NASA/TM-2000-210107

High-Speed Research Surveillance Symbology Assessment Experiment

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April 2000

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Abstract

Ten pilots with glass cockpit experience and familiarity with the Traffic Alert and Collision Avoidance System (TCAS) and head-up displays flew multiple approach and departure scenarios in a fixed-based simulation experiment of the proposed High-Speed Civil Transport. The purpose of this piloted experiment was to evaluate the utility of different airborne surveillance display concepts and to investigate associated surveillance research issues such as the type and display location of augmented surveillance information. The primary eXternal Visibility System (XVS) display and the Navigation Display (ND) were used to present tactical and strategic surveillance information, respectively, to the pilot. Three sensors, TCAS, radar, and the Automatic Dependent Surveillance-Broadcast system, were modeled for this simulation. Two types of surveillance symbology sets, representing the three sensors, were presented to the pilots in the different surveillance concepts. One surveillance symbology set used unique symbol shapes to differentiate among the sensors, while the other surveillance symbology set used common symbol shapes for the sensors (i.e., no sensor differentiation by symbol shape). In addition, surveillance information in the form of escape guidance from threatening traffic was also presented to the pilots. The surveillance information, which included the sensor symbols and escape guidance, was either presented head-up on the primary XVS display and head-down on the ND or head-down on the ND only (in addition to vertical escape information on the PFD). Both objective and subjective results demonstrated that the display concepts having surveillance information presented head-up and head-down have surveillance performance benefits over those concepts having surveillance information displayed head-down only. No significant symbology set differences (sensor differentiation vs. no sensor differentiation) were found for surveillance task performance.

Summary

Researchers within the eXternal Visibility System (XVS) element of the High-Speed Research program are developing and evaluating information display concepts that will provide the flight crew of the proposed High-Speed Civil Transport (HSCT) with integrated imagery and symbology to permit required path control and hazard avoidance functions while maintaining required situational awareness. The surveillance task, defined as the ability to detect, identify, prioritize, and avoid external hazards, as well as maintain overall potential hazard situation awareness, constitutes the XVS approach to hazard avoidance. The XVS must provide the pilot with an equivalent functionality as the forward windows found in today's transport aircraft with respect to the surveillance task. The purpose of this fixed-based simulator experiment was to evaluate the utility of different airborne surveillance display concepts and to investigate associated surveillance research issues such as the type and display location of augmented surveillance information. Ten pilots with glass cockpit experience and familiarity with the Traffic Alert and Collision Avoidance System (TCAS) and head-up displays flew multiple approach and departure scenarios. Although other displays (e.g., primary flight display, mode control panel, etc.) are part of the XVS concept, the primary displays used for comparing the XVS surveillance concepts were the head-up primary XVS display (PXD) and the head-down Navigation Display (ND). The PXD was used for presenting tactical surveillance information to the pilot, while the ND was used for presenting strategic surveillance information to the pilot. In this context, tactical information relates to information required to plan and conduct a flight maneuver or maneuver change. Strategic information referred to all other surveillance information of interest. Three surveillance sensors, TCAS, radar (the HSCT weather radar with a traffic detection mode), and the Automatic Dependent Surveillance-Broadcast (ADS-B) system, were modeled, each with unique update rates and accuracies. Two types of surveillance symbology sets, sensor differentiation vs. no sensor differentiation, were utilized in this experiment. In the sensor differentiation surveillance set, each sensor had a unique symbol shape associated with it. In the no sensor differentiation surveillance set, each sensor was represented by a common symbol. Standard TCAS symbols were used for the no sensor differentiation surveillance set symbols. In both surveillance symbology sets, symbol color was based on certified TCAS threat level specifications. In addition to sensor symbols, surveillance information came in the form of TCAS (or equivalent sensor system) escape guidance from threatening traffic. The study showed that the display concepts having surveillance information (sensor symbols and escape guidance from threatening traffic) presented both head-up on the PXD and head-down on the ND consistently provided surveillance performance benefits over the display concepts having surveillance information presented head-down only on the ND. The type of surveillance symbology set, sensor differentiation vs. no differentiation, did not provide any significant performance differences in tasks with the different concepts. The pilots overwhelmingly preferred the concepts having surveillance information presented head-up and head-down, but they were mixed in their preferences as to the type of surveillance symbology set they would like available to them.

Introduction

As part of the NASA High-Speed Research Flight Deck Systems (FDS) Program, a piloted simulation study was undertaken at the NASA Langley Research Center by members of the eXternal Visibility System (XVS) Element to address surveillance issues associated with replacement of the forward windows in a High-Speed Civil Transport (HSCT) with electronic display media (i.e., an external visibility system). The XVS will consist of a suite of sensors and supporting systems that will provide to the flight crew the information that would normally be available in a conventional cockpit through pilot vision in the forward direction. (See ref. 1.) An initial assumption made by members of the FDS was that the XVS, in combination with any conventional side windows, would provide each pilot with a field of view as least as great as the guidelines specified in ARP4101/2. (See ref. 2.) To satisfy the criteria of the

ARP4101/2 vision envelope, the current pilot display configuration contained in the FDS Benchmark consists of one XVS display each for the pilot and co-pilot, each containing 40° horizontal and 50° vertical field of view. The forward visibility provided by the XVS display is augmented by natural vision through the side windows.

The purpose of the XVS element is, in response to Industry requirements, to develop and demonstrate operationally viable, economically feasible, potentially certificable concepts, and associated technologies, data, and guidelines to enable a "No-Droop" configuration of the HSCT. (See ref. 3.) The "No-Droop" mission is defined as that which, in a HSCT, would support routine airline operations in environmental conditions and at facilities equivalent to current subsonic transport capabilities, without the requirement to articulate the forebody geometry for ground operations, takeoff, approach and landing. These capabilities include safe and efficient path control and hazard avoidance, during both surface and airborne operations. The surveillance task (ref. 4), is defined as the ability to detect, identify, prioritize, and avoid external hazards, as well as maintain overall potential hazard situation awareness, and it constitutes the XVS approach to hazard avoidance. The experiment described herein addressed the airborne surveillance task with an XVS. The XVS, then, must provide the pilot with an equivalent functionality as the forward windows found in today's transport aircraft, with respect to the surveillance task.

Previous research has identified an XVS Concept (refs. 1 and 3) which was developed to provide a framework for subsequent XVS research studies and experiments. The current XVS Concept consists of high resolution video sensors, high resolution primary XVS displays, navigation displays, a weather radar with a traffic detection mode, the Traffic Alert and Collision Avoidance System (TCAS), the Automatic Dependent Surveillance – Broadcast (ADS-B) system, Automatic Surface Detection Equipment, and side windows with sunlight control systems. Previous studies, experiments, and workshops have led to an XVS Surveillance Concept, which proposes a methodology to utilize concept elements to accomplish the hazard avoidance mission. Key precepts of that concept are:

1) In order to provide present-day equivalent safety and workload, it is assumed that XVS external scene video imagery is augmented by surveillance information from other sources, such as radar, ADS-B and TCAS. These surveillance sources will supplement the object/hazard information provided by visual observations of the flight crew.

2) The head-up primary XVS display (PXD) is used for presenting tactical surveillance information to the pilot, while the head-down Navigation Display (ND) is used for presenting strategic surveillance information to the pilot. In this context, tactical information relates to information required to plan and conduct a flight maneuver or maneuver change. Strategic information refers to all other surveillance information of interest. Although other displays (e.g. Primary Flight Display) are used in the XVS concept, the PXD and ND are the primary displays used for surveillance.

3) The airborne Surveillance Task is comprised of four sub-tasks, identified as follows:

   Detection: The requirement to discern the presence of airborne objects that pose a potential hazard to the aircraft, or could affect flight decisions.

   Identification: The requirement (if any) to discern specific information (altitude, speed, aircraft type, callsign) concerning specific airborne traffic.

   Prioritization: The requirement to decide whether or not airborne traffic poses a significant hazard to the aircraft, the significance of that hazard, and the immediacy of the threat.

Avoidance: The requirement to decide whether specific action must be taken to avoid a hazardous encounter with the traffic of interest, including information required to follow-up on that decision, and decide whether or not action taken is appropriate and effective.

The purpose of this experiment was to evaluate the utility of different airborne surveillance display concepts and investigate associated surveillance research issues. Areas of investigation included determining (1) where augmented surveillance information should be displayed (both head-up and head-down or head-down only) and (2) the format (shape, color, text, information content) of the displayed augmented surveillance information.

Abbreviations

AGCU	autopilot guidance control unit
AGL	above ground level
ALT ARM	altitude arm
ANOVA	Analysis of Variance
ADS-B	Automatic Dependent Surveillance-Broadcast
CRT	cathode ray tube
EP	evaluation pilot
ESD	engine systems display
FDS	Flight Deck Systems
FOV	field of view
ft	feet
HSCT	High-Speed Civil Transport
HUD	head-up display
KCAS	knots, calibrated airspeed
MSL	mean sea level
MCP	Mode Control Panel
NASA	National Aeronautics and Space Administration
ND	Navigation Display
nmi	nautical miles
PFD	Primary Flight Display
PXD	primary XVS display
RA	Resolution Advisory
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
TLX	Task Load Index
VISTAS III	Visual Imaging Simulator for Transport Aircraft Systems III
XVS	eXternal Visibility System

Methods

Subjects

Eight current line pilots with national commercial airlines and two NASA pilots, all with extensive glass-cockpit experience and familiarity with TCAS and head-up displays, acted as subjects in the experiment. Subjects were asked to complete a brief questionnaire (appendix A) describing their flight experience. The number of years flying commercial aircraft that subjects reported ranged from four to 30, with a mean of 10.85 years. Six of the ten subjects also had experience flying military aircraft, with a mean of 14.2 years. The total number of hours flying ranged from a low of 4,100 to a high of 14,000, with a mean of 7,680 hours flying. The total number of hours flying as pilot in command ranged from 1,800 to 9,750, with a mean of 4,528 hours. A summary of the flight experience of the pilots serving as subjects is given in table 1.

Table 1. Summarized Experience of Pilots in the Surveillance Symbology Assessment Experiment

	Pilot	Commercial Flying (years)	Military Flying (years)	Total Flying (hours)	Pilot In Command (hours)	Formal Education (years)	Glass Cockpit Experience (years)	HUD Experience (years)	TCAS Experience (years)	Tracking Radar Experience (years)
	F/O	5.5	11	5500	2200	19	1 to 5	> 5	> 5	11
	F/O	12	14	14000	4500	16	> 5	< 1	> 5	0
	C	17	14	12500	9750	16	> 5	< 1	> 5	5
	F/O	6	9	7600	3130	14	1 to 5	< 1	> 5	1
	C	13	27	10000	8500	18	1 to 5	1 to 5	> 5	0
	I	5	0	4800	3000	15	1 to 5	1 to 5	1 to 5	0
	F/O	4	0	4500	2000	16	> 5	< 1	> 5	0
	C	10	0	6800	1800	16	> 5	1 to 5	> 5	0
	C	6	0	4100	3900	18	1 to 5	1 to 5	1 to 5	0
	C	30	10	7000	6500	22	1 to 5	1 to 5	< 1	5
Total	10	108.5	85 N=6	76800	45280	170	0 years N=0 1-5 years N=6 5+ years N=4	<1 year N=4 1-5 years N=5 5+ years N=1	<1 year N=1 1-5 years N=2 5+ years N=7	22 N=4
Mean		10.85	14.2	7680	4528	17	N/A	N/A	N/A	5.5
Min		4	0	4100	1800	14	N/A	N/A	N/A	0
Max		30	27	14000	9750	22	N/A	N/A	N/A	11

where C stands for Captain, F/O stands for First Officer, and I stands for Flight Instructor.

Scenarios

Ten evaluation pilots with glass cockpit and TCAS experience flew two scenarios with autothrottles engaged in this experiment. Both scenarios included multiple simulated traffic encounters with small (Be-200), medium (B-737), and large (HSCT) aircraft. For consistency, the same number and type of traffic aircraft were used for each experimental run. However, to mitigate learning effects, the order of appearance of these aircraft was varied from run to run. The evaluation pilot's relative visual angle between his ownship and each traffic aircraft was the same for each experimental run, but the time of encounter between the ownship and traffic aircraft varied between runs. An approach scenario and a departure scenario, flown at different speeds, were chosen for this experiment so that the ownship would encounter both moderate and high-speed closure rates with other traffic. The motivation for having two scenarios was to examine moderate and high-speed closure rate effects while performing the airborne surveillance task with an XVS.

Approach Scenario

The first scenario consisted of an approach to the simulated runway, involving a downwind descent, base leg, and final approach segment. (See fig. 1.) A cloud layer at 13,000 feet was present during this scenario. The descent was flown at 250 KCAS, beginning at 12,000 feet AGL and ending (before the turn to base leg) at 1,500 feet AGL. After the turn to base leg was complete, the aircraft decelerated to its landing speed of 159 KCAS and continued flying the remaining legs (base and final) of the approach.

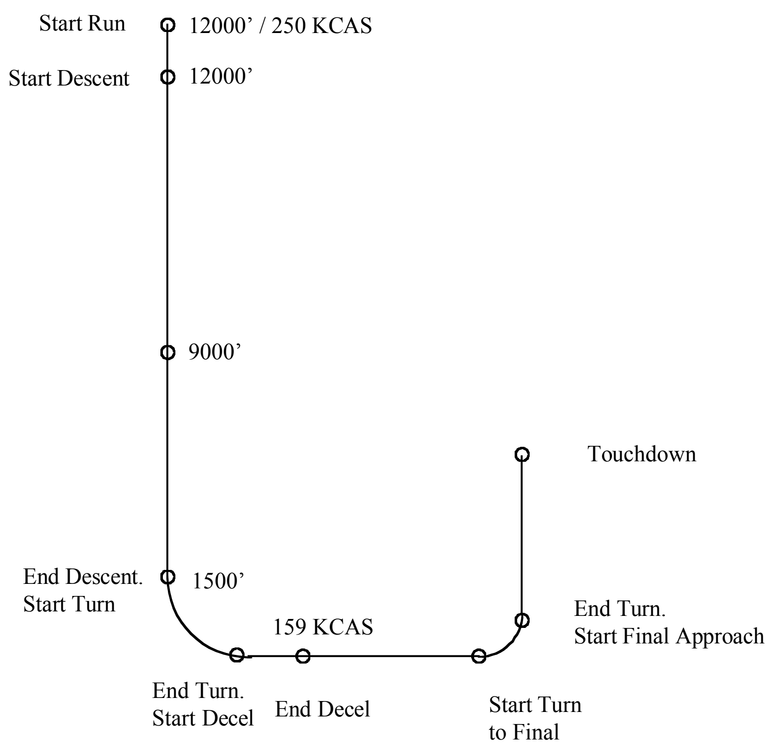


Figure 1. Overview of the Approach Scenario.

Departure Scenario

The second scenario was a simulated climbout, from a medium altitude (6000 ft MSL) overhead the airfield, to 24,000 ft MSL, with a 45 degree turn. (See fig. 2.) A cloud layer at 5,000 feet was present during this scenario. During the climb from 6,000 to 10,000 feet, the aircraft was flying at 250 KCAS. After the level off at 10,000 feet and 45 degree turn, the aircraft began accelerating to 350 KCAS and continued its climb to 24,000 feet. After reaching the level off altitude of 24,000 feet, the aircraft continued to fly at 350 KCAS for one minute after which the scenario concluded.

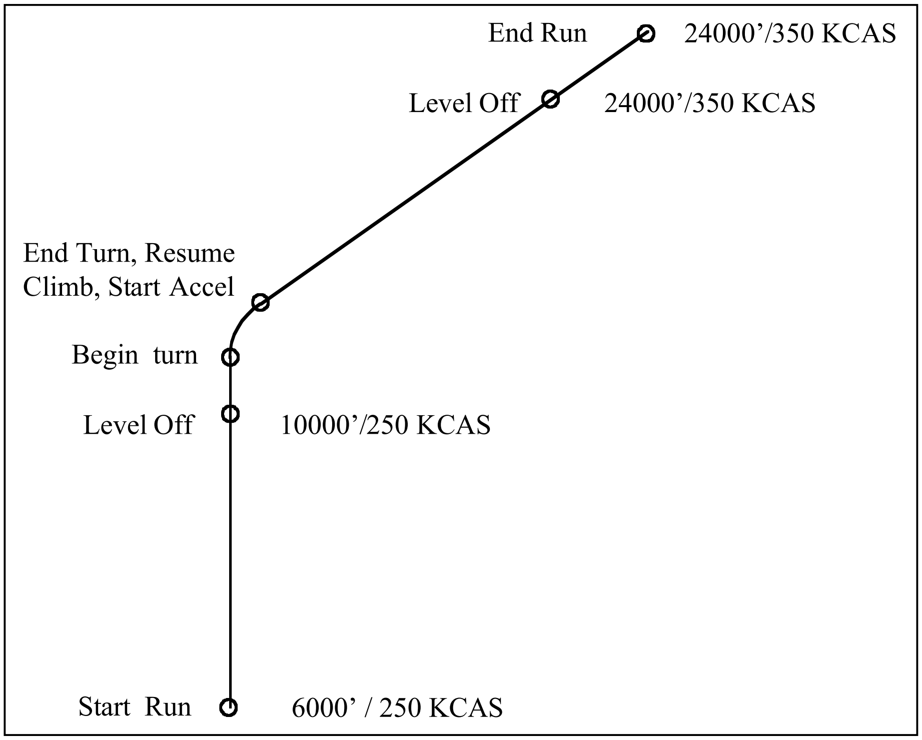


Figure 2. Overview of Departure Scenario.

Tasks

In order to ensure repeatable traffic encounters between runs, the simulation runs were flown with the autothrottles and autopilot engaged (scenario route and altitudes preprogrammed in the simulation setup). The experiment placed the evaluation pilot (EP) in simulated scenarios where potentially threatening traffic was encountered.

The EP was required to perform three tasks (surveillance, navigation, and systems monitoring) while flying the approach and departure scenarios. (See appendices B-D.) The primary task of the EP was the airborne surveillance task that was comprised of four sub-tasks, identified as follows:

Detection: The requirement to discern the presence of airborne objects that pose a potential hazard to the aircraft, or could affect flight decisions.

Identification: The requirement (if any) to discern specific information (altitude, speed, aircraft type, callsign) concerning specific airborne traffic.

Prioritization: The requirement to decide whether or not airborne traffic poses a significant hazard to the aircraft, the significance of that hazard, and the immediacy of the threat.

Avoidance: The requirement to decide whether specific action must be taken to avoid a hazardous encounter with the traffic of interest, including information required to follow-up on that decision, and decide whether or not action taken is appropriate and effective.

The remaining two tasks were a navigation task and a systems monitoring task. These two secondary tasks were used to better simulate real world workload while performing the surveillance mission.

Surveillance Task

For each experimental run, the EP's surveillance tasks were to:

1) visually acquire (detect) the presence of traffic on the PXD and in the side window

2) identify the detected aircraft

3) assess the threat of traffic through the use of the ND and visual scene (PXD and side window)

4) fly commanded escape guidance to avoid an impending collision with traffic generating a Resolution Advisory (RA)

The EP pressed the right button (the red one) on the sidestick controller the first time he visually detected traffic on the PXD or in the side window (not the ND). This red button was used as an event marker and pressing it recorded the time the EP visually acquired the traffic. After detecting the aircraft in the visual scene, the EP verbally identified it with respect to bearing and elevation. For example, he might say "I've acquired an aircraft at bearing 2-7-0 that's 3 degrees above the horizon." The EP was asked to comment on any other information (type, class, speed, altitude, etc.) that he felt was necessary to discriminate the traffic. Three types of traffic aircraft were simulated for this experiment: a Be-200, a B-737, and a HSCT.

If the EP believed that a traffic aircraft was going to become a threat, he touched that traffic symbol on the ND and verbalized his threat assessment. By touching the traffic symbol on the ND, the assumption was made that the EP was simultaneously performing the sub-tasks of detection, identification, and prioritization for that traffic. The ND had a touch-screen capability. The time and characteristics (aircraft type, relative position, etc.) of the traffic symbol the EP pressed on the ND were recorded. As the run proceeded, if the EP felt that the traffic was no longer a threat, he verbalized this opinion to the experimenter. If he noticed traffic on the PXD (instead of on the ND) that he believed was going to become a threat, the EP didn't need to transition to the ND to press the traffic symbol. Instead, he just verbalized his threat assessment and the experimenter recorded the EP's comments. Since the ND was used to present strategic information, it was assumed that most of the EP's threat assessments would be made using it instead of using the tactical PXD.

The EP disconnected the autopilot and manually flew commanded guidance maneuvers to escape a TCAS (or equivalent sensor system) Resolution Advisory. This guidance and its interpretation was briefed and demonstrated to the EP prior to data runs. To disconnect the autopilot, the EP pressed the left button (the black one) on the sidestick controller. Although the autopilot was disengaged, the autothrottles were still engaged after the black button was pressed.

The pilot was informed of this surveillance task during his Pilot Briefing and practiced the surveillance sub-tasks of detection, identification, prioritization, and avoidance during his Pilot Familiarization runs.

Navigation Task

The intent of the navigation task was to simulate allowing the autopilot to descend or climb past defined waypoint crossing altitudes, much as would exist in actual instrument arrivals and departures. This method increased the EP's workload and the realism of the task environment, and thus made the experimental runs more than just a monitoring task.

The EP was required to arm waypoint crossing altitudes on the Mode Control Panel (MCP) during experimental runs, with simulation software sensing violations of altitudes during climbs and descents which the EP hadn't yet armed. A thorough description of the touch-screen capable MCP can be found in the section entitled Simulator Description. For this experiment, the initial altitude displayed in the MCP was 12000 ft for the Arrival Scenario and 9000 ft for the Departure Scenario. At run initiation, the ALT ARM box on the MCP was not illuminated. It was the pilot's responsibility to arm the altitude by touching the ALT ARM box. The ALT ARM box remained illuminated in amber until (1) the pilot touched the dial to change the altitude or (2) the actual altitude exceeded the altitude displayed in the box. If either of these conditions was met, the box was no longer illuminated. During the simulation runs, the EP was required to set and arm defined waypoint crossing altitudes before those altitudes were reached. If a subject didn't correctly set and arm the waypoint crossing altitude, his inaction was recorded electronically and the ALT ARM light on the MCP was extinguished. The amber light illumination served as a visual reminder to the pilot to remain vigilant in the altitude-arming task.

For purposes of the simulation and time efficiency, runs did not end, nor did the autopilot vertical profiles change, if the EP violated the altitude arming procedure. The altitude arming procedure is described in more detail in appendix C. The pilot was informed of this navigation task during his Pilot Briefing and practiced the altitude arming procedure during his Pilot Familiarization runs.

Systems Monitoring Task

To further increase workload, the EP was required to monitor the levels of fuel in left and right tanks on the Engine Systems Display (ESD) and to maintain relatively equal amounts of fuel in each tank (within 2000 lbs of each other) using controls also on that display. (See appendix D.) During all runs, a leak of 1000 lbs/min occurred in either the left or right tank. This leak required the EP to perform a fuel transfer task. If the difference between the amounts of fuel in the left and right tanks was greater than 2000 lbs an entry was made in an electronic log, marking the fault and system time. If the relative fuel difference between the two tanks was greater than 3000 lbs, an amber caution light was illuminated. This caution light indicated either a fuel imbalance or system malfunction due to pilot error. A system malfunction caution occurred in either of two cases: 1) the pilot turned a fuel pump off before turning the crossfeed on or 2) the pilot turned the crossfeed off before turning a fuel pump on. The pilot was required to turn on one system before turning off another system, as in actual fuel balancing tasks, to avoid cutting boosted fuel to an engine. If he didn't, the amber caution light was illuminated and his mistake was recorded electronically, along with the system time. The pilot was informed of this systems monitoring task during his Pilot Briefing and practiced the fuel transfer task during his Pilot Familiarization runs.

Simulator Description

The experiment was conducted using the NASA Langley Visual Imaging Simulator for Transport Aircraft Systems III (VISTAS III) piloted fixed-base workstation, from the left crew station. (See fig. 3.) Crew station hardware includes a sidearm controller, rudder pedals, a dual-throttle system, a projected 36 degree horizontal by 26 degree vertical instantaneous field of view (FOV) side window display, a projected 40 degree horizontal by 50 degree vertical FOV PXD, and four head-down liquid crystal displays representing a MCP, Primary Flight Display (PFD), ND and ESD. The PXD is comprised of four high-resolution (1280 x 1024 pixel) CRT-based projection images tiled onto a single XVS display with a resolution of approximately 50 pixels per degree. Conventional simulators have a resolution on the order of 30 pixels per degree. By using a tiled PXD with increased resolution, pilots are able to detect traffic at ranges up to 7 nmi as opposed to conventional simulators where traffic detection is at ranges up to 3 nmi (based on empirical observation). Thus, the VISTAS III visual environment is more realistic with regard to performing the surveillance task of traffic detection than the simulation environments found in conventional simulators. The lab is supported by two Silicon Graphics multi-channel Onyx graphic systems that provide all the visual sources (including the head-down instrumentation), hosting of the aircraft model, and all input/output functions to the workstation. Simulation scene geometry and control laws are intended to approximate the HSCT aerodynamic and engine performance models, in medium (24,000 ft MSL) to ground level approaches to and departures from NASA Wallops Airfield.

Figure 3. Visual Imaging Simulator for Transport Aircraft Systems III (VISTAS III) Layout

Controls

The control inceptor used for pitch and roll inputs in this experiment was a spring-loaded sidestick controller. There were two buttons located on the sidestick. The left button was used as an autopilot disconnect switch and the right button (which was red) was used as an event marker. Yaw control was provided by rudder pedals and thrust control was provided through a dual-throttle system located on a center-mounted console.

Primary XVS Display

The PXD consisted of simulated video imagery from a high-resolution camera combined with the FDS Minimum Flight Symbology Set (appendix E) to present tactical information to the pilot. In some cases, the PXD also had surveillance information (sensor symbols and escape guidance) presented on it to aid the pilot in tactical decisions.

Surveillance Symbology Sets

The surveillance symbology presented on the PXD had three levels: 1) Sensor Differentiation Set, 2) No Sensor Differentiation Set, and 3) None. A brief description of each surveillance symbology level follows:

Sensor Differentiation Set: Each sensor had a unique symbol shape associated with it. (See fig. 4.) Symbol color was based on certified TCAS threat level specifications. The type of sensor detecting the individual traffic was specified by a unique symbol shape and by a description in the data field on the ND. (Note: data field was activated by touching individual traffic symbols on the ND.)

No Sensor Differentiation Set: All sensors were represented by a common symbol shape and color based on threat level to the ownship from other aircraft. For this experiment, certified TCAS shapes and colors were used. (See fig. 5.) The type of sensor detecting a traffic aircraft was only specified in the data field on the ND since no unique symbol shapes were used.

None: No surveillance symbology was presented on the PXD. Therefore, the pilot had no head-up visual aids (surveillance symbols) for traffic detection except for the traffic in the simulated video image itself.

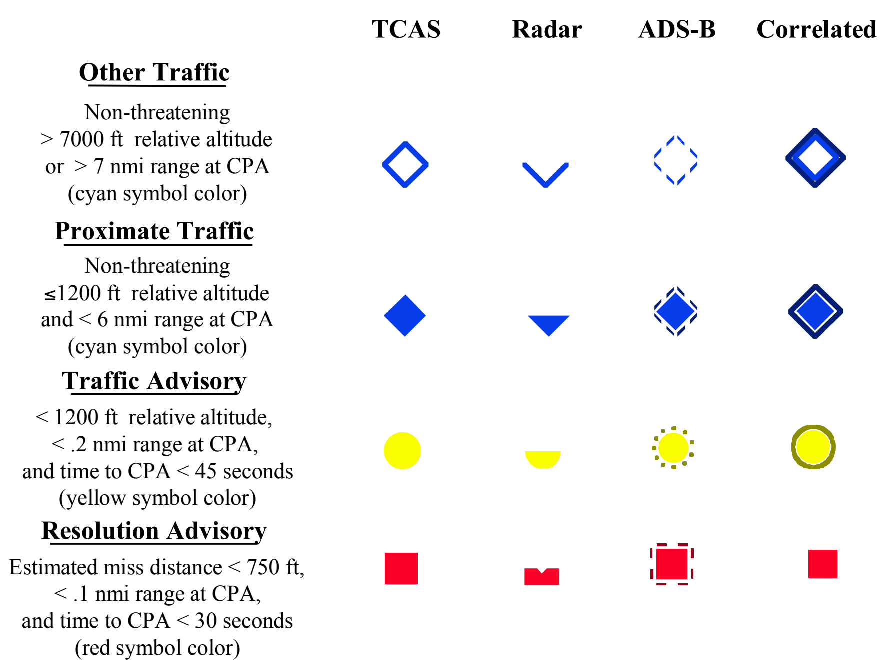


Figure 4. Sensor Differentiation Surveillance Symbology Set.

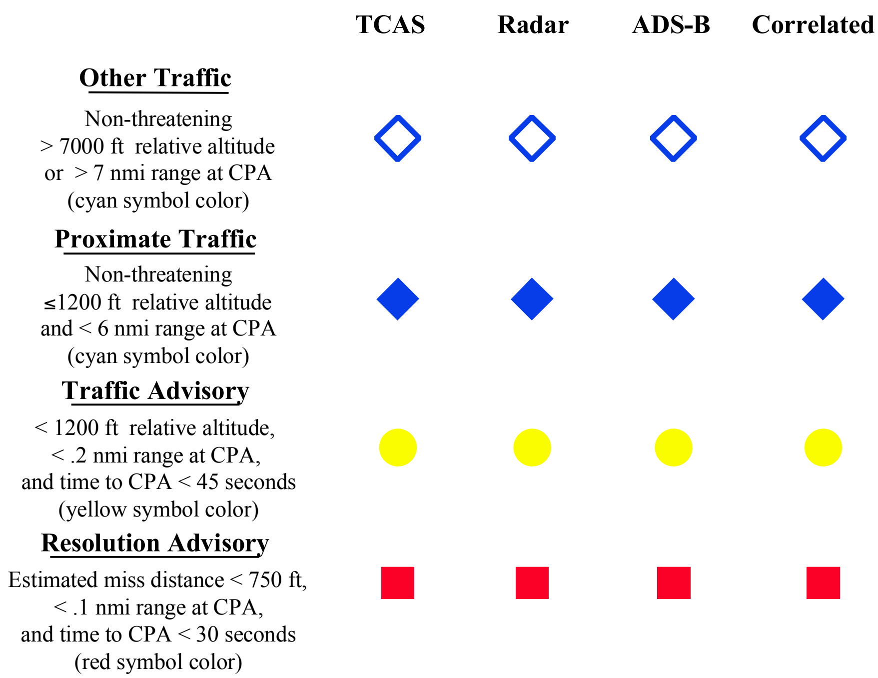


Figure 5. No Sensor Differentiation Surveillance Symbology Set.

To minimize clutter and traffic obscuration by the surveillance symbol on the PXD, only the outline of the surveillance symbols shown in figures 4 and 5 were drawn on this display. The outline of the surveillance symbol was the appropriate shape and color and it allowed pilot detection of traffic with the symbol itself. An example of the surveillance symbol outline is shown in figure 6 where a resolution advisory detected by the radar system is outlined in the appropriate shape and color on the PXD.

During some experimental runs, TCAS (or equivalent sensor system) Escape Guidance Symbology was presented on the PXD. The Escape Guidance Symbology presented on the PXD (fig. 6) had both lateral and vertical escape guidance. Current TCAS systems have only vertical escape guidance that is typically presented to the pilot on the Vertical Speed Indicator or Vertical Speed Tapes. The lateral and vertical escape guidance used in this experiment was defined at the Surveillance Symbology Workshop held at NASA Langley Research Center in July 1997 and is described below.

<u>Current Definition</u>: Once a RA has been initiated, the ghost aircraft symbol is simplified to the magenta flight director circle (currently located on the ghost aircraft's tail) and highlighted with a red outline. A green arc is drawn in the fly-to area of the PXD, indicating where the guidance fly-to circle should direct the pilot to fly. Once the ownship's flight path vector is in the "safe, fly-to zone," the red outline of the flight director circle turns green. After the RA is over, the circle abruptly reverts to the original guidance mode (magenta ghost aircraft). Currently, the flight director's circle is located 5 degrees from the specified path in a direction that most readily avoids the aircraft generating the RA with the ownship. The flight director circle will not command an escape maneuver that exceeds a 1/4-g.

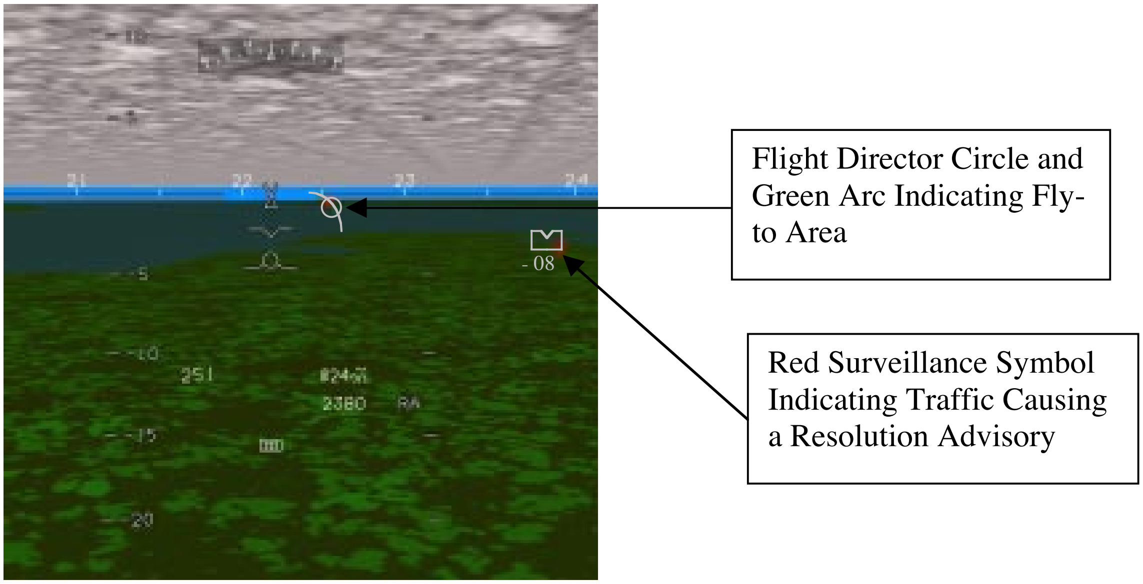


Figure 6. Resolution Advisory Escape Guidance on the Primary XVS Display.

This escape guidance symbology was intended to be representative of the type of symbology that might be used for TCAS (or equivalent sensor system) escape maneuvers on the PXD. For all runs with a TCAS (or equivalent sensor system) Resolution Advisory, vertical escape guidance (found in today's TCAS II systems) was always presented head-down on the PFD's vertical speed tape. No lateral TCAS escape guidance was available on the PFD. (See section entitled Primary Flight Display for a description of the PFD used in this simulation). Collision avoidance logic was extremely simple, consisting of one of eight preprogrammed positions around the velocity vector, chosen to oppose vertical and lateral drift.

Navigation Display

The ND (figs. 7-8) was used to present strategic information to the pilot. For this experiment, some of the information presented on the ND consisted of:

- a God's eye view of the pre-programmed flight path
- green dotted lines indicating the horizontal field of view of the PXD
- name and distance (in nmi) to next waypoint
- TCAS (or equivalent sensor system) Traffic Advisory (TA) and RA (Resolution Advisory) mode enunciators
- scaleable range circles (4/10/20/40/80 nmi)
- surveillance information (sensor differentiation information set or no sensor differentiation information set)
- data field with traffic aircraft information that includes call sign, type of aircraft, groundspeed, and type of sensor detecting traffic aircraft

• velocity vector on/off selection switch for displayed traffic

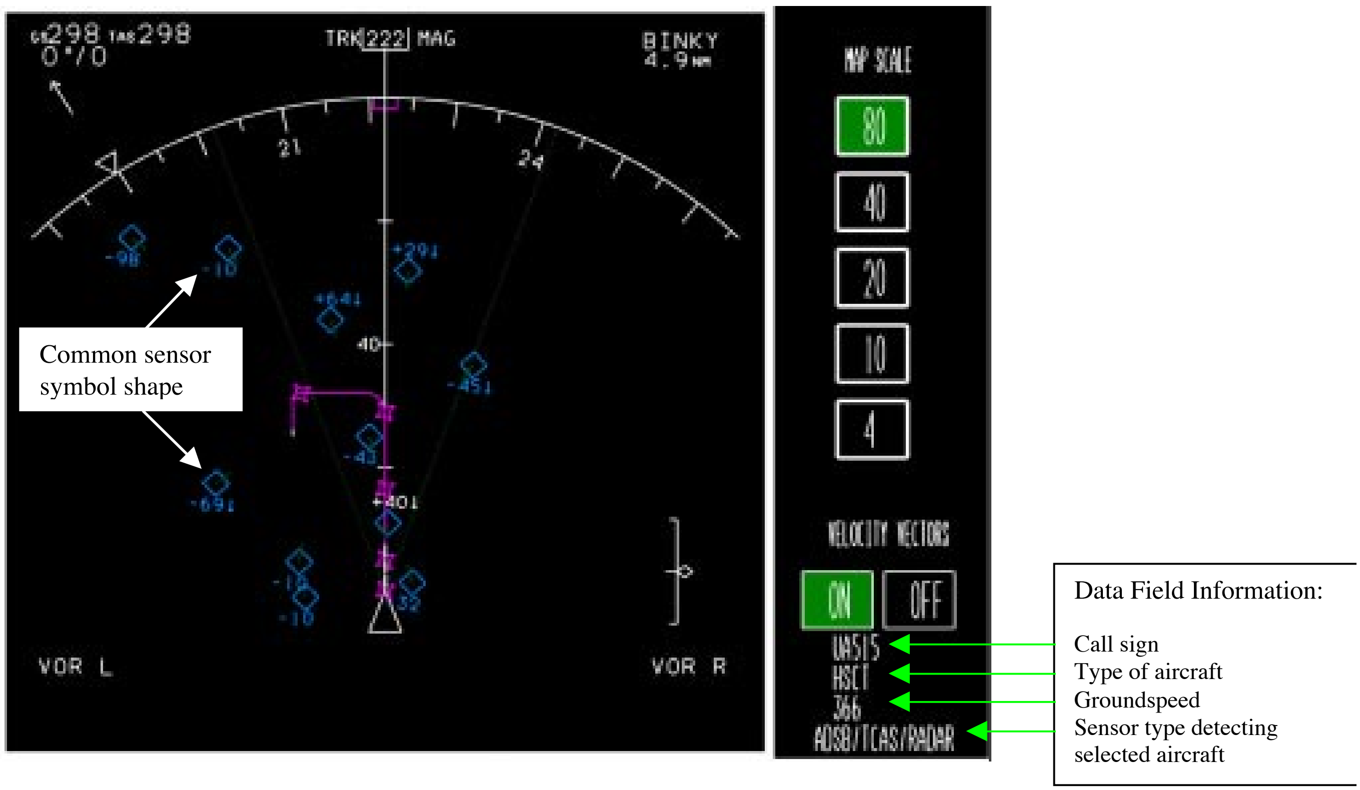


Figure 7. Navigation Display with No Sensor Differentiation Surveillance Symbology Set and Data Field Information.

During an evaluation run, the same surveillance symbology set (sensor differentiation or no sensor differentiation) used on the PXD was also used on the ND. For the runs that didn't have surveillance information on the PXD, the ND used either the sensor differentiation information set or the no sensor differentiation information set (equal number per pilot). As opposed to the PXD where only the surveillance symbol outline was drawn, the ND surveillance symbols were drawn exactly as indicated in figures 4 and 5. For the surveillance concepts that had surveillance information on the PXD, two capabilities were always present. First, if any traffic generated a TA or RA with the ownship, then it's surveillance symbol was automatically displayed on the PXD and remained displayed head-up until it was no longer a TA or RA. Second, the EP could momentarily transfer traffic information (surveillance symbol) from the ND to the PXD by pressing the ND's touchscreen at the traffic location. The surveillance symbol for the highlighted traffic would remain on the PXD for five seconds before disappearing. The surveillance symbol for the highlighted traffic was always present on the ND. For all runs, the EP could also access traffic information by touching the ND at the traffic location. The resulting ND data field (fig. 7) would have the following information: call sign, type of aircraft, groundspeed, and sensor type detecting selected aircraft. This data field information was located on the bottom right-hand corner of the ND and would remain active for five seconds.

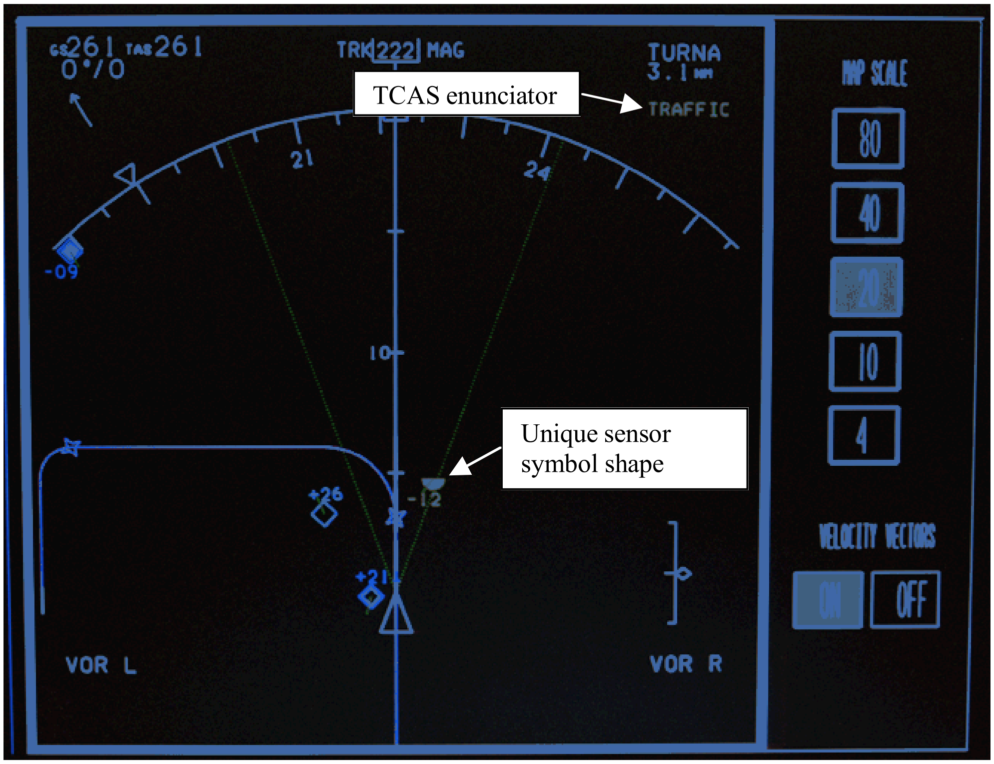


Figure 8. Navigation Display with Sensor Differentiation Surveillance Symbology Set and TCAS enunciator.

Primary Flight Display

The PFD (fig. 9) provided attitude, altitude, and speed information to the pilot. TCAS II escape guidance (vertical direction only) was always provided to the pilot on the vertical speed tape in the PFD whenever a RA was encountered by the ownship.

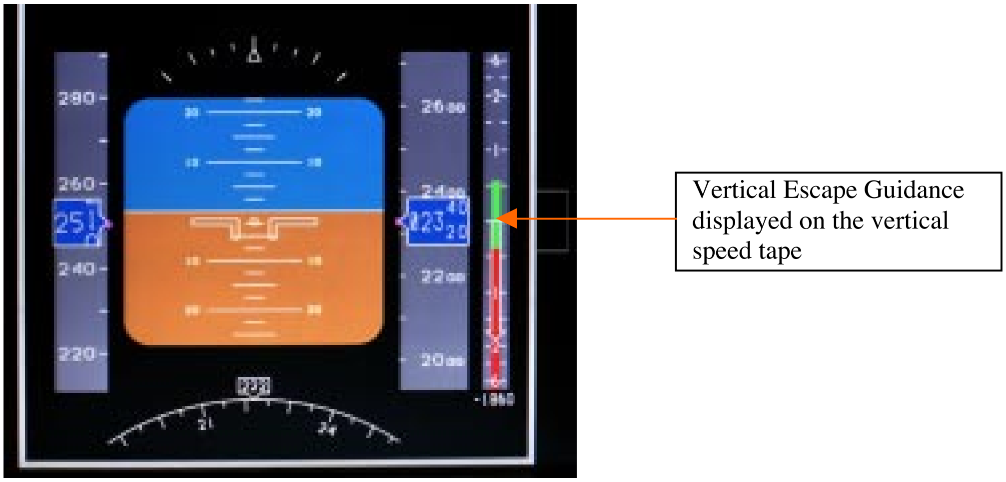


Figure 9. Primary Flight Display with Vertical Escape Guidance in the Speed Tape.

Engine Systems Display

The simulated fuel system was a 2-tank system (left and right) with 3 pumps to pressure the fuel lines to the 4 engines. (See fig. 10.) The fuel tanks were considered balanced if there was less than a 2000-lb difference between the tanks. The full capacity of each tank was 60,000 pounds. Each pump delivered fuel at the rate of 1000 lbs/min. Note that the fuel drainage was highly artificial and was not linked to the throttle state in any way. The engines required 2000 lbs of fuel per minute regardless of speed or throttle setting. The fuel system consisted of 3 pumps: a left tank pump, a right tank pump, and a cross feed pump. The nominal state of the pumps was: left pump on, right pump on, and the cross feed pump off. If there was a fuel imbalance, then it was necessary to turn on the cross feed pump and turn off the associated tank pump with low fuel. The tank pump for the associated high fuel tank should have remained on. Having both a tank pump on and the cross feed pump on drained fuel from the high fuel tank at 2000 lbs/min.

A Fuel Imbalance/Malfunction light was used to notify the pilot when an error condition had occurred. The Malfunction light remained lit until the error condition had been corrected. The Fuel Imbalance/Malfunction light illuminated when:

- A 3000 lb or more fuel imbalance existed between the left and right tanks
- One pump was off and the cross feed pump was off
- Both left and right pumps were off (gravity feed was an error)

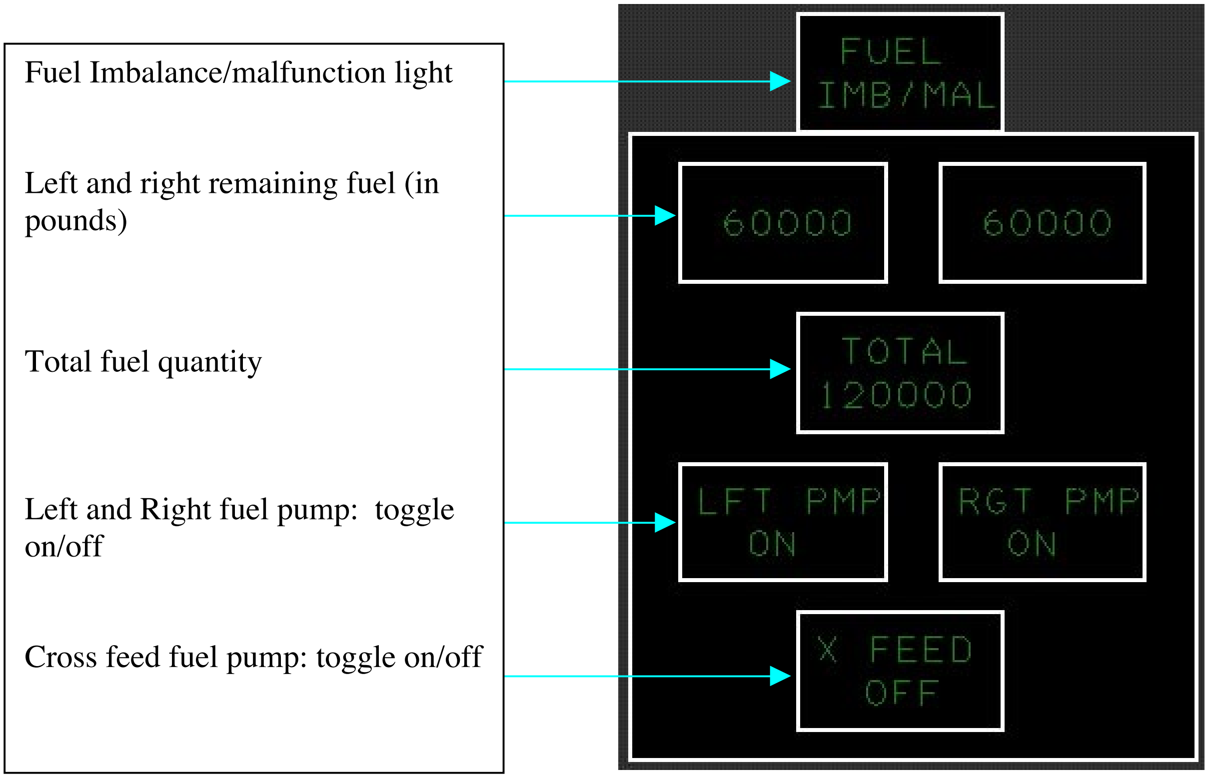


Figure 10. Description of Engine Systems Display

Mode Control Panel

The touch-screen capable MCP (fig. 11) had a number of control sections, but the only one used in this experiment was the altitude section. This section was comprised of the altitude window, increase and decrease arrows, set window resolution button, and the altitude arming button. The increase and decrease arrows were pushed to increase or decrease the number in the altitude window. When the set resolution button was pressed (and illuminated in white), the amount of change for each arrow press was 1,000 feet. When the set resolution button was not illuminated, the amount of change for each arrow press was 100 feet. The altitude arm button, ALT ARM, was illuminated in amber when it was pressed, indicating the altitude was armed. It extinguished when arriving at (or through) the armed altitude, or when either the increase or decrease arrows was pressed.

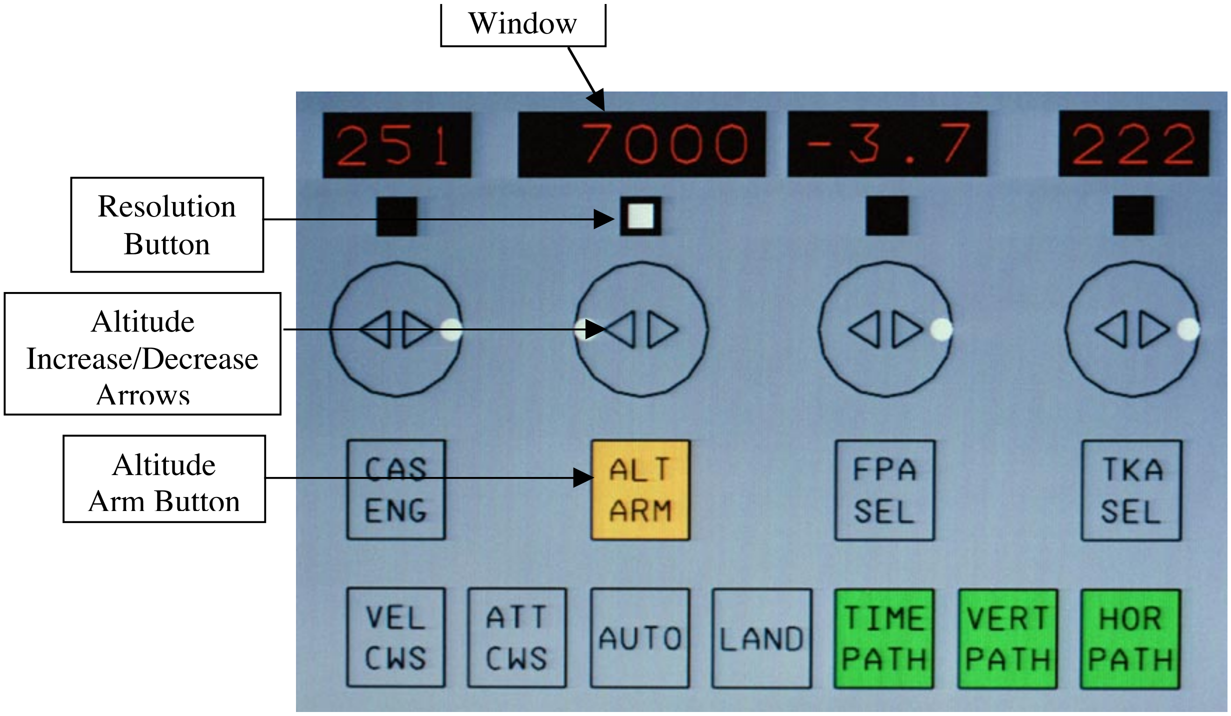


Figure 11. Mode Control Panel

Surveillance Sensors

Three sensor models – radar (the HSCT weather radar with a traffic detection mode), TCAS, and ADS-B – were used in this experiment. Each sensor model had different update rates and accuracies (angular and linear errors) associated with it. (See table 2.) Hence, there was a continuously varied error between the video image of traffic and the sensor surveillance symbol of that same traffic. It is assumed that ADS-B was the most reliable sensor of the three sensors modeled in this simulation. The simulated errors were composed of a static part and a dynamic part. The static part encompassed things like installation alignment error, sensor anomalies and biases, and the like. The dynamic errors accommodated the sorts of real world random measurement errors seen with these sensors. It was assumed that the static errors were 75% of the total maximum expected error, stayed the same for each run (though different for each traffic aircraft, and for each sensor parameter), and were chosen with a uniform probability density function about the (75%) expected range. It was also assumed that the dynamic errors varied with a gaussian probability density function with an expected value of zero error, and a one sigma value equal to 25% of the maximum expected total error. The dynamic errors were calculated and applied separately for each sensor update frame.

Table 2. Sensor Models Update Rates and Expected Errors

Sensor	Update Rate	Angular Errors	Linear Errors
Radar	3.0 sec	± 0.5 deg on elevation ± 1.0 deg on azimuth	± 200 m on range ± 5 m/sec on range rate
TCAS	1.0 sec	± 4.0 deg on azimuth	± 100 m on range ± 60 m on altitude
ADS/B	0.5 sec in air 0.2 sec on ground		± 30 m on altitude ± 5 m on latitude/longitude

The sensors assumptions made for this simulation were as follows:

Radar

40° horizontal by 50° vertical Field Of Regard
0 to 14 nmi range
If ownship < 5000 ft AGL and traffic altitude less than ownship and relative traffic speed between -50 to 50 knots of ground closure, don't sense traffic aircraft
Radar sensed all traffic meeting above criteria

TCAS

All azimuth angles
0 to 40 nmi range
Traffic aircraft altitude within ± 2700 feet of ownship
75% of traffic will be TCAS-capable

ADS/B

All azimuth angles
All ranges (within Navigation Display range scale: 4/10/20/40/80 nmi)
All altitudes above zero (airborne traffic only)
25% of traffic will be ADS/B-capable
If traffic is ADS/B-capable, it is also TCAS-capable

Surveillance Concepts

Five Surveillance Display Concepts were investigated during this simulation. (See table 3.) All of the surveillance display concepts had simulated video imagery and flight symbology on the PXD. The differences between Display Concepts 1 through 4 was the type of surveillance symbology (no sensor differentiation set vs sensor differentiation set) and the location of surveillance symbology (PXD and ND vs ND-only). Display Concepts 1 and 2 displayed surveillance symbology head-down only on the ND; while Display Concepts 3 and 4 presented surveillance symbology both head-up on the PXD and head-down on the ND. Common surveillance symbol shapes were used for Display Concepts 1 and 3; while unique surveillance symbol shapes were used for Display Concepts 2 and 4. Display Concepts 4 and 5 differed only in the location (PFD-only vs PFD and PXD) of TCAS (or equivalent sensor system) escape guidance. Each EP was exposed to all five Surveillance Display Concepts while flying multiple approach and departure scenarios.

Table 3. Description of Surveillance Display Concepts

Display Concept	Primary XVS Display (PXD)				Navigation Display (ND)	
	Video Imagery	No Sensor Differentiation Surveillance Set	Sensor Differentiation Surveillance Set	Escape Guidance	No Sensor Differentiation Surveillance Set	Sensor Differentiation Surveillance Set
1	X				X	
2	X					X
3	X	X			X	
4	X		X			X
5	X		X	X		X

Experiment Design

Independent Variables

Experiments One and Two

Hypotheses:

1. Inclusion of surveillance information on the PXD will increase a pilot's situational awareness of other aircraft and their threat to his or her ownship.

2. Delineation of sensor source by symbol shape on the PXD will enable a pilot to more quickly acquire traffic on the PXD because he or she will have a better feel for the nature of accuracy inherent in the information.

Both hypotheses were analyzed by comparing experimental runs from Display Concepts 1, 2, 3 and 4 in two different experiments. Experiment 1 involved systematically manipulating the type (sensor differentiation or no sensor differentiation) and placement (head-up and head-down versus head-down only) of surveillance information while performance data was collected as evaluation pilots flew the approach scenario. Each run consisted of a unique combination of surveillance information type and location. In addition, runs were replicated. All ten evaluation pilots performed all runs across each surveillance information type and location. Therefore, Experiment 1 was a 2 x 2 x 2 x 10 (Surveillance Information Type x Surveillance Information Location x Replicates x Subjects) factorial design. There were four separate Approach Scenario runs replicated twice per subject.

Experiment 2 used the same factorial design, but the evaluation pilots flew departure scenarios rather than approach scenarios. The rationale for evaluating the surveillance issues within both approach and departure scenarios was to examine the effects of moderate and high-speed closure rates.

Experiment Three

Hypothesis: Inclusion of TCAS (or equivalent sensor system) Escape Guidance on the PXD will increase a pilot's situational awareness of a Resolution Advisory and allow him or her to avoid the impending collision more readily.

This hypothesis was analyzed by comparing experimental runs from Display Concepts 4 and 5. Experiment 3 involved systematically manipulating the location (head-down only versus head-up and head-down) of TCAS (or equivalent sensor system) escape guidance information while performance data was collected as evaluation pilots flew both scenarios. Each run consisted of a unique combination of TCAS escape guidance location and scenario type. Runs were also replicated. All ten evaluation pilots performed all runs across each scenario and each escape guidance location. Therefore, Experiment 3 was a 2 x 2 x 2 x 10 (Location of Escape Guidance x Scenario x Replicates x Subjects) factorial design. There were two Approach Scenario runs and two Departure Scenario runs replicated twice each for a total of 8 experimental runs per subject.

Dependent Measures

During the evaluation runs, the EP's task was to visually acquire traffic on the PXD and/or in the side window; verbally identify visually-acquired aircraft; assess the threat of traffic through the visual scene (side window and/or PXD) and ND; manually initiate and fly commanded guidance maneuvers to escape a TCAS (or equivalent sensor system) Resolution Advisory; set and arm defined waypoint crossing altitudes; and maintain equal amounts of fuel in the left and right tanks. The objective metrics used to assess performance and concept utility were:

- Range when traffic was visually acquired (recorded by the EP depressing the event marker button on the sidestick controller)
- Reaction time for EP to disconnect autopilot and begin evasive action from a RA
- Maneuver time out of RA

The experimenter captured pilot call-outs of aircraft identification and pilot comments on threat assessments of the external traffic during the evaluation runs. Runs were terminated when TCAS (or an equivalent sensor system) no longer sensed an RA or upon collision with the traffic aircraft. Relative distances between ownship and traffic and time required to initiate appropriate actions were reconstructed during data analysis using the recorded data. The evaluation runs were videotaped with an over-the-shoulder view of the displays and control inceptor. These tapes provided another method of recording an EP's comments. The Test Parameters List recorded during each experimental run is found in appendix F.

In addition, several subjective measures were taken at selected points throughout the data collection trials. These measures were in the form of the NASA Task Load Index (TLX) instrument for estimating workload and fatigue (appendix G); a display questionnaire constructed to subjectively compare display concepts across surveillance conditions (appendix H); and a final questionnaire constructed to compare the utility of the display concepts for performing the surveillance tasks of detection, identification, prioritization, and avoidance (appendix I).

The NASA TLX is an instrument used to measure overall workload and its relationship to pilot performance. This measure divides workload into categories such as mental demand, physical demand, temporal demand, own performance, effort and frustration. Pilots give ratings on the individual categories, which are then combined to derive a summary score for overall workload on a specific task.

The scale used for this experiment ranged from 0 (low effort) to 100 (hard effort). Each pilot gave two TLX ratings during his simulation session. This subjective instrument was applied to the two surveillance concepts (Concepts 2 and 4) using the sensor differentiation symbology set.

The subjective metrics used to assess performance and concept utility were:

- Display questionnaire ratings
- Final questionnaire ratings
- NASA TLX Workload Assessment ratings
- EP comments
- Experimenter's comments on pilot use of displays and features, including side window, observed pilot workload, and performance

Organization of Runs

Runs from Experiments 1, 2 and 3 are summarized in table 4. The evaluation runs were blocked by repetition and randomized within each block. Runs 1, 3, 5, 7, 9 & 11 used scenario one, the approach flying task; while, runs 2, 4, 6, 8, 10 & 12 used scenario 2, the departure flying task. Data from runs 1-8 was used for Experiment 1 and Experiment 2 and data from runs 9-12 was used for Experiment 3. There were two replicates for each of the 12 runs, resulting in 24 runs for each pilot.

Table 4. Organization of Evaluation Runs for each Subject

Subject Number	Evaluation Run Sequence
1	8, 1, 6, 11, 4, 12, 9, 3, 10, 2, 5, 7
	10, 8, 4, 12, 11, 9, 6, 2, 1, 7, Q2, TLX, 3, Q1, TLX, 5, Q3
2	1, 5, 8, 11, 2, 4, 9, 3, 10, 6, 7, 12
	9, 12, 3, 6, 8, 7, Q2, TLX, 5, 10, 1, 4, Q1, TLX, 2, 11, Q3
3	11, 4, 8, 5, 10, 6, 3, 7, 12, 2, 9, 1
	4, 1, 9, 12, 5, 10, 8, 6, 7, Q2, TLX, 11, 3, Q1, TLX, 2, Q3
4	4, 9, 1, 5, 10, 8, 2, 7, 3, 6, 11, 12
	8, 11, 7, Q2, TLX, 4, 2, 6, 10, 12, 1, 3, Q1, TLX, 5, 9, Q3
5	2, 10, 3, 11, 8, 4, 6, 7, 9, 5, 1, 12
	11, 4, 7, 8, Q2, TLX, 6, 9, 3, Q1, TLX, 10, 1, 2, 5, 12, Q3
6	9, 6, 1, 11, 4, 8, 2, 5, 3, 7, 10, 12
	11, 5, 7, 3, 2, 10, 9, 1, 4, Q1, TLX, 12, 6, 8, Q2, TLX, Q3
7	6, 2, 11, 5, 1, 4, 3, 7, 9, 10, 12, 8
	5, 3, 4, Q1, TLX, 9, 12, 8, 7, Q2, TLX, 11, 10, 6, 1, 2, Q3
8	2, 8, 1, 10, 11, 12, 6, 9, 3, 5, 4, 7
	2, 11, 12, 1, 5, 6, 3, 7, 9, 4, Q1, TLX, 8, Q2, TLX, 10, Q3
9	4, 1, 9, 11, 3, 2, 7, 12, 6, 8, 10, 5
	1, 6, 7, 3, 4, Q1, TLX, 9, 5, 11, 10, 12, 8, Q2, TLX, 2, Q3
10	10, 2, 11, 4, 3, 1, 8, 7, 9, 6, 5, 12
	12, 7, 10, 11, 4, 6, 9, 3, Q1, TLX, 8, Q2, TLX, 2, 1, 5, Q3

where:

Run	Scenario	Display Condition
1	Approach	Surveillance Information head-down only; no sensor differentiation surveillance set
2	Departure	Surveillance Information head-down only; no sensor differentiation surveillance set
3	Approach	Surveillance Information head-down only; sensor differentiation surveillance set
4	Departure	Surveillance Information head-down only; sensor differentiation surveillance set
5	Approach	Surveillance information head-up/head-down; no sensor differentiation surveillance set
6	Departure	Surveillance information head-up/head-down; no sensor differentiation surveillance set
7	Approach	Surveillance information head-up/head-down; sensor differentiation surveillance set
8	Departure	Surveillance information head-up/head-down; sensor differentiation surveillance set
9	Approach	Surveillance information head-up/head-down; sensor differentiation surveillance set; no head-up escape guidance
10	Departure	Surveillance information head-up/head-down; sensor differentiation surveillance set; no head-up escape guidance
11	Approach	Surveillance information head-up/head-down; sensor differentiation surveillance set; head-up escape guidance
12	Departure	Surveillance information head-up/head-down; sensor differentiation surveillance set; head-up escape guidance

and

Subjective Assessment	Description
Q1	Questionnaire on displaying surveillance information head-down only.
Q2	Questionnaire on displaying surveillance information both head-up and head-down.
Q3	Questionnaire on format of surveillance information and overall impressions on surveillance philosophy.
TLX	NASA Task Load Index (TLX) Workload Assessment on surveillance concept

Procedure

Subjects' participation in the experiment lasted for a single day. Upon arriving at the simulation facility, the subject completed a pilot background questionnaire (providing such information as aircraft type ratings and years as a professional pilot) and signed a High-Speed Research Program non-disclosure agreement. After a description of the experiment and its purpose, the subject signed an Informed Consent form.

Training for the simulation experiment then began. Subjects were brought to VISTAS III and were introduced to all aspects of the workstation's flight deck operation. They first received training on the use of the side-arm controller, mode control panel, and engine systems display. For this training, the display concept used was the one where surveillance information was presented head-down only on the Navigation Display. The no sensor differentiation surveillance symbology set was used in the beginning of the training. The intent of using this combination of display set and surveillance symbology was to give the subjects displays similar to what they are used to flying during typical aircraft operations. Next, the subjects were briefed on the contents of the minimum FD symbology set, the types of surveillance symbology sets – sensor differentiation, no sensor differentiation, or none – that would be displayed on the PXD, and the surveillance task. Subjects were permitted to fly training trials during which they were exposed to each of the surveillance symbology sets and during which they practiced the surveillance task. Subjects were then briefed on the fuel monitoring task and permitted to fly two training trials (one with the no sensor differentiation surveillance set and one with the sensor differentiation surveillance set; both trials had a fuel leak of 800 lbs/min). The subjects were briefed on the two autopilot/autothrottles scenarios that they would be flying during the experiment. They were instructed on how to arm the defined waypoint altitudes on the mode control panel and how to manually fly commanded TCAS (or equivalent sensor system) escape guidance. Subjects were then permitted to fly training trials of each scenario during which they performed the altitude arming procedure and manually flew commanded TCAS escape guidance. The training trials continued until the subjects could simultaneously perform the surveillance task, the navigation task, and the systems monitoring task. The surveillance philosophy concept and experimental purpose were re-emphasized to the pilots and they had the opportunity to ask any questions for clarification. After a break, the experimental trials began.

Experimental Results and Discussion

All three Experiments were designed as full-factorial, within-subjects experiments. Experiments 1 and 2 had Pilots, Location of Surveillance Information, Type of Surveillance Symbology, and Replicates as the factors. Experiment 3 had Pilots, Location of Escape Guidance, Scenario Type, and Replicates as the factors. The dependent variables were visual acquisition range of traffic, reaction time to a RA, and maneuver time out of a RA. Since extensive pilot variability is expected, it was isolated from the rest of the analyses by its inclusion as a main factor in the experiments. The data collected in the experiments was analyzed at 1-percent and 5-percent significance levels using a univariate analysis of variance (ANOVA) for each metric. The more important objective results and supporting subjective results are presented and discussed for each experiment, followed by subjective results on the utility of the different airborne surveillance display concepts.

Experiment One and Experiment Two

Objective Data Analyses

For each scenario, an ANOVA was performed for the pilot's visual acquisition range of traffic. This acquisition range measurement was determined from the time the pilot first saw traffic either out the side window or in the PXD. The independent variables were pilots, location of surveillance information, type of surveillance information, and replicates.

For the approach scenario (Experiment 1), only two main factors, pilot ($F(9,965)=11.569$, $p=.000$) and location of surveillance information $F(1,965)=40.216$, $p=.000$), were highly significant for the measure of visual acquisition range of traffic. There were no significant interaction effects for this measure. As mentioned earlier, extensive pilot variability was expected. The location of surveillance information factor had two levels: (1) surveillance information presented both head-up (PXD) and head-down (ND) and (2) surveillance information presented head-down only (ND). The subjects were able to visually acquire traffic at a greater range, 1.10 nmi further, when the surveillance information was presented head-up on the PXD and head-down on the ND as compared to when it presented head-down only on the ND. The type of surveillance symbology set, sensor differentiation or no sensor differentiation, did not affect the pilot's ability to visually acquire traffic in the side window or in the PXD.

Similar results for the measure of visual acquisition range of traffic were seen for the departure scenario (Experiment 2). Again, only the main factors, pilot ($F(9,958)=3.261$, $p=.001$) and location of surveillance information ($F(1,958)=8.495$, $p=.004$) showed significant differences for the visual acquisition range of traffic. There were no significant interaction effects for this measure. Again, the type of surveillance information, sensor differentiation or no sensor differentiation set, did not affect the pilot's ability to visually acquire traffic, but the location of the surveillance information did affect pilot performance. The subjects were able to visually acquire traffic at a greater range, 0.45 nmi further, when the surveillance information was presented both head-up on the PXD and head-down on the ND as compared to when it was presented head-down only on the ND.

Objective results supported Hypothesis One that the pilot's situational awareness of other aircraft was increased when surveillance information was provided head-up on the PXD, but these results failed to support Hypothesis Two that delineation of sensor source by symbol shape would allow a pilot to acquire traffic more quickly since he or she would have a better feel for the nature of the accuracy inherent in the information for that sensor.

Subjective Data Analyses

Subjective ratings from questions found in the final questionnaire (appendix H) support the objective results obtained for the pilot's visual acquisition range of traffic. Histograms for the following statements are depicted graphically in figures 12-15:

- Using sensor symbols on the primary XVS display increases a pilot's ability to visually detect traffic.

- Should sensor symbols be presented on the primary XVS display rather than just on the Navigation Display?

- Using sensor symbols on the primary XVS display increases a pilot's situational awareness.

- Using sensor symbols on the primary XVS display adds too much clutter to this display.

Figure 12 supports the objective results that visual acquisition range of traffic was increased when surveillance information was provided on the PXD and ND as compared to when it was provided on the ND only. In fact, eight of the 10 pilots, strongly agreed with this statement. Figure 13 indicates that the pilots overwhelmingly preferred having surveillance information head-up and head-down as compared to head-down only. Figures 14 and 15 indicate a majority of the pilots felt that having surveillance information head-up increased a pilot's situational awareness while not adding too much clutter to the PXD. One pilot felt that no situational awareness gains were achieved by the addition of surveillance information on the PXD and that having this information head-up added clutter to the display. This particular pilot had difficulty immersing himself into the simulation environment and commented that he "was not good at playing video games." It is assumed that his rating was biased due to his inability to immerse himself into the HSCT simulation environment.

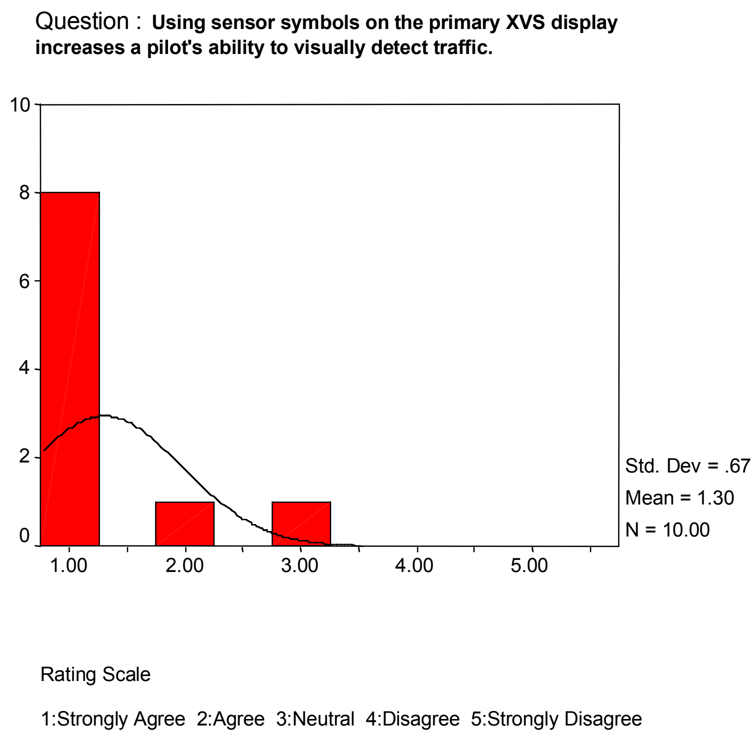


Figure 12. Histogram of Pilot Ratings for Displaying Sensor Symbols on the Primary XVS Display.

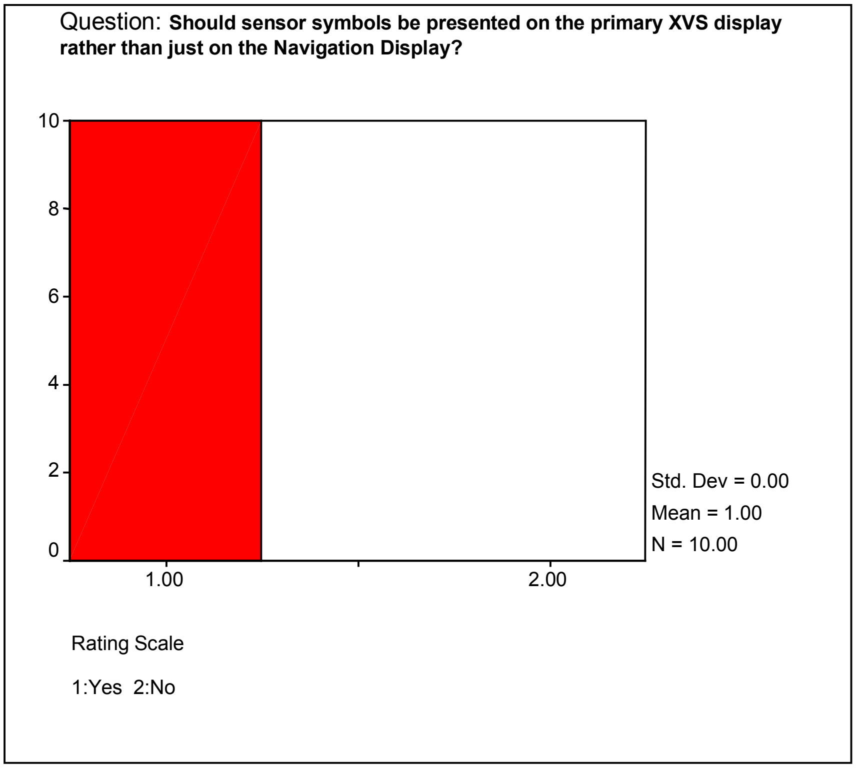


Figure 13. Histogram on Pilot Preferences for Displaying Sensor Symbols.

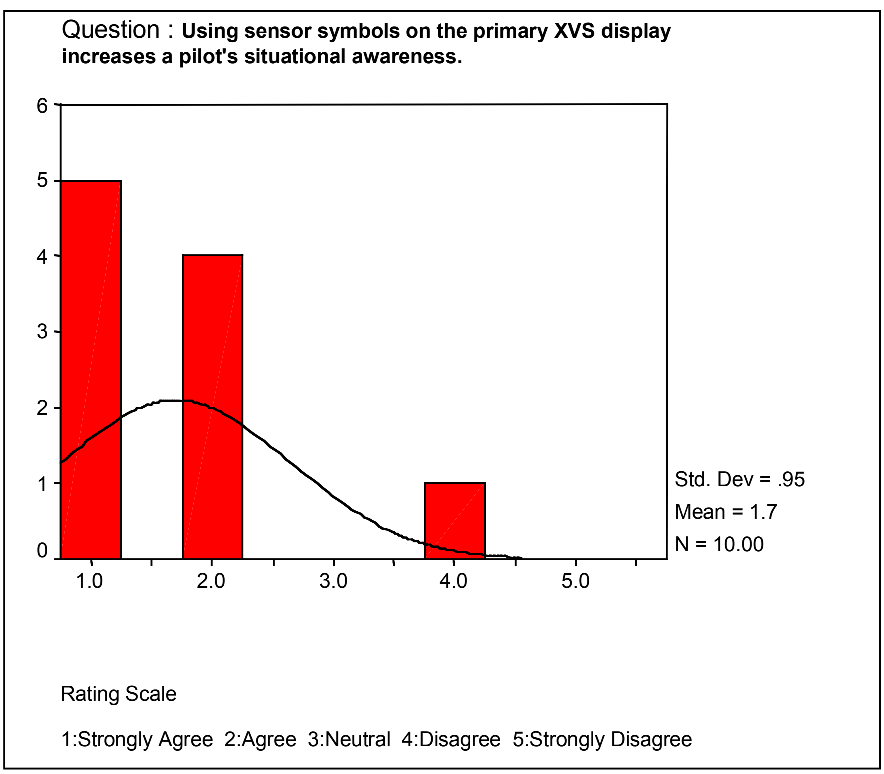


Figure 14. Histogram of Pilot Ratings on Increased Situational Awareness with Sensor Symbols on the Primary XVS Display.

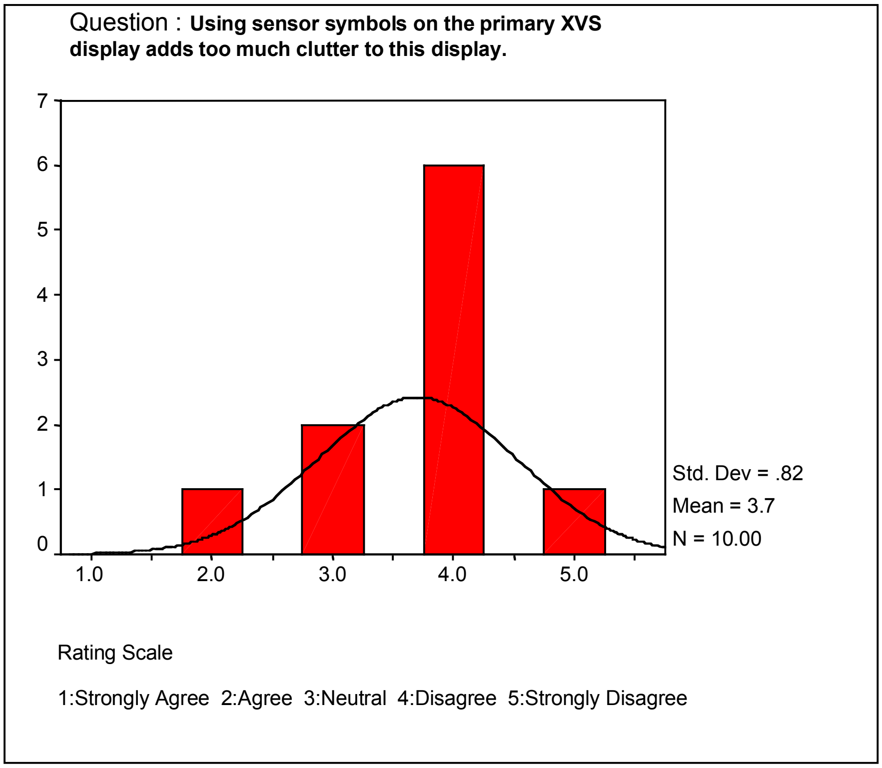


Figure 15. Histogram on Pilot Ratings on Increased Clutter on Primary XVS Display with the Inclusion of Sensor Symbols.

Experiment Three

Experimental runs from the arrival and departure scenarios were pooled together and an ANOVA was performed for the pilot's reaction time to a RA depending on whether or not he had escape guidance head-up on the PXD. It was assumed that a pilot's reaction time to escape guidance was independent of closure rate. This reaction time measurement was the time difference between when the RA first occurred and when the pilot disconnected the autopilot and manually flew the commanded escape guidance. A second ANOVA was performed for the pilot's maneuver time out of the RA for the Approach Scenario. Due to data reduction deficiencies, the pilot's maneuver time out of the RA was not available for the Departure Scenario. This time to maneuver measurement was determined from the time difference between when the pilot began manual flight and when the ownship was no longer in a RA condition. The independent variables for both analyses were pilots, location of surveillance information (head-up and head-down vs. head-down only), and replicates.

Objective Data Analyses

For the performance measure of reaction time to a RA, there were no significant main effects or interaction effects. The pilot's mean reaction time was only 0.69 seconds quicker when escape guidance was presented head-up on the PXD as compared to none head-up. Similar results were seen for the measure of maneuver time out of a RA. Again, there were no significant main effects or interaction effects for this measure. The pilot's mean maneuver time was only 1.52 seconds quicker when escape guidance was presented head-up on the PXD as compared to none head-up.

Although not statistically (or operationally) significant, objective results suggest some support of the hypothesis that escape guidance on the PXD would enable a pilot to more quickly detect and maneuver out of a threatening traffic situation caused by a RA.

Subjective Data Analyses

Figure 16 shows subjective results related to the pilot's reaction time to a RA and maneuver time out of a RA. This histogram indicates that eight of the 10 pilots felt that escape guidance should be displayed head-up. This preference appears to indicate that pilots like to be eyes-out, head-up when performing the airborne surveillance task and not eyes-in, head-down in the cockpit.

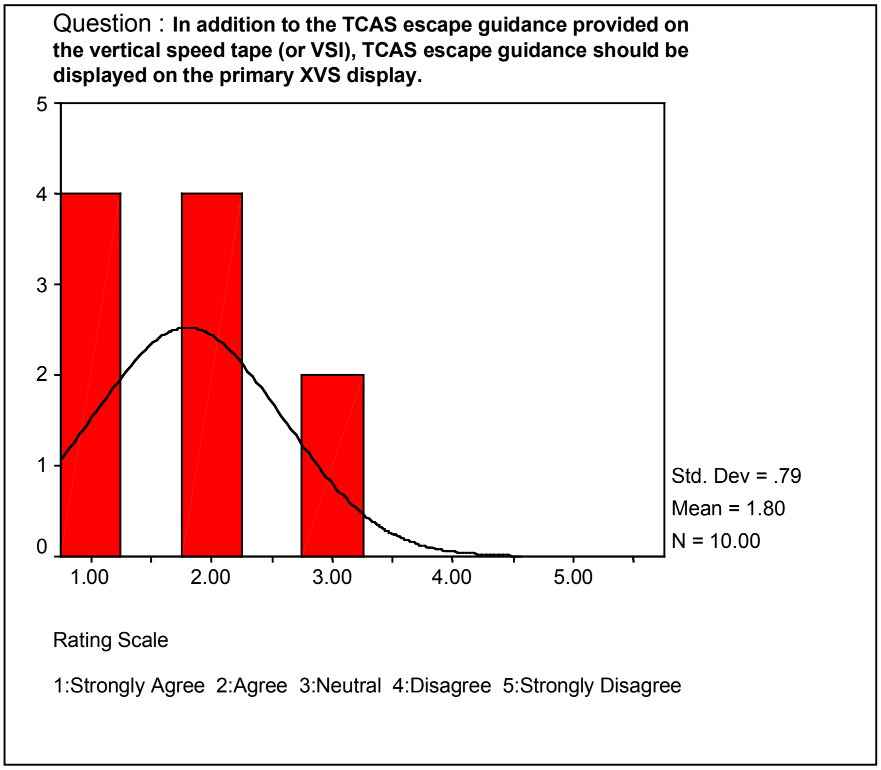


Figure 16. Histogram on Pilot Ratings on Providing Escape Guidance on the Primary XVS Display.

Other Subjective Results

NASA TLX Workload Ratings

Using the NASA TLX, subjects gave an overall workload rating on the surveillance task when using two surveillance display concepts. Both concepts used the sensor differentiation surveillance symbology set but the location of this surveillance information was head-up and head-down versus head-down only. Using a paired samples t-test, significant display differences ($t=4.762$, $df=9$, $p<.001$) were found for the overall workload rating on the surveillance task. The subjects felt that overall workload for the surveillance task was lower when surveillance information was presented head-up and head-down (mean rating = 32) as compared to when the surveillance information was presented head-down only (mean rating = 50).

Display Questionnaire Ratings

Each subject completed two display questionnaires – one for when the sensor differentiation surveillance symbology set was displayed head-down only on the ND and one for when the sensor differentiation surveillance symbology set was displayed both head-down on the ND and head-up on the PXD. Paired t-tests showed significant display differences for the following tasks and workload ratings:

- Ease in visually detecting traffic in the head-up display (PXD) and side window ($t=3.881$, $df=9$, $p<.004$)

- Ease in assessing whether traffic was going to be a threat ($t=2.586$, $df=9$, $p<.029$)

- Overall workload rating for performing surveillance task ($t=4.333$, $df=9$, $p<.002$)

- Workload rating for monitoring only airborne traffic (excluded navigation and systems monitoring tasks) ($t=4.714$, $df=9$, $p<.001$)

For both the tasks and workload ratings above, the pilots preferred using the surveillance display concept that presented the surveillance information both head-up on the PXD and head-down on the ND.

Pilot Comments

In addition to formal questionnaire results, pilots also provided the researchers with comments about the display concepts. Some of the more notable comments are the following:

> "I strongly feel the heads up/heads down combination is an excellent system that can be utilized safely in any environment."

> "Without head-up [symbology] your ability to prioritize and avoid is reduced but more importantly I think your ability to detect is 'severely' reduced – unsafe!"

> "30 to 40% of all announced traffic is never identified by the crew. I think it is extremely valuable to see a constantly updated representation of the traffic. There is a real uneasiness when there is proximate traffic no one can find. This [having surveillance information on PXD] eliminates that problem."

> "[Describing the display concept with surveillance information on PXD] Again the aircraft can be safely navigated both over land and water with a high degree of accuracy. In fact, in some cases of reduced visibility such as haze or fog, this is a better system than we have today with conventional windows."

> "Combining ND and XVS [PXD] gives (1) quicker and easier visual acquisition, especially once one learns to compensate for sensor lag, (2) more confidence that aircraft that are in TA will be acquired early enough to not represent a hazard, and (3) better ability to pick targets out of poor contrast situations (white targets/cloud background)."

> "Target locator box [surveillance symbols head-up on PXD] allows quick visual and therefore much easier detection and assessment of targets [traffic]."

Concluding Remarks

A fixed-based simulation experiment was performed in the Visual Imaging Simulator for Transport Aircraft Systems III to investigate airborne surveillance issues associated with the replacement of the forward windows in a High-Speed Civil Transport with an eXternal Visibility System (XVS). Both objective and subjective data were collected to determine if the type and location of surveillance information could effect a pilot's ability to perform the airborne surveillance task safely and effectively. Two types of surveillance symbology were presented to the subjects in this experiment – one where each sensor had a unique symbol shape associated with it and one where every sensor was represented by the same symbol shape. Both surveillance symbology sets used certified TCAS colors and threat criteria to represent the threat level of other aircraft to the ownship. The location of the surveillance information was either head-up and head-down or head-down only.

Objective and subjective results indicated that surveillance information (sensor symbols) should be presented both head-up on the primary XVS display (PXD) and head-down on the Navigation Display (ND) rather than just head-down on the ND. Subjective results indicated that escape guidance from threatening traffic should be presented both head-up on the PXD and head-down on the Primary Flight Display (PFD) rather than just head-down on the PFD. Significant display differences were seen in a pilot's visual acquisition range of traffic. The pilots were able to detect traffic at a greater range when surveillance information was presented on the PXD and ND as compared to the ND only. This difference in acquisition range (0.45 nmi for departure scenario and 1.10 nmi for arrival scenario) is operationally significant because it would increase a pilot's maneuver time in a hazardous flight situation. Similarly, significant display differences were seen in subjective ratings, with the pilots preferring to have the surveillance symbology head-up and head-down as compared to head-down only. Pilot visual acquisition range was not affected by the type of surveillance symbology (sensor differentiation vs. no differentiation) that was presented to the pilot. Although pilots performed about the same with and without discrete sensor information imbedded in the symbology, they had mixed preferences about the type of surveillance symbology they wanted presented to them. Pilots preferred having escape guidance from threatening traffic displayed on the PXD and on the primary flight display (PFD) as compared to the PFD only. However, no significant display differences were seen for the measures of pilot reaction time to a RA or maneuver time out of a RA when using either of these display concepts.

Pilots overwhelmingly thought that the XVS surveillance philosophy was viable for the "No-Droop" mission. In order for pilots to perform the airborne surveillance mission safely and effectively, surveillance information, including traffic symbols and escape guidance, should be presented both head-up on the PXD and head-down on the ND. The type of surveillance information, sensor differentiation or no sensor differentiation didn't appear to have an effect on pilot performance. Further testing of surveillance issues is required with an inboard field of view display and a right side window present.

Appendix A

Pilot Questionnaire

Pilot Background Questionnaire

General Information

Full Name: ____
First, Middle, Last

Address: ____
Street and Number, or P.O. Box

____
City, State, Zip Code, and Country (if not USA)

Home Phone: (___) _____________ Work Phone: (____) ____________
Area Code Number Area Code Number

Birth Date: _______________
Month/Day/Year

Do you wear corrective lenses when you fly? Yes ❑ No ❑

General Experience Information

Current/Most Recent Airline:____

Current/Most Recent Position: ____
Captain, First Officer, Engineer, etc.

Are you currently flying military? Yes ❑ No ❑

Years Flying Commercial (approximate): ________

Years Flying Military (approximate): ____________

Total Hours Flying (approximate): ____________

Total Hours Flying as Pilot-in-Command (approximate): ______________

Years of formal education: ________ (e.g. high school graduate = 12)

Specific Aircraft Experience Information

Please list the types of aircraft on which you have experience, beginning with the most recently flown.

For each aircraft, please check the columns to indicate your
approximate number of hours flying experience, and
approximate number of hours simulator experience.

If you were an Instructor (I) or a Check Airman (CA) on any of these aircraft, please indicate by checking the last column.

Aircraft Type	Hours in Type			Simulator Hours			I/CA ?
	< 300	300-1000	> 1000	0	< 50	> 50	

Please check the appropriate column to indicate the approximate number of years of experience you have for each of the following categories:

Specific Aeronautical Experience	Years Experience		
	< 1	1-5	> 5
Long-range, Over-water (Class II) Operations (2 engines)			
Long-range, Over-water (Class II) Operations (> 2 engines)			
Total Multi-Engine (Captain or F/O, Military or Civil)			
Glass Cockpit (i.e. EFIS/CRT or FMS)			
TCAS experience			

Have you had any flight experience with radar systems that track other aircraft? yes ❑ No ❑
If yes, please list type of radar system, aircraft on which it was flown, and amount of time using this equipment.

Radar System	Aircraft Type	Years Experience

Appendix B

Surveillance Task

Surveillance Task

The surveillance task is defined as the requirement to detect, identify, prioritize, and safely avoid external hazards, as well as maintain overall potential hazard situation awareness. The XVS approach to hazard avoidance must accommodate surveillance task performance, as well as its subtasks, and other mission tasks. **The present experiment addresses the airborne surveillance task.** To be acceptable to regulatory agencies, manufacturers, airline companies, and the public, it is assumed that the XVS must provide the pilot with an equivalent functionality as the forward windows found in today's transport aircraft, with respect to the surveillance task.

For purposes of this experiment, the current XVS concept consists of high resolution video sensors, high resolution primary XVS displays, navigation displays, radar (a weather radar with a traffic detection mode), TCAS, ADS-B, and side windows. Previous studies, experiments, and workshops have led to an XVS Surveillance Concept, which proposes a methodology to utilize concept elements to accomplish the hazard avoidance mission. Key precepts of that concept are:

1) In order to provide present-day equivalent safety and workload, it is assumed that XVS external scene video imagery is augmented by surveillance information from other sources, such as radar, the Automatic Dependent Surveillance – Broadcast (ADS-B) system, and the Traffic Collision and Avoidance System (TCAS). These surveillance sources will supplement the object/hazard information provided by visual observations of the flight crew.

2) The head-up Primary XVS display (PXD) is used for presenting **tactical** surveillance information to the pilot; while, the head-down navigation display (ND) is used for presenting **strategic** surveillance information to the pilot. In this context, tactical information relates to information required to plan and conduct a flight maneuver, or maneuver change. Strategic information refers to all other surveillance information of interest. **Although other displays are used in the XVS concept, the PXD and ND are the primary displays used for surveillance.**

3) The Surveillance Task is comprised of four sub-tasks, identified as follows:

   a) **Detection**: The requirement to discern the presence of airborne objects that pose a potential hazard to the aircraft, or could affect flight decisions.

   b) **Identification**: The requirement (if any) to discern specific information (altitude, speed, aircraft type, callsign) concerning specific airborne traffic.

   c) **Prioritization**: The requirement to decide whether or not airborne traffic poses a significant hazard to the aircraft, the significance of that hazard, and the immediacy of the threat.

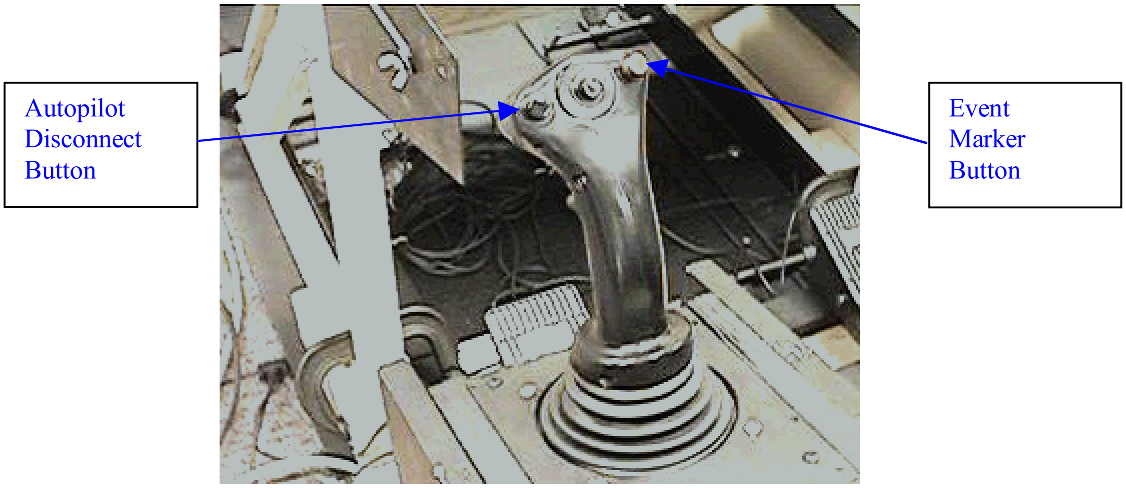
d) **Avoidance**: The requirement to decide whether specific action must be taken to avoid a hazardous encounter with the traffic of interest, including information required to follow-up on that decision, and decide whether or not action taken is appropriate and effective.

The current experiment will place you in simulated scenarios where potentially threatening traffic will be encountered. Research data will be taken to measure how you respond to these scenarios, using the XVS concept provisions and surveillance methodology presented above. In that context, data will be sorted into each of the above surveillance sub-task phases. The quantitative data will consist of traffic positions, types, and times when you observe them, or make decisions relating to them. Qualitative data will consist of your opinions and comments relating to the scenarios and experiment. The researcher's determination about how and when to parse the data into the sub-task phases will depend on event markers (button and display presses) and verbal comments you make during the runs. Specific procedures are as follows:

For each experimental run, your surveillance tasks are to:

- acquire (detect) the presence of traffic on the Primary XVS Display (PXD), the side window, and the Navigation Display (ND)
- identify the detected aircraft
- assess the threat of traffic through the use of the ND and visual scene (PXD and side window)
- fly commanded guidance to escape an impending collision with traffic generating a Resolution Advisory (RA)

You are asked to **press the right button** (the red one) on the sidestick controller **the first time** you **visually detect a piece of traffic** on the PXD or in side window (**not** the ND). This red button is used as an event marker and pressing it will record the time you visually acquire the traffic.



After detecting the aircraft in the visual scene, you are asked to **verbally identify it**, with respect to **bearing and elevation.** (For example, you might say "I've acquired an aircraft at bearing 2-7-0 that's 3 degrees above the horizon"). You may comment on any other information (type, class, speed, altitude, etc.) that you feel is necessary to discriminate the traffic. Three types of aircraft will be simulated for this experiment: a Be-200, a B-737, and a HSCT. The experimenter will record your comments.

If you believe that a piece of traffic is going to become a threat, you are asked **to touch that traffic symbol on the ND and verbalize your threat assessment**. (By touching the target on the ND, we are assuming that you are simultaneously performing the sub-tasks of detection, identification, and prioritization for that piece of traffic.) The ND has a touch-screen capability. The time and characteristics (aircraft type, relative position, etc.) of the target you press on the ND will be recorded. As the run proceeds, if you feel that the traffic is no longer a threat, verbalize this opinion to the experimenter. If you notice a piece of traffic on the PXD (instead of on the ND) that you believe is going to become a threat, you don't need to transition to the ND to press the traffic symbol. Instead, you can just verbalize your threat assessment and the experimenter will record your comments. Since the ND is used to present strategic information, we believe that most of your threat assessments will be made using it instead of using the tactical Primary XVS Display.

You are asked to **disconnect the autopilot** and **manually fly commanded guidance maneuvers** to escape a TCAS (or equivalent sensor system) Resolution Advisory. This guidance and its interpretation will be briefed and demonstrated to you prior to data runs. To disconnect the autopilot, you must press the left button (the black one) on the sidestick controller. Although the autopilot will be disengaged, the autothrottles will still be engaged after you press the black button.

Following each run, you will be asked for additional comments concerning the run. Periodically (during the evaluation period), you will also be asked to fill out a questionnaire and task workload assessment pertaining to a specific surveillance concept.

Appendix C

Navigation Task

Altitude Arming Procedure

The altitude arming procedure is used to better simulate real world workload while performing the surveillance mission. The intent is to simulate allowing the autopilot to descend and climb past defined waypoint crossing altitudes, much as would exist in actual instrument departures and arrivals.

The Autopilot Guidance Control Unit (AGCU) has a number of control sections, but the only one used in this experiment is the altitude section. This section is comprised of the altitude window, increase and decrease arrows, set window resolution button, and the arming button. The increase and decrease arrows may be pushed to increase or decrease the number in the altitude window. When the set resolution button is pressed (and illuminated in white), the amount of change for each arrow press is 1,000 feet. When the button is not illuminated, the amount of change for each arrow press is 100 feet. The altitude arm button illuminates (in yellow) when it is pressed, indicating the altitude is armed. It extinguishes when arriving at (or through) the armed altitude, or when either the increase or decrease arrows are pressed.

For the scenarios, you are requested to treat the below procedures as though on a real world arrival or departure (i.e., lives are at stake). For purposes of the simulation and time efficiency, runs will not end, nor will the autopilot vertical profiles change, if you violate the procedures. The error will be recorded and used to assess workload and performance during the runs.

The following are specific procedures for the scenarios (depicted on the next page) in the simulation:

1. Arrival Scenario:

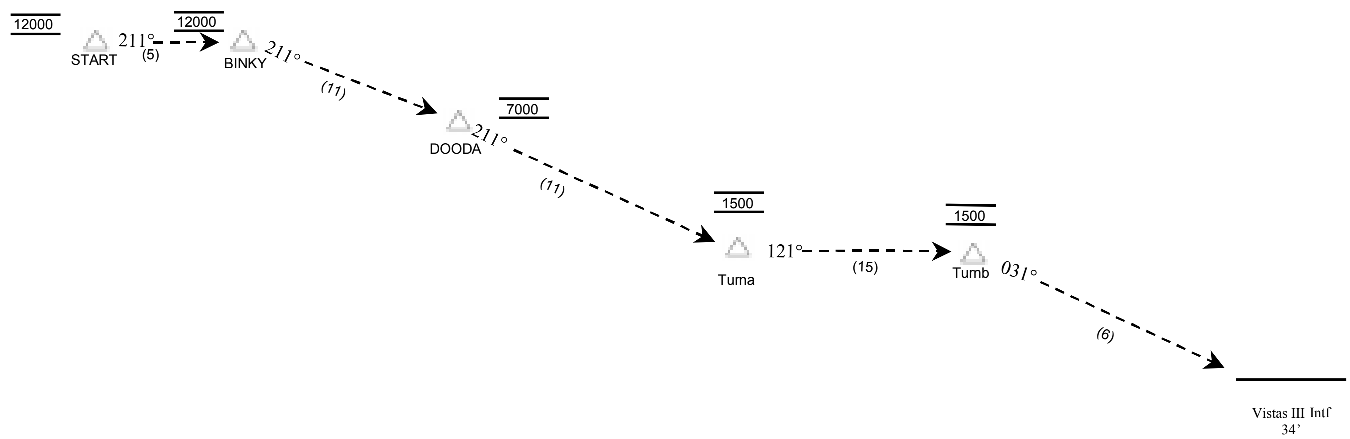
The Arrival Scenario begins at 12,000 feet, with the altitude arm window at 12,000 feet, and not armed. At the first waypoint, “BINKY”, the autopilot will begin descending the aircraft toward the next waypoint, “DOODAH”, where the crossing altitude is 7,000 feet. When **within 3 miles of BINKY, select 7,000 feet in the altitude arm and press the “Arm” Button**, to allow the descent. **When within three miles of “DOODAH”, select 1,500 feet in the altitude arm and press the “Arm” Button**, to allow continued descent toward “TURNA.” You may leave 1,500 feet in the altitude arm window for the remainder of the run - the approach will automatically start past “TURNB.”

2. Departure Scenario

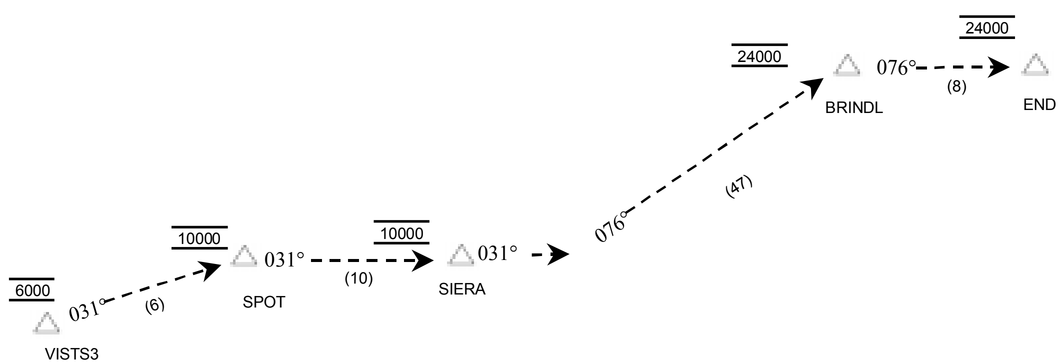
The Departure Scenario begins at “VISTS3” in a climb at 6,000 feet, with the altitude arm window at 9,000 feet, and not armed. Anytime **prior to the next waypoint, “SPOT”,** you should **select the level-off altitude, 10,000 feet, in the altitude arm window**, **and press the “Arm” Button**. At the next waypoint, “SPOT”, the autopilot will level off at 10,000 feet. When **at the next waypoint, “SIERA”, select the next level-off altitude, 24,000 feet in the altitude arm and press the “Arm” Button**, to allow the climb. The autopilot will complete the turn at

"SIERRA" and begin the climb toward "BRINDL." Ensure 24,000 feet is armed prior to completing the turn. You may leave the altitude arm window at 24,000 feet for the remainder of the run.

Arrival Vertical Profile



Departure Vertical Profile



Appendix D

Systems Monitoring Task

Fuel Balancing Task

The simulated fuel system is a 2-tank system (left and right) with 3 pumps to pressure the fuel lines to the 4 engines. The full capacity of each tank is 60,000 pounds. Each pump delivers fuel at the rate of 1000 lbs/min. Note that fuel drainage is highly artificial and is not linked to the throttle state in anyway. The engines require 2000 lbs of fuel per minute regardless of speed or throttle setting. You are to monitor the left and right fuel tanks to ensure proper fuel balance. The fuel tanks are considered balanced if there is less than a 2000 lb difference between the tanks.

The fuel system consists of 3 pumps: a left tank pump, right tank pump and a cross feed pump. The nominal state of the pumps is: left pump on, right pump on and the cross feed pump off. If there is a fuel imbalance, then it is necessary to turn on the cross feed pump and turn off the associated tank pump with low fuel. The tank pump for the associated high fuel tank should remain on. Having both a tank pump on and the cross feed pump on will drain fuel from the high fuel tank at 2000 lbs/min.

Errors

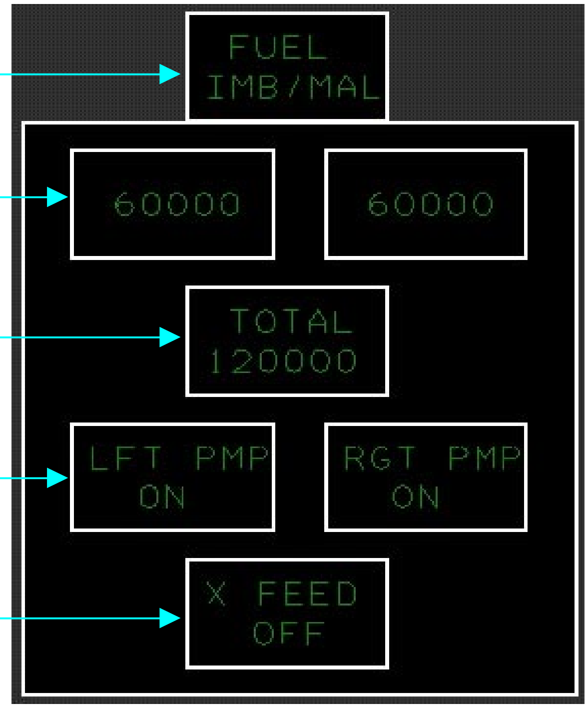
A Fuel Imbalance/Malfunction light is used to notify the pilot when an error condition has occurred. The Malfunction light will remain lit until the error condition is corrected. The Fuel Imbalance/Malfunction light will illuminate when:

1. A 3000 lb or more fuel imbalance between the left and right tanks
2. One pump is off and the cross feed pump is off
3. Both left and right pumps are off (gravity feed is an error)

The following are errors which do not illuminate the error light but are logged:

1. All pumps on greater than 3 seconds
2. A Fuel imbalance greater than 2000 lbs but less than 3000 lbs

1. Fuel Imbalance/malfunction light
2. Left and right remaining fuel (in pounds)
3. Total fuel quantity
4. Left and Right fuel pump: toggle on/off
5. Cross feed fuel pump: toggle on/off



Appendix E

Minimum Flight Deck Symbology

The eXternal Visibility System Element sponsored a Flight Deck Systems symbology workshop in the Fall of 1996 to agree on a minimum symbology set that would be used within the Flight Deck Systems Elements, when possible, as a basis for all experiments. Included in this Appendix are the notes from that Workshop.

Fall 1996 XVS Workshop

Minimal HUD Symbology Set Definition

by

Steve Williams
Crew Vehicle Integration Branch
NASA Langley Research Center

September 11, 1996

Symbology Elements

The XVS Workshop Minimal HUD is a combination of 12 symbology elements as seen in figure 1. In this depiction, all elements except element numbers 2, 3, and 4 are displayed with a contrast enhancement technique called 'haloing.' Haloing involves first drawing the element in black with a thick pen (3 or 4 pixels wide), and then in white (or the elements chosen color) in a thinner pen (1 or 2 pixels wide). It is recommended that some contrast enhancing technique is used on all hud elements.

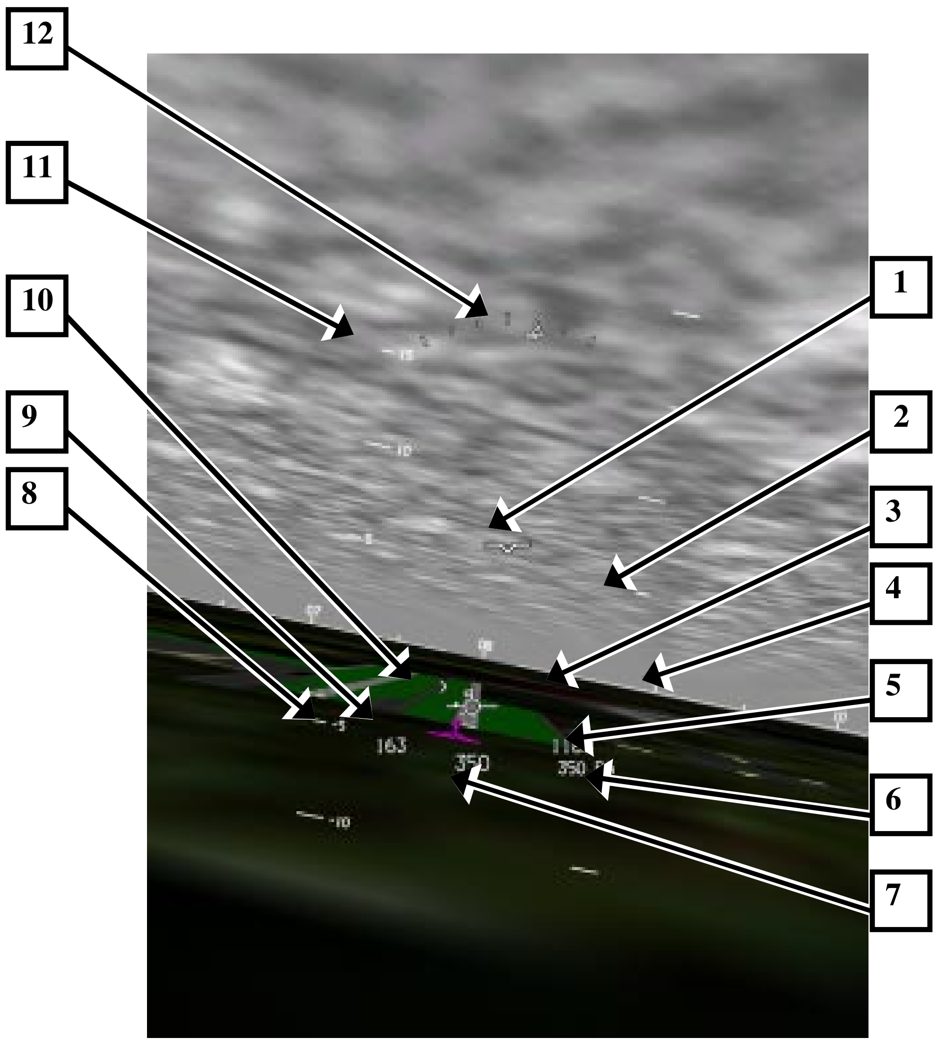


Figure 1. XVS Workshop Minimal HUD

1. Aircraft (pitch) symbol reference.

This symbol represents the waterline of the aircraft, and in combination with the pitch tape (element 2), indicates the current pitch angle of the aircraft. The symbol is a single V with wings and has a total width of 2.4 degrees and a height of 0.4 degrees. Each wing is 0.8 degrees in length. This symbol is fixed to the display surface (does not move) as the XVS system is attitude centered.

2. Pitch Tape.

The Pitch Tape consists of large (1.5 degrees wide) tick marks at 10 degree intervals and short (0.7 degrees wide) tick marks at 5 degree intervals. The outside edges of the ticks are aligned and the left side of the tape is labeled. The outer sides of the ticks are 17 degrees apart. The pitch tape slides left and right along the horizon so that the flight path vector symbol (element 10) is always in the center of the tape.

3. Horizon Line.

The horizon line extends across the display at the 0 degree point of the pitch tape. The horizon line has a 4 degree gap centered around the flight path vector symbol (element 10).

4. Compass Heading Numbers and Ticks.

Along the horizon line (element 3), there are compass ticks every 5 degrees. Every ten degree tick is labeled. The 5 degree ticks are 0.3 degrees tall and the 10 degree ticks are 0.4 degrees tall. The heading numbers are centered above the ticks and are 0.5 degrees in height. Heading numbers and ticks are clipped out of (not drawn) in a region that is +/- 1.0 degree on either side of the center of the horizon line gap (element 3). NOTE: The 80 degree heading indication and tick mark in figure 1 are incorrectly displayed.

5. Barometric Altitude.

The center of the barometric altitude numeric readout is located 4.5 degrees to the right and 2.0 degrees down from the center of the flight path vector symbol (element 10). This symbol moves with the flight path vector symbol and pegs on the edges of the display. The barometric altitude numerical readout is 0.75 degrees in height and the value is truncated to 20 foot increments.

6. Radar Altitude.

The center of the radar altitude numeric readout is located 4.5 degrees to the right and 3.2 degrees down from the center of the flight path vector symbol (element 10). This symbol moves with the flight patch vector symbol and pegs on the edges of the display. Four dashed lines ("- - - -") are displayed when the radar altitude is invalid (above 2500 feet AGL). The radar altitude is truncated to 10 foot increments above 50 feet, 5 foot increments above 10 feet and below 50 feet, and 1 foot increments below 10 feet. The radar altitude is adjusted to read '0' at main gear touch down at a nominal flare attitude. The radar altitude numeric readout is 0.7 degrees in height.

The letters 'RA' are displayed next to the radar altitude numeric readout at all times (even when dashed).

7. Landing Phase Radar Altitude.

At 500 feet AGL, the LAnding PHasE Radar ALTitude (LAPHER ALT) numeric readout appears. Once the LAPHER ALT is displayed, the radar altitude must ascend above 550 feet AGL before it is removed. The readout is located 3.0 degrees down from the flight path vector symbol (element 10) and is 0.85 degrees in height. The LAPHER ALT moves with the flight path vector symbol and pegs on the edges of the display.

8. Indicated Airspeed.

The indicated airspeed is located 4.5 degrees to the left and 2.0 degrees down from the center of the flight path vector symbol (element 10). This symbol moves with the flight path vector symbol and pegs on the edges of the display. The indicated airspeed numerical readout is 0.75 degrees in height and the value is truncated to 1 knot increments.

9. Flight Guidance.

One of three types of flight guidance will be provide.

1) Traditional Flight Director guidance where a single circle is displayed (0.4 degrees diameter) in magenta indicating directly the amount of pitch and roll suggested. The pilots task is to position the flight path vector symbol (element 10) so that the flight director guidance circle is center in the flight path vector circle.

2) Ghost Aircraft Pursuit guidance where a ghost aircraft symbol is displayed according to the principles and guidelines suggested in NASA TM-104027 "Some VTOL Head-Up Display Drive-Law Problems and Solutions" (1993) by Merrick. The ghost lead time used for HSR approaches varies from 15 seconds to 5 seconds based on the following equation:

```
ghost lead time = (Rad Alt)/50.0
if (ghost lead time > 15.0) ghost lead time = 15.0
if (ghost lead time < 5.0) ghost lead time = 5.0
```

The geometric description of the ghost aircraft is describe in NASA TM-102216 "A Head Up Display for Application to V/STOL Aircraft Approach and Landing" (1990) by Merrick, Farris, and Vanags. The ghost is displayed in magenta and the 'X' symbol for the beacon has been replaced by a circle 0.4 degrees in diameter.

3) 3 Degree Flight Path Reference Line which is displayed at a constant 3 degrees down from the horizon line (element 3). This symbol is a white dashed line that is 15 degrees wide and has a 3.0 degree gap in the center. The 3 degree flight path reference line slides left and right with the flight path vector symbol (element 10) so that the flight path vector symbol is always center in the gap. The 3 degree flight path reference line is always parallel to the horizon line.

10. Flight Path Vector.

The Flight Path Vector symbol is made up of four sub elements as seen in figure 2. The first element (1) is the flight path vector symbol itself. This element consists of a circle 1.0 degree in diameter, two horizontal wings 1 degree in length on each side, and one vertical tail 0.6 degrees tall. The center of the circle indicates the inertial flight path of the aircraft (track angle and gamma). The second element (2) is a side slip/skid indicator. The slip/skid flag grows in the direction of the rudder correction required. The third element (3) is a speed error tape. This tape indicates relative error to the commanded airspeed. If the tape is above the wing, the aircraft is faster than the commanded airspeed. The tape grows below the wing to indicate that the aircraft is to slow. The tape is scaled such that 1 degree of tape indicates a 20 knot speed error. The fourth element (4) is an x-body axis acceleration indication. If the carrot is above the wing, the aircraft is accelerating. If the carrot is below the wing, the aircraft is decelerating. The acceleration carrot is scaled such that a 1 degree deviation from the wing indicates 2 feet/second/second acceleration.

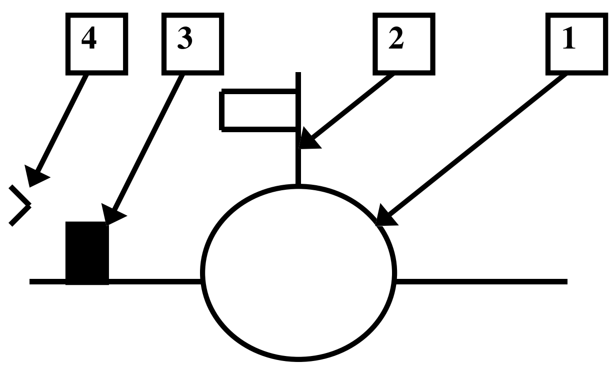


Figure 2. Flight Path Vector Symbol

11. Roll Scale.

The roll scale is a collection of tick marks nominally indicating 0, +- 10, +- 20, and +- 30 degrees of bank angle. The 0 and +/- 30 degree indications are long tick marks (0.5 degrees in length), and the +/- 10 and the +/- 20 degree indications are short tick marks (0.25 degrees in length). If the aircraft bank angle exceeds 35 degrees, +/- 45 degree ticks (short) and +- 60 degree ticks (long) are drawn. The bottom of the 0 degree roll tick mark is 11.75 degrees from the center of the display.

12. Roll Indicator.

The roll indicator symbol is a triangle that moves along the bottom of the roll scale (element 11) to indicate current bank angle. The indicator is a triangle that has a base length of 0.5 degrees and a height of 0.75 degrees. Side Slip/Skid is indicated by a rectangle attached to the bottom of the roll indicator. The rectangle is 0.15 degrees tall and moves in the direction of rudder correction required.

Appendix F

Test Parameters List

- absolute altitude, h, feet
- altitude rate, hdot, ft/s
- angle of attack, α, deg
- angle of line-of-sight to target (laterally), deg
- autopilot disconnect switch position (on/off)
- bank angle, ϕ, deg
- button press time, sec
- calibrated airspeed, ft/sec
- distance to target, ft
- dynamic pressure, q, lb/ft^2
- flight condition (run number, date, time)
- flight path angle, γ, deg
- groundspeed, V_{cas}, ft/sec
- groundtrack, deg
- heading angle, deg
- inertial position x, ft
- inertial position y, ft
- inertial position z, ft
- lateral acceleration, A_y, g units
- longitudinal acceleration, deg/sec^2
- ND target press time, sec
- normal acceleration, A_n, g units
- pitch angle, θ, deg
- pitch rate, q, deg/sec
- radar altitude above the ground, h, ft
- roll rate, p, deg/sec
- sideslip angle, β, deg
- surveillance display type (1,2,3 or 4)
- throttle command, percent
- throttle position, percent
- time, t, sec
- true airspeed, V, ft/sec
- yaw angle, ψ, deg
- yaw rate, r, deg/sec

Appendix G

NASA Task Load Index (TLX)

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Place a mark at the desired point on each scale:

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

Appendix H

Display Questionnaire

Subject Number ___

Surveillance Display Questionnaire

Check to indicate the Surveillance Display Concept being evaluated:

☐ Surveillance Information Provided Head-down Only (Navigation Display)

☐ Surveillance Information Provided Both Head-up and Head-down (Primary XVS Display and Navigation Display)

1. With this display concept,

A. The ease in detecting traffic was

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

B. The ease in accessing whether traffic was going to be a threat was

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

C. The ease of detecting traffic in the head-up display and side window was

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

2. Rate your overall "workload" for performing the surveillance task.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

3. Rate your workload in monitoring the autopilot functions and fuel tanks while performing the surveillance task.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

4. Rate your workload in monitoring only airborne traffic.

very hard	somewhat hard	neutral	somewhat easy	very easy
☐	☐	☐	☐	☐

5. Please discuss the advantages of this display concept:

____
____
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6. Please discuss the disadvantages of this display concept:

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7. What improvements would you suggest for this display system?

____
____
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____

8. Was there any symbology in this display concept that either appeared confusing or should be changed?

9. Based on your experience now, how strongly do you feel that the HSCT surveillance task could be flown safely and effectively using the XVS Concept? The surveillance task is defined as the ability to detect, identify, prioritize and avoid external hazards as well as maintain overall potential hazard situation awareness.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

Why or why not?

10. Suggestions/comments:

Appendix I

Final Questionnaire

Subject Number ___

Final Questionnaire

1. Useful information is conveyed through the use of distinct symbol shapes for each sensor source?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

2. Should sensor symbols be presented on the primary XVS display (head-up display) rather than just on the Navigation Display (head-down display)?

☐ yes ☐ no

3. Using sensor symbols on the primary XVS display increases a pilot's situational awareness.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

4. Using sensor symbols on the primary XVS display adds too much clutter to this display.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

5. Using sensor symbols on the primary XVS display increases a pilot's ability to visually detect traffic.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

6. In addition to the TCAS escape guidance provided on the vertical speed tape (or VSI), TCAS escape guidance should be displayed on the Primary XVS display.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

7. Traffic considered to be a threat – TCAS (or equivalent) Traffic Advisories and Resolution Advisories – should *automatically* be transferred from the Navigation Display to the Primary XVS display?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

8. Pilots should be able to *manually* transfer any traffic from the Navigation Display to the Primary XVS Display.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

9. A pilot should be able to *manually* transfer any traffic from his Primary XVS Display to his co-pilot's Primary XVS Display.

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
☐	☐	☐	☐	☐

10. Knowing now that each sensor has different accuracies and characteristics associated with it, do you care to know which type of sensor the displayed surveillance information came from?

☐ yes ☐ no

If you answered yes, please check the ways you would like that sensor type information displayed. (It is perfectly acceptable to check more than one choice.)

☐ in a data field on the Navigation Display (e.g., spell out “RADAR” or “TCAS” in a dedicated area on the ND)

☐ in a data field on the Primary XVS Display (e.g., spell out “RADAR” or “TCAS” in a dedicated area on the PXD)

☐ by shape of sensor symbol on the Navigation Display

☐ by shape of sensor symbol on the Primary XVS Display

☐ by shape of sensor symbol displayed on both the Navigation Display and Primary XVS Display

☐ Other options: Please list.

11. Other Suggestions/Comments.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	**2. REPORT DATE**	**3. REPORT TYPE AND DATES COVERED**
	April 2000	Technical Memorandum

4. TITLE AND SUBTITLE
High-Speed Research Surveillance Symbology Assessment Experiment

5. FUNDING NUMBERS
577-60-10-01

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17957

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2000-210107

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 3 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Ten pilots flew multiple approach and departure scenarios in a simulation experiment of the High-Speed Civil Transport to evaluate the utility of different airborne surveillance display concepts. The primary eXternal Visibility System (XVS) display and the Navigation Display (ND) were used to present tactical and strategic surveillance information, respectively, to the pilot. Three sensors, the Traffic Alert and Collision Avoidance System, radar, and the Automatic Dependent Surveillance-Broadcast system, were modeled for this simulation and the sensors' surveillance information was presented in two different symbology sets to the pilot. One surveillance symbology set used unique symbol shapes to differentiate among the sensors, while the other set used common symbol shapes for the sensors. Surveillance information in the form of escape guidance from threatening traffic was also presented to the pilots. The surveillance information (sensors and escape guidance) was either presented head-up on the primary XVS display and head-down on the ND or head-down on the ND only. Both objective and subjective results demonstrated that the display concepts having surveillance information presented head-up and head-down have surveillance performance benefits over those concepts having surveillance information displayed head-down only. No significant symbology set differences were found for surveillance task performance.

14. SUBJECT TERMS
External Visibility System, Surveillance Symbology, and High-Speed Research

15. NUMBER OF PAGES
68

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL