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Conceptual Design Standards for eXternal Visibility System (XVS) Sensor and Display Resolution

Randall E. Bailey, Susan J. Wilz, and Jarvis (Trey) J. Arthur III
Langley Research Center, Hampton, Virginia

February 2012

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This report documents the conceptual design standards required for the development of an eXternal Visibility System to support a low-boom/no-boom supersonic aircraft. This work builds on a significant body of work that was conducted previously under NASA's High Speed Research (HSR) program and extends it based on technology and programmatic efforts completed since that time. References are cited where appropriate, although much of the HSR work was not be fully disseminated due to limited release restrictions in place at that time. The many individuals who contributed toward the HSR eXternal Visibility System element are too numerous to cite. However, the contributions of Russ Parrish, Mike Lewis, Lynda Kramer, R. Michael Norman, Steven Harrah, Steve Williams, Lou Glaab, George Boucek, Rich Edwards, Mike Johnson, and Jerry Rousch merit specific acknowledgement.

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Nomenclature

AC	Advisory Circular
AFL	Above Field Level
ANSP	Air Navigation Service Provider
C	Contrast
CFR	Code of Federal Regulations
DERP	Design Eye Reference Point
FAA	Federal Aviation Administration
EFVS	Enhanced Flight Vision System
EV	Enhanced Vision
EVO	Equivalent Visual Operations
EVS	Enhanced Vision System
FAR	Federal Aviation Regulation
FOV	Field of View
H	Horizontal
HD	High Definition
HDTV	High Definition Television
HSCT	High Speed Civil Transport
HSR	High Speed Research
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IOD	Image Object Detection
KIAS	Knots, Indicated Air Speed
L	Luminance
LCD	Liquid Crystal Display
MSL	Mean Sea Level
MTF	Modulation Transfer Function
NTSC	National Television Standards Committee
NASA	National Aeronautics and Space Administration
ppd	pixels per degree
SV	Synthetic Vision
SVS	Synthetic Vision System
TIFS	Total In-Flight Simulator
UAV	Uninhabited Air Vehicle
V	Vertical
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
XVS	eXternal Visibility System
$(\cdot)_{min}$	Minimum Value
$(\cdot)_{max}$	Maximum Value

Abstract

NASA is investigating eXternal Visibility Systems (XVS) concepts which are a combination of sensor and display technologies designed to achieve an equivalent level of safety and performance to that provided by forward-facing windows in today's subsonic aircraft. This report provides the background for conceptual XVS design standards for display and sensor resolution.

XVS resolution requirements were derived from the basis of equivalent performance. Three measures were investigated: a) human vision performance ; b) see-and-avoid performance and safety; and c) see-to-follow performance. From these three factors, a minimum but perhaps not sufficient resolution requirement of 60 pixels per degree was shown for human vision equivalence. However, see-and-avoid and see-to-follow performance requirements are nearly double.

Two areas are identified for additional investigation: a) the need to verify and validate these analytically-derived values by in-flight testing; and, b) the development of XVS display and sensor resolution requirements using modulation transfer function-based criteria as a measure of optical performance.

This report also reviewed historical XVS testing. The trends in commercial video systems are very favorable such that emerging technology has the potential to meet the needs of an XVS system. Proof-of-concept testing has identified potential limitations.

1. Introduction

A successful low boom supersonic aircraft design drives the shaping and configuration of the vehicle. One such conceptual configuration is shown in Figure 1. As evident in this figure, the forward visibility for the flight crew is severely compromised as a result of the vehicle shaping.

The National Aeronautics and Space Administration (NASA) is performing fundamental research, development, test and evaluation of flight deck and related technologies which may provide the required pilot visibility for these low-boom, supersonic configurations by use of an eXternal Visibility System (XVS). XVS is a combination of sensor and display technologies designed to achieve an equivalent level of safety and performance to that provided by forward-facing windows in today's aircraft. In this memorandum, conceptual standards for "equivalent performance and safety" are offered as a basis for the design of an XVS. Further, testing results for sensor and display resolution are briefly reviewed.

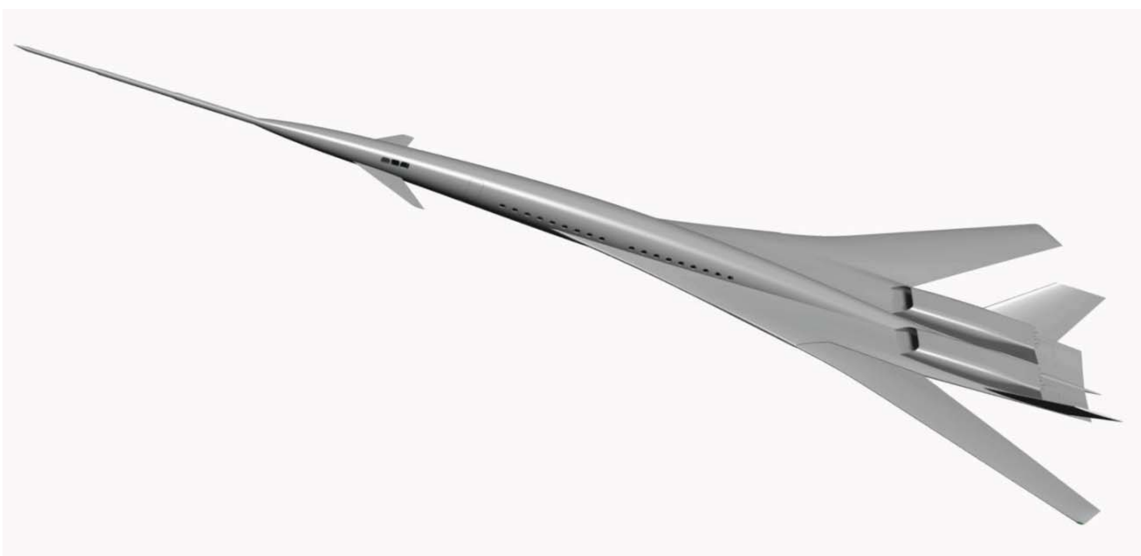


Figure 1: Conceptual Low-Boom Supersonic Aircraft Configuration

The XVS conceptual design standards are only notional and imply nothing more, since a formal basis for certification of an XVS has not yet been established by the Federal Aviation Administration (FAA) or other certification authority. However, these notional standards are offered using current FAA regulations and advisory material with support from previous NASA research and other related research areas. Using these notional standards, further research needs are identified by which to verify and validate these requirements.

This report provides the background and summarization of notional XVS design standards for display and sensor resolution. Citations are used for textbooks and analytical and simulation models where more detailed factors associated with these requirements (e.g., visual acuity, sensor acuity and other factors) are necessary. This report is intended to summarize the pacing requirements and technologies while identifying the research and technology development required to produce validated and verified XVS acuity requirements to support low-boom Supersonic Aircraft emerging within the 2015-2025 time frame.

Two significant requirements which interact with the sensor and display resolution in an XVS design are not addressed in this work – Field-Of-View (FOV) and display collimation. These issues are discussed but standards are not provided. These should be addressed in forthcoming XVS research.

2. Background

The Concorde and TU-144 supersonic aircraft used a mechanism which drooped the aircraft nose to enable pilot visibility from forward-facing windows for terminal operations including takeoff, landing, departure, arrival, and surface operations. For an aircraft of the class anticipated for the High Speed Civil Transport (HSCT) aircraft, the maximum takeoff weight of a fixed-nose configuration design using an XVS was 3.2% lower than that of a drooped-nose configuration. This substantial weight difference created a significant cost-benefit for the development of an XVS (Andrastek, 1999).

Figure 2: TU-144 Drooped Nose Deployed

Without an XVS or a drooped nose, the pilot of a low-boom supersonic aircraft cannot see in front of the aircraft by using their natural vision, since the fuselage obstructs extensive portions of the view where transparent windows would normally be located. Such a design would violate Chapter 14 of the Code of Federal Regulations (14 CFR) Part 25.773 which stipulates that "the flight deck windshield must provide sufficient external vision to the pilot to safely perform any maneuvers within the operating limits of the aircraft." FAA Advisory Circular (AC) 25-773 further instantiates this requirement as stipulating a clear area of vision, as shown in Figure 3.

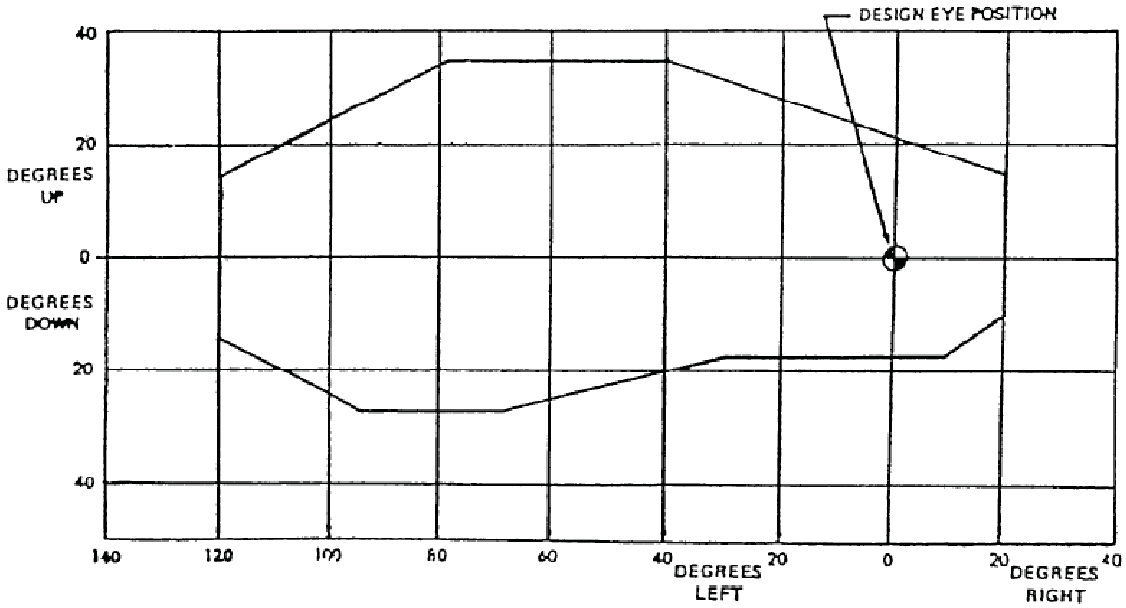


Figure 3: Clear Area of Vision as per AC25-773

In addition, the FAA requires under 14 CFR Part 91.113, *across all classes of airspace,* that "when weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft." The lack of outside visibility due to the fuselage obstructing significant areas required to be "clear" would be further grounds to deny certification.

Even *if* certification of this configuration were to be awarded, the lack of forward visibility by the pilot would – at best – severely restrict aircraft operations and airspace usage. For instance, it might be possible to receive special handling and stipulate that all flights and flight operations are flown under Instrument Flight Rules (IFR). The rationale would be that an aircraft without sufficient pilot visibility is essentially the same as one flying during Instrument Metrological Conditions (IMC).

From an operational standpoint, the supersonic aircraft without an XVS or drooped noise would be incapable of flying under Visual Flight Rules (VFR) and would require "special handling." Both of these conditions are operationally problematic, for example:

- The lack of a VFR capability would prohibit operations to certain airspace classes and airports (e.g., see Drumm et al, 2004) where operational limitations around some airports and facilities cannot provide continual IFR services, such as those located in mountainous regions where radar coverage is not available.
- The lack of a VFR capability can create inefficient flights during actual VFR conditions since pilots can no longer "cancel IFR" and go direct to their destinations or accept a visual approach clearance. IFR aircraft spacing and routing is dictated by Air Navigation Service Provider (ANSP) regulations and procedures.

- “Special handling” by the ANSP necessitates that the ANSP is integral to the planning and execution of all flights. The Concorde required “special handling” in the United States to meet certification requirements. While this was viable for the fourteen Concorde aircraft that operated world-wide, this scenario is not economically viable for any reasonable volume of supersonic aircraft.
- Finally, emerging Next Generation Air Transportation System (NextGen) concepts run counter to the concept of “special handling.” These concepts are exploring ways to optimize traffic flow *without* direct ANSP control over flight operations and shifting some traditional ANSP roles and responsibilities for aircraft separation to the flight deck.

Significant research was conducted under NASA’s High Speed Research (HSR) program during the 1990s on the design and development issues associated with an XVS for a conceptual HSCT aircraft. What emerged from this work – which still holds true today – is that the key challenge for an XVS design exists during VFR operations and when it is assumed that flight crew have natural visibility (even though they may be operating on an IFR flight plan).

The driving XVS design standards emerge from the three tenets of VFR operations:

1. “see-and-avoid”
2. “see-to-follow”
3. “self-navigation”

These VFR operational requirements apply to all aircraft, not just to low-boom supersonic aircraft. The issues and requirements for these other vehicles are discussed in the following sections as their experiences are applicable to the design of an XVS.

As one example, an emerging challenge - being brought forth in the evolution of NextGen - is the concept of *Equivalent Visual Operations* (EVO). The EVO concept is notionally the ability to achieve or even improve on the safety of current-day VFR operations, maintain the operational tempos of VFR, and even perhaps, retain VFR procedures - all independent of the actual weather and visibility conditions. While EVO capability is not required for a successful supersonic aircraft, the technologies and operational requirements to develop EVO are in many ways equivalent to XVS. As such, current research in the use of synthetic and enhanced vision systems and other interface modalities as enabling technologies to meet the EVO operational concept are pertinent to this work.

EVO technologies strive to create VFR operations for today’s aircraft when flying in actual IMC whereas XVS technologies try to enable an IMC cockpit (i.e., low-boom supersonic aircraft) to operate under VFR.

3. Design Standards Basis

Design standards are drafted in the following on the basis that the XVS must provide equivalent levels-of-performance and safety to that of a pilot's natural vision through a forward-facing window.

First, equivalent levels of performance and safety emerge from "human vision equivalence." Secondly, equivalent levels of performance and safety can be derived from the three tenets of VFR operations – "See-to-follow," "See-and-Avoid," and "Self-Navigation." These VFR tenets are engrained in the FAA regulations and advisory materials. As such, these materials and associated analyses are used as a basis from which to define design standards for XVS display and sensor resolution.

While three tenets to VFR operations must be met - based on past HSR and other research - the driving XVS requirements for sensor and display resolution are those necessary to enable "see-to-follow" and "see-and-avoid" operations. "Self-navigation" has not been found to be a driving factor and is not included in these standards development (e.g., see Summers, 1998). Self-navigation, in this context, includes the ability to identify and fly with respect to visual flight references (such as navigation with respect to cultural objects - roads, rivers, large man-made structures, etc) and the ability to conduct visual approaches, landings, and take-off operations. For example, flight testing has shown that pilots can safely conduct approach and landing operations, (i.e., "self-navigate") even with severely restricted forward fields-of-view and minimal resolution (e.g., Perry, Dana, and Bacon (1967), Layton and Dana (1966), and Gaidsick, Dana, and McCracken (1969)) These works show that the tenet of "self-navigation" does not drive the resolution requirements of an XVS.

The XVS design standards are derived using the following principles:

1. XVS design standards are first derived by requiring equivalent performance to that provided by the human visual system. These requirements are briefly reviewed in Section 4.
2. Additional XVS design standards are established by assuming "equivalent" visual acuity from advisory material associated with "the pilot's role in collision avoidance" – that is, "see-and-avoid." Regulatory guidance is employed in defining XVS requirements for display and sensor resolution based on "see-and-avoid" in Section 5.
3. Visual acuity requirements based on the capability to "see-to-follow" are presented in Section 6. "See-to-follow" is a capability - not a regulatory requirement. Therefore, advisory material does not exist, but one might consider that this requirement is derived from 14 CFR Part 25.1301 – satisfying the intended function of an XVS as being "functionality equivalent to that of a forward-facing window" and thus, enabling VFR operational capability.

Background information for functional requirements for an XVS can also be found in Summers (2008). These functional requirements were derived during NASA's HSR program, using similar methodology. The HSR functional requirements are more comprehensive than those presented in the following; however, these HSR-XVS requirements are colored by operational assumptions invoked at that time and they are also predicated by the technologies and operational concepts prevailing and foreseen at that time (circa 1999). The requirements given in the following reflect the present regulatory and operational environment and should be considered an update to these HSR-XVS requirements.

4. Human Vision Equivalence

Various factors influence the perceived image quality of an electro-optical sensor and display system including (Holst, 2008):

- Sensor Performance
  - Resolution
  - Sensitivity
  - Noise
  - Output/Input Transformation
- Display / Monitor
  - Resolution
  - Luminance
  - Contrast
  - Distance from Observer
- Scene Content
  - Target Characteristics
  - Background Characteristics
  - Lighting
  - Motion
  - Clutter
- Atmospheric Transmittance
  - Haze
  - Fog
  - Rain
  - Dust
  - Clouds
  - Etc.

All of these factors are, of course, critical in the assessment and evaluation of an XVS image. However, only the effects of resolution for the sensor and display systems are considered directly in the following as they pertain to the ability of an XVS to provide equivalent performance and safety to that of forward-facing windows.

Human vision "equivalent performance" is impossible to summarize in one or two concise requirements. Human vision performance is described in numerous textbooks (e.g., Westheimer, 1972); the details of which are not repeated here. Nevertheless, some basic standards associated with human visual performance are investigated as XVS design standards for display and sensor resolution.

It should be noted that the effect of the aircraft windows are neglected in this analysis. While some optical distortion and vision modifications due to the transparencies are always present, these effects must be minimal during aircraft certification (see Chapter 14 Federal Aviation Regulations Part 25.773) and are therefore, not considered a significant factor. In addition, testing during the HSR program showed that the influence of the transparencies on human vision performance was in fact negligible (Quinn, Larson, Roush, and Johnson, 1996).

The most commonly used, but not necessarily sufficient, measure of human visual acuity is provided by Snellen-type acuity tests. This standard is most often invoked as an XVS design standard. The rationale is simple: a) it is easily understood; and b) it is one for which virtually everyone has been tested; so familiarity is ensured.

Display system performance is evaluated by viewing a Snellen acuity target (and others analogous to it, e.g., Landolt C) through the XVS sensor and display. Equivalent human visual acuity is said to occur if the user is able to demonstrate 20/20 vision (or 6/6 for metric assessments) – see Figure 4.

By this measure, normal human visual acuity equates to the ability to resolve one arc minute. As a display image is created by pixels, it is often convenient to express visual acuity in terms of the number of pixels to define a degree (analogous to dots per inch (dpi) in printing). Thus, a display system resolution of less than 60 pixels per degree (ppd) would mean that the display is the "limiting" resolution – i.e., it cannot provide resolution at least equal to that of human vision. To relate Snellen acuity to display and sensor resolution, display resolutions which are "equivalent" to Snellen acuity values are listed in Table I.

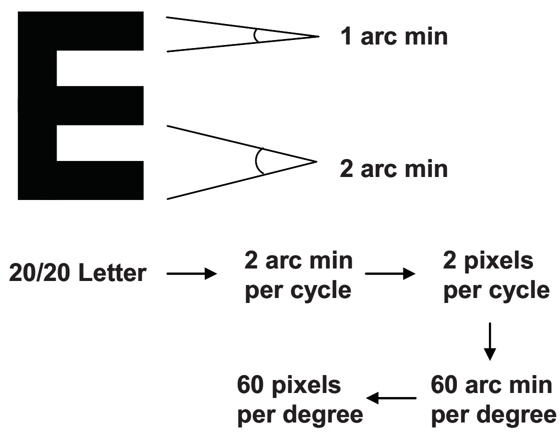


Figure 4: Snellen Acuity Related to Display Resolution

To illustrate how this acuity test relates to XVS design standards, US broadcast television display standards are compared. (In these examples, the camera and display are assumed to be "loss-less" and they show their native resolutions without a magnification or minification - i.e., a so-called "unity" or "conformal" field-of-view - whereby the camera field-of-view subtends the same visual angle as the display when viewed from the observer eye point. The observer is assumed to sit 25 inches from the display.)

In Figure 5, the effect of changing the field-of-view with a constant resolution 640x480 video system is shown. The field-of-view is changed because a different monitor size is used as the display device while conformality is maintained. The abscissa shows the diagonal dimension of the display. The data also shows the horizontal and vertical FOV displayed. (Note that this example does not use the 525 line resolution National Television Standards Committee (NTSC) video standard. Instead, Video Graphics Array (VGA) resolution of 640 horizontal (H) x 480 vertical (V) video is assumed to be equivalent for convenience.)

Table I: Snellen Acuity Related to Display Resolution

Snellen Acuity	Min. Angle of Resolution (arc minute)	Pixels per Degree Resolution
20 / 200	10	6.0
20 / 160	8	7.5
20 / 125	6.3	9.5
20 / 100	5	12.0
20 / 80	4	15.0
20 / 60	3.2	18.8
20 / 50	2.5	24.0
20 / 40	2	30.0
20 / 30	1.6	37.5
20 / 25	1.25	48.0
20 / 20	1	60.0
20 / 16	0.8	75.0
20 / 12.5	0.63	95.2
20 / 10	0.5	120.0

The display resolution varies between 30 and 15 ppd for the 640x480 display system. This display system provides the Snellen-equivalent resolution of between 20/40 (12 inch diagonal) and 20/80 (25 inch diagonal monitor). The higher acuity is provided by the smaller display size because of the higher pixel density, providing only 20 degrees field-of-view. As the display surface increases in size, the same number of pixels (640x480) is now spread over a larger field-of-view. Thus, when this video is displayed across almost 40 degrees field-of-view, the pixel density drops to 15 ppd; hence, the poorer visual acuity.

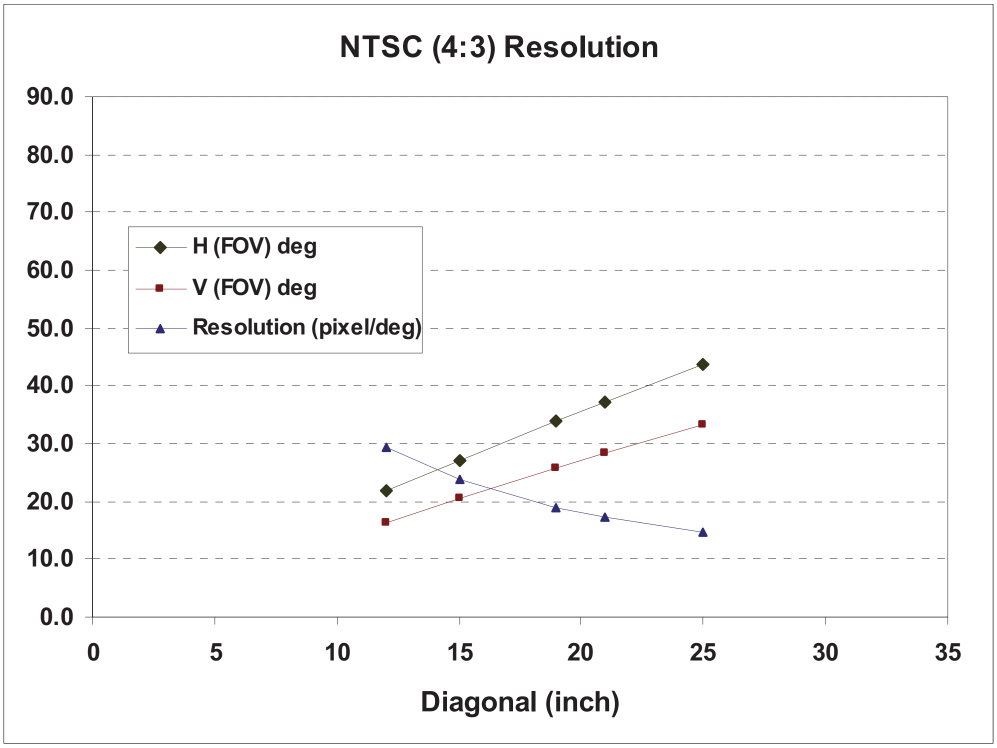


Figure 5: Visual Acuity and FOV vs. Display Size, Using NTSC Resolution

High Definition Television (HDTV) video examples are shown in Figure 6. In these examples, HDTV is portrayed using 1920 H by 1080 V pixel resolution. The increased display resolution from HDTV provides between 81 and 40 ppd for monitors sized between 12 inch and 25 inch diagonal. These displays provide a Snellen-equivalent acuity better than 20/15 (15 inch diagonal monitor) and better than 20/30 (25 inch monitor). This does not imply that a person with 20/20 vision will be able to have 20/15 vision by using this system. Rather, the system has enough resolution to accurately display a scene with 20/15 acuity. This resolution improvement over VGA clearly highlights the attraction for the HDTV revolution in the US. The data shows that 20/20 Snellen acuity is provided by a "loss-less" HDTV system if the display is 16 inch diagonal (or smaller), subtending ~20^{o} V x 30^{o} H FOV.

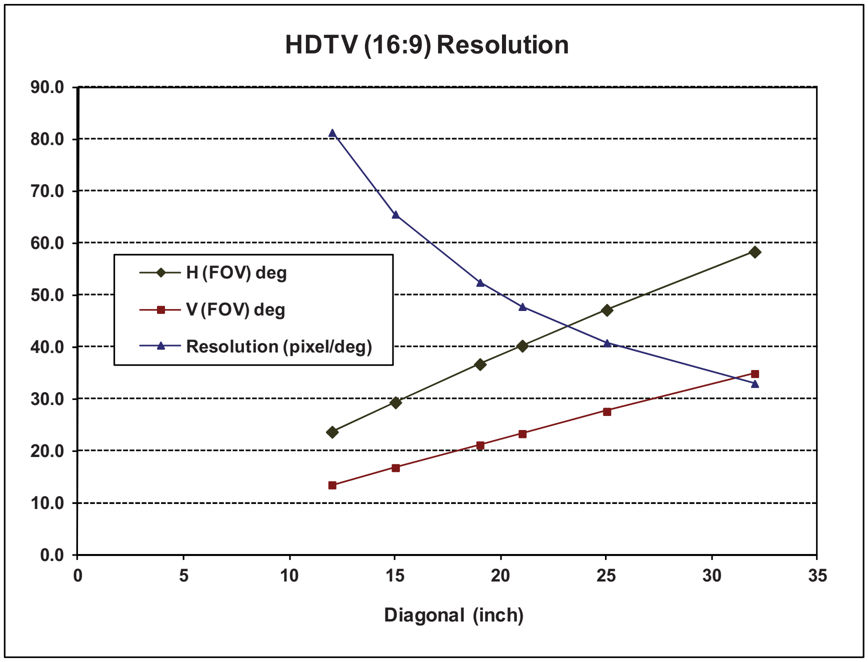


Figure 6: Visual Acuity and FOV vs. Display Size, using HDTV Resolutions

Snellen acuity must be considered a necessary, but perhaps not sufficient, prerequisite for the XVS display and sensor design standard. As mentioned before, Snellen acuity is just one measure of human vision performance. For instance, the test employs "full" contrast targets; that is, the test uses a fully lit black "target" with a white background. The Snellen acuity represents the spatial frequency at which the observer's eye can no longer discriminate differences in the light and dark transitions in the image. Human visual acuity and discrimination associated with color and variations of contrast are not considered at this time.

XVS acuity should optimally be evaluated using Modulation Transfer Function (MTF) testing. Display contrast (C) is defined as:

$$C = \frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min})}$$

where L_{max} is the maximum luminance and L_{min} is the minimum luminance of the displayed imagery. The MTF measures the displayed image contrast compared to the input image contrast as a function of spatial frequency (Holst, 2008). Because the eye is normally considered to require an image contrast of approximately 3% in order to distinguish the light-to-dark transitions in the bars, the limiting resolution using a Snellen-type acuity test can be considered as the spatial frequency at which the MTF has fallen to a value of three percent. Thus, the Snellen acuity test represents just one point on a MTF. The MTF would capture the contrast sensitivity performance of the XVS display and sensor system.

Ideally, the MTF should be used as a basis for XVS display system performance evaluation. At this time, however, MTF criteria for XVS applications have not been established.

Even if 20/20 Snellen acuity is measured, other human vision capabilities suggest much higher pixel densities than the 60 ppd Snellen-equivalent are necessary (Hooper, 2000). Glint, vernier line comparisons, etc. suggest pixel densities as high at 1500 ppd might be required. Thus, XVS resolution and system performance to achieve 20/20 Snellen acuity or better (60 ppd) must be considered a minimum but perhaps not sufficient XVS prerequisite. Other test parameters should also be considered (e.g., see Sweet and Giovannetti, 2008 and Winterbottom et al, 2004).

Even if Snellen-equivalent performance is demonstrated, it may be difficult to *prove* human vision equivalence, especially since some human vision performance capabilities far exceed that required for Snellen vision equivalence (Hooper, 2000). Functional performance requirements, such as those in Sections 5 and 6, may be necessary to demonstrate equivalent performance.

5. Visual Acuity for “See-and-Avoid”

The flight rules prescribed in Part 91 of the Federal Aviation Regulations (FARs) set forth the concept of “see-and-avoid.” See-and-avoid serves three primary functions (Australian Transport Safety Board, 1991):

1. Self-separation of aircraft outside controlled airspace
2. As a separation procedure for VFR aircraft in control zones, where the pilot is instructed to see and avoid another aircraft. This procedure only operates when the pilot can see the traffic and is therefore significantly different to other types of see-and-avoid which may involve unalerted searches for traffic.
3. Last resort separation if other methods fail to prevent a conflict, regardless of the nature of the airspace.

The merit of see-and-avoid operations and the associated human visual, human attention, and operational issues have been studied extensively (e.g., see Australian Transport Safety Board, 1991; Graham, 1989). Whether see-and-avoid actually is effective or not is immaterial. The FAA requires under 14 CFR Part 91.113 *across all classes of airspace* that “when weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft.”

For certification of an XVS, a formal safety analysis would be performed to quantify the required equivalent levels of safety for see-and-avoid. This type of safety analysis to the see-and-avoid problem is currently being performed by the Uninhabited Aerial Vehicle (UAV) community (e.g., see Kuchar, 2004). Their work is of great interest to an XVS design problem, but to apply this analysis directly to an XVS design, is difficult at best. The difference is that the UAV community is trying to develop “sense-and-avoid” whereby “see-and-avoid” is provided by a combination of sensors and computer processing, not a human pilot. Thus, the difficulty arises primarily from trying to sufficiently quantify and validate XVS performance as it impacts the “visual acquisition” component of this analysis. In sense-and-avoid, the process is deterministic (i.e., the sensor either can or cannot acquire and track other traffic to avoid). In see-and-avoid, the unquantifiable capabilities (and limitations) of the human are involved.

The visual acquisition task in see-and-avoid is, in essence, a “target detection” problem of which a wealth of military data and research are available. Target detection research shows that the probability that a target will be recognized (by a human observer) is a function of:

- the probability that the observer is searching an area that is known to contain a target, looks with his/her foveal vision for a specified glimpse time (l/3 s) in the direction of the target; and,
- the probability that the displayed target image is viewed foveally for one glimpse period with sufficient contrast and size to be detected;

In the development of these XVS design standards, the issues associated with how and how efficiently a pilot "visually scans" a display is ignored even though it is an important design issue (e.g., see Boff and Lincoln, 1998). For instance, the amount of time to visually scan a larger field-of-regard to locate a target is theoretically longer than scanning a smaller field-of-regard.

Also, these analyses do not consider the role of surveillance alerting that can alter and/or improve visual search importance, vigilance, and localization (e.g., where surveillance alerting might be generated from sources such as Air Traffic Control surveillance radar or Traffic Collision Alerting Systems). Data suggest that an alerted search is eight to nine times more successful in visual acquisition than an un-alerted search (Andrews, 1991 and Boff and Lincoln, 1988).

The analyzes shown here only consider if a visually displayed target image is of sufficient contrast and size for visual detection. This component of human visual target acquisition is shown to be directly proportional to the target angular size and the apparent target-background luminance ratio (Boff and Lincoln, 1988). Thus, the resolved target contrast and size are the only determinants used for establishing the required XVS display and sensor resolution.

A series of experiments (Ratches et al, 1997) attempted to quantify the target detection probability as a function of the resolution of the sensor/display system (i.e., the target angular size). This work showed that, whether using an unaided eye or other sensors, such as night-vision goggles or thermal imaging systems, four tasks were involved in the target acquisition process:

1) *Detection:* correctly discriminating an object in the image from background and system noise.
2) *Orientation:* correctly determining the detected target aspect or direction of movement.
3) *Recognition:* correctly determining the class membership of the target. For example, is it a truck? A tank? etc.
4) *Identification:* correctly determining the exact identity of the target, e.g., for automobiles, is it a Ford or Chevrolet?

These same and similar processes in detection, recognition, and identification for air-to-air target acquisition tasks have also been found (e.g., see Rohrer, 1996).

Experimental data led to the development of Johnson's criteria for target acquisition (Ratches et al, 1997). Johnson's work presumed that the ability of the observer to detect, recognize and identify a target were a function of how well a critical dimension of the target could be resolved by the sensor-display system. An example of the data is shown in Figure 7, indicating the probability of detection and recognition (of a man or a vehicle) is a function of the number of sensor-display cycles (sensor/display line pairs) depicting the object.

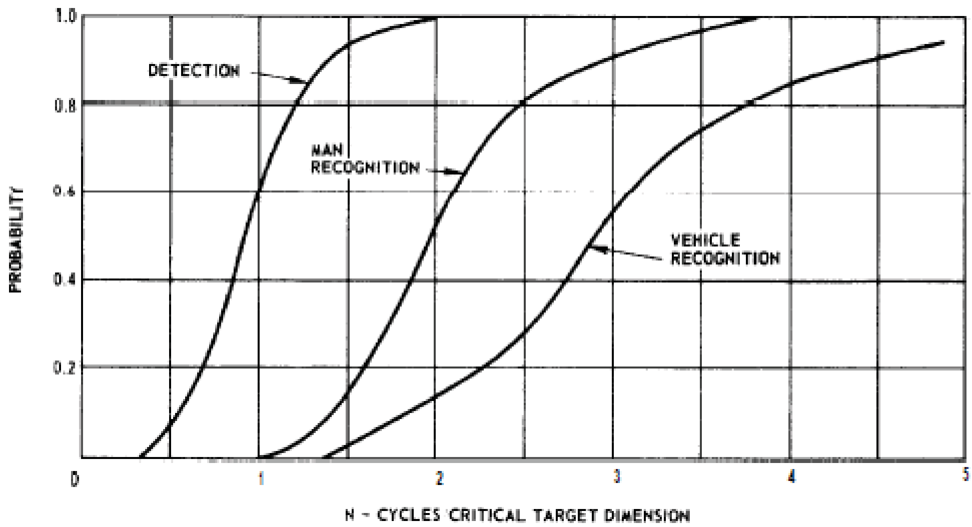


Figure 7: Probability of Detection and Recognition vs. System Resolution (from Ratches, 1997).

Johnson's work evolved into straight-forward criteria for display and sensor requirements for visual acquisition as shown in Table II. The "critical target dimension" was based on intuition and was usually chosen to be the minimum dimension.

Table II: Johnson's Criteria - Resolution Requirements

Task	**Line Resolution per Minimum Dimension**
Detection	1.0 ± 0.25 line pairs
Orientation	1.4 ± 0.35 line pairs
Recognition	4.0 ± 0.8 line pairs
Identification	6.4 ± 1.5 line pairs

These criteria *only* pertain to the image size of the visual target detection task; that is, the target angular size and the associated resolution of the display and sensor to generate the image for human visual acquisition. The other component of the visual acquisition task – the apparent target-background contrast - is dependent upon many other factors such as atmospheric conditions (clouds, fog, haze, moisture content, etc.), target color/material, background illumination and color, sun angle, background (sky/ground), etc, and sensor/display contrast performance. Even though these are critical issues to the task, these are *not* influenced by the display resolution directly and therefore, are *not* considered herein.

Johnson's criteria has been shown to be a rough, first-order approximation as numerous analyses have shown it to be flawed in several respects (McDonald and Vorst, 2002). Other, more elaborate analyses may more accurately predict human detection performance and should be referenced (e.g., see Aviram and Rotman, 2000 and 2001, Vollmerhausen, Jacobs, and Driggers, 2004); however, for the comparative analyses in the following, Johnson's criteria should be sufficient as it provides an intuitive measure for display and sensor resolution effects on visual target acquisition.

5.1 Resolution Requirements Based on See-and-Avoid and Johnson's Criteria

Johnson's criteria are used with FAA advisory circular material to derive XVS resolution requirements to meet see-and-avoid precepts. The objective is to provide a rough order of magnitude assessment of XVS resolution requirements for equivalent safety and performance levels in the absence of a formal safety analysis.

Under FAA AC90-48C - Pilot's Role in Collision Avoidance – pilot recognition and reaction times are published for detection, decision, and evasive action in a see-and-avoid, mid-air collision scenario. These times are shown in Table III.

Table III: Recognition and Reaction Times – AC90-48C

Recognition and Reaction Tasks	Times
See Object	0.1 sec
Recognize Aircraft	1.0 sec
Be Aware of Collision Course	5.0 sec
Decision to Turn Left or Right	4.0 sec
Muscular Reaction	0.4 sec
Aircraft Lag Time	2.0 sec
Total:	*12.5 sec*

The recognition and reaction times stipulated in Table III are applied along with Johnson's criteria (Table II) to develop see-and-avoid XVS display resolution requirements using the following guidelines and assumptions:

1. From Table II, the number of pixels required for detection, orientation, recognition, and identification are equal to 3, 4, 9, and 14, respectively (i.e., approximately twice the number of line pairs plus one).
2. From Table III, a minimum of 12.5 seconds is needed between when detection of an aircraft is made and a mid-air collision can be averted. This function corresponds to the detection task in accordance with Johnson's criteria (Table II). This time defines the distance between two aircraft on a collision course which, of course, depends on their closure speeds and geometry. The XVS resolution is determined by this distance and the fact that 3 pixels of the XVS sensor/display system must resolve the target aircraft.
3. From Table III, the pilot has a minimum of 6.4 seconds before the collision to recognize that the two aircraft are on a collision course and maneuvering is required to avert the collision. This function corresponds to the orientation task in accordance with Johnson's criteria (Table II). Depending upon the closure rate between the aircraft, this time defines the distance between the two aircraft. The

XVS resolution is determined by this distance and the fact that 4 pixels of the XVS sensor/display system must resolve the target aircraft.

A worst case, head-on mid-air collision scenario is assumed (Figure 8).

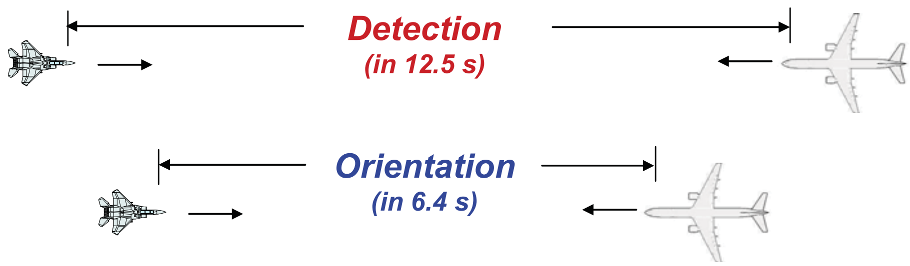
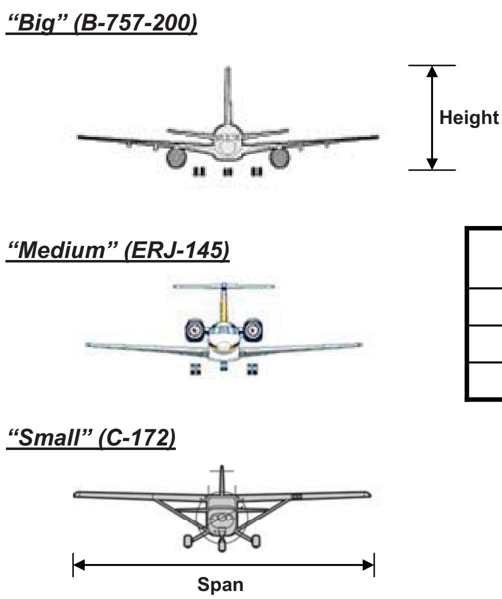


Figure 8: God's Eye View of Worst-Case Head-On See-and-Avoid Scenario

The most demanding mid-air scenarios requiring see-and-avoid occur in uncontrolled airspace below 10,000 ft Mean Sea Level (MSL) (e.g., see Drumm et al, 2004**)**. Assuming worst-case, ownship and the "target aircraft" are flying at 250 knots indicated airspeed (KIAS) in opposite directions at 10,000 ft altitude generating a closure rate of 578 knots.

Three general classes of aircraft "size" were arbitrarily assumed for this analysis. These are shown in Figure 9. These aircraft were picked to demonstrate the influence of target size on the "see-and-avoid" problem. They scale by approximately a factor of 2. Note that the critical dimension under Johnson's criteria is the minimum distance (aircraft height for the head-on collision scenario), but in this work, both vertical and horizontal (wing span) extent of the target aircraft are used. Other analyses use the target cross-sectional area (e.g., Andrews, 1991).

Under these assumptions, the XVS resolution requirements are shown in Table IV.



Aircraft "Class"	Span	Height	Length
"Big"	124.8 ft	44.5 ft	178.6 ft
"Medium"	65.8 ft	22.2 ft	98.0 ft
"Small"	36.1 ft	8.9 ft	27.2 ft

Figure 9: Dimensions of Aircraft in See-and-Avoid Analysis

With a head-on closure in this analysis, detection of the target aircraft has to occur slightly inside of 2 nmi separation to meet the guidance of AC90-48C. Recognition has to occur slightly inside of 1 nmi separation. These separation distances are not unreasonable. They generally meet the expectations of subject matter experts (i.e., experienced intercept pilots, Rohrer, 1996).

Table IV: See-and-Avoid-Based XVS Resolution Requirements

Vehicle Size		Detection	Orientation
	Range	*12210 ft*	*6252 ft*
	Resolution Reqr'd	*3 pixels*	*4 pixels*
Big	Height	14.4 ppd	9.8 ppd
	Span	5.1 ppd	3.5 ppd
Medium	Height	28.8 ppd	20.0 ppd
	Span	9.7 ppd	6.7 ppd
Small	Height	71.8 ppd	50.0 ppd
	Span	17.7 ppd	12.1 ppd

The XVS resolution requirements, based on Johnson's criteria, show that the detection task is the most demanding.

The XVS resolution requirements also show that the required resolution in pixels per degree (ppd) is highest for the smallest vehicle. This result is intuitively obvious. The data show that a C-172-sized aircraft on a head-on collision course would require more than 70 ppd resolution for the pilot to correctly detect the target on the XVS in time to avert a mid-air. This result would initially seem peculiar based on a C-172 flying at 250 KIAS. However, Very Light Jets, such as the Eclipse, are not radically different in size from a C-172 (or military jets for that matter). So the results are relevant.

5.2 Adequacy of See-and-Avoid Based on FAA AC90-48

An alternative analysis is performed to assess the FAA's published timeline for evasive action in the see-and-avoid/collision avoidance task.

Under emerging standards for "sense-and-avoid" systems (ASTM, 2007), sensing must be sufficient that "detection of the collision threat shall be at a range to allow a resolution maneuver that results in a required miss distance of 500 ft or greater."

In this analysis, the same "worst-case" head-on collision scenario is assumed but a 500 ft collision resolution requirement is imposed. XVS resolution requirements are again derived and the implications of this requirement can be judged against FAA AC90-48C.

Two aircraft – ownship and an intruder – are flying in opposite directions at co-altitudes. Both ownship and the target aircraft are flying at 250 KIAS at 10K ft (578 knot closure rate). The vehicle sizes are varied as per Figure 9. Ownship maneuvers to avoid the mid-air collision but the target aircraft does not.

The analysis is conducted in reverse sequence for simplicity. The 500 ft separation distance is required and is used as the final time. The preceding times (and distances) for ownship to achieve this separation standard are calculated as shown in the following figure. The final condition is sketched in Figure 10.

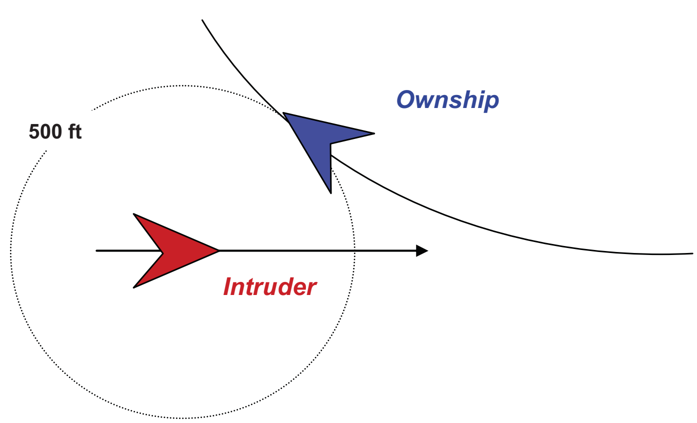


Figure 10: God's Eye View of Final Encounter Position

To achieve this final position, constant altitude turns using 3 values of normal acceleration for ownship are used as a separation maneuver. The normal acceleration values are 1.25g, 1.50g, and 2.0g – not atypical for transport category aircraft. For constant altitude, constant speed conditions, the turn rate and turn radius are computed from kinematics. Ownship is flying at 250 KIAS which equates to 488 ft per second true airspeed (v). The bank angle (ϕ) required to achieve the target normal acceleration values are:

g levels	Bank Angle (ϕ)
1.25 g	37 deg
1.50 g	48 deg
2.00 g	60 deg

By kinematics, the respective turn rates ($\dot{\varphi}$), equal to $\frac{g \tan(\phi)}{v}$, are as follows:

g levels	Turn Rate ($\dot{\varphi}$)
1.25 g	2.8 deg/sec
1.50 g	4.2 deg/sec
2.00 g	6.5 deg/sec

With the respective turn radii (R), equal to $\frac{v^2}{g \tan(\phi)}$, being:

g levels	Turn Radius (R)
1.25 g	9850 ft
1.50 g	6613 ft
2.00 g	4270 ft

The final geometry for the separation between ownship and the non-maneuvering target is sketched in Figure 11. A 500 ft radius circle is assumed around the target at the final position. Ownship has been turning at a constant altitude, constant speed, and constant turn rate. The turn rate and radius of turn, R, depended upon the g-level of the separation, as shown in the data above.

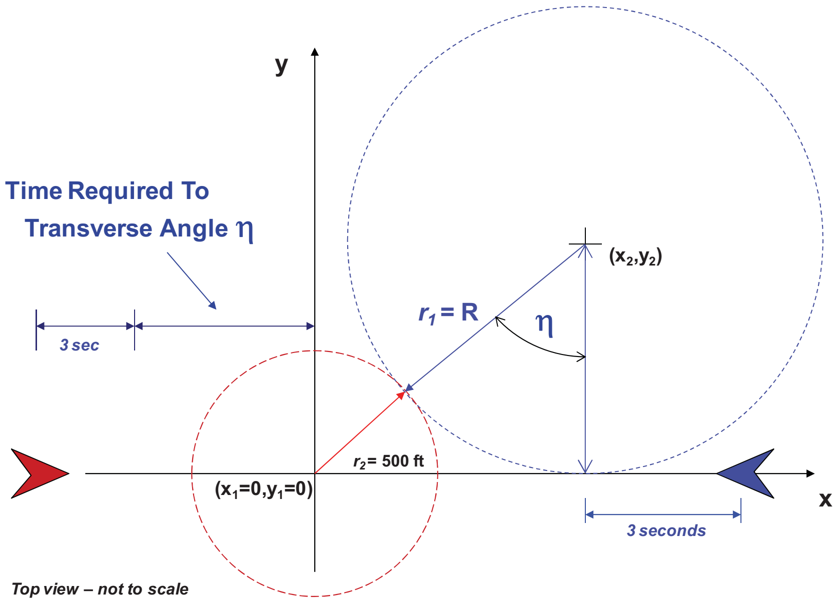


Figure 11: God's Eye View of Encounter Geometry

For this final position, the two circles are tangential to each other. Two circles with centers at (x_1, y_1) and (x_2, y_2) with radii of r_1 and r_2, are mutually tangent if $(x_1 - x_2)^2 + (y_1 - y_2)^2 = (r_1 + r_2)^2$ (Weisstein, 2009). For the target aircraft, the separation circle is $x_1 = y_1 = 0$ with $r_1 = 500$ ft. Knowing that $y_2 = R$, the position x_2 is derived as $x_2 = \sqrt{(500 + R)^2 - R^2}$.

The heading angle (η) that ownship must turn to create this separation geometry is computed as *arctan(x_2/R)*. The time to compute this turn is computed using the turn rate for each g-loading, as follows:

g levels	Turn Angle (η)	Time to Turn η
1.25 g	17.9 deg	6.3 sec
1.50 g	21.6 deg	5.1 sec
2.00 g	26.5 deg	4.0 sec

To simplify the analysis, it was assumed that 3 seconds prior to starting this separation maneuver, the ownship aircraft begins rolling to the target bank angle (either 37, 48, or 60 degrees) but *without* generating any turn rate or lateral separation. This assumption is pessimistic and admittedly not realistic; however, it makes the calculations trivial.

The time from the beginning the rolling maneuver to achieve a 500 ft separation and the distance between ownship and a non-maneuvering target aircraft is given in Table V.

Table V: Time and Distance to Achieve 500 ft Separation in Head-On Scenario

g-Level	Time to Complete	Distance Between

	Separation Maneuver	Aircraft
1.25	9.3 sec	9237 ft (1.5 nm)
1.5	8.1 sec	8096 ft (1.3 nm)
2.0	7.0 sec	7061 ft (1.2 nm)

This simple analysis shows that between 9.3 and 7.0 seconds are required to achieve 500 ft separation in a worst-case, mid-collision scenario. The data of Table V also show that the higher g-levels create the required separation in shorter times – as one would logically expect.

More importantly, these times are significantly longer than the 2.4 seconds required in AC90-48C (Table III) to begin the separation maneuver. At best, 4.6 seconds more time is needed to create the 500 ft separation than stipulated in AC90-48C. This extra 4.6 seconds – for a total of 17.1 seconds for the see-and-avoid process - equates to 4494 ft additional separation between the two aircraft required in the detection and orientation phase. These new see-and-avoid distances suggest that that the XVS resolution would have to be closer to 98 ppd or 84 ppd for successful detection and orientation, respectively, of the "small" aircraft's most critical dimension (instead of the 71.8 ppd and 50.0 ppd shown in Table IV).

Formal safety analysis, based on various sources to mathematically model and predict human and sensor performance (i.e., determine a probability of detection) in "see-and-avoid" environments, should be performed. These types of analyses (for instance, a Mid-Air Collision Assessment Tool (MARCAT®)) have generated probabilistic risk assessment, providing objective data on collision scenarios and risk mitigating avoidance strategies (see Schaefer, 2004).

The analyses of Schaefer (2004) suggest that the human vision process for see-and-avoid is inadequate to prevent mid-air collisions. This work and others (Drumm et al, 2004) suggest that 12.5 seconds may not be sufficient for detection and maneuvering to create a 500 ft separation. The analyses performed herein and the data of Table V corroborate these modeling efforts.

While the inadequacies of human vision (and vigilance) for see-and-avoid are well-documented (Australian Transport Safety Board, 1991; Graham, 1989), it should be noted, however, that the analytical models of Schaefer (2004) are not supported by accident data statistics. The accident statistics are not as bad as implied by the analytical tool results.

In summary, the see-and-avoid analyses show that:

- See-and-avoid is problematic – human observers are neither very efficient nor continually vigilant – but the accident data, especially with the advent of automatic surveillance and alerting services, such as Traffic alert and Collision Avoidance System, and increased pilot training and awareness does not indicate that it is problematic. In any event, see-and-avoid is a regulatory requirement as per 14 CFR Part 91.113.

- Target detection primarily depends upon the displayed target size and contrast compared to its background and the atmospheric conditions through which the target is observed. A simple, rough order of magnitude approximation to quantify an observer's ability to detect a target, determine its orientation and direction of flight, recognize its type, and identify the target is provided by Johnson's criteria (Table II).
- AC90-48C offers times required for target detection and determining its collision course in time to avert a mid-air collision (Table III). A worst-case, head-on mid-air course was assumed and, using Johnson's criteria, shows that 72 ppd for XVS camera and display resolution are required.
- Analyses for a head-on collision also shows that the times shown in AC90-48C are optimistic. To create a 500 ft separation, a target should be detected almost 17 seconds – not 12.5 seconds - before the collision point. The XVS resolution to detect the target at this range is almost 98 ppd. This requirement, however, is unsubstantiated by present accident data statistics or certification advisory material.

6. Visual Acuity for "See-to-Follow"

"See-and-avoid" is a regulatory requirement applicable to all aircraft, in all airspace classes. On the contrary, "see-to-follow" is an operational capability – one of the tenets of VFR operations. It might be possible to operate an XVS-equipped aircraft strictly on an IFR basis; however, its economic viability could be marginal. For this reason, the display/sensor resolution requirements for "see-to-follow" operations are briefly examined in the following.

The applicability of Cockpit Display of Traffic Information (CDTI) for aiding pilot separation in this task is not analyzed in the following analyses. Obviously, these electronic aides (e.g., Prinzo and Hendrix, 2003, McAnulty and Zingale, 2004, and Bone et al, 2004) would significantly ease the task, at a minimum, and might eliminate the need for natural vision in the future. But since these new operations are not yet operational nor can it always be assured that these types of non-visual separation procedures would be used, the "worst-case" scenario of using actual vision (albeit provided by an XVS display) will be analyzed.

Minimum separation and spacing requirements for today's "see-to-follow" operations can be derived from current wake turbulence standards and procedures. As per US FARs, a pilot, when sshe has accepted ANSP instructions to visually follow another aircraft, is responsible to maintain in-trail separation and to accept responsibility for wake turbulence separation. Standard separation from other than a "heavy/B757" aircraft is 3 miles. Wake turbulence separation of a small aircraft from a "heavy/B757" is 5 miles.

Johnson's criteria is again used as a rough, first-order approximation to the visual task requirements for "see-to-follow." Unlike the visual target acquisition task, the corollary between Johnson's criteria using detection, orientation, recognition, and identification phases (Table II) to the see-to-follow task is not obvious.

In this analysis, the following assumptions are used:

- The search is likely a directed search; that is, the flight crew knows the general direction in which to look for the traffic. This directed search is most often obtained from direct ANSP radio communication (e.g., "follow traffic on base, 3 miles at your 2 o'clock, level at two thousand"). Since directed searches are up to 9 times more effective than un-alerted searches (Andrews, 1991 and Boff and Lincoln, 1988), the detection task is not included in this analysis. (It is assumed to be successful.) In addition, this task may occur at distances much greater than the 3 to 5 mile separations.
- The flight crew, focused on a detected object, must correctly determine that the object is an aircraft and it must correctly determine its trajectory. This task should correspond to Johnson's "recognition" task.
- Following recognition, the flight crew should positively identify that the aircraft it is following is indeed the correct aircraft. This task should correspond to

Johnson's "identification" task, whereby the flight crew determines that the aircraft is a C-172, and not a Beech King Air.

Under these assumptions, the XVS resolution requirements are derived by using the worst-case requirements – the smallest aircraft at the greatest distances. These are approximated by using the "small" C-172 dimensional data at a 3 mile separation standard and the "big" B-757 dimensional data at a 5 mile separation standard (see Figure 9). The results of these analyses are shown in Table VI.

Table VI: See-to-Follow-Based XVS Resolution Requirements

Vehicle		Recognition	Identification
	Range	*15840 ft*	*15840 ft*
	Resolution Reqr'd	*9 pixels*	*14 pixels*
C-172	Height (8.9 ft)	300 ppd	467 ppd
	Length (27.1 ft)	90 ppd	140 ppd
	Span (36.1 ft)	69 ppd	108 ppd

Vehicle		Recognition	Identification
	Range	*26400 ft*	*26400 ft*
	Resolution Reqr'd	*9 pixels*	*14 pixels*
B-757	Height (44.5 ft)	90 ppd	140 ppd
	Length (178.6 ft)	23 ppd	36 ppd
	Span (124.8 ft)	33 ppd	52 ppd

The minimum dimension for both a B-757 and C-172 is its height. Using these numbers, the XVS resolution requirements to recognize and identify a C-172 at 3 miles requires 300 to 467 ppd, respectively. These resolution requirements are 5 and 8 times the 60 ppd equivalent of Snellen visual acuity. Pilot opinion suggests that a C-172 cannot be seen head-on at 3 miles. Consequently, these resolution requirements don't seem to reasonably approximate human vision equivalent. They far surpass them and hence, would unreasonably tax the design requirements for an XVS.

More likely, the recognition and identification requirements for see-to-follow depend on the perception of the length and span of the aircraft. A target aircraft, once off of the pure head-on/tail-on aspect, begins to show significant visual area (i.e., its wing and body). Using the smaller dimension of the length or span, the worst-case XVS display resolution requirement requires between 69 to 140 ppd to recognize and identify a C-172 at 3 miles. The B-757 at 5 miles requires less display resolution since its much larger visual area more than offsets the additional 2 miles of range between it and the ownship vehicle.

7. Technology Trends and Associated Research Needs

The preceding analyses show that:

a) 60 ppd may meet a Snellen visual acuity equivalence but other human visual properties require higher resolution. 60 ppd and Snellen equivalence to 20:20 vision should be an absolute minimum requirement.

b) Assuming see-and-avoid scenarios and applying associated AC material, higher resolutions, nearing 100 ppd, are required; and,

c) See-to-follow capabilities require even higher display/sensor resolutions because greater distances are involved. A rough, first-order approximation shows that up to 140 ppd is required to meet see-to-follow operations.

Under the HSR program, designs to achieve 60 ppd XVS display were investigated. Methods to achieve these resolutions were extremely difficult, given the hardware available at that time.

HDTV equipment was in its infancy during the time period of the HSR program. Prototype HDTV equipment was procured and flight-tested. As shown in Figure 12, a Cathode Ray Tube HDTV monitor, weighting approximately 175 lbs, was installed in the Total In-Flight Simulator (TIFS) flight test vehicle. The monitor was 22.75" wide x 12.75" high, providing approximately 49^o H x 29^o V field-of-view from a 25" design eye reference point (DERP) view. This monitor provided approximately 40 ppd. With this resolution, a Snellen acuity of approximately 20/30 should be yielded. Field-tests of Snellen acuity showed between 20/40 and 20/50 performance. The differences between theoretical and actual acuity is likely due to imperfection in the video performance of the HDTV monitor and camera systems – i.e., the system was not "loss-less." MTF tests were not performed. (In addition to the forward field-of-view HDTV monitor, an in-board FOV monitor was also installed to meet foreseen FOV requirements – see Summers, 1998.) During this flight test, see-to-follow or see-and-avoid tasks were not performed. The evaluations primarily emphasized self-navigation tasks. Self-navigation with this Snellen acuity was not a problem.

Figure 12: TIFS Flight Test HDTV XVS Display

Following this flight test, a prototype XVS was flight-tested. This prototype hardware is shown in Figure 13. The desired 60 ppd resolution display was met, albeit only over a small field-of-view. The overall size of the display met HSR field-of-view requirements. The monitor provided 40^{o} H x 50^{o} V field-of-view from a 25" DERP, using three (3) tiled, 1280x1024 projectors with a rear-screen projection. The 60 ppd inset was only 21^{o} H x 17^{o} V – smaller than today's typical Head-Up Display field-of-view. The display resolution outside of this inset was only about 33 ppd. Symbology was overlaid on the XVS video by use of chroma-keying.

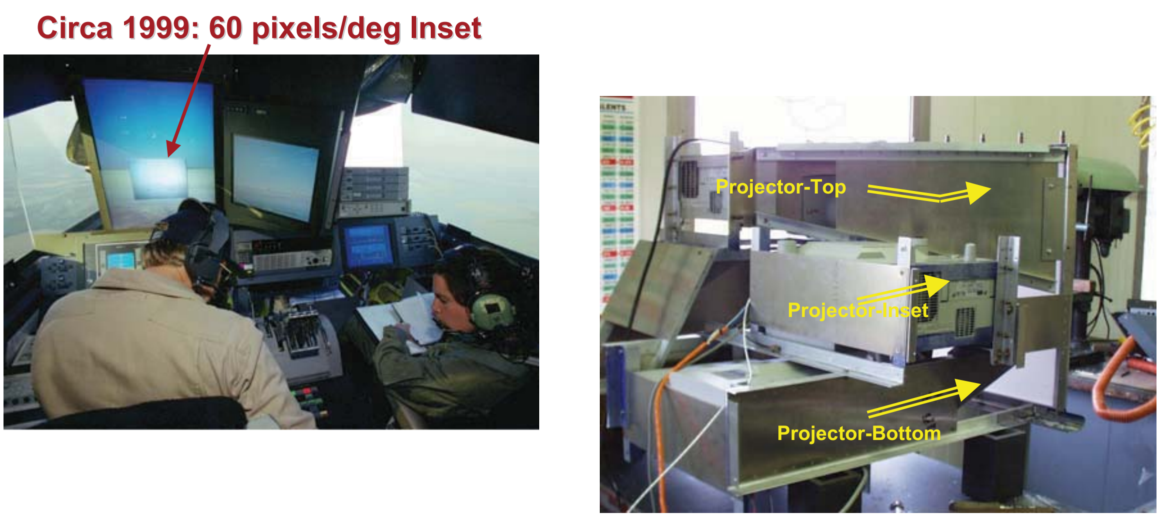


Figure 13: FL5 Flight Test XVS Prototype Display

During this flight test (the so-called "FL5" flight test) a fairly elaborate series of see-to-follow and see-and-avoid flight test maneuvers were flown. Unfortunately, significant portions of the data, especially the human performance aspects of this test were not analyzed because the HSR program ended just at the conclusion of the FL5 flight test. However, this work did feed Image Object Detection (IOD) algorithm development as part of the "see-and-avoid" functionality for HSR (see Gandhi et al (2003) and Yang

(2000)) which continues today as essentially part of the UAV "sense-and-avoid" program.

This flight test also provided valuable development and validation of flight test maneuvers to operationally characterize and assess the performance of an XVS (or other vision-based system devices) for see-and-avoid and see-to-follow operations. In Appendix A, the most pertinent of these tests maneuvers are described.

Since the NASA HSR program, display technology has significantly progressed in areas which impact resolution. These advances have primarily been driven from four thrusts.

1. HDTV has emerged as a commercial standard. As such, HDTV resolutions in many monitor sizes are now available at very affordable pricing.
2. Video refresh rates for these HDTV systems are often designed to meet the demanding video-gaming / entertainment user, not just the 24 Hz cinematic requirement.
3. The medical industry is moving toward eliminating film and using digital record archival. This change necessitates that digital storage and display resolutions approach that of X-Ray films.
4. The cost of Field Programmable Gate Arrays and Digital Signal Processors has dropped by orders of magnitudes and programming of these devices is now a relatively easy and inexpensive task. Custom video hardware and software applications are now an "everyday" event so affordable merging, tiling, and seamless integration of video streams is no longer a technological hurdle. It's just an engineering task.

The state-of-the-art in today's technology is so-called "Quad-HD" – that is, four times HDTV resolution or 3840x2400 pixels. Numerous venders are releasing commercially available Quad-HD monitors in various sizes, but so far, none have been in the XVS required form-factor.

In 2001, a limited run of Quad-HD resolution monitors – the IBM T221 (Figure 14) – was made. The flat panel displays provide over 90 ppd resolution across an approximate 40^{o} H x 26^{o} V FOV, when viewed from 25 inches DERP.

Figure 14: IBM T221 Quad-HD Resolution Display

The T221 monitor came in different versions and was sold by various vendors. The versions differed by their installed video cards and digital video interfaces which influenced the resultant resolution and associated refresh rates. The native refresh rate was reported to be 48 Hz. The refresh rates could vary from 13 Hz up to 48 Hz. An Iiyama AQU5611D liquid crystal display, which is based on the IBM T221 Model 9503-DG3 monitor, was used as the display for an XVS proof-of-concept evaluation.

Under Department of Defense funding, two cameras were specially built to drive the IBM T221 monitor directly, exercising their native resolution. This Quad-HD camera (Figure 15) utilizes custom field programmable gate array circuitry to generate and drive the IBM display with real-time video. Unfortunately, MTF or other similar test data have not been found documenting the results of using this camera and display system.

If the native resolution of the display and a "loss-less" video system is assumed, better than 20/15 Snellen acuity could be provided by this system. This monitor and display system would nearly meet the projected XVS requirements for see-and-avoid and see-to-follow.

One limitation with this camera and display combination for an XVS application is the inability to insert head-up symbology onto the video. The camera directly drives the display so chroma-keying (i.e., symbology insertion) cannot be easily performed. The camera would have to be mounted behind a collimated display (e.g., a Head-Up Display) to create overlaid symbology.

Figure 15: Quad-HD Camera

7.1 XVS Proof-of-Concept Evaluation

An alternate means of creating an XVS display using the T221 Quad-HD monitor was developed. The goal was to quickly assess the problem of adding symbology while achieving display resolutions near those required for an XVS.

Four separate HDTV video cameras (Sony Model EV1-HD1) were used to drive the four HDTV inputs to the Quad-HD monitor. (For laboratory testing purposes at this time, the problem of aligning these four separation cameras to make a seamless single image is not important to this analysis.)

To add symbology to this monitor, four HDTV frame grabbers (Foresight Accustream 170) were installed into a PC. The sketch of this system is shown in Figure 16

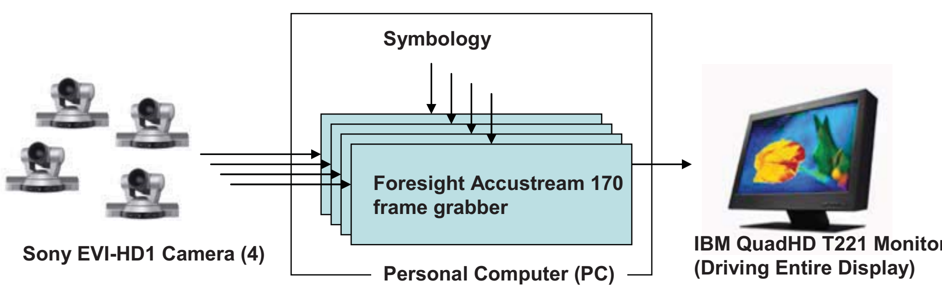


Figure 16: Quad-HD XVS Proof-of-Concept System

Snellen acuity tests were conducted with this system. Snellen acuity of 20/20 was obtained. These data are slightly worse than expectations but not terribly so. Rigorous analysis of the resolution results, such as the computations of the MTF, has not yet been conducted. The cameras used in this set-up are not state-of-the-art by any means. They were selected to provide a convenient 1920x1080 video source.

While the primary objective of this test was an XVS resolution proof-of-concept, a critical constraint to this design is the system latency. A Snellen acuity test is a static image test, however, the content of the XVS display is dynamic. Camera systems have latencies associated with acquiring an image and sending the video signal of the scene. In addition, the monitor has refresh updates and video bandwidth constraints. Displaying symbology on the XVS image can also introduce another source of lag or latency as the symbology is computed and merged with a frame grabber image. The combined effect of all these time delays can have a significant effect on visual perception and pilot performance during use of the XVS. The latencies must be considered in determining the overall effectiveness of the XVS system. If latencies are too high, the system can be un-flyable.

An end-to-end latency test (camera acquisition, transmission, capture, process via frame grabber, symbology overlay and display interface and refresh) was conducted. Timer software was written and displayed on the Quad-HD monitor. This timer is then viewed by the camera system and displayed on the same computer monitor via frame grabber software. The camera image is captured by a frame grabber card. The total camera system latency can be determined by subtracting the computer displayed time minus the frame capture time.

In Figure 17, a screen capture of the computer timer and the same timer captured and rendered by the camera and display system are shown. The T221 monitor was configured for a display resolution of 3840x2400 at 13Hz. Each camera was outputting a 1080i, 60Hz format signal that was captured by a frame grabber. The camera latency was measured as the difference between the two time displays. The system latency was between 300 and 330 milliseconds. This latency has been found to be unacceptable (Bailey, Arthur, and Williams, 2004). A reasonable requirement of 100 msec latency maximum for an XVS is suggested.

This same latency test method was used to diagnose the prominent latency sources in our proof-of-concept XVS.

- First, four parallel video streams were reduced to a single video input. The video capture process was still used as our symbology generation method. With this set-up, the latency was reduced to 230 msec. This result indicates that there was approximately 100 msec of latency associated with the overhead of running 4 parallel capture cards and displaying this Quad-HD video on the T221 monitor.
- Next, the Quad-HD monitor was replaced with a commercial off-the-shelf Samsung (Model LN32A550) HDTV monitor, running 1920x1080 resolution. With this set-up the latency was reduced to 200 msec. This result indicates there was only 30 msec of additional latency associated with the T221 monitor compared to a present-day liquid crystal HDTV monitor.
- Finally, the video capture cards were bypassed and the HDTV video cameras directly drove the Samsung HDTV monitor, running 1920x1080 resolution. With this set-up the latency was reduced to 155 msec. This result indicates that approximately 45 msec of latency is associated with the frame grabbing process.

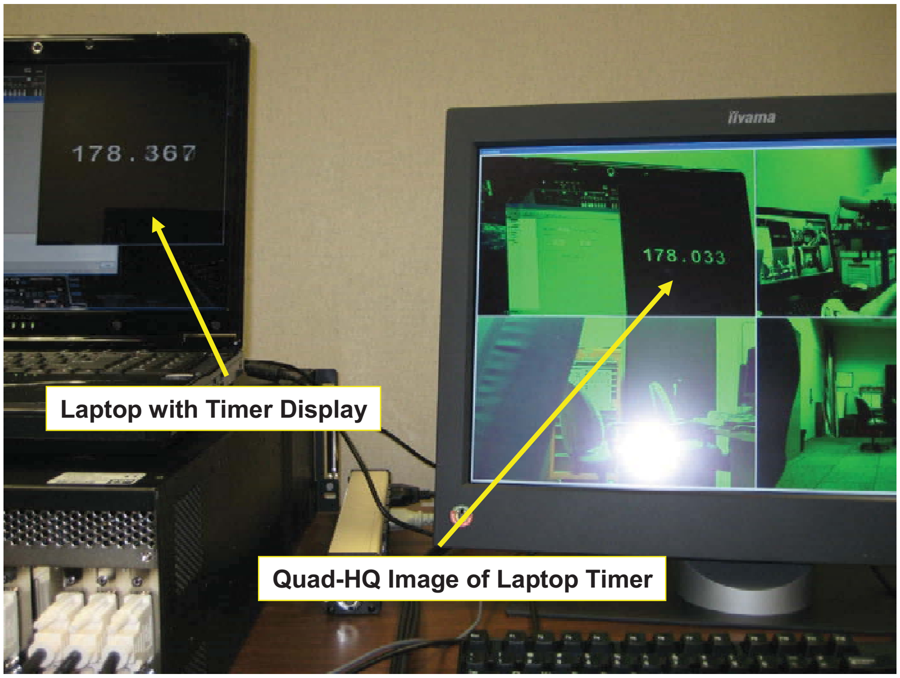


Figure 17: XVS Proof-of-Concept Quad-HD End-to-End Latency Test

Detailed investigations into the exact processes that are causing these latencies have not yet been undertaken. The data suggest that two significant factors are influencing these results.

First, the HDTV cameras being used are not providing a sufficient real-time video source. The latency for just the camera and HDTV monitor is 155 msec. Even if the camera was running as slow as a 24 Hz frame rate, the minimum expected latency would be on the order of 41.67 msec. Since the measured latency is so much greater than this minimum, it indicates that there are significant other factors included in the camera system (e.g., frame buffering, sensor element integration and processing, etc.) that degrade real-time performance.

In addition, the T221 monitor used in this proof-of-concept employs a limited refresh rate. While the data does not indicate that the monitor is a major latency source, the new Quad-HD monitors expected in the near future will have significantly improved video refresh rates and video processing circuitry which should reduce the latency contribution.

Before diagnosing and creating remedies for this XVS proof-of-concept, better cameras and monitors should be procured. Once this happens, the hardware and software processes which control the video frame grabbers will have to be addressed to overcome the 100+ msec of latency that they contribute.

8. Concluding Remarks

This report provides the background for conceptual XVS design standards for display and sensor resolution.

The resolution requirements were derived from the basis of equivalent safety and performance to forward-facing windows currently used and certificated for "conventional" aircraft. Three measures for equivalent safety and performance were investigated: a) human vision performance equivalence; b) see-and-avoid performance and safety; and c) see-to-follow performance.

From these three factors, a minimum but perhaps not sufficient resolution requirement of 60 pixels per degree was shown for human vision equivalence. However, see-and-avoid and see-to-follow performance requirements are nearly double. These results need to be verified and validated by in-flight testing.

XVS display and sensor resolution requirements should be developed using modulation transfer function-based criteria instead of simple pixel per degree measures. The MTF measures would more accurately capture the true system performance and more accurately reflect in-flight performance.

This report also reviewed historical XVS testing. The trends in commercial video systems are very favorable such that emerging technology should be available to meet the needs of an XVS system. Proof-of-concept testing has identified one significant limitation however. The latency of the XVS can be a significant technical hurdle. Methods for commercial off the shelf architectures are being explored, but custom-video processing may be needed instead. Fortunately, custom video work is no longer a technological hurdle, but merely an engineering task. This work should be done to increase the Technology Readiness Levels for XVS technology so the lack of forward-facing windows will not be a risk-factor in the successful launch of commercial and business supersonic aircraft.

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Appendix A
Recommended XVS Flight Test and Evaluation Maneuvers

The following maneuvers are a subset of evaluation tests recommended for the research, development, test and evaluation of XVS and other "visionic" systems. The term "visionics" is used as the name for a generic device which provides a pictorial representation of the external scene (i.e., the environment in which the aircraft is flying), generated by electronic means such as electro-optical sensors, radars and/or a database (synthetic vision). In this case, the XVS (or "visionic" system) is used to replicate the functionality of a forward-facing window for see-and-avoid and see-to-follow.

These maneuvers are a subset of those which have been previously used during the HSR program in the initial development of an XVS (Yang et al, 2000, Gandhi et al, 2003) and are also being used for "sense-and-avoid" testing for UAVs (Shakernia et al , 2007).

For each of the test maneuvers that follow, some brief operational background and specific test objectives is given. The test scenario is then described. Extensions and modifications to these maneuvers can be easily made to accommodate different operational contexts. Some of these are briefly discussed in the "operational background" for each task.

The general term – "visionics" – is used in an attempt to remain technology agnostic.

"See-and-Avoid" – Visual Target Detection

1. *Operational Background*

Visionics devices may provide visual flight reference information sufficient to allow operational capabilities enabling equivalent Visual Flight Rules operations; that is, the ability to see-and-avoid other aircraft. The ability of the pilot (operator) to see other aircraft (i.e., "targets") is critical for the purposes of self-separation and see-to-follow.

Comparative testing is used to quantify the ability of the pilot, when using a visionics device, to meet this see-and-avoid / see-to-follow requirement. Comparative testing is necessary since absolute criteria are not available.

2. *Test Objectives:*

The test objective is to measure the ability of the visionics device to provide the visual cues to enable the evaluation pilot to detect, recognize, and identify other aircraft traffic. Pure "expansion" (i.e., the target is represented by an increasing number of pixels without a translation or change in the position of the target on the display) of a target is typically tested as it represents the most difficult recognition task.

3. *Test Scenario Definition*

The following maneuver highlights one of numerous verification tests which may be used for comparative evaluation against laboratory or simulation tests for in-flight determination of traffic (target) detection, recognition, and identification (Figure A-1). This test emphasizes visual traffic (i.e., "target") detection by the evaluation pilot using "expansion" along a horizontal trajectory away from the evaluation pilot. This maneuver should also be conducted in the reverse direction (i.e., ownship overtaking the target) to test for "expectancy" effects on the part of the evaluation pilot.

Other trajectories, across path, along path, with and without vertical trajectories, may also be performed to evaluate (in-flight) visionics performance and operator detection (of "just noticeable differences") such as Pure Expansion with Pitch Trajectories, False Expansion, Pure Translation Expansion with Pitch, and Expanding Background Expansion with Translation.

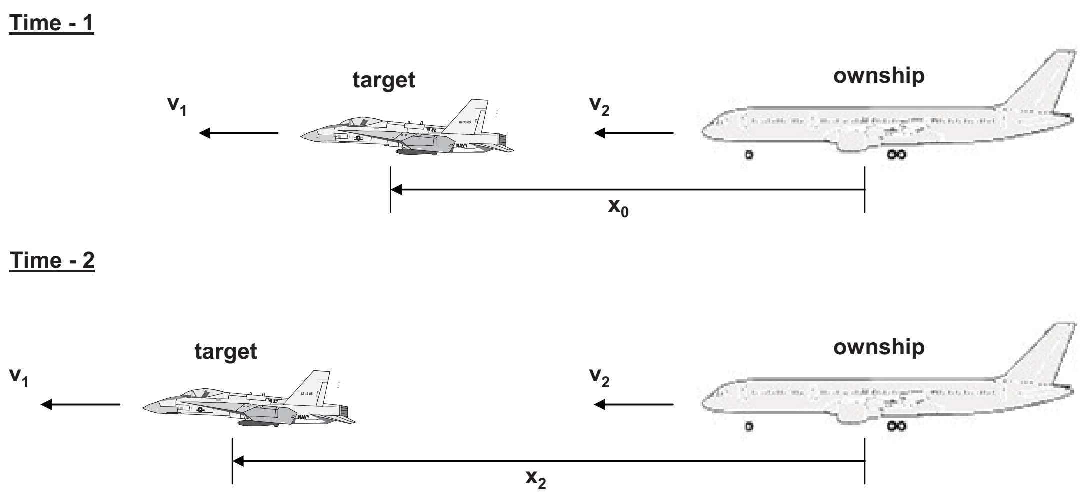

Figure A-1: Visual Target Detection - Expansion With Horizontal Trajectories

The intent of this scenario is to evaluate the visual (acuity and contrast) performance of the visionics system in-flight for target detection, recognition and identification. The target aircraft (labeled "Target" in Figure A-1) presents a traffic situation to the evaluation pilot who is flying ownship aircraft:

- The task begins with the target aircraft flying in loose formation to the left or right and behind ownship.
- When the evaluation pilot with the visionics device is ready, the pilot will radio the target aircraft to move into the task starting position ahead of ownship on the same heading.
- The target aircraft begins the task at the same speed, altitude and heading of ownship and positioned nominally 100 feet ahead (Time 1 in Figure A-1). Ownship maintains constant altitude, speed, and heading.
- On a mark from the evaluation pilot (i.e., data "event marker" triggered and radio transmission of "Start Maneuver"), the target aircraft accelerates to a constant

airspeed and pulls away from ownship (Time 2), maintaining heading and altitude.
- The first test-point occurs when the target is no longer discernible to the evaluation pilot using the visionics device.
- If comparative testing can be done in real-time, a second test-point occurs when the target is no longer discernible to another observer using natural vision.

Weather, atmospheric obscurants and conditions, and time-of-day variations may significantly affect the results of these tests; thus, measurements of these conditions should be made, as possible and practical, and repeated measurements taken for statistical reliability. The results will also be influenced by the observers' visual acuity so individual testing should be made and numerous observers used.

Important performance metrics are as follows:

- Aircraft separation distance when target aircraft is no longer visible, with and without the visionics device.
- Comparison against "theoretical" visual target recognition, and identification criteria.

"See-and-Avoid" – Departure Level-off

1. *Operational Background*

The following maneuver is analogous to the "See-and-Avoid – Visual target detection" task with the notable exception that ground clutter is a significant component to the target identification and recognition.

This task is also critical in that it is an all-too-often operational scenario. In this case, the "ownship" aircraft is being vectored toward an airport and the target aircraft is departing on opposite headings. The target aircraft on a departure climb-out errs and flies through an Air Traffic Control "level-off" altitude with ownship flying a constant altitude. This maneuver tests the ability of the visionics system to support pilot detection of the target aircraft blunder.

2. *Test Objectives:*

The test objective is to measure the ability of the visionics device to provide the visual cues to enable the pilot to identify other aircraft traffic, follow that traffic, and maintain separation in the landing pattern in the presence of ground clutter.

3. *Test Scenario Definition*

The following maneuver highlights one of numerous verification tests which may be used for comparative evaluation against laboratory or simulation tests for in-flight determination of traffic (target) detection, recognition, and identification (Figure A-2).

This task emphasizes visual traffic (i.e., “target”) detection by the evaluation pilot using “expansion” toward the evaluation pilot in ground clutter. This maneuver should also be conducted in the reverse direction (i.e , target aircraft flying away from ownship) to test for “expectancy” effects on the part of the evaluation pilot.

Other trajectories, across path, along path, with and without vertical trajectories, may also be performed to evaluate (in-flight) the visionics performance and operator detection (of “just noticeable differences”) such as Pure Expansion with Pitch Trajectories, False Expansion, Pure Translation Expansion with Pitch, and Expanding Background Expansion with Translation but these are lower priority.

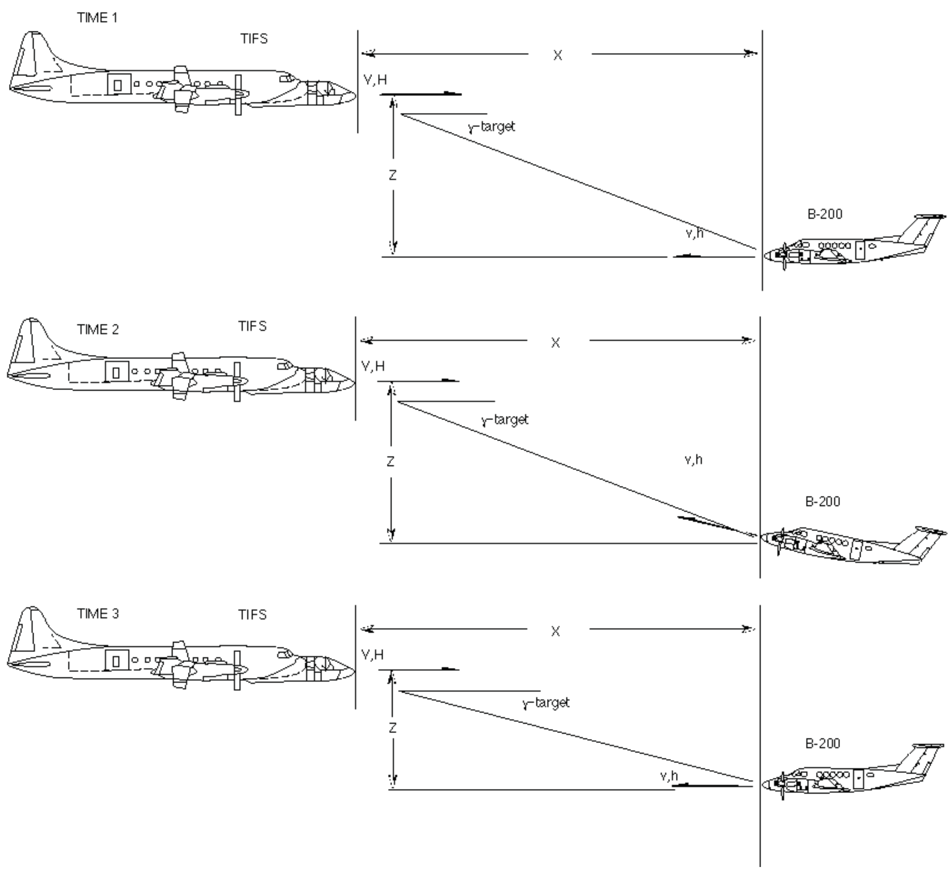

Figure A-2: Visual Target Detection - Departure Level-Off

The intent of this scenario is to evaluate the visual (acuity and contrast) performance of the visionics system in-flight for target detection, recognition and identification. The target aircraft (labeled B-200 in Figure A-2) presents a traffic situation to the evaluation pilot who is flying ownship aircraft:

- The task begins with the target aircraft (labeled "B-200" in Figure A-2) and ownship (labeled "TIFS" in Figure A-2) flying in opposite directions, separated in altitude (labeled "Time 1").
- When the evaluation pilot with the visionics device is ready, the pilot will radio the target aircraft to begin the task.
- The target aircraft begins the task at the same speed but opposite heading of ownship. The altitude separation is based on geometry (as follows) and flight test considerations.
- The target aircraft begins a climb ("Time 2" in Figure A-2) to achieve a constant angle climb as seen by ownship. Airspeed and climb rate are determined by flight test considerations to maintain this constant angle on the visionics device ("Expansion" testing without target translation).
- The target aircraft levels-off the climb to maintain an altitude buffer as required for safety of flight.
- The first test-point occurs when the target is detected (and/or recognized, identified) by the evaluation pilot using the visionics device.
- If comparative testing can be done in real-time, a second test-point occurs when the target is detected (and/or recognized, identified) by another observer using natural vision.

Weather, atmospheric obscurants and conditions, and time-of-day variations may significantly affect the results of these tests; thus, measurements of these conditions should be made, as possible and practical, and repeated measurements taken for statistical reliability. The results will also be influenced by the observers visual acuity so individual testing should be made and numerous observers used.

Important performance metrics are as follows:

- Aircraft separation distance when target aircraft is no longer visible, with and without the visionics device.
- Comparison against "theoretical" visual target recognition, and identification criteria.

See-to-Follow Performance – Self-Separation and Flight-Following

1. *Operational Background*

The following outlines a methodology – one of several – for evaluation (validation) of visionics devices as a way to evaluate equivalent visual operations, in this case, for "see-to-follow" capabilities.

2. *Test Objectives:*

The test objective is to measure the ability of the visionics device to provide the visual cues to enable the pilot to identify other aircraft traffic, follow that traffic, and maintain separation in the landing pattern.

The following maneuver highlights one of numerous "typical" VFR operational problems associated with traffic following and self-separation (Figure A-3). This one emphasizing traffic positions inboard of the evaluation pilot who in this case is seated in the left-hand seat.

3. *Test Scenario Definition*

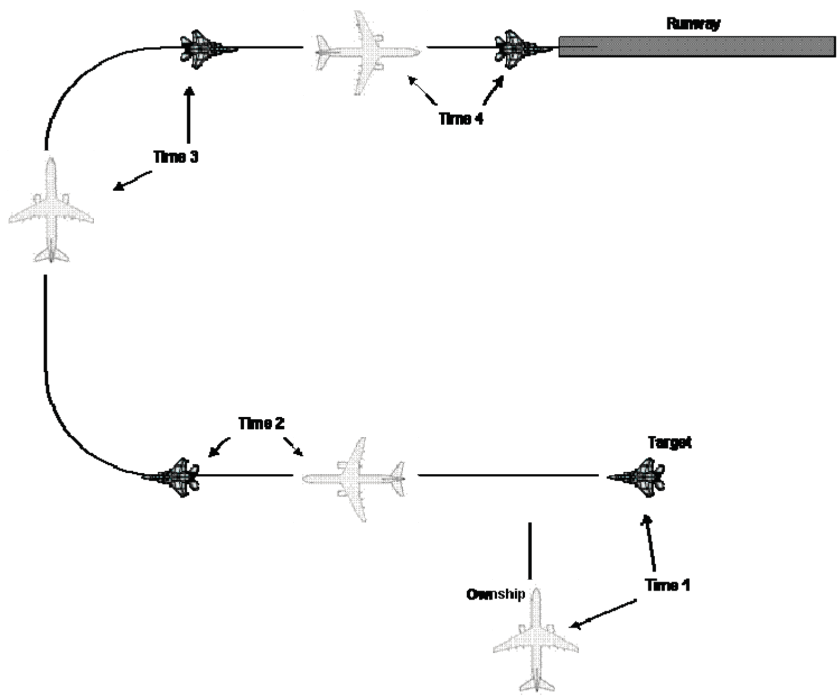

Figure A-3: See-to-Follow Equivalent Visual Operation

The intent of this scenario is to have the target aircraft (labeled "Target" in Figure A-3) present a traffic situation to the evaluation pilot who is flying ownship aircraft during the entry of the downwind leg of a nominal approach to landing which requires close monitoring of the incoming traffic to ensure adequate separation. The evaluation pilot must identify and observe the target aircraft's movement to enter the traffic pattern behind it.

- The ownship aircraft begins a circling holding pattern in a loiter area abeam the downwind leg.
- The target aircraft ("Target") begins on a downwind leg of a right-hand traffic pattern, at 1500 ft above field level (AFL), holding a constant approach airspeed.
- The evaluation pilot will maneuver the ownship aircraft to maintain a constant in-trail spacing (e.g., 3 nm, or 5 nm) spacing on the target aircraft and follow it to landing (Time 2).
- On the base turn, the target will descend to 1000 ft AFL. The target will hold this altitude until glideslope intercept. Ownship will maintain 1500 ft AFL until glideslope intercept.

- Both aircraft continue the landing approach through Time 3 and Time 4. The target aircraft will execute a go-around at 200 ft AFL, ending the evaluation.
- This same scenario may also be conducted for a left-hand approach, emphasizing traffic positions outboard of the evaluation pilot who is seated in the left-hand seat.

The test data should reflect when the target is detected, recognized, and identified by the evaluation pilot using the visionics device. If comparative testing can be done in real-time, second test-points occur when the target is detected, recognized, and identified by another observer using natural vision. The ability to maintain separation (spacing) should be recorded. Different targets also provided different levels of visionics performance testing.

Weather, atmospheric obscurants and conditions, and time-of-day variations may significantly affect the results of these tests; thus, measurements of these conditions should be made and repeated measurements taken for statistical reliability. The results will also be influenced by the observers visual acuity so individual testing should be made and numerous observers used.

See-and-Avoid / See-to-Follow Performance – Parallel Runway Ops

1. *Operational Background*

The following outlines a methodology – one of several – for evaluation of visionics devices as a way to evaluate equivalent visual operations, in this case, for "see-to-follow" capabilities during parallel runway operations.

2. *Test Objectives:*

The test objective is to measure the ability of the visionics device to provide the visual cues to enable the pilot to identify other aircraft traffic, follow that traffic, and maintain separation in the landing pattern.

The following maneuver highlights one of numerous "typical" VFR operational problems associated with see-and-avoid and see-to-follow in VFR operations, in this case, during parallel runway operations (Figure A-4). This one emphasizes traffic positions forward and inboard of the evaluation pilot who is seated in the left-hand seat (until the final approach).

3. *Test Scenario Definition*

The intent of this scenario is to have the target aircraft (labeled "Target" in Figure A-4) present a traffic situation to the evaluation pilot who is flying ownship aircraft during opposite traffic patterns, serving parallel runway approach and landings. The task requires close monitoring of the opposite direction traffic to ensure adequate separation. The evaluation pilot must identify and observe the target aircraft to maintain safe separation and monitor for potential "blunders."

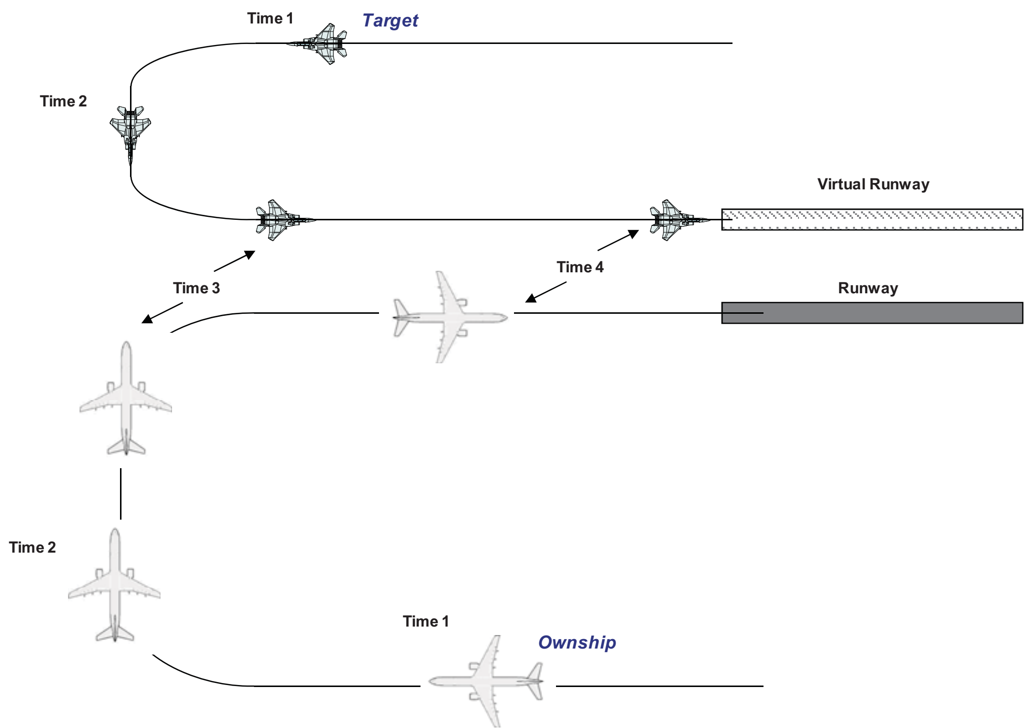

Figure A-4: See-and-Avoid / See-to-Follow Performance – Parallel Runway Ops

- Both the target and ownship aircraft begin on downwind legs to parallel runways using left- and right-hand patterns, respectively. The target aircraft ownship can be a "virtual runway" to ease operational constraints (e.g., by using waypoints for vectors). The spacings between the parallel runways should be varied to test visionics performance.
- The size and aircraft spacings in the traffic pattern are designed based on flight test considerations, as follows.
- The target aircraft ("Target") begins on a downwind leg ahead of ownship in the pattern ("Time 1") so that: a) some reasonable amount of time is provided to the evaluation pilot flying ownship to visually acquire the target while on opposite facing base legs ("Time 2"); and, b) if executed in a timely fashion, the ownship and target aircraft will have 2 nm, 3 nm or 5 nm spacings (experimentally varied) on final to their respective runways ("Time 3").
- The evaluation pilot will maneuver the ownship aircraft to maintain a constant in-trail spacing (e.g., 2 nm, 3 nm, or 5 nm) spacing on the target aircraft and follow it to landing ("Time 4").
- A test for awareness may be experimentally varied by having the target aircraft, unbeknownst to the evaluation pilot flying ownship, fly to the wrong parallel runway (i.e., incurring onto ownship's runway).
- This same scenario may also be conducted for a right-hand approach by ownship.

The test data should reflect when the target is detected, recognized, and identified by the evaluation pilot using the visionics device. If comparative testing can be done in real-time, second test-points occur when the target is detected, recognized, and identified by another observer using natural vision. The ability to maintain separation (spacing) should be recorded. Finally, separation spacing and runway spacing can be varied to assess visual acuity and contrast performance. Different targets should also be used to test different levels of visionics performance.

Weather, atmospheric obscurants and conditions, and time-of-day variations may significantly affect the results of these tests; thus, measurements of these conditions should be made and repeated measurements taken for statistical reliability. The results will also be influenced by the observers visual acuity so individual testing should be made and numerous observers used.

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14. ABSTRACT
NASA is investigating eXternal Visibility Systems (XVS) concepts which are a combination of sensor and display technologies designed to achieve an equivalent level of safety and performance to that provided by forward-facing windows in today's subsonic aircraft. This report provides the background for conceptual XVS design standards for display and sensor resolution. XVS resolution requirements were derived from the basis of equivalent performance.
Three measures were investigated: a) human vision performance; b) see-and-avoid performance and safety; and c) see-to-follow performance. From these three factors, a minimum but perhaps not sufficient resolution requirement of 60 pixels per degree was shown for human vision equivalence. However, see-and-avoid and see-to-follow performance requirements are nearly double. This report also reviewed historical XVS testing.

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