traffic event, the intruder must maneuver despite the variance in the pilot's trajectory. This is achieved by this thesis' application of robust intruder guidance. The intruder dynamics are based on an outer loop model aircraft using the equations of motion presented by Johnson [26]. Johnson's aircraft model was initially implemented in an air traffic simulation [27] and then modified for this simulation. The aircraft has seven states and four targets as shown in Table 3. However, only one vertical target is used at a time (either the altitude or vertical speed target).

To simulate the aircraft motion, the equations shown in Table 4 yield the state derivatives, which are integrated using Runge-Kutta fourth order integration [28] with a time step of 0.1 seconds. The limits in aircraft performance and gains shown in Table 5 and Table 6 were selected to yield performance similar to and reasonable for a large transport aircraft. The K_A term is a modifier to easily allow more aggressive turning if desired for a scenario. These were tuned by hand by comparing outputs of trajectories for a variety of step inputs until the aircraft trajectory seemed reasonable and appropriate based on the performance of a transport aircraft, as observable on the TSD.

The guidance assesses the outputs of this aircraft model (i.e. aircraft state) and computes the targets (target speed, heading, and altitude or vertical speed) for the aircraft model to track to specified waypoints. The guidance also recognizes when a

Table 4: Equations of Motion for Intruder Aircraft

$$\dot{l} = \frac{1}{3600} V_{kts}\ cosd(\gamma)\ \frac{sind(\psi)}{60 cosd(\mu)} \tag{1}$$

$$\dot{\mu} = \frac{1}{3600} V_{kts}\ cosd(\gamma)\ \frac{cosd(\psi)}{60} \tag{2}$$

$$\dot{z}_{ft} = V_{fps}\ sind(\gamma) \tag{3}$$

$$V_{min} \leq V_T \leq V_{max} \tag{4}$$

$$\dot{V} = K_V\ (V_T - V); |\dot{V}| \leq \dot{V}_{max} \tag{5}$$

$$\dot{\psi} = \frac{tand(\phi) g}{V_{fps}} \tag{6}$$

$$\text{turnRate} = \begin{cases} 3K_A & \text{if } V_{kts} < 250 \\ 1.5K_A & \text{otherwise} \end{cases} \tag{7}$$

$$\phi_{T_{max}} = atand(\frac{V_{fps} cosd(\gamma) \text{deg2rad}(turnRate)}{g} \tag{8}$$

$$\Delta\psi = \psi_T - \psi = [-180, 180) \tag{9}$$

$$\phi_T = K_\phi(\frac{V_{fps}}{g} K_\psi(\Delta\psi) - \phi); |\phi_T| \leq \phi_{T_{max}} \tag{10}$$

$$\dot{\phi} = K_\phi(\phi_T - \phi) \tag{11}$$

$$\dot{z}_T = \begin{cases} K_z(z_T - z_{ft}) & \text{if} |VS_T| < 0.1 \\ VS_T & \text{otherwise} \end{cases} = [-VS_{max}, VS_{max}] \tag{12}$$

$$\dot{\gamma} = K_\gamma(asind(\frac{\dot{z}_T}{V_{fps}}) - \gamma) \tag{13}$$

Table 5: Aircraft Limits

Constant	**Symbol**	**Value**	**Units**
Min Speed	V_{min}	150	kts
Max Speed	V_{max}	533	kts
Max Vertical Speed	VS_{max}	83.3	$^{ft}/_{s}$
Max Acceleration	$\dot{V}_{\max}$	2.0	$^{\text{kts}}/_{s}$

Table 6: Aircraft Gains

Gain	Value	Impacts
K_ψ	2.5	ψ
K_ϕ	2.0	ϕ
K_γ	2.0	γ
K_z	1.0	z
K_V	0.1	V
K_A	2.0	turnRate

waypoint has been passed, and it advances to calculate targets defining a trajectory towards the next waypoint. A waypoint has the properties as shown in Table 7. The equations shown in Table 8 compute the targets defining trajectories towards waypoints.

Table 7: Waypoint Properties

Waypoint Property	Symbol	Units
Longitude	l_{WP}	Degrees
Latitude	μ_{WP}	Degrees
Altitude	z_{WP}	Feet
Distance	d_{WP}	Feet
Time	t_{WP}	Seconds
Current Time	t	Seconds
Earth Radius	radius	20,902,231 ft

Table 8: Aircraft Guidance Equations

$$\Delta\ t = t_{WP} - t \tag{14}$$

$$\begin{gathered} a = sind(\tfrac{\mu_{WP}-\mu}{2})^2 + cosd(\mu)cosd(\mu_{WP})sind(\tfrac{l_{WP}-l}{2})^2 \\ c = 2\ atan2(\sqrt{a}, \sqrt{1-a}) \\ d_{WP} = \sqrt{[(\text{radius} + \tfrac{z_{WP}+z_{ft}}{2})c]^2 + (z_{WP} - z_{ft})^2} \end{gathered} \tag{15}$$

$$\psi_T = \psi_{\text{direct}} = atand2((l_{WP} - l)cosd(\mu_{WP}), (\mu_{WP} - \mu)) \tag{16}$$

$$z_T = z_{WP} \tag{17}$$

$$V_T = \frac{d_{WP}}{\Delta\ t} \tag{18}$$

Inspired by the work by Johnson [26], various types of waypoints have been implemented. The scenario shown in Figure 6 illustrates these waypoint types. First, a trigger waypoint activates the intruder aircraft at a specific location when the target aircraft passes a waypoint on its nominal path. Next, the intruder tracks toward a normal 4D waypoint(Lat/Lon/Alt positions at a specified time relative to the start time). Then, an intruder is commanded to a synchronization waypoint in which it varies its speed to reach the waypoint at the time when the target aircraft reaches a specified location. The guidance computer then actively steers the intruder to a predictive 7D waypoint, matching three dimensions on position, three on velocity, and one on time.

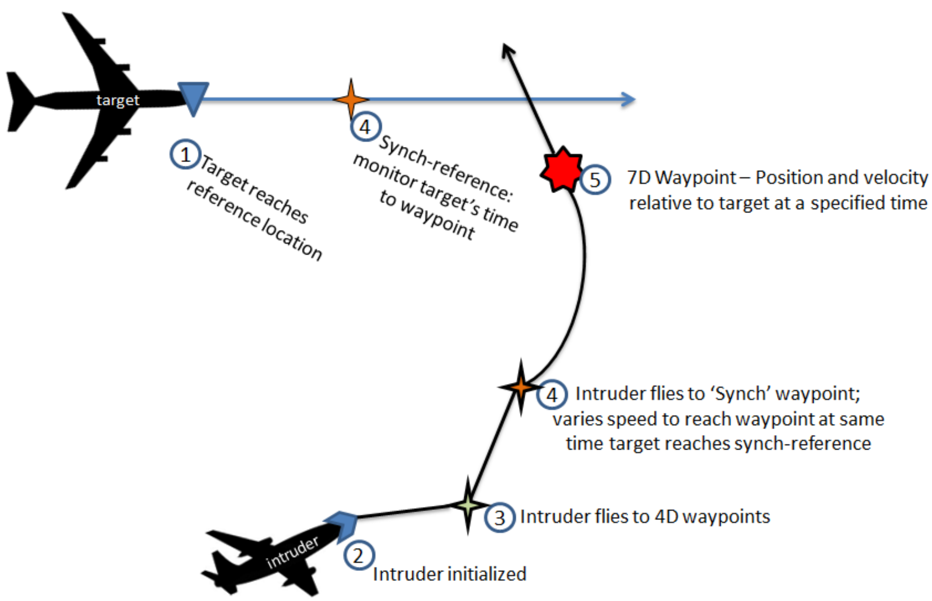


Figure 6: Intruder Waypoint Types Implemented

The 7D waypoint is novel in its ability to specify a specific flight path for the intruder in seven dimensions. Each of the waypoint's dimensions may be specified in absolute amounts or relative to a reference aircraft. The waypoints may command targets outside of the flight envelope of the intruder; the flight dynamics are constrained to stay within the limits given in Table 5 to maintain realism. In the event that the intruder cannot make the planned waypoint, it will advance to the next waypoint after either passing through the specified coordinates, disregarding altitude, or after passing through the specified waypoint time. For example, a 7D waypoint may specify the intruder to fly to a point 10NM directly in front of and level with the ownship 30 seconds in the future, with a velocity of 250 knots; additionally it should pass through the waypoint with a vertical rate of 200fpm and heading of 30^o. When this waypoint is given reasonable (reachable) specifications, it is robust and affords various methods to establish repeatable control over the intruder guidance.

For the intruder trajectory to reach the spatial location with the specified rates at a specified time, there is a difference between the direct path and a curved path which, when passing the waypoint, will yield the correct heading. An example of this navigation guidance during the 7D waypoints is shown in Figure 7 illustrating that the current heading target (ψ_T) is not the heading directly to the waypoint (ψ_{direct}). Additionally, the distance flown is not the straight distance to the waypoint (d_{wp}), but instead the aircraft flies along a longer curved distance to the waypoint (cd_{wp}). This allows the intruder to arrive at the waypoint with the specified heading and speed. A similar calculation ensures that the aircraft arrives at the waypoint with the correct vertical speed and altitude.

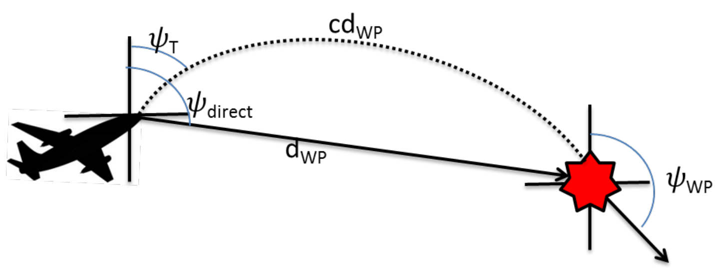


Figure 7: Illustration of Lateral Navigation of 7D Waypoint

The 7D waypoints have the properties shown in Table 9. To allow better tracking for the 7D waypoints, the equations are changed to those shown in Table 10 when an aircraft is flying to a 7D waypoint. Additionally, the guidance equations are updated to choose aircraft command targets which steer the aircraft correctly towards a waypoint and cause it to cross the waypoint with the specified rates, as shown in

Table 10. Additionally, a low pass filter is applied to the speed target using the last four commanded targets to compute a current target, which simulates the lag inherent in jet engines.

Table 9: 7D Waypoint Properties

7D Waypoint Property	**Symbol**	**Units**
Heading	ψ_{WP}	Degrees
Vertical Speed	VS_{WP}	ft/s
Speed	V_{WP}	Knots
Curved Distance	cd_{wp}	Ft
Gain	**Symbol**	**Value**
Turning Gain	K_{ψ}	50
Speed Gain	K_V	1.0

Table 10: Equations of Motion and Guidance When Tracking 7D Waypoint

$$\dot{\psi} = \text{turnRate} = K_{\psi}\ \Delta\psi\ , = \begin{cases} [-30, 30] & \text{if } V_{kts} < 250 \\ [-15, 15] & \text{otherwise} \end{cases} \tag{19}$$

$$\dot{z} = \dot{z}_T \tag{20}$$

$$\Delta\ t = t_{WP} - t \tag{21}$$

$$\begin{gathered} a = 2tand(\psi_{direct} - \psi_{WP})d_{WP}\sqrt{1 + tand(\psi_{direct} - \psi_{WP})^2} \\ b = 2d_{WP}asinh(tand(\psi_{direct} - \psi_{WP})) \\ cd_{WP} = \frac{a+b}{4tand(\psi_{direct} - \psi_{WP})} \end{gathered} \tag{22}$$

$$\psi_T = 2\psi_{\text{direct}} - \psi_{WP} \tag{23}$$

$$VS_T = 2\frac{z_{WP} - z_{ft}}{\Delta\ t} - VS_{WP} \tag{24}$$

$$\begin{gathered} V_{T0} = V_{WP} \pm \frac{cd_{WP}}{d_{WP}}\sqrt{|2(0.1g)(cd_{WP} - V_{WP}\ \Delta\ t|} \\ \alpha_{t-0} = 0.5; \alpha_{t-1} = 0.25; \alpha_{t-2} = 0.15; \alpha_{t-3} = 0.10 \\ V_T = \sum_{i=0}^{3} V_{Ti}\alpha_{t-i} \end{gathered} \tag{25}$$

Once the desired traffic event is achieved (either TA or RA), the tracking guidance is replaced with appropriate commands. For a TA, the guidance commands a strong descent if the intruder is below the target, or a climb if the intruder is above, to rapidly establish a diverging trajectory that will not also trigger an RA. For an RA, the intruder 'coasts' and maintains a current heading, velocity, and altitude rates, such that the current TCAS RA can be followed to escape the traffic. (If the intruder was commanded away itself, the RA would be unnecessary to follow; if the intruder continued to track the ownship, it would be unable to escape the traffic despite following TCAS.)

3.3 Implementing Desired Traffic Events

This thesis' contribution of intruder aircraft dynamics and guidance enables computational simulations to search through aircraft trajectories for traffic events of interest. A technique known as Rapidly-Exploring Random Tree (RRT) examines a large number of these trajectories to identify regions which could cause a specific RA [29]. Because of the large number of dimensions, this is an effective way to sample the space and characterize the relation between trajectories and RAs. Each trajectory was put into the TCAS logic to attain a map of which trajectories most reliably achieve RAs of specific strengths and senses.

RRT operates by simulating two aircraft. The initial set of six dimensional states are chosen for both the ownship and the intruder aircraft. The ownship continues along its current trajectory with its current rates. A seven dimensional waypoint is selected relative to the ownship, and the intruder adjusts its targets to fly to this waypoint. The simulation continually steps forward by one second to provide updates to the TCAS logic. Once TCAS issues an alert, or some maximum simulation time has been exceeded, the results are recorded, and RRT moves on to the next simulation run. The intruder initial conditions and intruder waypoints are varied along a specified range and number of possible discrete steps by the RRT algorithm. The output is separately analyzed by MATLAB scripts.

Current efforts seek to control the behavior of the intruder after the target aircraft receives an RA to further create strengthening or weakening RAs. This is accomplished by specifying a third waypoint for the intruder to advance to as soon as an RA is received. In the RRT assessment of the best location for this waypoint, the ownship follows whatever vertical speed target is commanded by TCAS, and the intruder's third waypoint is varied to create the desired change in RA.

For the real-time, pilot-in-the-loop runs, an intruder is defined by its waypoints, as well as some boolean flags as desired to change the behavior of the intruder outside of normal waypoint following. One flag determines if the intruder should generate just a TA. As discussed, a TA-only aircraft diverts with a climb or descent once the TA is achieved, while an RA aircraft continues until an RA is achieved and then 'coasts' by setting its command targets to its current state. Another flag allows the intruder to initialize and hold at a specific altitude for a specified duration. This is useful to initialize the intruder while the target is changing altitudes (and may be projected to be much lower in the future but will be leveling off at a known altitude as dicted by transcripts for ATC clearances).

In the first experiment of TCAS by the Cognitive Engineering Center, scenarios which used the RRT to define intruder waypoints yielded 110 RAs achieved out of 112 attempts. Each RA was specified to be a specific type (e.g. climb RA) and was successful in 82% of the runs that used RRT [29]. During the first experiment with sixteen pilots, eight pilots reported seeing no patterns in the traffic events. The other eight indicated some level of pattern recognition either in the traffic events or in the intruder. In three of the reports, pilots specifically indicated an ability to predict the intruder aircraft would cause an RA in some of the runs. However, the pilots did not specify the source of the predictability [25].

In conclusion, the simulator setup has been completely integrated. The intruder aircraft are simulated as described, and are capable of reliably generating traffic events, including RAs of prespecified strength and sense. This setup was used for the first three pilot experiments of TCAS by the Cognitive Engineering Center.

CHAPTER IV

OBJECTIVE 2: TRAFFIC SITUATION DISPLAY DESIGN

The second objective of this thesis is to examine new TSD features using a structured display design process. The first set of features, called the "TSD+," focuses on small, incremental changes that can be feasibly implemented or retro-fitted in a current generation cockpit. The second set of features, called the "Future TSD," gives an open look at a futuristic TSD spanning a larger screen and using novel display constructs such as synthetic vision.

The TSD design process presented in this thesis is an iterative loop as shown in Figure 8. First, the information that pilots would need to understand TCAS was considered. This was compared to several flightdeck displays to identify potential points of confusion and *design* initial display features. Next, the designs features were implemented in rough *prototypes.* Three airline pilots then served individually as subject matter experts (SMEs) to brainstorm and *evaluate* the first prototypes; their comments lead a *re-design* and *prototyping* before the SMEs returned a second time to *evaluate* the displays.

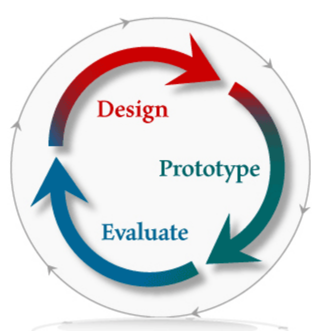


Figure 8: Iterative Design Process

The TSD design process followed the considerations and design process described in the book *Display and Interface Design* by Kevin Bennett & John Flach [30]. The book is written from the perspective of cognitive systems engineering and ecological interface design. It uses a triadic approach of domain, human, and interface to step through the display and interface design process. The book notes that interface design is not as simple as following a recipe. Instead, it provides core ideas and good practices, but notes that designs are usually an iterative process beginning with some "seed" (usually a problem or accident). The seed for this thesis is: "TCAS is difficult to understand." This differs from previous work on CDTI, which primarily focused on improving pilot awareness and understanding of the traffic [13].

4.1 Information for Pilot Understanding of TCAS

An earlier investigation of ASRS reports provided insights into how pilots may be confused by TCAS [2]. Of the investigated 278 reports, 7.9% conveyed a negative impression of TCAS citing these reasons: unclear information on the TSD (13.6%); pilot thought TCAS assigned a collision course (50.0%); the pilot was overloaded (9.1%); or some other reason (27.3%). Some these ASRS reports also described specific points of confusion. For example, "*Just then our TCAS gave an RA, 'Descend, crossing, descend.' The Captain said something to the effect of, 'I'm not doing that. He's descending, we'll descend right into him' and did not follow the TCAS RA*" (ACN:854932).

To increase pilot understanding of the TCAS logic, then, may require pilots to know more information about TCAS. However, the complexity of the TCAS logic is illustrated in Figure 9 [10]. Further, the ecology of the flight deck also includes other air traffic, ATC, and the airspace system. In a broader look at the ecology, it is difficult to imagine the pilot understanding TCAS without also understanding many aspects of the underlying traffic geometry and air traffic patterns. Therefore, it is important to present the underlying traffic geometry to the pilot in an efficient way which is consonant with the TCAS advisories and the underlying logic.

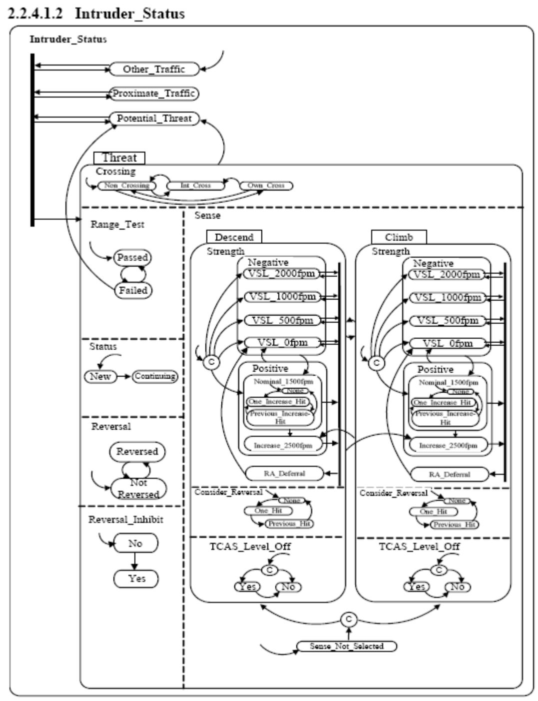


Figure 9: Illustration of the TCAS Logic from the MOPS (copied from [10]).

Further, definitions of "understanding of TCAS" were considered based on the FAA's Introduction to TCAS [9]. Based on its explanations of TCAS, the five items in Table 11 are a part of understanding of TCAS. They can be broken into phases of detection, resolution generation, and the outcome anticipated from following an RA.

Table 11: Definitions of Understanding of TCAS

- Understanding of tau and its dependence on rates
- Ability to predict when TCAS will issue advisories based on its horizontal and vertical thresholds (e.g. ZTHR, DMOD, range tau, and vertical tau)
- Knowledge of the types of RAs that may be generated
- Ability to predict which advisory will be given (e.g. maneuver selection based on ALIM, strength selection, and crossing RA bias)
- Understanding of the outcome of following an RA

For this thesis, the most important aspects of the TCAS alerting logic were identified as shown in the flowchart in Figure 10. First, TCAS uses slant range to perform a range test. It uses numerical differencing to compute range rate, and both range and range rate are compared to estimate range tau (time to closest point of approach). The range is compared to DMOD and the tau is compared to a critical threshold (with different DMOD and tau thresholds for a TA versus an RA and varying with altitude). If either condition is met, a similar vertical test is performed using relative altitude; if either vertical condition is met, the vertical test is passed and TCAS triggers an advisory. Thus a TA or an RA can be triggered by any combination of proximity and convergence in both slant range and altitude.

Once the criteria for a resolution advisory is met, TCAS chooses the maneuver sense as shown in Figure 11. TCAS uses the intruder's relative altitude, vertical speed, and time to CPA to predict the intruder's altitude at CPA. Nominal climb and descent maneuvers (1500 feet per minute) are projected to estimate the vertical separation achieved by the maneuvers. If the non-crossing maneuver achieves ALIM, that maneuver is selected. This preference for non-crossing maneuvers is referred to as the crossing RA bias. Otherwise, the maneuver sense which provides the greatest separation is selected.

Once a maneuver sense has been selected, TCAS then chooses the least disruptive RA strength (i.e. one which causes minimal changes to the flight path) as shown in Figure 12. The first vertical speed strength evaluated is zero feet per minute and the maneuver is simulated to predict the vertical separation at CPA for the given vertical speed. If ALIM is not achieved, progressively stronger maneuvers are evaluated, each adding 500 feet per minute until a strength is found that provides ALIM at the CPA.

Based on this summary of the TCAS logic, variables important to TCAS are shown in Table 12. A more extensive list of TCAS variables is included in Appendix A relative to potential display features that can portray them.

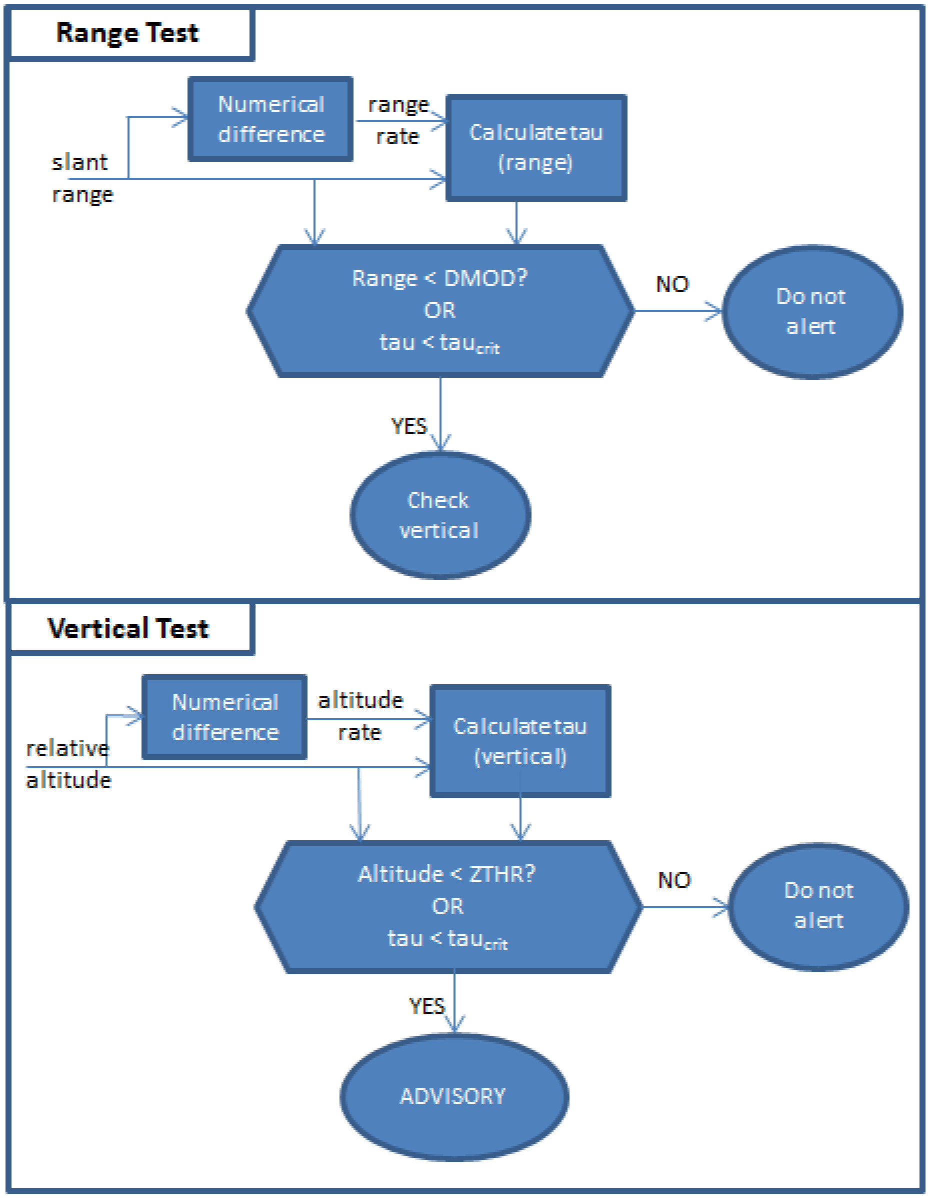


Figure 10: Simplified Flowchart of the TCAS Logic for Alerting

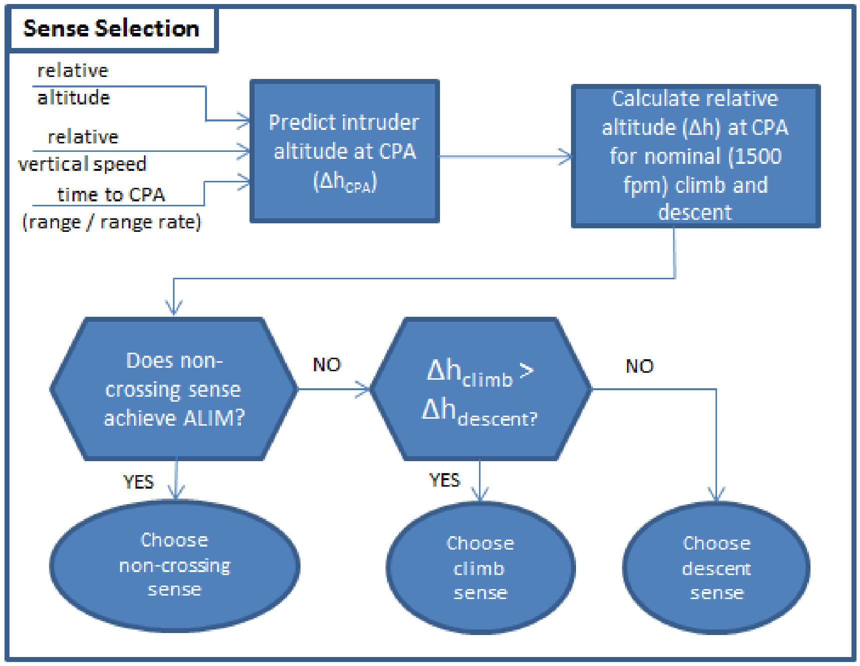


Figure 11: Simplified Flowchart of the TCAS Logic for Sense Selection

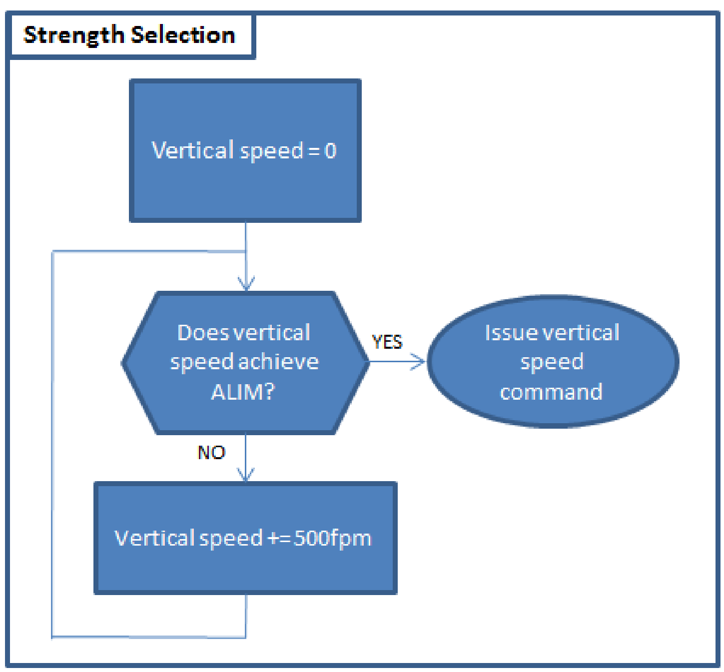


Figure 12: Simplified Flowchart of the TCAS Logic for Strength Selection

Table 12: Key Variables Important to the TCAS Logic

- Range
- Range rate
- Range tau
- Range $tau_{threshold}$
- DMOD
- Relative altitude
- Altitude rate
- Vertical tau
- Vertical $tau_{threshold}$
- ZTHR
- ALIM
- Predicted Relative Altitude for Climb and Descent Maneuvers

The information content of TCAS was also examined via an abstraction hierarchy of TCAS and collision avoidance, as developed by Ho and Burns [14] and displayed in Figure 13. Based on this abstraction hierarchy and knowledge of TCAS, Ho and Burns identified the features shown in Table 13 as important to understanding of TCAS during a traffic conflict. Small differences between Table 12 and Table 13 reflect the focus of this thesis on understanding of TCAS compared to their focus on an understanding of the traffic picture.

It is important to note that Ho and Burns describe tau as a measure of predicted time until closest point of approach. However, no one tau value represents the set of important TCAS variables. TCAS modifies the tau alerting boundaries to account for aircraft at close ranges and slow closure rates because of DMOD. Additionally, TCAS separately evaluates the horizontal range rate to calculate range tau and the vertical altitude rate for vertical tau [9].

In Table 13, the last four items regarding trajectories are a part of the *physical function* within the abstraction hierarchy. Though not discussed in [14], these items can be further broken down into their respective *physical forms*, which include the following:

Table 13: TCAS Features from Abstraction Hierarchy by Ho and Burns

• Tau	• CPA
• Lateral Separation	• Ownship Path & Predicted Path
• Vertical Separation	• Intruder Path & Predicted Path
• Lateral Closure Rate	• Avoidance Maneuver Path
• Vertical Closure Rate	• Collision Threat Invoking Path

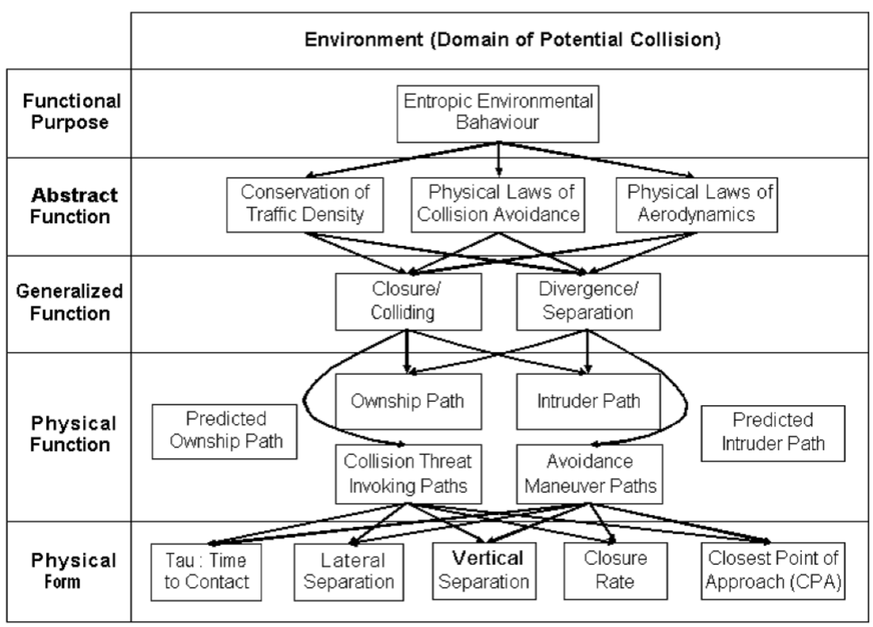


Figure 13: Abstraction Hierarchy of TCAS Collision Avoidance

- Current Path (Ownship & Intruder)
  - Three dimensional location
  - Groundspeed
  - Vertical rate
- Predicted Path (Ownship & Intruder)
  - Horizontal location at future time
  - Vertical location at future time
  - Waypoints where the path may change
- Collision Threat and Avoidance Maneuver Paths
  - Vertical rate commanded
  - Separation provided by commanded path

In summary, Table 12 reflects the key variables important to the TCAS logic. In theory, they could allow the pilot to do two things: predict when an advisory will be issued, and understand the commanded maneuver and the vertical separation it affords. The next section discusses how these variables can be represented in the flightdeck.

4.2 Representing TCAS on Flightdeck Displays

There are currently five common flightdeck display types: (1) a *2D Front View* is a Y-Z (i.e. side-to-side relative to heading and up-down relative to current altitude) view most similar to a current PFD with a view out the front of the airplane; (2) a *2D Plan View* is a top-down, X-Y (i.e. side-to-side and along-track) view, and is normally used for current TSD; (3) a *2D Side View* is an X-Z (i.e. a vertical profile ahead of the aircraft) view of altitude versus distance, and is often called a Vertical

Situation Display (VSD); (4) a *3D Egocentric View* is similar to the PFD, with a 3D depiction of the aircraft out of the front window view; and (5) a *3D Exocentric View* is most similar to the navigation display, as the pilot can see the ownship and path, but uses a 3D depiction. A sixth display type provides a *Timeline View*.

Each of these six display types were considered during the initial brainstorming for how to display traffic geometry in a manner consonant with TCAS advisories. Each of the key variables important to TCAS, listed in Table 12, was evaluated as to how it could be depicted on each of these five displays. The full table, including other TCAS variables, is produced in Appendix A describing potential display features for each aspect of TCAS.

However, in selecting which information to represent, it is useful to consider both "What would the pilot like to know?" and a physics or air traffic view such as "What does the pilot need to know for appropriate responses?" For example, pilots have been shown to prefer TSDs which include directional information, but these TSDs have not been shown to improve (or hinder) performance [21]. There are other similar trade-offs, such as showing raw traffic data versus the TCAS computations of that data (such as calculations of tau from range and range rate), and continuing with familiar displays versus implementing novel displays.

The following sub-sections discuss how these aspects of TCAS can be represented on each display type. Some of the features were developed after iterating with the subject matter experts. The displays will be discussed in full here, with subject matter experts evaluations described in Section 4.3. Of note, every type of display (2D Plan, 2D Side, 2D Front, 3D Egocentric, 3D Exocentric, and Timeline) may be better or worse at representing different conditions, such as TCAS' response to different traffic geometries. Thus, trade-offs inherent to the design of each display are noted throughout, including identifying characteristics of traffic event that each display is better (or worse) at representing.

4.2.1 2D Front View TSD

As shown in Appendix A, many of the TCAS variables cannot be represented very well on a 2D Front View, such as portraying traffic on a PFD. This display could easily become cluttered by traffic targets, and traffic information may distract from the main use of the attitude indicator and flight director. Additionally, traffic not on a parallel course is hard to display because the display's field of view is straight ahead. Thus, traffic converging from the side will be outside the display for most of an initial convergence course, and the traffic will transit across the display quickly once it is in view.

Further, arrows and trends can be misleading on this type of display. An up arrow next to an aircraft could be an indication of climbing as on the traditional TSD, but some symbolic representation is also needed in this display to indicate when the traffic is moving further ahead or behind.

A previous study did examine displaying traffic on the PFD during the special case of closely spaced parallel approaches [31]. In this experiment, the traffic was depicted relative to the own aircraft flight path symbol to indicate horizontal position and relative altitude. Text adjacent to the symbol indicated the third dimension, i.e., intruder distance in front of or behind the ownship. After using this type of display during the experimental task of maintaining safe separation from aircraft blundering from closely spaced parallel approaches, pilot opinions were mixed (different pilots criticized and praised the same features). This display caused pilots to perform less-early maneuvers, but pilot performance was degraded with the enhanced displays (evidenced by a significantly higher incident, or near miss, rate). Additionally, this display tended to increase pilot non-compliance to TCAS-like commanded maneuvers.

4.2.2 2D Plan View TSD

As mentioned previously, a 2D plan view TSD naturally emphasizes spatial proximity, which does not always correspond with the most threatening intruder. Additionally, the display promotes reasoning in the horizontal plane by the pilot, and thus horizontal resolutions. However, TCAS issues vertical advisories. Altitude information is shown in text which requires semantic processing. Altitude rate is shown in only one of two discrete senses: climbing or descending more than 500 feet per minute is shown by an up or down arrow respectively, while the absence of an arrow implies a vertical rate less than 500 feet per minute.

Because the origin of the display is moving with the ownship, horizontal relative motion of two aircraft can be confusing. For example, consider a speed vector oriented in the direction of the intruder's track. Because both the ownship and intruder aircraft are moving, the pilot must work to determine if the aircraft are on a collision course and how to avoid it. The speed vector also changes depending on if it shows absolute or relative motion. For example, if a speed vector is absolute and pointed directly at the ownship, the intruder is no threat; it will pass behind as the ownship moves forward and out of the way. Instead, the troubling cases are when the intruder and ownship will end up at the same future location in front of the ownship (requiring estimates of relative motion). Additionally, the traffic does not appear to move along its absolute speed vector: the intruder will often appear to track a different path on the TSD. This difference in the relative motion of two aircraft versus the TSD is illustrated in Figure 14, where the aircraft are on a collision course; the relative position of the aircraft are converging yet the absolute speed vector is not pointed 'at' the ownship.

Showing the heading (or track) of the intruder is possible with new data sources such as ADS-B, and may help ameliorate some of these concerns. Aircraft directional symbols can be taken from an established symbol set [33], as shown in Table 14. A

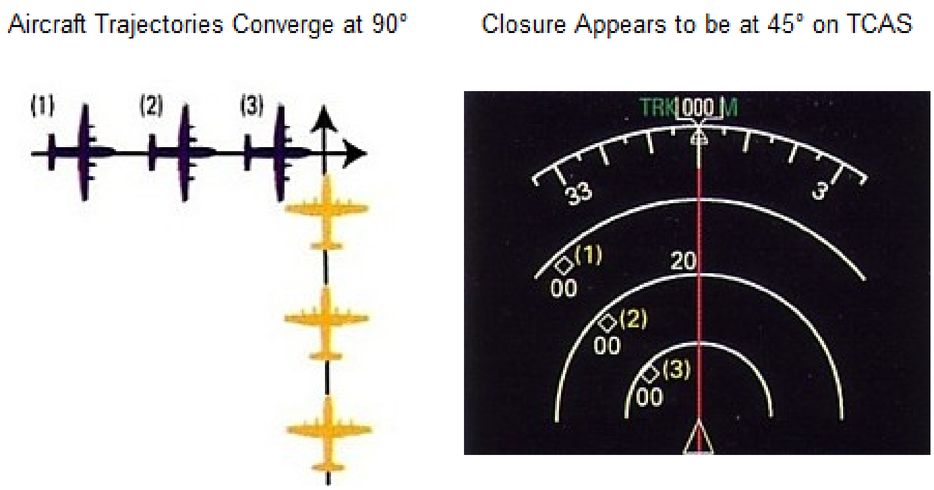


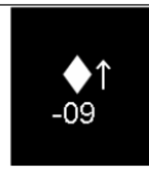
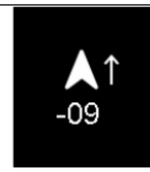
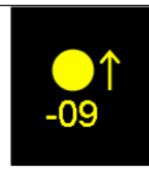
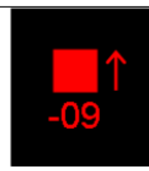
Figure 14: Aircraft Relative Motion on a Converging Course (copied from [32])

study by Olson found these symbols did not have a negative impact on pilot response to TCAS [21].

As another mechanism for display intruder track, breadcrumbs can display the previous locations of an intruder aircraft. Each 'crumb' is a small dot, the same color as the intruder, 'dropped' every few seconds (or other configurable amount). Breadcrumbs can also be selected for absolute or relative coordinates; this choice is not a standard and could lead to confusion if implemented differently (or if pilots think that one is the other). As shown in Figure 15, the relative coordinates show the aircraft's previous position on the TSD, and thus the direction of travel suggested by the breadcrumbs does not match the directional symbol of the intruder aircraft. The absolute coordinate breadcrumbs do follow the intruder's directional symbol, but would need to shift on the display by the ownship's movement.

The display of absolute speed vectors for the ownship and intruder aircraft based on groundspeed can reveal aircraft on a converging course. The vector's length can be set to represent a fixed time. In particular, setting the length of the line to the horizontal tau approximation time to CPA can be used to visualize the future location of both aircraft at CPA, as shown in Figure 16.

Table 14: Standard and Directional TCAS Symbols (copied from [21])

TCAS Symbol State	**Standard Symbol**	**Modified Symbol**
Other Traffic		
Proximate Traffic		
Traffic Advisory (TA)		
Resolution Advisory (RA)		

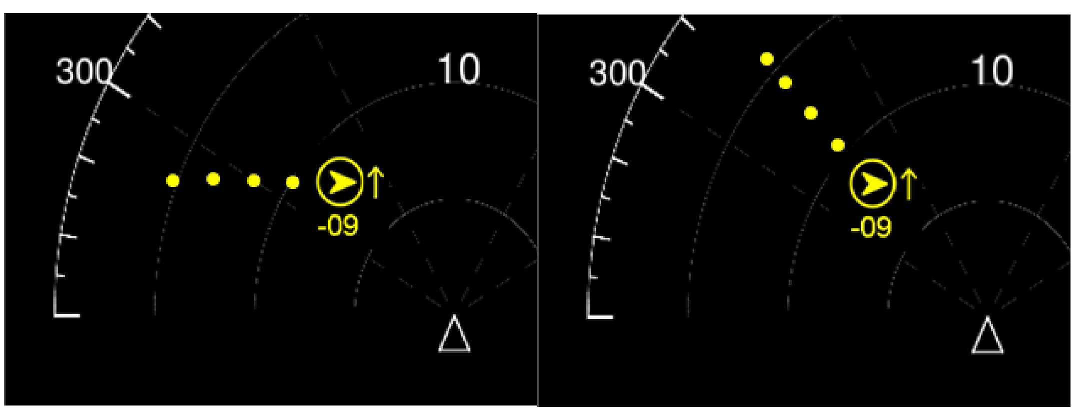


Figure 15: Breadcrumbs in Absolute (left) and Relative (right) Coordinates

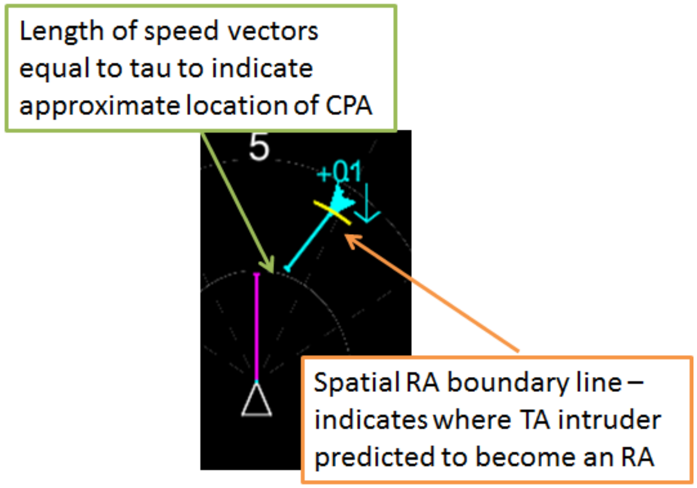


Figure 16: Variable Length Speed Vector and Spatial Boundary Line

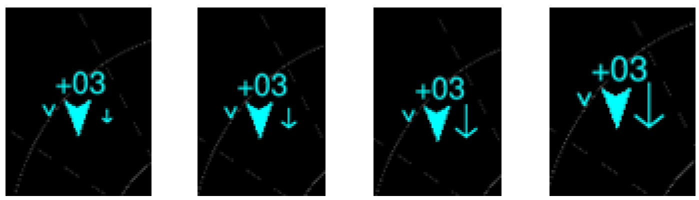


Figure 17: Target Squawking VFR and Variable Sized Descent Arrows

Finally, a spatial representation of TCAS' alerting thresholds on tau can reveal when an intruder has satisfied the range tau threshold for TCAS by passing a boundary line as shown in Figure 16. If the target also satisfies the vertical criteria, it will become a TA or an RA target. The location of the boundary line is based on the current sensitivity level for the range tau threshold and one of two things: either range rate, or the ratio of intruder current range to intruder current range tau as shown in equation 26.

$$r_{boundary} = \tau_{threshold} \times \dot{r}_{intruder} = \tau_{threshold} \times \frac{r_{intruder}}{\tau_{intruder}} \tag{26}$$

It is also possible to encode additional information in the symbology as shown in Figure 17. For example, a small 'v' next to a target could be used to identify targets squawking VFR. With increased altitude information from aircraft, the climb or descent arrows could scale with vertical rate.

The inclusion of all these features — particularly on a multi-function display that has other uses beyond a TSD — raises concerns with clutter. These concerns were discussed extensively with the subject matter experts, as discussed later in Section 4.3. Methods for ameliorating concerns with clutter include triggering the display features only in certain conditions of interest.

4.2.3 2D Side View TSD

While 2D side view displays, or VSDs, are now being implemented in flight decks, traffic is not currently shown on them. Guidance for VSDs suggest that they should only display information from a swath, i.e., a horizontal cross-section of the flight path ahead of the aircraft, and that the swath should be depicted on the navigation display [34]. An example of a VSD is shown in Figure 18. In this figure, lines on the plan display (above) indicate the width of the swath; if objects inside the swath are shown on the VSD (below), only 'A' would be shown in the VSD. This makes sense for static features such as terrain or weather, but does not work for depicting traffic; for example, even though an aircraft at the current time may be outside of the swath, the traffic may be converging and generate a TCAS advisory before entering the swath.

Instead, traffic may be projected onto the swath in two ways. In Figure 18, aircraft 'B' could be projected by its along-track component and shown at 'B1,' or it could be projected according to its range, which would place it at location 'B2'. Either method of projection may cause ambiguity or confusion. Cross-track projection shows the same traffic at different ranges on the 2D plan view than the VSD. Additionally, as the ownship turns, the target may appear to change range as its cross track projection changes. On the other hand, projecting traffic based on its absolute range, regardless of bearing, could be confusing relative to other aircraft and display features (e.g. terrain). These other features may appear on the VSD to

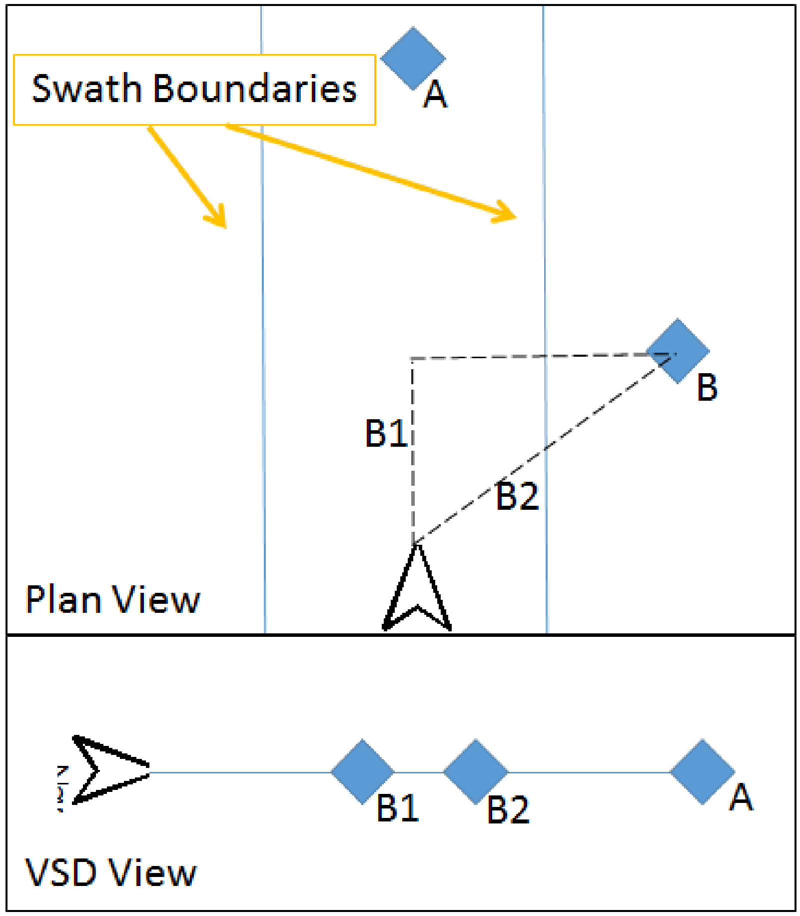


Figure 18: Features from a Plan View (above) Shown on a VSD (below)

be co-located with the traffic despite being at different bearings, and can imply that traffic is straight ahead when it is to the side or behind. Additionally, multiple targets may need to be displayed at similar ranges from different bearings although they may be at different altitudes; such concerns with overlapping traffic may be mitigated by prioritizing traffic information by only displaying the most imminent traffic [35].

Similar to speed vectors on the 2D plan view, showing the vertical speed vector on a VSD could indicate an absolute or relative speed with respect to the ownship vertical speed. Again, both choices are reasonable and depict good, but different, information. Additionally, vertical speed vectors could display a total value or a projected value of speed based on cross-track (similar to projections of range on the VSD).

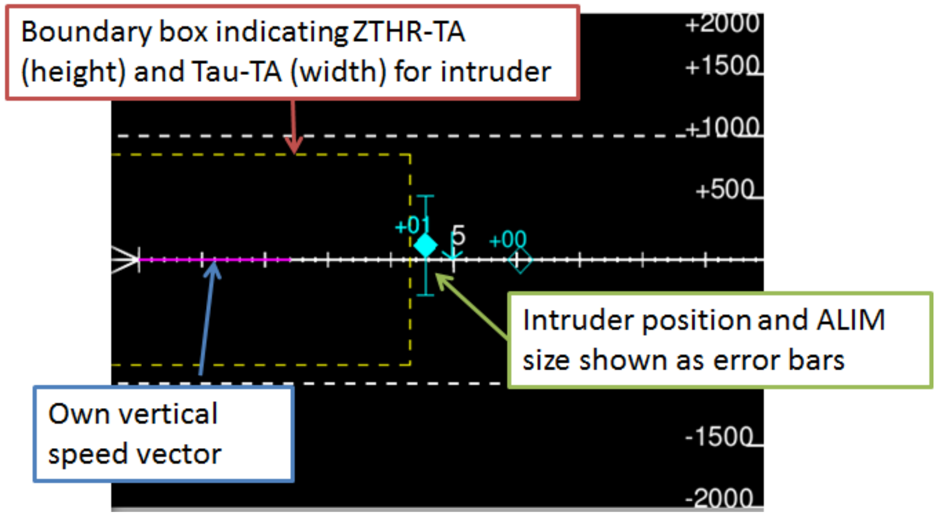


Figure 19: Annotated VSD During TA

A VSD prototype was implemented in this thesis. It is shown in Figure 19 during a TA. The VSD depicts an intruder on a display with range on the horizontal axis and altitude on the vertical axis; the ownship is fixed to the left edge of the screen. The intruder is positioned to the right based on range and does not consider the horizontal bearing to the intruder (e.g. an intruder 3 miles behind will still be depicted on the 3 mile mark ahead on the VSD). It uses the color and intruder symbology to match the 2D plan view (i.e. the symbol changes with the TA and RA).

A swath was chosen for the VSD to be $\pm 30^o$ of bearing, which matches lines currently being drawn on the implemented 2D plan view TSD. This is a reasonable choice for traffic as it allows a wider look ahead area at greater distances, and concentrates on the area in front of the ownship. Further, any intruder triggering a TA or RA is automatically shown regardless of its bearing. However, VSD presentations of other features, such as weather and terrain, may prefer a different swath. Thus some trade-offs may need to be considered for integrating traffic into multi-function displays.

The VSD has these selectable features: vertical speed vectors of both the ownship and intruder, intruder altitude limit (ALIM) boundary lines, horizontal tau boundary lines, and vertical rate goal lines. The vertical speed vector depicts the ownship vertical rate. It is fixed to the ownship and drawn in white. In Figure 19, the rate is zero and therefore the line is horizontal and hidden by the axis line. The vertical speed vector is based on vertical speed and groundspeed.

The intruder's vertical speed vector, also based on absolute vertical speed and absolute groundspeed, can be shown fixed to the intruder. This can depict the absolute (non-projected and non-relative) vertical and horizontal rate of the intruder; the color can match the color of the intruder's symbol. However, unless new information sets are available (such as ADS-B), this can represent a fairly noisy variable.

The ALIM boundary lines are depicted as lines extending vertically from the center of the intruder, similar to error bars, representing the altitude that the TCAS advisory seeks to avoid. In Figure 19, ALIM is 300ft above and below the intruder, but ALIM varies based on sensitivity level. Thus, the height of these boundary lines can vary.

The boundary box shown in Figure 19 represents the protected volume of TCAS, similar to the spatial tau boundary line on the 2D plan view TSD. The width of the box to the right of the ownship corresponds to the mimimum of either the tau threshold on range given the current range rate or DMOD. The height corresponds with the altitude for which an intruder will alert based on ZTHR. An intruder with a high relative vertical rate may be vertically outside of the box but cause an advisory because it is projected to enter the box by CPA.

The pilots' task changes during an RA when the TCAS output also includes a commanded maneuver, allowing new features as shown in Figure 20. The vertical rate goal line depicts the commanded TCAS RA maneuver, shown in red from the ownship. To emphasize the avoidance area, it is filled with has marks. The maneuver is projected to climb to cross above the intruder by an altitude exceeding ALIM at CPA. However, if the intruder has a significant vertical rate then the projected ALIM

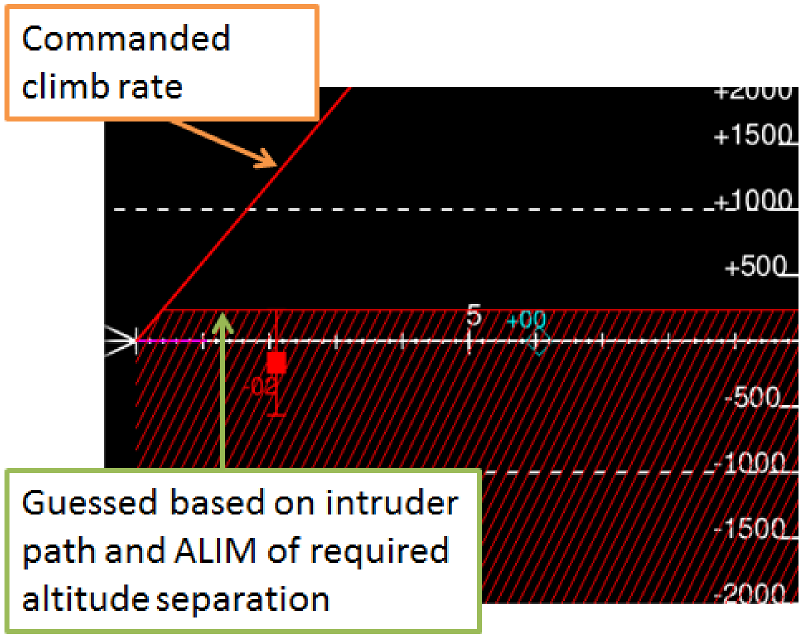


Figure 20: Annotated VSD During RA

altitude target at CPA can be quite different from the sum of current intruder altitude and ALIM. Further, the projection will change as the intruder varies its vertical rate. Thus, only portraying boundary lines showing ALIM relative to the current intruder altitude does not show the actual altitude target. Additionally, showing the immediate estimate of ALIM at CPA would require additional symbology in this limited display space, and would portray a changeable projection.

Similarly, the maneuver sense and strength selection could be shown by comparing various climb and descent commands. However, this information easily clutters the display and is hard to depict. Sense selection is only calculated by TCAS at the time an RA is triggered (preventing preview by the pilots), and might be too much to interpret during an RA when the pilot is expected to make a quick response. The pilots later indicated that they prefer this type of information to be hidden, and TCAS should just tell the pilots what maneuver is best.

Once the ownship has flown the RA and achieved ALIM, TCAS often weakens the alert to "monitor vertical speed." It is possible to predict this level-off altitude

Figure 21: Example Egocentric Display (copied from [36])

by comparing the projected the ownship and intruder future locations (in the same manner TCAS does) with the current ALIM threshold. The current estimate of the future level-off altitude is shown with the hash marks in Figure 20, and the estimate becomes more accurate as the RA progresses.

4.2.4 3D Egocentric View TSD

A 3D egocentric view is most similar to the current PFD. It differs in that, when used in synthetic vision displays, external features such as terrain are often depicted using a 3D perspective view. This is often overlaid with symbols reflecting an orthogonal viewpoint (e.g. a pitch ladder) and other text and symbols. An example of an egocentric view is shown in Figure 21.

If an intruder is visible in the field of view, it can easily be depicted on the screen. If the traffic is off-screen, an icon or docked symbol can show an approximate direction (and aid the pilot in visual scanning). Intruders can be drawn with appropriate symbology to match the fidelity of the data (i.e., symbols can be large and blocky for approximations of intruder locations; ADS-B equipped aircraft could be shown with a more photo-realistic symbology). Because of the familiarity of the current TCAS display and symbology, traffic displayed on a 3D egocentric display should use similar conventions. The symbols could be drawn as 3D shapes (diamond, sphere, and cube or directional delta versions of these), or the symbols could be more shaped like an aircraft and highlighted with circles or squares during an alert.

However, this display view does not inherently show the range to the intruder, requiring some coding or additional semantics. For example, the traffic symbol can be sized based on range; it can be difficult, though, to discern the difference in size between aircraft symbols. Traffic is comparatively small compared to an external scene, and thus the symbols may need to be larger than life. Additionally, the traffic grows quickly as it gets closer (a phenomenon referred to as blooming). Thus, distant traffic may need to be enlarged, and proximate traffic may need to be shrunk so that it does not fill the screen. Other methods of depicting range include using text as discussed for the 2D front view. Thus, it is not clear if there is a benefit from drawing traffic on an egocentric display, similar to the concerns noted in Subsection 4.2.1.

However, as on the PFD, the resolution maneuver can be portrayed on an egocentric display. The maneuver guidance could replace any drawn route information (such as carpet paths to follow or tunnel-in-the-sky depictions), or provide a second path following the RA. An example of a egocentric display with a tunnel in the sky route is shown in Figure 22. Or, the display could instead use a more traditional trapezoid, such as what is currently drawn on the PFD, to illustrate a climb or descent, again either overlaid over the route defined before the RA or removing this route. The 3D egocentric display display may also support depictions of altitude ceilings or floors. For example, a floor drawn below could indicate where, when crossed, an advisory will be issued.

Figure 22: Example Tunnel in the Sky (copied from [37])

4.2.5 3D Exocentric View TSD

The SAE Aerospace Recommended Practice ARP5430 "Human Interface Criteria for Vertical Situation Awareness Displays" discusses many of the challenges for depicting a three dimensional exocentric view [34]. An example of an exocentric view is shown in Figure 23 showing the ownship depicted in a 3D dessert scene following a route over a lake (on approach to Lake Tahoe).

The exocentric view is able, in theory, to combine all of the features from the 2D Plan View and the 2D side view. The information can be combined into a 3D world and then collapsed onto a 2D screen. This collapsing determines the location on the display for each object in the scene similar to an eye viewing a scene through a glass window. This collapsing can be accomplished using various projection methods (e.g. perspective or orthogonal) which determines the location on the display for

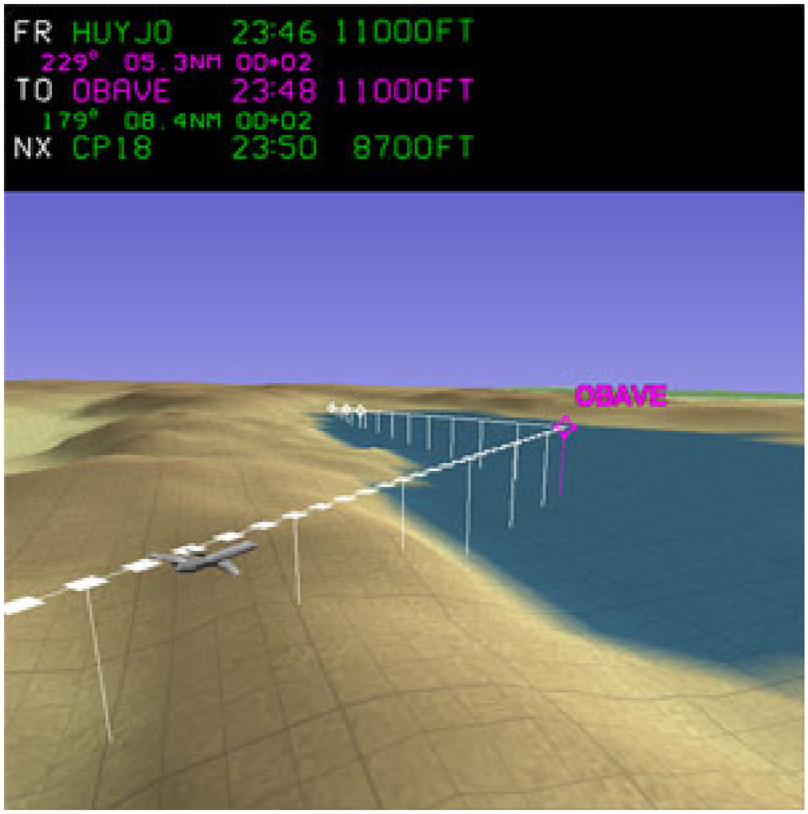


Figure 23: Example Exocentric Display (copied from [36])

each object. There are many variables shown in Figure 24 which change the image displayed; these vary to control the view on the screen.

Reference symbology (such as a grid overlaid on the ground and altitude drop-lines as shown in Figure 23) can be used to restore lost information (e.g. depth) or ambiguous information (e.g. positions in horizontal and vertical axes when they are not aligned with the viewing axes). Other issues discussed in ARP 5430 include directionality, occluded symbols, layering, symbology, field of view, range, look behind, clipping, clutter, alerting, and controls [34].

However, the depth into the display is lost in a 3D representation. For example, in Figure 25 the altitude of other aircraft is exactly portrayed but it is not possible to discern range from the ownship path to each aircraft. Raising the viewing angle to that of Figure 26 projects a small component of range onto the 2D presentation, bu t

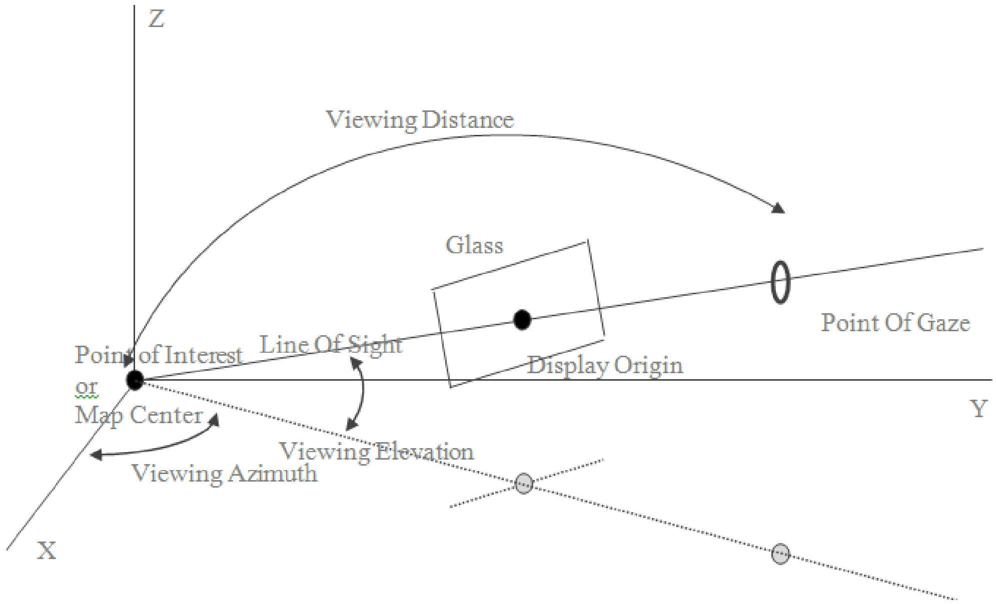


Figure 24: 3D Projection Parameters (copied from [34])

not enough to use location of the symbol on the screen to discern range; the vertical drop-lines and shadows on the ground are required as further cues. Figure 27 shows a view from directly behind the ownship; again it is difficult to view the depth, or distance to an aircraft in this case. Finally, Figure 28 shows a more elevated viewing angle which helps to discern range and horizontal placement. However, now altitude is harder to understand, requiring vertical drop lines and text next to each aircraft.

Some of these views may be more useful than others depending on the traffic

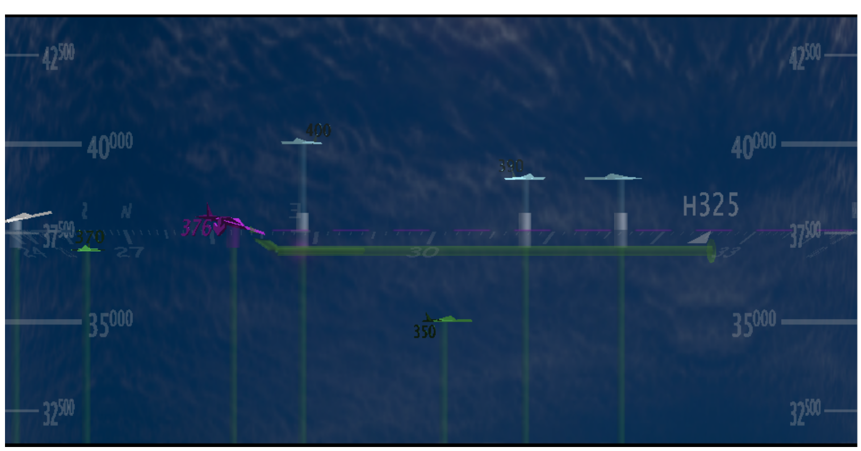


Figure 25: 3D Exocentric Display - Side View with an Elevation of 0^o (from [22])

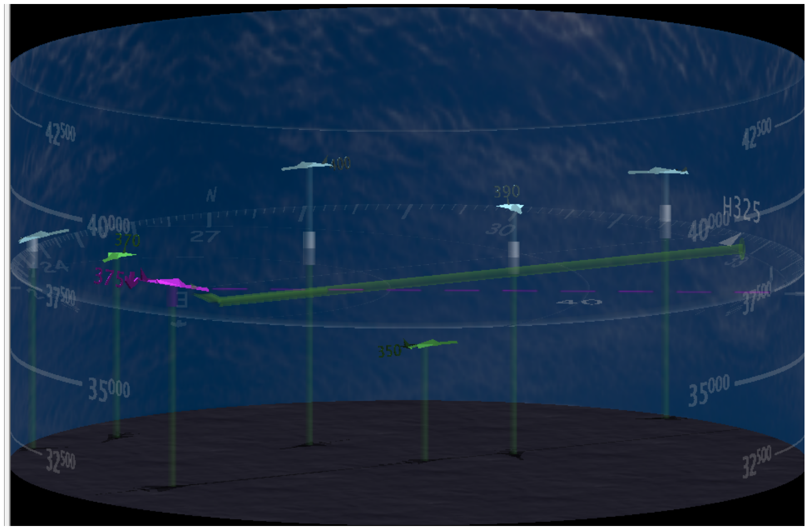


Figure 26: 3D Exocentric Display - Side View with an Elevation of 10^o (from [22])

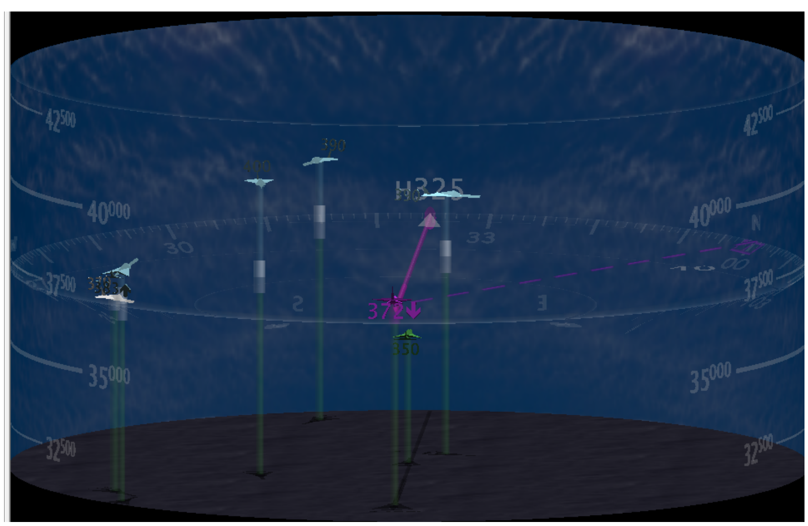


Figure 27: 3D Exocentric Display - Front View from Behind Ownship (from [22])

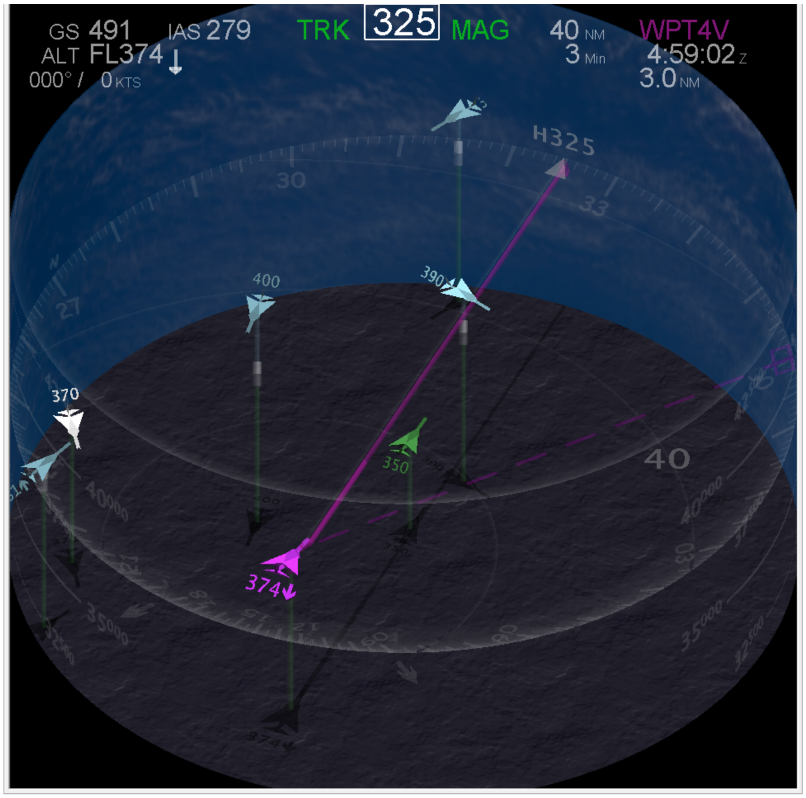


Figure 28: 3D Exocentric Display - View with Elevation of 45^o (from [22])

geometry. The NASA Ames 3D CDTI Route Assessment Tool allows a pilot to evaluate a traffic event from multiple perspectives [22]. Or, the display could dynamically reorient to help resolve ambiguities during traffic events; however, this could cause problems by requiring pilots to also monitor and comprehend the display's changing viewpoint.

Given these trade-offs, studies have found that these three dimensional views can promote "safer" (defined by conflict detection ability and time-in-predicted conflict) maneuvering compared to a plan display, but not as much as a two-dimensional coplanar display [13].

4.2.6 Timeline View TSD

A novel display prototype provides a timeline view of the traffic situation, portraying the intruder's range tau as provided by TCAS computations. Such a timeline view is shown in Figure 29. This does not map to any current cockpit displays. In this view, the ownship is fixed to the left half of the screen. A single horizontal line expands to the right, with tick marks to indicate seconds. The intruder is drawn on this scale to corresponding to the time to CPA as projected by TCAS. Vertical lines in red and yellow indicate the current tau thresholds for TA and RA. As the intruder tau decreases, it is shown to move on the timeline; when the intruder crosses a threshold, it may or may not change threat level because this only reflects the range criteria; the vertical criteria also needs to be met for an advisory to be triggered. An alert triggered by DMOD would also not be represented on this display.

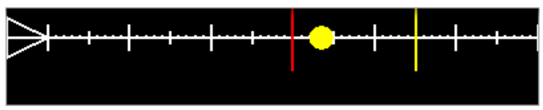


Figure 29: Timeline View from Initial Design

4.3 Subject Matter Experts

Three airline pilots were brought in individually as SMEs. All three pilots has received civilian flight training. Two were first officers and the other was a captain. Two were in their 30's and one in his 40's. The total flight hours were 1,000, 2,700, and 4,500, respectively. Two pilots were current in the CRJ-200 and CL-65; the other was a current flight instructor in the Learjet 60.

Recalling that the display design is an iterative process, the pilots were brought in twice after the initial display prototyping. First, each pilot joined in participatory design by brainstorming problems and solutions with the current TCAS TSD [38]. In the second round, each pilot performed a heuristic evaluation in which they searched for any usability problems [39]. The following two sections summarize these two rounds of evaluation.

4.3.1 Step 1: Brainstorming on Display Design

The brainstorming was set up to first allow each pilot to provide unbiased feedback on the TSD, and then evaluate and iterate on the display prototypes. The full brainstorming protocol is documented in Appendix B. The pilot interviews were recorded to organize the opinions and transcribe relevant pilot quotes.

The guided interview first discussed any problems the pilot self-identified with the TSD they currently use. Each pilot then helped brainstorm solutions to these problems. Finally, each pilot was shown the rough prototypes to provide an initial impression, iterate on the design, and provide feedback into future designs. Each pilot ranked each potential design change. Each interview allowed for an exploration of focused questions and ensured pilot understanding of the new TSD. The pilot's comments and rankings are also provided in Appendix B.

Prototypes of the plan view TSD, timeline view TSD, and VSD were programmed and implemented in OpenGL [40] such that the display would update and respond to inputs from a simulated TCAS intruder. Each feature could be toggled on and off, and it could also be reconfigured with different parameters (e.g. size, length, scale). This allowed the pilots to visually understand, interact with, and change each display feature during the brainstorming session.

The initial prototype of the plan-view TSD shown to the pilots contained four features, as seen in Figure 30. The display depicts an intruder that has already triggered a TA, with sixty second speed vectors, about to cross the spatial RA boundary line.

The initial prototype of the VSD shown to the pilots is shown in Figure 31 during a TA and Figure 32 during an RA. The VSD included ownship and intruder absolute vertical speed vectors, ALIM boundary bars, spatial boundary lines based on range tau, and a depiction of the RA commanded vertical speed.

The pilots suggested that they did not want to see all of the features on both

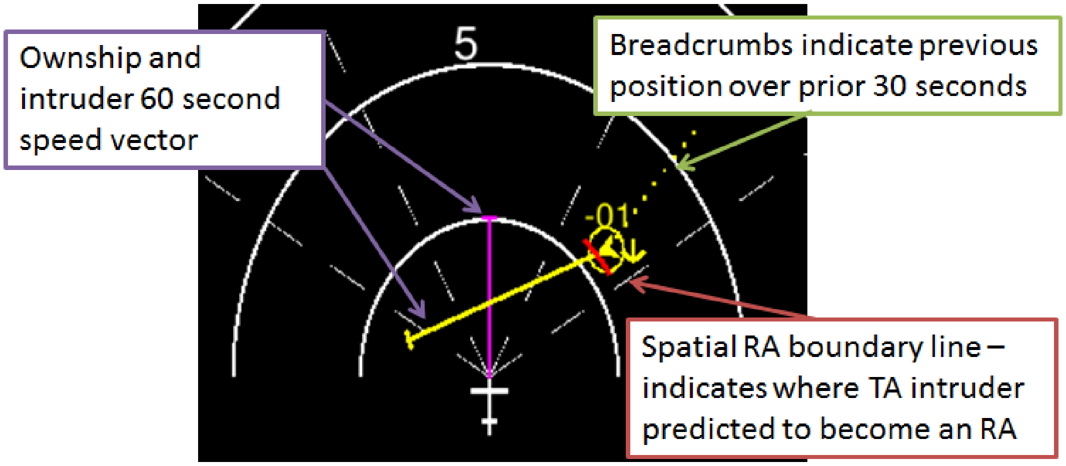


Figure 30: Plan-View TSD Initial Prototype

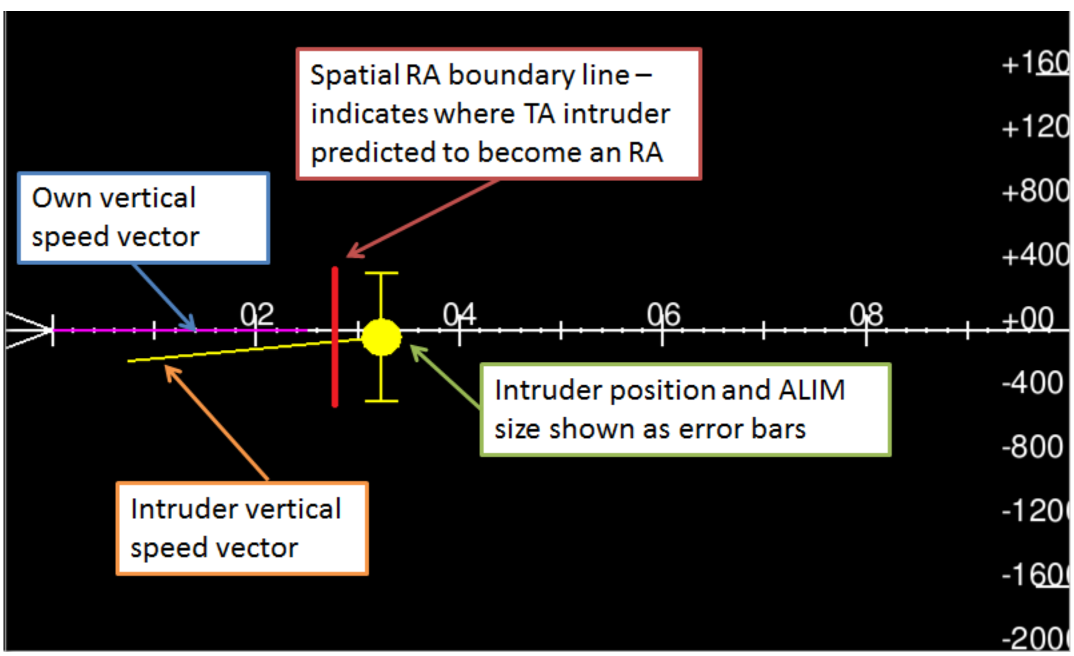


Figure 31: VSD Prototype During TA

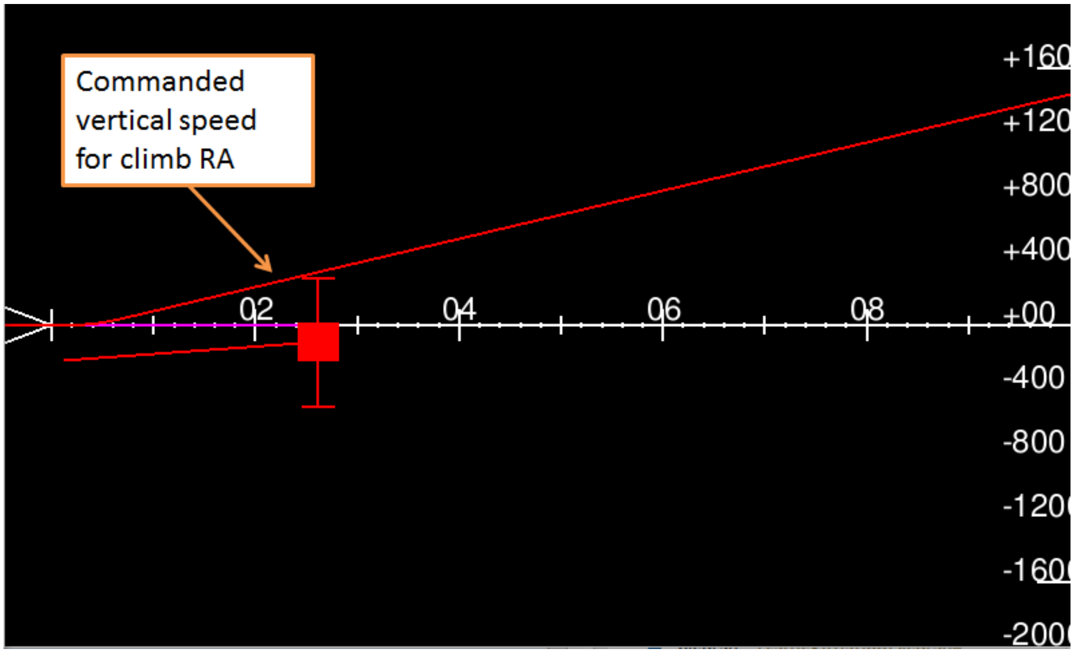


Figure 32: VSD Prototype During RA

displays all of the time. Some of the information is only needed in the seconds leading up to a TA. Otherwise the display can become very cluttered. On the plan view TSD, the information which the pilots wanted to pop-up were the speed vectors, breadcrumbs, and spatial tau boundary lines. They otherwise wanted these features hidden or turned on by pilot selection. However, the pilots always wanted to see directional symbols. Similarly, on the VSD the pilots only wanted the protected volume and ALIM bars to appear just before a TA.

Therefore, there is a need for criteria to trigger the display of some features, timely and just before a TA. For this thesis, an adjustable criteria was developed to use the time between the tau-RA and tau-TA threshold to alert and allow the pilot to anticipate the TA. For example, at sensitivity level five where the tau-RA is 25 seconds and the tau-TA is 40 seconds, there are 15 seconds in between the two advisories; thus, here the display criteria is set at a threshold of 40+15=55 seconds. When an aircraft's time to CPA is projected to be less than this criteria, the speed vector, breadcrumbs, and spatial TA/RA boundary line appear on the plan view

TSD, and the projected volume and ALIM bars appear on the VSD.

Following the human factors criteria for design of multifunction displays, a 'traffic' mode is annunciated to the pilot when this criteria trigger, as shown in Figure 33 [41]. Because the simulator set-up uses a standalone traffic display, many other criteria are not applicable to the display. However, in a multifunction display, the other guidance should be followed (e.g. layering, prioritization, switching, consistency, simplicity, etc.). This method of pop-up was later evaluated in the second round of evaluations. However, the pop-up information may clutter the display or have the same effect as frequent false alarms [35].

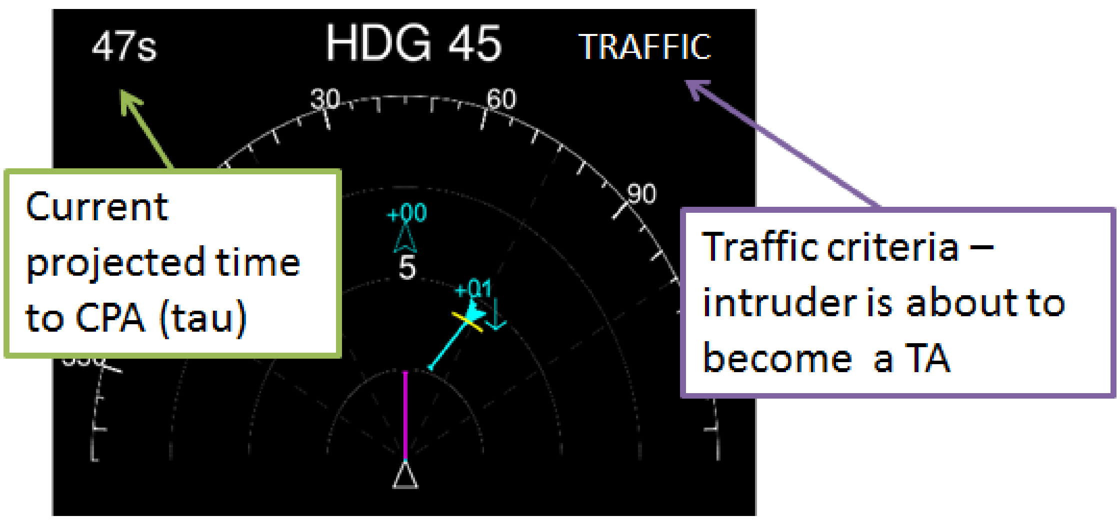


Figure 33: TSD Before Traffic Alert

On the plan view TSD, two new features were suggested by the pilots and incorporated as shown earlier in Figure 17. First, variable length vertical trend arrows were proposed with five steps from largest to smallest in fpm: greater than 1250, 1000, 750, 500, and 250. The second addition was a small 'V' next to aircraft which are squawking 1200, i.e., are VFR targets.

An additional option for the speed vector length was also suggested and implemented on the plan view TSD. Instead of the length being fixed to a static time value (30s or 60s), the length for both the ownship and intruder aircraft can be selected to the tau value of the intruder. This option should allow the pilot to predict the ownship and intruder aircraft projected locations at the CPA and is shown in Figure 33. It was then evaluated by the SMEs in the second round.

However, the pilots did not want to see the vertical speed vectors. The pilots indicated the information was overwhelming, unclear, and not as useful as the other information. Regarding the vertical speed vectors and the VSD, one pilot said, "*I don't want to see all those lines everywhere. Keep it simple stupid. Just show me what I need to follow at the time for the most important intruder.*" Therefore, the intruder vertical speed vector was removed from this prototype.

The pilots also suggested the depiction of the ZTHR vertical alert threshold to the pilot as a dashed horizontal line, along with the range boundary shown as a vertical line. This could help a pilot to understand why an aircraft converging in range may not issue a TA or an RA if it is above or below this boundary. This bounding box only appears with the other features just before a TA and was previously shown in Figure 19.

One of the pilots suggested displaying a goal altitude, or a target safe zone, on the VSD. This could be computed by searching for the intruder predicted altitude at the CPA, and adding or subtracting ALIM to find a safe altitude. This is a simplistic look at the TCAS logic, and it also does not account for multiple intruder aircraft. Preliminary tests with the programmed display look like this is a reasonable depiction, though it needs to be further tested to determine if this is a reliable method for showing a goal altitude during an encounter. After reaching this altitude in tests, TCAS changes the alert to "monitor vertical speed," (an indication that safe separation has been achieved and the aircraft should level off to not further maneuver outside its ATC clearance). The goal altitude is shown as a safe altitude, with the area that is unsafe shown hashed out as shown previously in Figure 20.

During the brainstorming, pilots were also asked how future cockpit displays (incorporating 3D views or touchscreens) may change their interaction with TCAS, and ways to improve the problem that TCAS is hard to understand. Several scenarios were discussed, and each pilot sketched what a future display may look like with traffic information. The pilots made some sketches and discussed symbology. But, as noted in Appendix B, they were mostly interested in discussing how the traffic picture would look and not using the display to improve an understanding TCAS.

4.3.2 Step 2: Evaluations of Display Design

Throughout each iteration on the display prototypes, it was observed that the plan view TSD and the VSD may each improve pilot understanding in some scenarios, but may also degrade understanding in others. Therefore, when the pilots returned to evaluate the displays, each of the pilots stepped through ten traffic scenarios that represented both "good" and "bad" traffic events. Each pilot answered a questionnaire following each flight to note anything that was potentially confusing, suggest changes, give opinions on the display features, and discuss how the traffic would appear on a 3D display. The evaluation protocol followed for each pilot is documented in Appendix C. Once again, the interviews were recorded to organize the opinions and quotes.

A cognitive walkthrough was considered for the heuristic evaluation [38], although it could not be used in the exact manner used in HCI evaluations because pilot interaction with TCAS is different from a typical computer system. The pilot interacts with an airplane and not with TCAS directly; the TCAS TSD updates itself every second, and typically does not require any input from the pilot. However, in the style of a cognitive walkthrough, the simulator could be paused at the critical moments to allow the pilots to reflect on the display. First, the entire sequence was played without pausing so that the pilot can get the full effect of a continuously updating display. Next it was replayed and paused when the pilot wanted, such as when an intruder first appeared, became proximate, a TA, an RA, the RA changed, or clear of conflict.

Thus, of the ten metrics used in a typical heuristic evaluation for computer applications [39], only five of them were relevant to pilot interaction with TCAS. Each pilot commented on each of these items and marked each as acceptable or not:

1. Visibility of TCAS alert status
2. Match between TSD and the real world
3. Consistency and standards
4. Recognition rather than recall
5. Aesthetic and minimalist design

As shown in Figure 34, both the plan view TSD and the VSD are hypothesized to impact pilot understanding of TCAS both positively and negatively in various scenarios. These scenarios fall into six categories of confusion:

1. "Why did TCAS not issue a TA or RA?" has cases where the intruder traffic may appear to trigger one of the alert criteria (particularly when a display includes a feature such as the tau range threshold boundary), but does not actually violate both the horizontal and vertical alert criteria.

2. "Why did TCAS issue a TA or RA?" has cases where the display may clarify which criteria has been satisfied, or it may emphasize another criteria that was not met. The plan view TSD may emphasize DMOD and horizontal tau whereas the VSD may emphasize the horizontal tau and ZTHR.

3. "Where is the traffic?" can be asked when traffic is compressed from various bearings onto the VSD, and from various altitudes onto the plan-view TSD.

4. "Why did TCAS choose that maneuver?" can be a concern in any case, but particularly be a concern with crossing maneuvers.

Table 15: Challenging Traffic Scenarios

- Preventive RA
- Corrective RA
- Crossing RA
- Traffic from the side past 30^o (outside of swath)
- Traffic inside ZTHR (low vertical rate)
- Traffic outside ZTHR (test passed by vertical tau)
- Proximate non-threat traffic combined with distant converging advisory traffic

5. "Why did a TA or RA suddenly appear?" refers to two sets of cases. The first set of cases includes when the traffic does not appear on the display until the TA, such as traffic that is above or below the altitude filter on the plan view TSD or outside the swath on the VSD. The second set includes traffic which is level and safely separated, but changes altitudes or turns suddenly to cause an advisory.

6. "Why did a TAS or RA suddenly disappear" can arise when an intruder appears to be a threat on the display without pilot awareness that the intruder has turned away to resolve the conflict.

Based on these hypothesized impacts, the scenarios used to test the displays are summarized in Table 15. The full specifications of these scenarios are included in Appendix C.

During the pilot evaluations, each pilot also commented on each of the TSD display features. If anything was described as confusing, the pilot was asked to mark it on a printed version of the display. The pilot was also asked how it could be better depicted and given the chance to sketch what may be better. Finally, the pilot was asked how the scenario may have appeared on a futuristic 3D cockpit display, noting

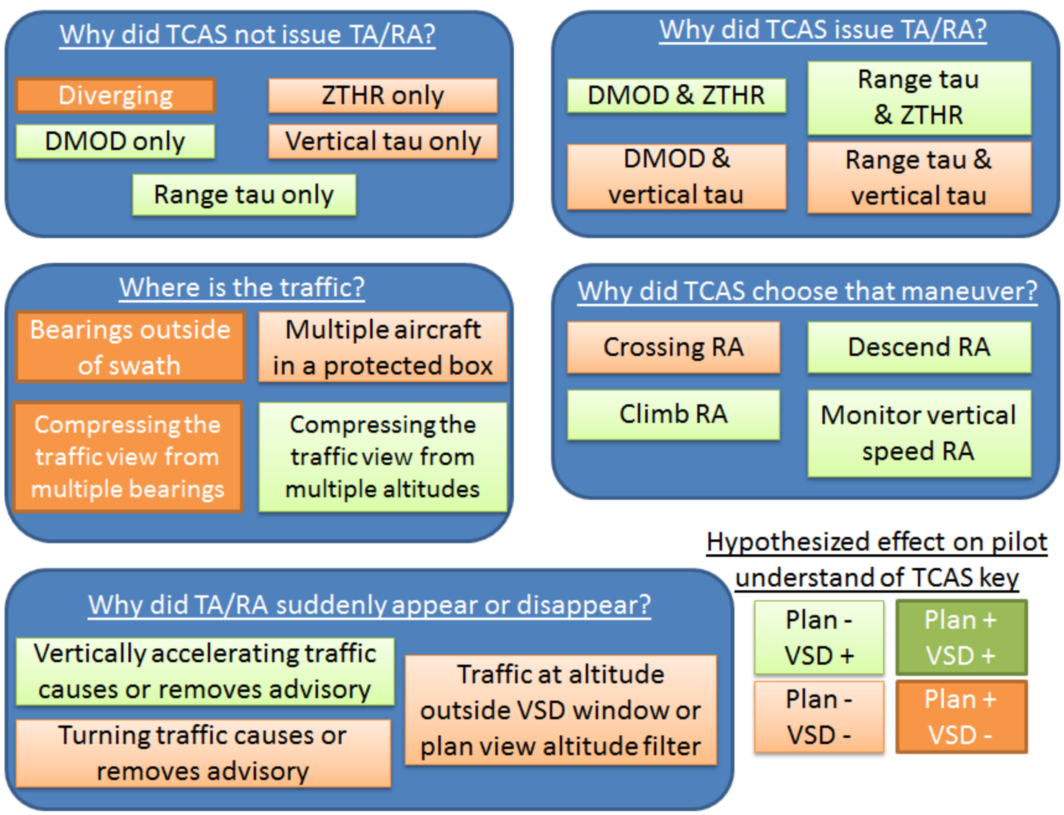


Figure 34: Challenging TCAS Scenarios for Plan View TSD and VSD

anything that may be confusing or good about this display format.

Throughout the evaluation, they were primarily evaluating each display feature in isolation. At the end of the total evaluation, the pilot was asked to discuss the set of display features as a whole. This was seeking to identify any relationships or coupling between the display features. For example, one pilot preferred to not see breadcrumb information unless the speed vector information was not available.

The results and opinions of the subject matter experts are detailed in Appendix C. In general, the pilots liked the displays and only suggested a few very minor changes. However, all of the pilots thought the ownship vertical speed line was distracting during the RA. Pilots were confused, as expected, when only some of the alert criteria had been satisfied.

The final plan view TSD prototype is shown in Figure 35. It includes the following previously discussed changes: directional arrows, spatial TA/RA lines, speed vectors, breadcrumbs, variable climb arrows, and VFR traffic indications.

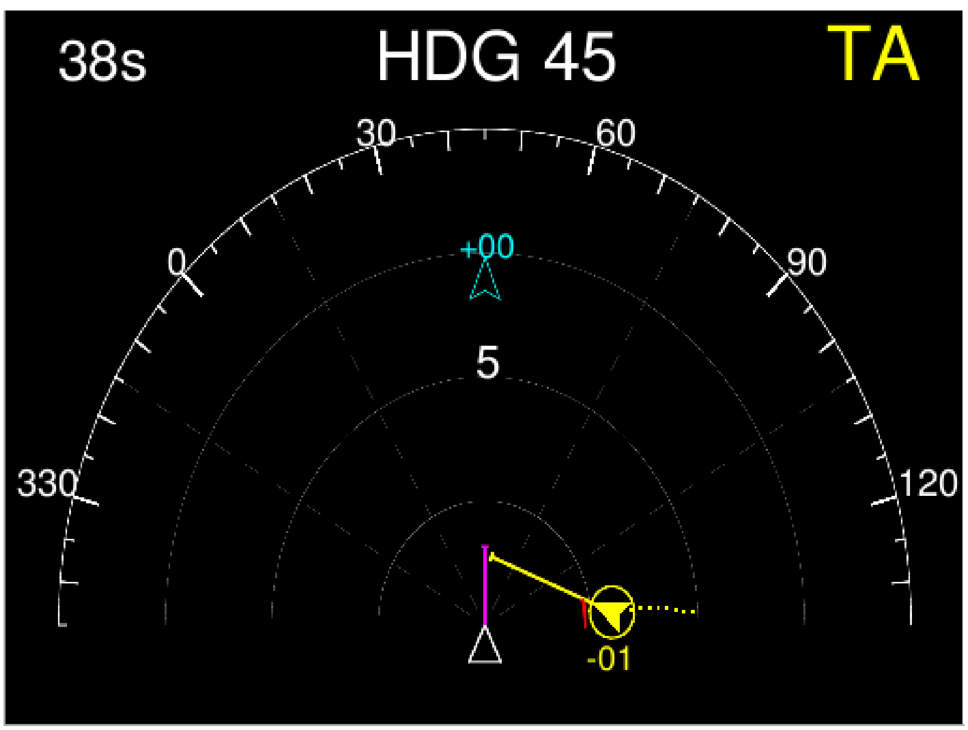


Figure 35: Final Plan View TSD During TA

The final VSD prototype is shown in Figure 36 during a TA and Figure 37 during an RA, when the avoidance maneuver is displayed. It includes the following previously discussed changes: intruder absolute range, intruder altitude, spatial TA/RA boundary box, ownship vertical speed, RA maneuver command, RA exclusion area, and prediction of RA's goal altitude.

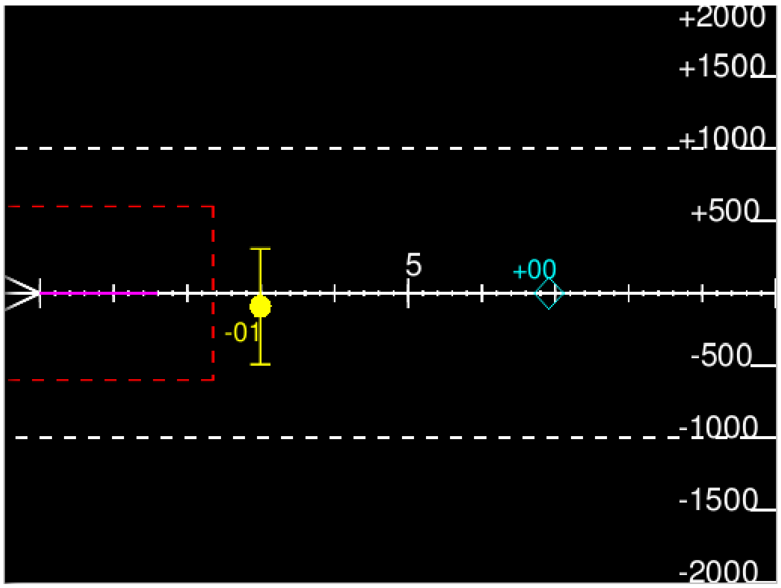


Figure 36: Final Side View VSD During a TA

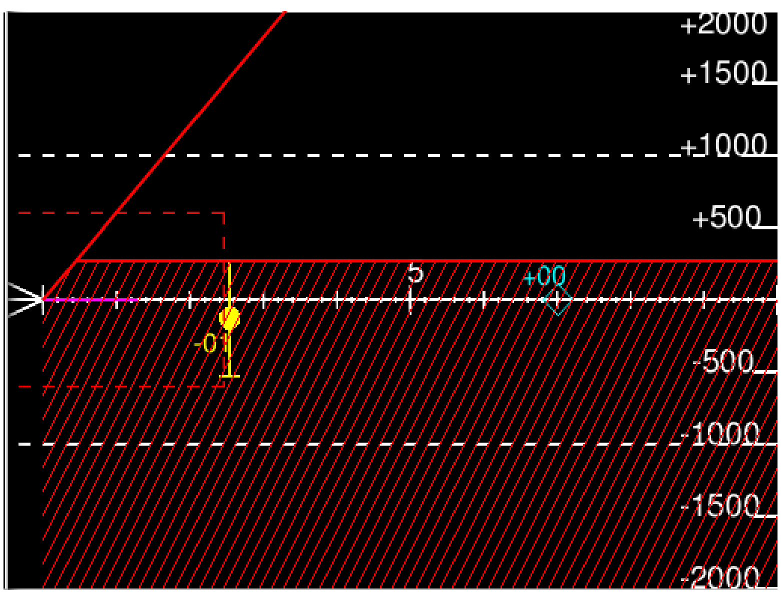


Figure 37: Final Side View VSD During an RA, with a 'Climb' Advisory

Both the plan TSD and VSD have been programmed in OpenGL and are able to interface with the simulator environment. All of the features are configurable as options to easily reconfigure features or to change parameters.

Again the pilots were asked to discuss drawing the traffic events on futuristic 3D displays. The pilots brought up a few new ideas, as discussed in Appendix C. For example, the pilots suggested a docked symbol or indicator to show the direction to look out the window for traffic that is off-screen (outside the field of view). Two pilots independently suggested using floors or ceilings to depict protected areas for intruder aircraft (similar to the hashed area on the VSD).

4.4 Summary

New TSD features have been examined using a structured display design process. Two iterative loops of designing displays, prototyping them in OpenGL, and evaluating them with SMEs was used to produce a programmed display and set of useful display features.

Meaningful symbology was used to explain the key variables used in the TCAS logic to aid pilot understanding of TCAS. This included the DMOD and range tau for the horizontal alerting criteria, and the ZTHR and vertical tau for the vertical alerting criteria.

Six display types were each examined for display features that may aid pilot understanding of TCAS. Additionally, challenges associated with each display, bot in general and in particular to traffic situations, were identified.

The opinions and suggestions from the SMEs shows mostly favorable opinions on the prototypes created here. However, it is important to note that pilot opinion is not the sole determiner. Instead, the display must be used in ways that aid pilot understanding of TCAS and does not detract from pilots' ability to maintain safe separation.

The discussion includes metrics by which a new display should be evaluated. Several challenging scenarios were identified within which such evaluations should be conducted.

In conclusion, pilots most wanted to see directional information on the plan view TSD to remove targets from their assessment of potential threats. Pilots enjoyed using the VSD to see traffic, as it provided an external representation that helped them form an internal understanding of the vertical dimension.

CHAPTER V

CONCLUSIONS

5.1 Summary

This thesis explored how the TSD can impact pilot understanding of TCAS. Pilot interaction with TCAS has not followed assumptions inherent to its original design, as demonstrated by pilots use of, and response to, TCAS. However, TCAS is difficult to explain and understand, creating two challenges in the design and test of displays to improve pilot interaction with TCAS.

Thus, the first objective addressed the challenge of creating an appropriate simulation environment for pilot-in-the-loop test and evaluation of TSDs (and other aspects of TCAS). This simulation environment integrates many aspects of both the flight deck and ATC. This thesis specifically contributed guided intruder aircraft that use 7-dimensional waypoints that generate traffic events of interest by specifying trajectories in coordinates either absolute or relative to the ownship. Fast-time computational simulations can use this intruder model to categorize which trajectories will cause specific RAs. Commanding these trajectories in the real-time simulator thus determines the RAs experienced by the pilot, as demonstrated by the first three pilot-in-the-loop evaluations of TCAS by the Cognitive Engineering Center.

Further, the second objective examined the challenge of identifying if the TSD can aid pilot understanding of TCAS. Because of the complexity of TCAS, it is not clear that any display can enable pilots to completely understand TCAS, nor is it clear if this pilot understanding is desirable or what depth of knowledge would be appropriate. However, this thesis helped identify the extent to which such display aiding is possible, and where it may not be possible.

Novel TSD designs were prototyped via an iterative design process that included two evaluations by subject matter experts. The information necessary to explain TCAS was evaluated to identify where it could be incorporated into flightdeck displays. A plan view TSD and VSD were programmed with a variety of reconfigurable features. These displays specifically emphasized key TCAS variables and thresholds (e.g. spatial range boundary lines based on tau). Using a vertical representation further enables differentiation between the horizontal and vertical alert logic. The vertical display may help emphasize vertical maneuvers. However, no one display appears sufficient to explain TCAS in all traffic events.

5.2 Contributions

This research provides several contributions. First, the results provide greater insight into the problems with the current TCAS TSD relative to pilot understanding of TCAS advisories. This research helps highlight some of the current problem areas and show some ways to improve the understanding of TCAS by changing the TSD. Additionally, this research identified challenging traffic scenarios which make for good test conditions for evaluating various types of TSDs. This type of information is useful for evaluating future displays as part of safety analyses and certification/operational approval decisions.

Future upgrades of TCAS may incorporate information from additional sources (such as ADS-B) which may enable the display to show additional information about other aircraft. This additional information could lead to a future upgrade of TCAS which will utilize this additional information. Some information on the displays examined in this thesis have assumed access to this information (e.g. groundspeed and heading of intruder aircraft). This study informs the design of futuristic cockpits incorporating new sensing and data capabilities into the design and evaluation of novel TCAS TSDs or ACAS-X displays for general aviation.

Finally, because the TSD was designed to reveal some of TCAS's inner aspects, pilots are likely to form a mental model, correct or incorrect, about how TCAS works based on their experiences with the novel TSD. If pilot understanding of TCAS operations is indeed improved, the new TSD could be used in simulations as a training aid to help pilots learn about TCAS, even when they normally fly aircraft with a traditional TSD.

5.3 Future Work

It is not clear whether pilots will ever be able to understand TCAS. The displays developed in this thesis provide a better, although still incomplete, picture of how TCAS operates. Three major sources of misunderstandings are summarized here. First, the TSD portrays a simplified picture of TCAS logic. Second, the TSD hides the noise inherent to TCAS sensor data. Finally, TCAS does not know intent whereas the pilot may be aware of either ownship or other aircraft plans, based on air traffic instructions, which obviate the need for a TCAS advisory.

Timing is important to the understanding of TCAS. In low workload periods prior to TCAS events, pilots may allocate more time to studying the TSD and determining potential conflicts and escape maneuvers. At such times, the increased display content may be welcome and may help the pilot form an expectation that later supports a good response to a subsequent TCAS advisory. In high workload situations, notably including during an RA when the pilot only has seconds to respond, pilots may want to know only the necessary information. In these situations the increased display content may slow the pilot down or obstruct identifying the important information. Thus, depending on the comparative effects of a better-informed expectation versus a perhaps-cluttered display during advisories, pilot response time to TCAS advisories and pilots response to an RA may be improved or degraded as a result of changing the TSD.

A pilot's understanding of TCAS goes hand-in-hand with trusting TCAS. When pilots understand and agree with TCAS over time, they will increasingly trust TCAS. The traffic display can help pilots understand events involving TCAS so that their a priori assumptions are better informed in future events. However, simply viewing the aggregate effect on trust is insufficient; the pilot also needs to understand what is happening in each instance.

Building trust in TCAS is difficult because the data from TCAS is noisy, and the TSD masks these uncertainties. In this thesis, simulations used for developing the TSD assumed perfect knowledge and ignored the noise inherent in real-world TCAS data. To further examine the effects of uncertainty, subsequent simulation runs incorporated an important source of variance in TCAS sensory data into the TSD, namely a standard deviation of 20 feet in the altitude information. This caused the target to visually jump up and down on the vertical situation display. During an RA, the predicted level-off altitude, based on a simple time-derivative of the altitude, had even more noticeable variance. These errors in the vertical information could cause the pilot to trust TCAS less. On the other hand, filtering techniques and the availability of ADS-B information may enable high-fidelity vertical displays.

In addition to the noise inherent in the data, TCAS uses state information whereas airspace is commonly designed based on intent. State information refers to the current state of the world, e.g. an aircraft is climbing and projected to lose separation with respect to the ownship. Intent information refers to the planned route an airplane will take, e.g. the departure course or controller instructions have this same aircraft leveling off 1,000 feet below. TCAS uses the current state of aircraft to generate advisories, without considering intent. Pilots have insight into this intent, and they may use this information to second-guess TCAS. In this example, the aircraft that is climbing, but intending to level off, may generate an RA while in its climb. The pilot may have knowledge that the aircraft is planning to level off; for the pilot to disregard the RA using this intent data creates a situation where the pilot depends on the other aircraft to follow its intentions. Given the frequency at which intent is not followed (e.g. altitude busts), this could degrade safety.

On the other hand, future high-traffic-density operations may require aircraft to fly closely-spaced trajectories with intricate flight profiles, i.e. these aircraft may be issued specific intended trajectories. Where the intended trajectories diverge and current states converge, TCAS may issue advisories based on current state. These alerts highlight a future location where, if the intended trajectory is not followed, a conflict can occur. However, maneuvering in response to these TCAS advisories may be disruptive to closely-spaced airspace design. In high traffic densities, such deviations may ripple out to impact other aircraft as well. Therefore, future work will require a resolution of the conflict between state-based TCAS alerts and intent-based airspace trajectories.

This thesis has focused on improving pilot understanding of TCAS, while avoiding the philosophical question of how much do pilots actually need to know. Indeed, the exact benefit of pilots' improved understanding of TCAS is unclear. This research is instead a start in addressing the question of whether pilot understanding can even be increased by novel TSDs. Examining the sample of three pilots consulted here reveals that they seemed to generally better understand the differentiation between the horizontal and vertical alerting logic. However, the pilots were confused for aircraft that satisfied the horizontal criteria but not the vertical criteria, or traffic that did not cause an alert (e.g. aircraft passing overhead by more than ZTHR). With a representation of the vertical maneuver and separation on the VSD, the pilots were observed to level-off before TCAS reduced the RA maneuver shown on their primary flight display. Future research may need to address these potential effects.

Thus, further research can measure to what extent pilot understanding of TCAS is improved by new TSDs and its impact on pilot use of the TSD and of TCAS advisories. To start, a pilot-in-the-loop study with airline pilots by the Georgia Tech Cognitive Engineering Center (CEC) will evaluate TCAS scenarios which may cause pilot misunderstanding using the TSDs. As a probe of their understanding of TCAS, pilots should fly a variety of traffic geometries which exercise different aspects of TCAS alerting and maneuver-generation logic. This thesis identified scenarios in which the TSD's portrayal of the TCAS logic may be simplistic. Thus, pilots should fly scenarios spanning a range of combinations of satisfying the horizontal alert criteria by either DMOD or tau, along with satisfying or not satisfying the vertical criteria by either ZTHR or tau. Finally, juxtaposing pilot self-reports and questionnaires (i.e. what the pilot thinks happened) with simulator output and pilot response (i.e. what the pilot actually did) will yield insight into these questions:

- Did the pilot use the TSD or the TCAS advisories to avoid the traffic?
- Did the pilot trust the information from the TSD or the TCAS advisories?
- Did the pilot understand or follow the TCAS advisory?
- Is pilot understanding of TCAS improved after using the new TSD?

Thus, the results of this study will give insights into the types of scenarios that should be included in FAA certification of future displays. It may also inform if these display changes improve pilot understanding of TCAS, highlight potential concerns with future TSDs, and inform future TCAS upgrades.

APPENDIX A

TCAS VARIABLES VERSUS DISPLAY TYPE

To support the display brainstorming, a list of relevant TCAS variables is presented. First, Table 16 indicates whether TCAS senses the data directly or computes it. Next it indicates if this information is visible directly to the pilot on the traditional TSD or is visible partially or indirectly to the pilot.

Table 16: Comparison of TCAS Variables - Sensed, Computed, and Visible

	TCAS Sensed Directly	TCAS Computes in Logic	Visible directly to Pilot	Visible partially or indirectly to Pilot
Own Altitude	x		x	
Own Altitude Rate		x	x	
Intruder Range	x		x	
Intruder Bearing	x		x	
Intruder Altitude	x		x	
Intruder Discretized Alt.Rate		x	x	
Intruder Altitude Rate		x		x
Intruder Velocity		x		x
Intruder Direction of Travel		x		x
Intruder Range Rate		x		x
Intruder Tau		x		
Time to Co-Altitude		x		
Vertical Miss Distance at CPA		x		
Predicted Position		x		
Sensitivity Level		x		
Climb Inhibited		x		
Descent Inhibited		x		
Alim		x		
Z-threshold		x		
DMOD TA Threshold		x		
DMOD RA Threshold		x		
Tau TA Threshold		x		
Tau RA Threshold		x		
Coordinated Maneuver		x		
Time to maneuver		x		
Predicted Miss Distances		x		
Sense Selection		x		
Commanded Maneuver		x		

All of the variables are repeated in Table 17 to indicate methods of displaying them on various displays: 2D Plan, 2D Side, 2D Front, 3D Egocentric, and 3D Exocentric.

Table 17: Comparison of Potential Display Features to Represent TCAS Variables

	2D Plan (TSD, X-Y) View	2D Side (X-Z) (VSD) View	2D Frontal (PFD) (Y-Z)	3D Egocentric (PFD)	3D Exocentric (ND)
Own Altitude		Symbol Location	Symbol Location	Symbol Location	Symbol Location
Own Altitude Rate		Vector		Path	Path
Intruder Range		Symbol Location		Symbol Size and Location	Symbol Size and Location
Intruder Bearing			Symbol Location	Symbol Location	Symbol Location
Intruder Altitude		Symbol Location	Symbol Location	Symbol Location	Symbol Location
Intruder Discretized Alt.Rate	Arrow				
Intruder Altitude Rate	Variable Length Arrow	Vertical Speed Vector	Vertical Speed Vector	Vertical Speed Vector	Vertical Speed Vector
Intruder Velocity	Speed Vector			Speed Vector	Speed Vector
Intruder Direction of Travel	Directional Symbol			Directional Symbol	Directional Symbol
Intruder Range Rate	Breadcrumbs				
Intruder Tau		Symbol Location			
Time to Co-Altitude		Vertical Speed Vector			
Vertical Miss Distance at CPA		Vertical Speed Vector			
Predicted Position	End of Speed Vector	End of Speed Vector	End of Speed Vector	End of Speed Vector	End of Speed Vector
Sensitivity Level		SL Boundary Lines	SL Boundary Lines	SL Boundary Lines	SL Boundary Lines
Climb Inhibited		Boundary Line	Boundary Line	Boundary Line	Boundary Line
Descent Inhibited		Boundary Line	Boundary Line	Boundary Line	Boundary Line
Alim		Boundary above/below intruder symbol	Boundary above/below intruder symbol	Boundary above/below intruder symbol	Boundary above/below intruder symbol

Table 17 (continued)

	2D Plan (Top-Down, X-Y) View	2D Side (X-Z) (VSD) View	2D Frontal (PFD) (Y-Z)	3D Egocentric (PFD)	3D Exocentric (ND)
Z-threshold		Boundary lines across display above/below ownship	Boundary lines across display above/below ownship	Boundary lines across display above/below ownship	Boundary lines across display above/below ownship
DMOD TA Threshold	Protection volume				Protection volume
DMOD RA Threshold	Protection volume				Protection volume
Tau TA Threshold	Spatial TA Line	Spatial TA Line			Spatial Boundary Lines
Tau RA Threshold	Spatial RA Line	Spatial RA Line			Spatial Boundary Lines
Coordinated Maneuver		Depiction of Intruder's Maneuver			Depiction of Intruder's Maneuver
Time to maneuver	Location of Maneuver Start	Location of Maneuver Start			Location of Maneuver Start
Predicted Miss Distances		Line showing the result of following maneuver			Line showing the result of following maneuver
Sense Selection		Line showing the result of other maneuver			Line showing the result of other maneuver
Commanded Maneuver		Goal vertical rate line	Trapezoid	Carpet / Tunnel	Goal vertical rate line

APPENDIX B

SME BRAINSTORMING PROTOCOL AND RESULTS

B.1 SME Brainstorming Protocol

The brainstorming interview with the SMEs was broken into seven steps. Each step is discussed, along with a script which was loosely followed.

B.1.1 Overview of TSDs and Purpose of Interview

"Hi, I'm William. Thanks for agreeing to serve as a Subject Matter Expert. Just as a reminder, you are serving as a consultant which does not carry expectations of confidentiality. If this is a problem at any point please let me know. During our time today I will be asking you for your insights about flight deck design, not in any way taking any measures of performance as a pilot. None of these questions have any right or wrong answers."

"I'm working on trying to improve the TCAS Traffic Situation Display. As you've seen before, this is a TSD <show sample TSD Figure 38>. My work is trying to improve pilot understanding of TCAS by changing the TSD."

B.1.2 Interpret TCAS TSD Scenarios

"I'd like to start by discussing some situations that may happen with the current TCAS TSD. For each one, would you please interpret what is going on (i.e. what is TCAS doing, why is TCAS doing it, what is the other aircraft doing, what would you like to know that the display does not show you, and how should you respond). We will write some notes on the whiteboard for your interpretations of how TCAS works."

<Show RA Scenarios Powerpoint> - Includes a description of scenario, aurals

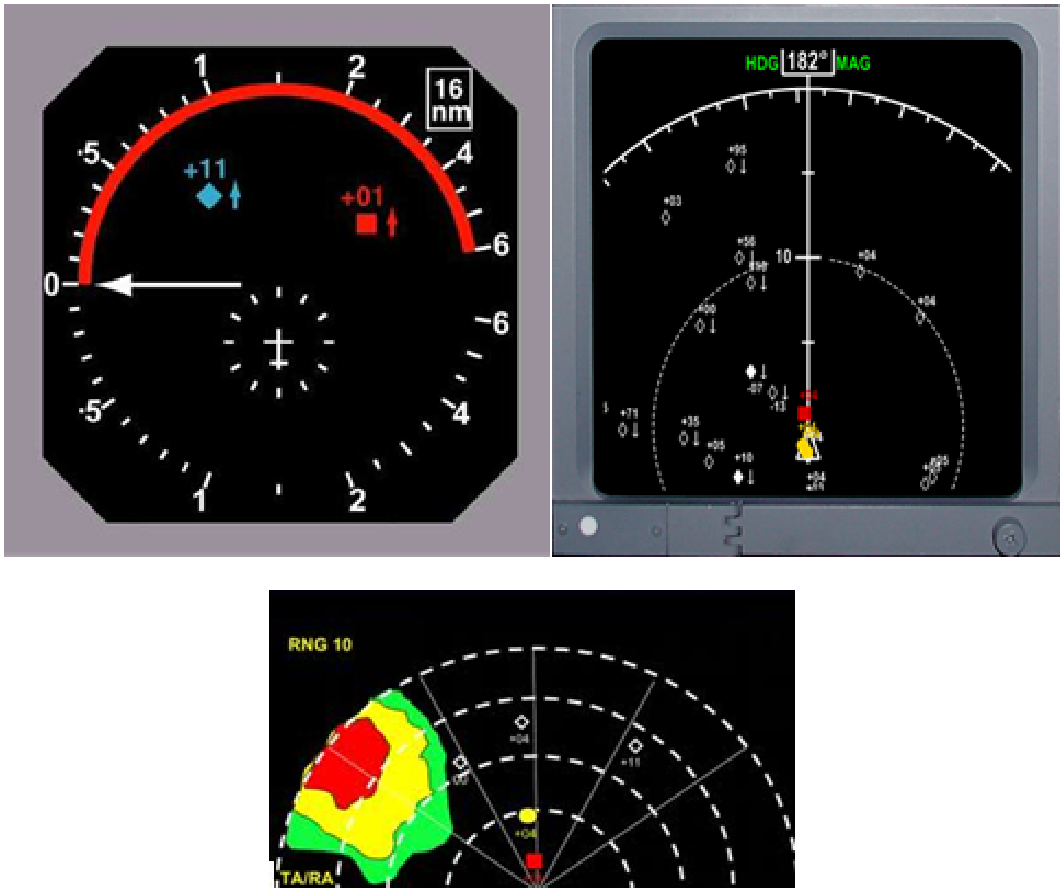


Figure 38: Sample TSDs

given, the PFD, and TSD for the following scenarios. It additionally prompts the questions above.

- Normal RA
- High convergence rate RA
- Crossing RA
- Reversal RA
- Conflicting ATC information

B.1.3 Explanation of TCAS

I will step through how TCAS works and note anything conflicting with their previous understanding.

"Thank you, now I want to explain TCAS to you. I'm sure you already know

most of this, but I do want to go into a bit more detail than pilots typically receive in training. At any point feel free to stop and we can return to the whiteboard with ideas of things to include in a future TSD. I will step through select slides from a TCAS training program developed by my colleague."

<Show TCAS Explanation Powerpoint> - Based on the training program developed in [42]. Includes a description TCAS and these topics:

- Overview of TCAS
- Overview of TSD & symbology
- Traffic advisory
- Resolution advisory
- Thresholds & Sensitivities (Tau, DMOD, ZTHR, ALIM)
- Sense selection
  - Weakening RAs
  - Crossing RAs
  - Strength selection
- Alert Boundaries
- Possible types of RAs
- Example timeline of events
  - Generic RA
  - Crossing RA
  - Reversal RA
- RA Display
- Excessive response problem
- ATC Interaction
- Clear of Conflict

B.1.4 Brainstorm Changes to Current TSD

Here I will each SME what changes to the current display would be appropriate to help improve whatever level of understanding of TCAS would be appropriate.

Okay, so now I'd like to spend some time and try to come up with changes that could be made to the TSD which would help improve the understanding of TCAS. Note that the TSD does not need to fully explain TCAS as I have done; instead I want to focus on the information that would be beneficial to you as a pilot in your *decision making process during a TCAS event. I'd like to brainstorm for ways that we could visualize these things to improve your understanding.*

Pilots will be asked to sketch on 2D displays that shows traffic for these scenarios:

- Following an aircraft on same arrival, 6nm ahead
- Aircraft on departure route 1000 ft below, climbing and crossing our route.
  - Aircraft misses the level off, TCAS issues a climb RA to climb over traffic
  - Aircraft misses the level off, TCAS issues a Descend/Crossing RA
- VFR traffic is level 500 ft below. TCAS instructs "Monitor vertical speed"
- Any other situation which the pilot would like to depict as interesting

As the pilots sketch the information they would like to see on the display, if any of their ideas closely match one of the prototypes already created in OpenGL, that will be shown to them. Also, if any idea is simple and quick to program, it will be done on the spot.

B.1.5 Brainstorm Traffic for Futuristic Displays

Imagine you get into a futuristic cockpit dominated by glass displays. <Show futuristic cockpit displays, Figure 39, Figure 40, Figure 41>.

Figure 39: Airbus A380 Cockpit (copied from [43])

Figure 40: Garmin G2000 (copied from [44])

Figure 41: Future Concept Touchscreen (copied from [45])

Can you imagine any other ways to display traffic which would be beneficial? Do you have any ideas or any solutions to the problem that TCAS can be hard to understand?

Here the pilots will be asked to sketch traffic situation on an egocentric and exocentric display for the following configurations. They may also draw these on the 2D displays if they want.

- Aircraft is 5 miles ahead and moving away (following on arrival)
  - A second aircraft is 8 miles ahead, same bearing as first aircraft, 500 ft below and coming towards us
  - Second aircraft is now 4 miles ahead, same bearing, climbed to 300 ft

below, and TCAS issues a climb RA

- Aircraft has a relative bearing of 45 degrees but is level 1000 ft below. We are descending into his flight path. TCAS issues a climb RA
- Aircraft has a relative bearing of 45 degrees and is set to cross our flight path. They are 1000 ft below and climbing. TCAS issues a descend-crossing RA

B.1.6 Show Own Designs - Discuss, Brainstorm, Iterate

Finally I'd like to show you some of the ideas I've had to improve the TSD. I waited to show you these as to not bias your opinion for novel ideas.

I'd like to talk about these displays and features which could be implemented in a new display. For each design:

- *Does the display make sense as depicted/described?*
- *Would the display be beneficial during a TCAS event?*
- *Is there anything you would change or iterate on about this display to help with the problems we've discussed?*

<Show OpenGL Demo - introduce each feature one at a time>

- Including more information on current TSD
  - Groundspeed vectors
  - Changed directional information
  - Spatial TA/RA Line
  - Breadcrumbs
- Timeline Display
- Vertical Situation Display

  - Display can pop-up or be separate
  - Intruder relative altitude and vertical flight path
  - Intruder avoidance area (ALIM)
  - Ownship position and performance relative to instructed maneuver
  - Horizontal axis can be time based or distance based

Additionally, show concepts in powerpoint from other authors:

- Ho & Burns [14] - predicted collision area, groundspeed vectors, protected volumes, time to loss of separation
- Cleveland [46] - pop-up relative altitude VSD & maneuver performance

As possible, pilots will select or deselect features they prefer. They may draw new concepts or changes to the presented concepts on appropriate sample displays. With a different color pen, they may add information to the displays drawn by them before.

B.1.7 Prioritize Display Features

Finally I'd like to talk about which displays were most important and least important. I'd like to rank the most important design changes, and understand why you find them most important. I'd also like to know which would be the least important designs and why.

At the end of the interview, the pilot was shown NASA Ames's 3D CDTI tool. A brief demo was shown for how it works. The pilot was given a chance to interact with the tool and view the traffic display. The pilot is then asked for any opinions on the display and anything they might change about that display or their previously drawn displays.

B.2 SME Brainstorming Results

All of the pilots were excited about the changes to the current plan view TSD. In general, they wanted to have the ability to query more information about traffic. *"That is one thing that we do talk about a lot is that we don't know [about traffic unless we watch the TSD]; we can see how he is coming at us, what direction he is coming from, or whatever. But all air traffic controller says is traffic 2 o'clock descend, or something like that. You don't know what it is, where it's going, or what his actual altitude is."*

All of the pilots found the directional symbols on the TSD to be the most useful change. Each pilot described it as their favorite implemented feature and made no suggestions for changes.

Next, the pilots all liked the TA/RA boundary line as depicted, as they thought anticipation of alerts would be helpful. One pilot suggested instead to show it as a line the ownship crosses, but after seeing it implemented, decided the original implementation was better.

The other two features (speed vectors and breadcrumbs) the pilots reported as useful but not as beneficial as the first two. They each said they liked these ideas, but that they would not want to see them all of the time. They did think these items would be beneficial to pop-up just before the TA or RA.

Additionally, two of the pilots wanted to see more information about the traffic on the TSD. They both said they wanted anything possible; the most important feature for both of them was indicating if the traffic was VFR. One of the pilots suggested that could be done with a little 'V' symbol next to the target. The other suggested an alternate color for VFR or 'Not TCAS equipped traffic'. Examples from the pilot drawings are shown: one pilot also suggested having aircraft type information depicted, as in Figure 42, and another suggested having the traffic route depicted, as in Figure 43.

Figure 42: Pilot Drawn Intruder Symbol - Indicating VFR and Traffic Type

Figure 43: Pilot Drawn TSD - VFR and Intruder Path Indications

Another novel idea conceived for the traditional TSD was variable size arrows. The length or size of the arrows could give an indication of climb rate. The pilot suggested: *"The climb arrow could be a representation of the climb rate. We don't have the time to do the math, but just as a length of an arrow you can notice that 'whoah that's a big arrow.' That's not something that we would be looking at during the RA, but by this point we already have a plan formulated. But to see that from way out or to see that during a TA."*

One pilot thought the timeline display was useful, and liked having a focused, separate display annunciator during traffic event. One pilot was not sure; he thought it could be useful during an event, but was redundant with the spatial TA/RA lines on the TSD and the VSD. The last pilot disliked the timeline display and found it distracting. The pilots did not draw or offer any suggestions for changes to a timeline view.

Two of the pilots liked the VSD in general and found it helpful. The other pilot thought it could be helpful leading up to an RA, but would mostly distract from the avoidance task during an RA. In general, this pilot did not want to see any traffic on the VSD.

The pilots overall thought the method of displaying traffic on the VSD worked well. They indicated that it is not confusing to show aircraft off the path or swath. *"I would be accepting that there is an aircraft at the depicted range in my flight path... Whether it is offset to the left or right doesn't throw me off that much... It helps to put my mind thinking in a vertical representation."*

All of the pilots thought the most useful feature of the VSD was a depiction of the TCAS maneuver (vertical rate goal line). They thought it was helpful to be able to compare the own vertical trend to the commanded trend (in addition to seeing it on the VSI).

All of the pilots thought the TA/RA boundary line was useful on the VSD. The line helps to "*get head in game when intruder crosses the line*."

The pilots were less excited about the other two features: ALIM boundary lines and the vertical speed lines. One pilot thought ALIM was "*cool*" to see during the TA, but not useful during an RA. The pilots did not seem to really use or appreciate the intruder vertical speed line. One pilot said, "*I don't want to see all those lines everywhere. Keep it simple stupid. Just show what I need to follow at the time for the most important intruder*."

One iteration on the VSD a pilot wanted to see was a display of a non-transgression zone depicted, along with a safe altitude to climb to. Rather than seeing the ALIM of the target directly, he wanted that depicted as unsafe airspace to not enter.

Sometimes the pilots asked for things that could be confusing or unhelpful. The pilots also could usually only think of explaining things with arrows. For example, one pilot suggested drawing a second arrow next to a target to indicate if it had been given guidance during a coordinated RAs as shown in Figure 44. This obviously could be very confusing if the target is climbing but receiving a descent command. It is unclear what the second arrow could mean without an explanation.

Figure 44: Pilot Drawn RA Symbol During Coordinated Maneuver

Displaying traffic on a futuristic display was discussed with the subject matter experts during the brainstorming. Generally the question was asked how they would imagine seeing a specific traffic situation develop on the displays. The pilots discussed what information should be included and where they would look for it. The pilots had a hard time trying to explain how TCAS works or understanding the goal of improving pilot understanding of TCAS. Instead they focused on what type of features they wanted to see, which was mostly based on current depictions of traffic.

All of the pilots wanted to see traffic on an exocentric 3D ND. One pilot wanted traffic constantly shown on the egocentric 3D PFD as well, and the other two wanted traffic or guidance shown only during an RA. All of the pilots suggested the size of the intruder scale with range in some way, either discrete steps or continuous scaling without taking over the entire screen.

For obscured traffic, a pilot suggested a dot, similar to a web browser tab, to indicate multiple targets. Another pilot suggested the targets could be translucent or have a specific color to indicate multiple targets.

One of the pilots wanted to see an indication for potential threats while planning a route change. He thought it would be helpful, when dialing in an altitude change, for a potential threat could be highlighted with a color or a circle around the target as shown in Figure 45.

Figure 45: Pilot Drawn Traffic Conflict During Route Planning

The pilots generally wanted the same symbology for traffic targets as the traditional display. Two of them used the normal symbols for all drawings. The other started with normal symbols, but later changed them to 3D directional symbols saying, "*Showing the speed vector would be pretty easy on the exocentric display. Instead of a dot, it could be a 3D diamond kind of like the icon on The Sims.*"

At the end of each brainstorming session, the NASA Ames's 3D CDTI Route Assessment Tool was demonstrated to the pilot [22]. All of the pilots thought it was very interesting and useful to see and to play with. They did not have any further comments or changes to the brainstorming based on this interaction.

APPENDIX C

SME EVALUATIONS PROTOCOL AND RESULTS

C.1 Protocol

The SMEs were brought back in a second round to evaluate the TSD+. In the second round, each pilot performed a heuristic evaluation in which they searched for any potential usability problems [39]. The heuristics relate to principle and guidelines of design and are listed in [38].

A cognitive walkthrough was considered for the heuristic evaluation [38], but could not be used in the exact manner used in HCI evaluations, as pilot interaction with TCAS is different from a typical computer system. The pilot interacts with an airplane and not with TCAS directly; the TCAS TSD updates continuously every second, and typically does not require any input from the pilot. However, in the style of a cognitive walkthrough, the simulator can be paused at the critical moments to allow the pilots to reflect on the display. First, the entire sequence is played without pausing so that the pilot can get the full effect of a continuously updating display. Next it is replayed and paused when an intruder first appears, becomes proximate, becomes a TA, becomes an RA, any changes to the RA, and clear of conflict.

There are 10 metrics used in a typical heuristic evaluation suited for computer applications. However, only five of them were relevant to pilot interaction with TCAS. The pilot evaluated the display based on these five metrics. The heuristics were selected from [33], removing ones that are not applicable. The pilot may comment on any of these items and choose to mark it as acceptable or not.

First, the setup of what is happening is explained to the pilot. They are told that they will be flying various scenarios, evaluating the usability of the TSD, and providing feedback for any design changes to the TSD and Futuristic TSDs.

The discussion then explains the usability heuristics that each pilot should consider for each display as below:

- **Visibility of TCAS alert status:** The TSD should always keep pilot informed about what is going on with TCAS, through appropriate feedback within reasonable time.
- **Match between TSD and the real world:** The TSD should speak the pilots' language, with words, phrases and concepts familiar to the pilot, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.
- **Consistency and standards:** Pilots should not have to wonder whether different words, situations, or actions mean the same thing. Follow flight deck conventions.
- **Recognition rather than recall:** Minimize the pilot's memory load by making objects, actions, and options visible. The pilot should not have to remember information from one moment to another.
- **Aesthetic and minimalist design:** TSD should not contain information which is irrelevant or rarely needed. Every extra unit of information in a display competes with the relevant units of information and diminishes their relative visibility.

The pilots stepped through the following traffic scenarios to exercise each of the following potentially confusing traffic cases:

- Nominal single intruder in front of aircraft various RA types:

  (1) Climb RA

  (2) Descend RA

  (3) Monitor Vertical Speed - VFR Traffic

  (4) Crossing RA

- Multiple aircraft; background traffic in front (following in) and intruder from various bearings: (5) 0^o, (6) 45^o, (7) 90^o, (8) 135^o, (9) 180^o

- (10) Converging courses, with intruder is 1000ft above, within DMOD, and descending

For each scenario, first the pilot flew the scenario in normal speed. After clear of conflict, pilot evaluated each display feature. Then the scenario was stepped through at the pilots discretion, pausing at each display change (intruder appears, proximate traffic, caution traffic, TA traffic, RA traffic, RA change, or clear of conflict) for any additional pilot feedback. If anything is confusing, the pilot was asked to mark what is and why it is confusing on a printed version of the display. Additionally, the pilot could sketch an improvement to the display. Finally, the pilot was asked how the traffic situation should be represented on a futuristic cockpit display.

Screenshots from some sample scenarios are shown below to demonstrate the prototypes evaluated here, along with some of the challenges or potentially confusing scenarios which the pilots will be evaluating.

Accelerating traffic is shown in Figure 46 and Figure 47, where the tau criterion is shrinking on the VSD and the plan TSD. Traffic is at 45 degrees, and the VSD shows two intruders compressed onto one view. In Figure 48, traffic has now progressed from a TA. In Figure 49, the traffic has triggered a climb RA for the ownship.

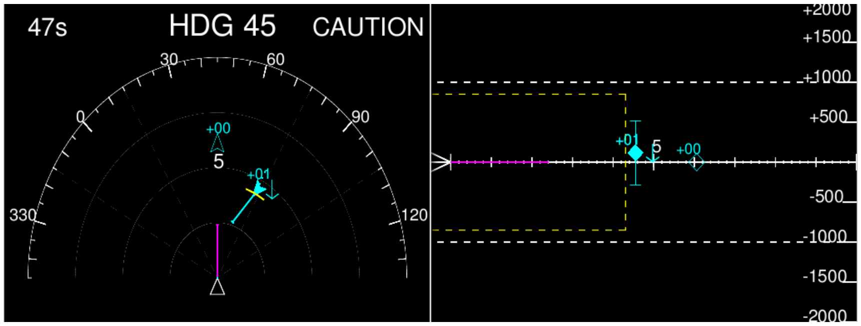


Figure 46: Accelerating Traffic - Before TA 1

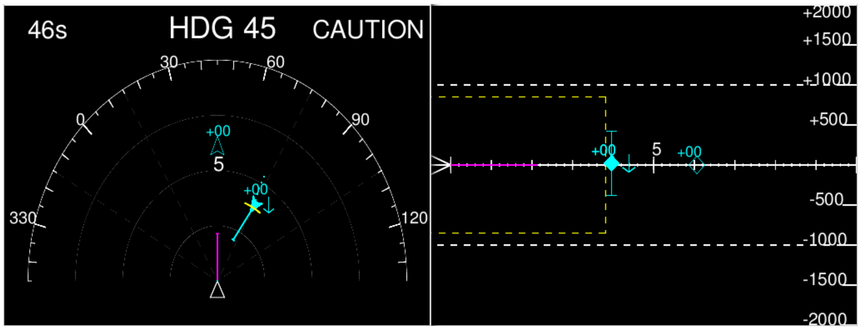


Figure 47: Accelerating Traffic - Before TA 2

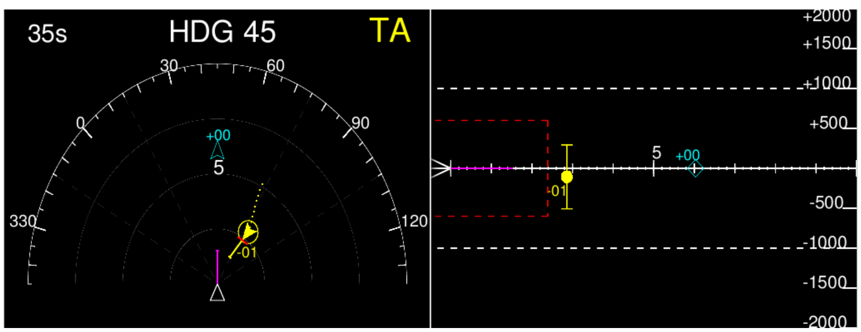


Figure 48: Accelerating Traffic - During TA

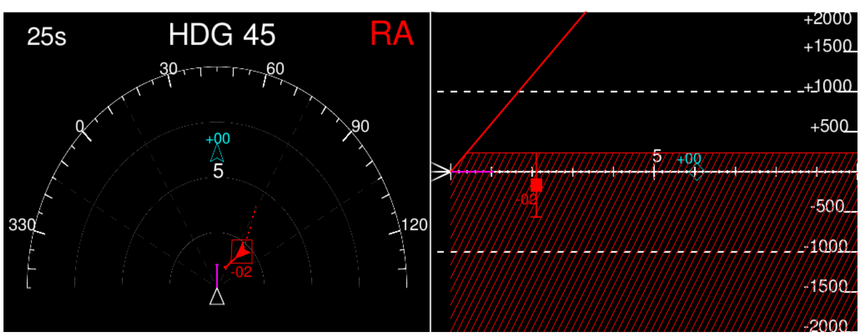


Figure 49: Accelerating Traffic - During RA

In Figure 50, traffic at a 90^o bearing is not shown until it becomes an imminent threat in Figure 51.

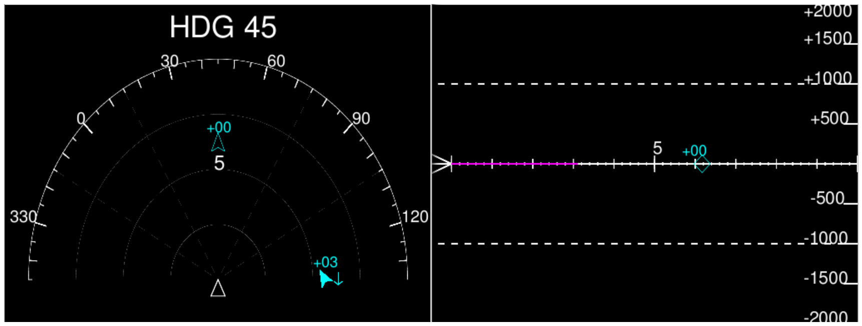


Figure 50: Traffic Not Shown on VSD

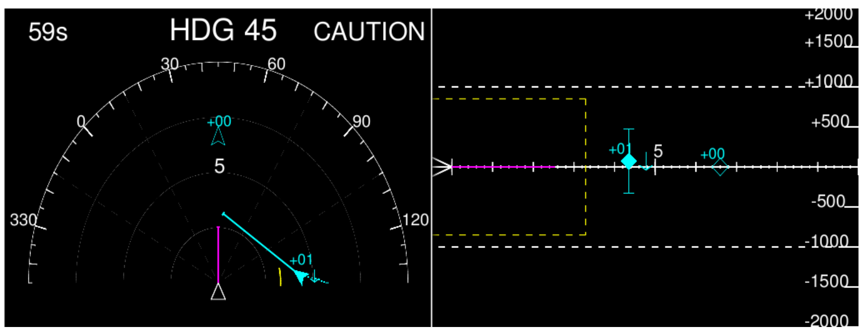


Figure 51: Imminent Traffic Shown on VSD

In Figure 52, the traffic is inside of the range tau criteria, but still not generating an RA because it is outside of the vertical criteria. In Figure 53, the traffic is below; the RA is a crossing descent.

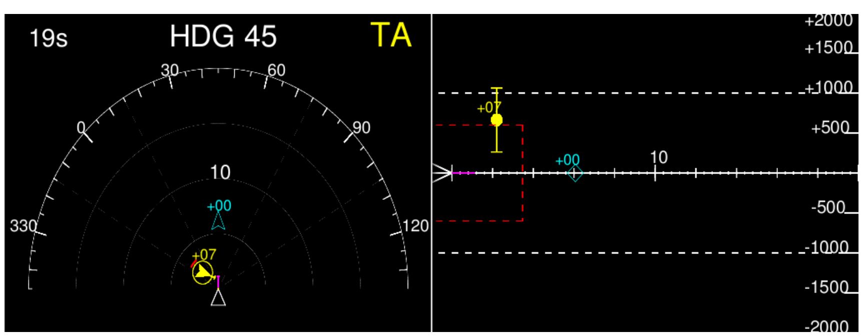


Figure 52: Traffic Passing Horizontal but not Vertical TCAS Test

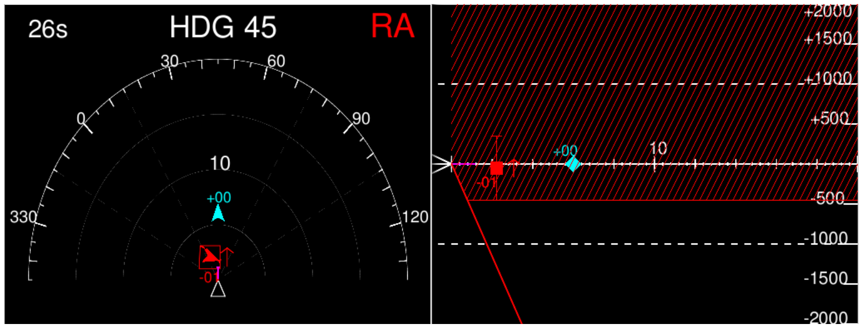


Figure 53: Traffic Display During Crossing Descent

These specific display features are evaluated for overall opinion and usefulness on a scale from 1-10, with 10 representing the best rating:

TSD:

- Directional Arrows
- Pre-TA Traffic annunciator text
- Timing of pre-TA traffic warning
- Spatial TA line
- Spatial RA line
- Speed vector in general
- Speed vector before TA
- Speed vector during TA
- Speed vector during RA
- Breadcrumbs in general
- Breadcrumbs before TA
- Breadcrumbs during TA

- Breadcrumbs during RA
- Variable size climb arrows
- VFR Traffic indication (‘v’)

VSD:

- Intruder inclusion criterion (+/- 30^o bearing)
- Intruder ALIM boundary line
- Spatial TA/RA boundary line on range
- Spatial TA/RA boundary line with ZMOD/ztau
- Ownship vertical speed line
- Commanded RA maneuver depiction
- Intruder Climb/Descent Arrow
- Intruder Relative Altitude Text
- Hashed out RA exclusion area
- RA goal altitude prediction

At the conclusion of the scenarios, the pilot was asked for overall opinions on the display. The pilot noted which set of display features are most important and why, and noted any coupling between display features.

C.2 Results

All of the pilots liked the changes to the plan view TSD. All of the pilots thought the VSD view of traffic could be useful, but also commented that the information may be distracting. All of the pilots did not want the ownship vertical speed line included. One of the pilots wanted the display to completely dim or fade during an RA, so that the focus would be on the TSD and PFD.

In general, the usability heuristics were rated very high. The combined plan view and VSD prototypes received the highest rating for the visibility, match, and consistency usability criteria by everyone. The recognition and aesthetic tended to be lower, but also tended to increase as the pilots became accustomed to seeing traffic on the VSD.

Sometimes the pilots marked an item lower for a specific reason. For example, one pilot did not recognize the 'V' meant VFR traffic, so he marked that lower.

The overall ratings at the end of each evaluation for each display feature are shown in Table 18.

Two of the pilots had trouble with traffic from behind on the VSD. They wanted the display to shift to show the traffic behind the aircraft, as shown in Figure 54.

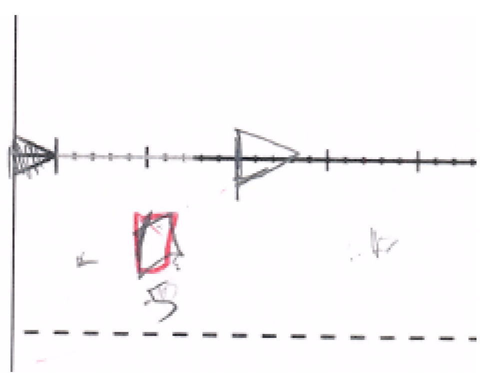


Figure 54: Pilot Drawn VSD with Traffic from Behind

All of the pilots were able to intuitively understand what most of the display features meant. The features were explained only after they asked, and they usually

Table 18: Pilot Ratings of Displays During Evaluation

Feature	Pilot 1	Pilot 2	Pilot 3
Directional Arrows	10	10	10
Traffic Mode	10	5	7
Traffic Mode Timing	10	8	7
Spatial TA Line	9	10	10
Spatial RA Line	9	2	10
Speed Vector	9	10	3
Breadcrumbs	9	8	10
Variable Sized Arrows	9	10	1
VFR Traffic Indicator	9	10	1
Overall VSD	8	10	8
Intruder Inclusion Criterion	9	7	8
Intruder ALIM	8	10	7
Spatial Boundary Box	9	10	10
Ownship Vertical Speed	7	10	1
Commanded RA Maneuver	9	10	1
Hashed Exclusion Area	10	10	10
Goal Altitude	9	5	1

had the right idea of how it worked.

They were most confused by the scenarios in which an aircraft had exceeded the range tau criteria, but had not yet exceeded ZTHR. Two of the pilots correctly understood that the traffic was not a threat because it well separated vertically.

In general, the features on the plan view TSD were rated higher. The visual traffic warning and its timing before the TA was good. The pilots all liked the spatial TA line. Two liked the spatial RA line but the other did not (as he was already watching the traffic, so it was not providing any information to him). Two of the pilots liked the speed vector, and the other did not think it provided any new or useful information (he liked the breadcrumbs and thought that was all he needed). All of the pilots liked the breadcrumbs, but one rated them lower during the RA (because he was trying to focus on the PFD). Two of the pilots liked the variable sized climb arrows and VFR traffic indicator, but the other did not think that was useful information to him.

As before, the pilots thought the directional information the most useful feature.

"*My favorite thing all together is the directional indicator. Trying to figure out where a little diamond is going is impossible.*"

The VSD was rated overall as useful by all of the pilots. The pilots thought the intruder inclusion criterion was appropriate, but one noted that it should be better based on statistics and perhaps pilot selectable. The pilots thought the intruder ALIM error bars were good. The TA/RA boundary box was rated very high. Two of the pilots rated the ownship vertical speed line highly at the end of the interview (though they had previously commented while using the displays that the line was very distracting) and the other rated it very low. One of the pilots rated the other RA specific features low as he did not want to see anything on the VSD during the RA, but the other two rated it all very highly. Regarding the hashed area, one pilot said, "*I like how it keys you in with a big red box telling me do not go here. It definitely keys you in to it.*"

Regarding the VSD in general, one pilot said: "*There is nothing I'd want to see differently. Now that I'm used to it, everything makes sense. It doesn't matter where he is on the VSD. It just matters that he's a target and I've got to get away. On the plan view it's cluttered, but that's unavoidable with traffic behind because there is a lot there.*"

Two of the pilots thought the breadcrumbs were not as useful or necessary because of the speed vector. They wanted to see the breadcrumbs on their current displays, but did not need them with the speed vectors. A pilot commented that he does not care where the intruder was if he knows where he is projected to be. After one scenario, a pilot said, "*[The displays] felt well integrated in [that scenario]. I could see I was following [intruder one]. In that scenario, I didn't need the breadcrumbs. Once it became a conflict, I liked being able to reference my protected volume on the VSD.*"

A small change was made to the speed lines on the plan view at the suggestion of the pilot. He wanted to see a 10 second mark on the line to help indicate scale since it varies in length. Once that change was made he thought it was great. The pilot drawn change is shown in Figure 55.

Figure 55: Pilot Drawn Speed Vector with 10s Indicator

One of the pilots suggested changing the VFR indicator to make it more clear. He suggested either moving it into the text with altitude (so everything being read is in the same place) or using a serif font so that it does not look like a descent chevron. The pilot drawn change is shown in Figure 56.

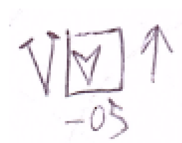


Figure 56: Pilot Drawn VFR Indicator

One of the pilots also suggested changing the way the VSD draws targets to make them more readable. During the RA, the hashed exclusion area obscures the symbol and text of the intruder. He wanted it blacked out around the symbol, so that it could be read as shown in Figure 57.

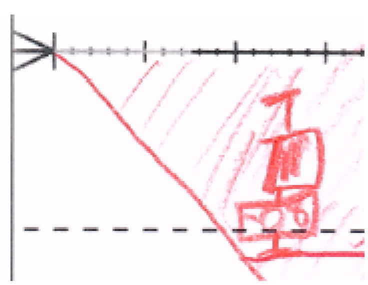


Figure 57: Pilot Drawn VSD During RA with Excluded Area for Readability

The pilots generally all wanted the same things for the scenarios depicted in synthetic vision. They once again were more focused on understanding the traffic picture than understanding TCAS. They wanted to see the traffic on the exocentric display unless it was a TA (or about to be a TA) threat. The pilot drawn exocentric display during a TA is shown in Figure 58. The imminent traffic could be drawn on the egocentric display if it was in view, but otherwise an indicator on the edge of the display could indicate which direction to look visually for the traffic.

Figure 58: Pilot Drawn 3D Exocentric Display During a TA

The pilots did not care about the exocentric display during the RA. They suggested it was okay to draw the ownship maneuver, but they probably wouldn't even look at the display. One pilot drew a carpet on the exocentric display in Figure 59 to indicate the maneuver commanded by the RA. Another pilot draw a line for the maneuver on the exocentric display in Figure 60.

One pilot liked the hash exclusion area and suggested it should be drawn inside of a trapezoid as showin in Figure 61.

For traffic off screen during a traffic event, two pilots wanted the traffic docked or half-symbol drawn on the egocentric and exocentric displays using symbols indicating its directionality. An egocentric display with off screen traffic is drawn in Figure 62.

Figure 59: Pilot Drawn 3D Exocentric Climb Maneuver Carpet

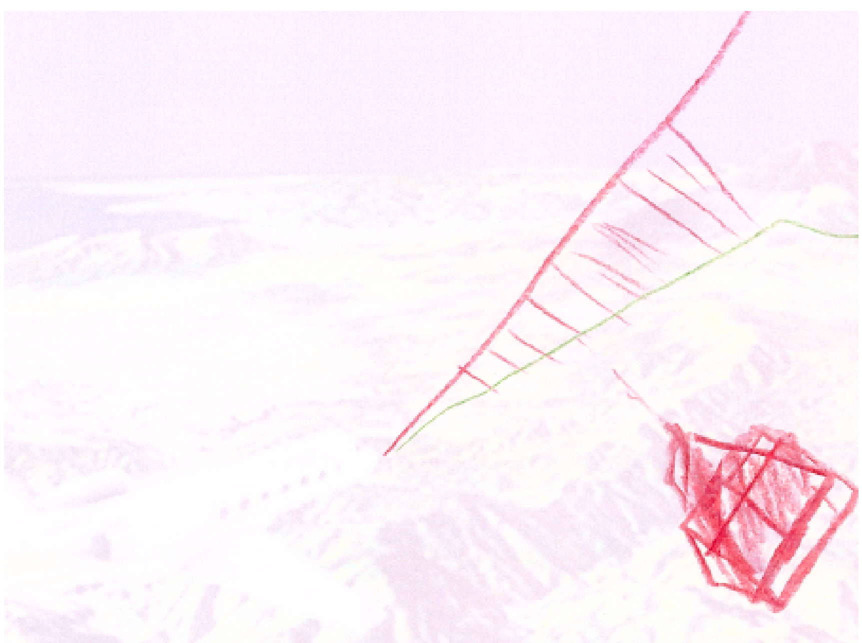


Figure 60: Pilot Drawn 3D Exocentric Climb Maneuver Line

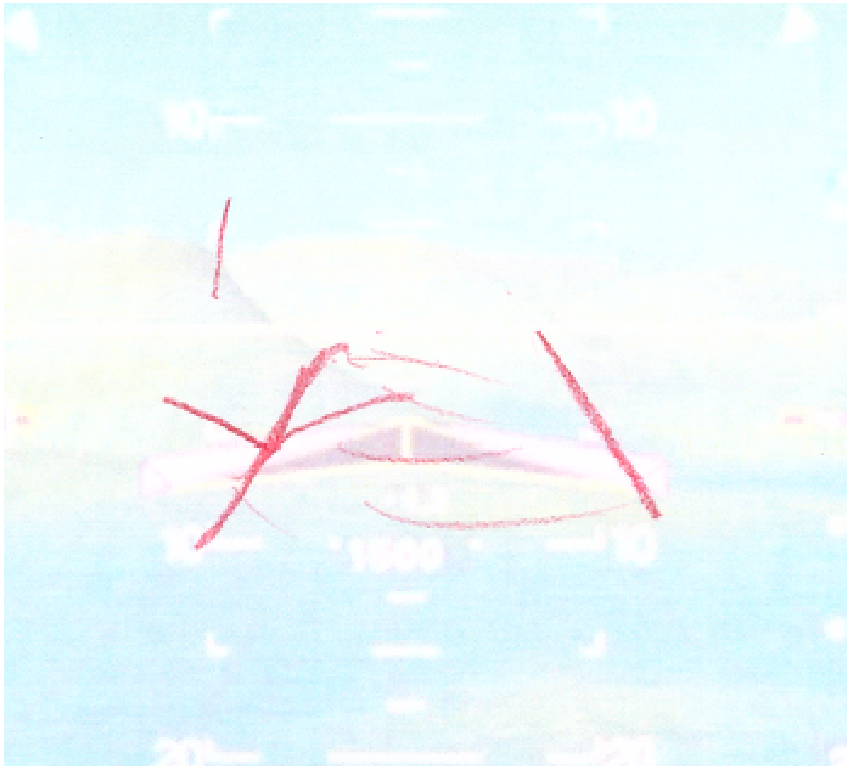


Figure 61: Pilot Drawn PFD with Exclusion Area Inside Trapezoid

On the exocentric display, a pilot thought the speed vector should still be drawn to indicate CPA and would be able to infer the conflict from the docked symbol and speed vector as shown in Figure 63.

Two of the pilots suggested using some sort of ceiling or floor depicted for avoiding traffic. They liked having an altitude exclusion area for traffic avoidance. A ceiling shown during a TA on an egocentric display is shown in Figure 64. A floor during an RA on the egocentric display (by a different pilot) is shown in Figure 65. They also suggested that a preventative floor could be drawn on the exocentric display as shown in Figure 66.

At the end, all of the pilots said they hoped to one day fly with these new displays. They all thought the displays were a good step forward and provided useful information.

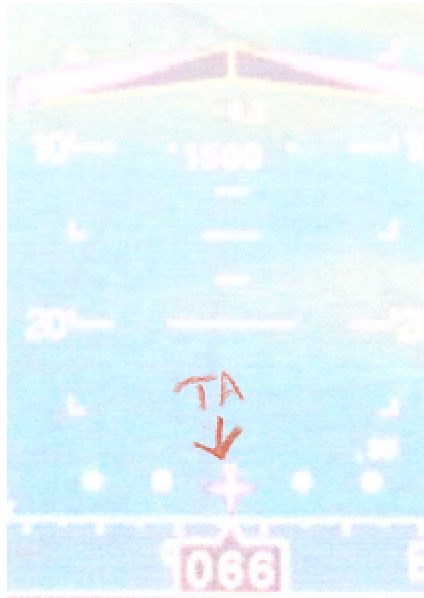


Figure 62: Pilot Drawn 3D Egocentric with Traffic Offscreen

Figure 63: Pilot Drawn 3D Exocentric with Traffic Offscreen

Figure 64: Pilot Drawn 3D Egocentric TA Ceiling

Figure 65: Pilot Drawn 3D Egocentric Floor

Figure 66: Pilot Drawn 3D Exocentric Floor

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