

X-59 EXTERNAL VISION SYSTEM FLIGHT TESTING

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Abstract

The National Aeronautics and Space Administration's (NASA) Quesst mission seeks to overcome a key barrier to future faster air transportation by accomplishing two goals. The first is to prove advanced technologies and design techniques that enable the design of supersonic aircraft that creates a soft thump sound instead of a loud sonic boom when they fly at supersonic speeds. The second is to gather data on how communities respond to this thump sound and supply that data to the FAA and international rulemaking agencies to support the development of new standards for acceptable levels of sound from supersonic flight over land. To accomplish these goals NASA has developed the X-59 supersonic research aircraft, designed specifically to create a sonic thump sound signature during supersonic cruise flight. The forward fuselage/nose shaping of the X-59 design is one of the critical elements of this design, but, as a result, forward-facing windows are impractical.

NASA designed and delivered an eXternal Vision System (XVS) as government-furnished equipment for installation on the Lockheed-Martin-built X-59 that, with other aircraft systems and subsystems, may ensure safe and efficient operations in all phases of flight by providing an electronic means of forward visibility.

XVS technologies have been researched in the past by NASA and others but the X-59 represents the first operational vehicle reliant on an electronic means of vision in lieu of forward-facing windows in all phases of flight.

This paper presents the design of the X-59 XVS and the findings, to date, of the X-59 XVS and the challenges of flight without forward-facing windows.

Keywords: external vision system, flight test, supersonics, vision systems, avionics

1. Introduction

NASA is developing the X-59 aircraft (Figure 1) as the key element of the Quesst mission to demonstrate quiet supersonic design capabilities and to provide data to support the development of a sound level-based standard for supersonic flight over land [1].



Figure 1 – X-59 First Flight, 28 Oct 2025

The overall configuration and forward fuselage/nose shaping of the X-59 design are critical to

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meeting the program goals for a quiet supersonic acoustic signature. But this shaping significantly impacts the natural vision for the pilot provided by cockpit windows. Forward-facing windows are just not practical for this design.

NASA designed and built an eXternal Vision System (XVS) that, with other aircraft systems and subsystems, will ensure safe and efficient operations in all phases of flight. The X-59 XVS is a combination of display, sensor, and computing technologies which create an electronic view, forward of the cockpit, analogous to forward-facing windows. XVS is designed to support timely, routine access to and operations within the National Air Space by providing an electronic means to sense and display the environment external to the aircraft to the pilot in lieu of the natural visibility traditionally provided by cockpit windows/windscreen.

2. Background

The location of the flight deck/cockpit and the design location of flight deck windows / windscreen for the pilot has historically been a design challenge [2]' A clear view of environment external to the aircraft is critical to safe operations of the aircraft.

2.1 Natural Vision Design Challenges

A notable aircraft design that challenged the conventional use of windows was the Spirit of St. Louis.. In 1927, Charles Lindbergh needed an aircraft capable of flying non-stop from the United States to Europe (Figure 2). Lindbergh made the design decision to eliminate forward-facing windows. The Spirit of St. Louis was a single mission aircraft flying over the ocean mostly at night and without other air traffic. Forward visibility was provided for take-off and landing by use of a periscope.



Figure 2 - Spirit of St. Louis[1]

The next most prominent examples of the trade-off between aircraft design (principally, drag) and cockpit visibility were the Concorde and TU-144 aircraft [2, 3]. These supersonic aircraft met the visibility challenge by keeping a streamlined forebody during almost all phases of flight, but mechanically drooped the nose (Figure 3) for the pilot during the taxi, take-off, and final approach and landing phases of flight. An XVS, in lieu of a mechanically-drooped nose, was estimated that it could provide a 3.2% reduction in takeoff gross weight for the design of a follow-on to the Concorde [4].

[1] Images downloaded from https://www.si.edu/object/ryan-nyp-spirit-st-louis-charles-lindbergh:nasm_A19280021000. This content was marked with the Creative Commons Zero icon and is declared to be in the public domain (free of copyright restrictions).



Figure 3 - Concorde Drooped Nose[2]

2.2 Electronic Means of Vision

Electronic means to create a clear view of the environment external to the aircraft in lieu of windows has been researched in the past by NASA and others, especially as consumer-grade electronics, with clear upgrade paths to avionics applications, have grown more capable and less expensive.

In the 1990s, NASA launched, in partnership with a significant portion of the US aviation industry, a research and development effort that might enable the next generation of the Concorde to be built – the High Speed Civil Transport (HSCT).

One of the principal flight deck challenges [5-11] was the design of an electronic means of vision/visibility in lieu of a drooped nose (see Figure 4 where it was labeled as “synthetic vision” at the time of this work).

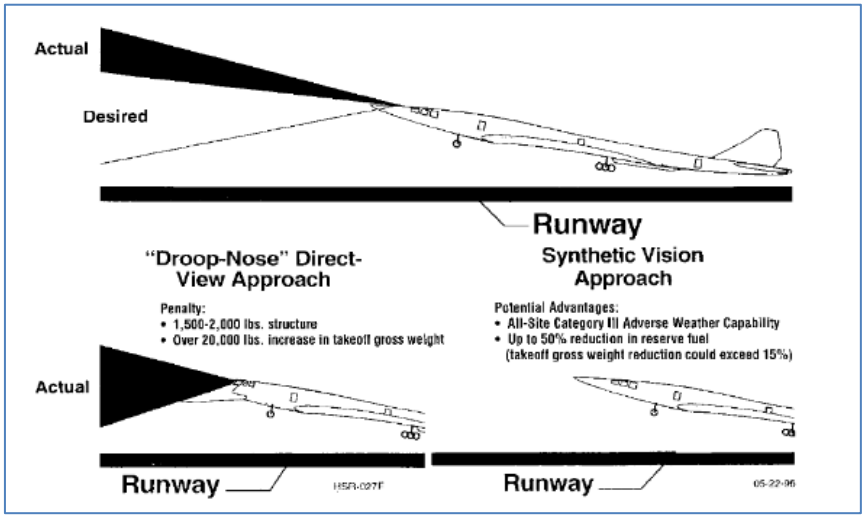


Figure 4 - XVS for the NASA High Speed Civil Transport Concept

NASA continued research and development investment in XVS technologies [12-14] with the knowledge that XVS technologies are not just needed for approach, landing, and take-off, but that forebody shaping will be paramount to quiet supersonic technologies across the flight envelope which essentially runs counter to the installation of windows and visibility for the flight crew.

[2] Image downloaded as https://commons.wikimedia.org/wiki/File:Concorde_landing_Farnborough_Fitzgerald.jpg. Permission is granted to copy, distribute and/or modify this image under the terms of the GNU Free Documentation License, Version 1.2.

Other vision systems technologies have been gaining prominence in aviation as well. In particular, the Federal Aviation Administration (FAA), in developing new rule-making for Enhanced Flight Vision Systems (EFVS), established the precedence whereby an electronic means of vision may be used in lieu of natural vision to descend below the published decision altitude/height or minimum descent altitude and land on certain straight-in instrument approach procedures under instrument flight rules (IFR) [15].

3. The X-59 Supersonic Research Aircraft

NASA designed and delivered an XVS based upon this research legacy as government-furnished equipment for installation on the Lockheed-Martin-built X-59 that, with other aircraft systems and subsystems, will ensure safe and efficient operations of the X-59 in all phases of flight and within the design constraints of the aircraft such as the outer mold line.

3.1 Cockpit Installation of XVS

Reuse and integration of existing, proven subsystems was one method by which an affordable X-59 was developed while maintaining the integrity of the outer mold line that was paramount to the aircraft's mission. This philosophy included reusing the aft cockpit of a T-38 aircraft for the X-59.

In Figure 5, the vision polar (azimuth and elevation mapping from the pilot's Design Eye Reference Point, DERP) is shown for the X-59, indicating the visual angles subtended by the forward side windows with obscuration due to the canards, the forward aircraft structure and canopy rails, and the head-down Primary Flight and Navigation Displays (i.e., Collins Adaptive Flight Displays, AFDs). The largest Ultra-High Definition (UHD) monitor able to fit in the available volume was installed as the XVS display. Glareshield controls included the XVS control panel and power switch.

The pilot's view aft of the canopy rails is clear per the T-38 rear seat canopy design.

The vision polar of Figure 5 also shows the upper and lower bounds, between which an aircraft windscreen would normally provide clear areas for pilot vision in conventional aircraft, based on Federal Aviation Administration (FAA) Advisory Circular (AC) 25-773 ("Pilot Compartment View Design Considerations"). This clear area has been found by the FAA to provide sufficient external visibility to "permit the pilot to safely perform any maneuvers within the operating limits of the aircraft."

3.2 XVS Equipment

The design of the X-59 XVS was to be 'near' state-of-the-art to meet required performance goals but also had to be pragmatic and not jeopardize program schedule and cost goals. The development challenge was that much of the selected equipment was Commercial Off-The-Shelf (COTS), without avionics flight qualifications. The XVS design had to be concurrently developed, tested, flight-qualified, and integrated as the aircraft itself was being designed and built. The design was structured to be upgraded and modified as data and experience from the X-59 flight test was gained.

The X-59 (Figure 6) design includes the XVS display (i.e., monitor), a 4K camera located on the top of the aircraft fuselage, an XVS pallet installed in the forward payload bay, and a Forward Vision System (FVS) camera which is located on the lower fuselage.

3.2.1 4K (Upper) Camera

The 4K camera is the IO Industries Flare 12M180CCX-M color camera. This COTS camera was ruggedized for flight and qualified for the X-59 flight envelope including altitudes up to 60K ft.

A fixed 40 mm focal length lens was selected for design simplicity and to match the 4K field-of-regard (FOR) - differing by less than 10% from the monitor field-of-view (FOV) when viewed by the pilot from the DERP. This requirement is based on replicating window requirements for an un-minified display (i.e., an un-minified display does not introduce a depth distortion or misperception).

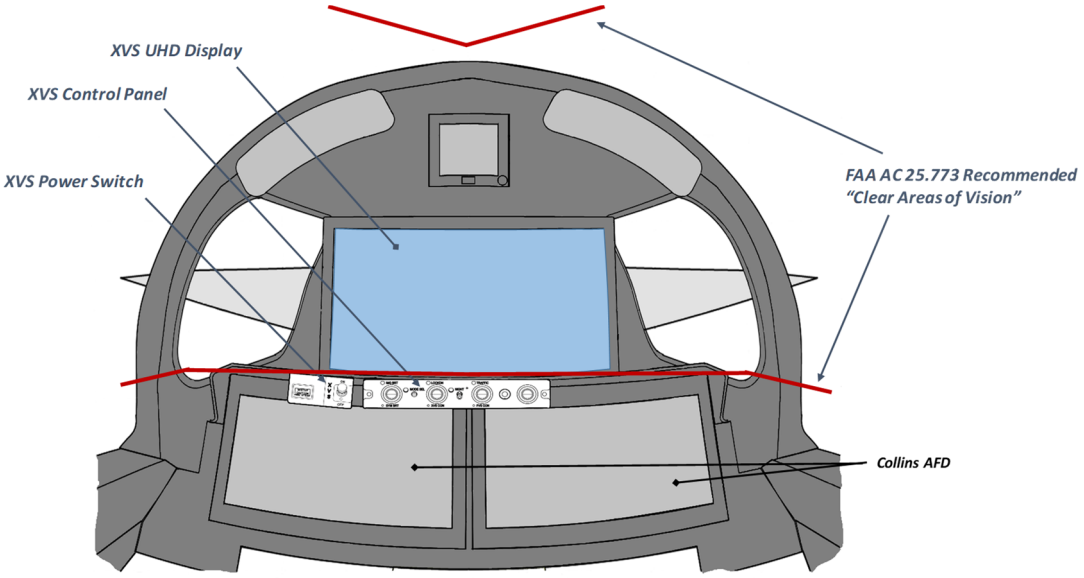


Figure 5 – Vision Polar for LBFD Aircraft.

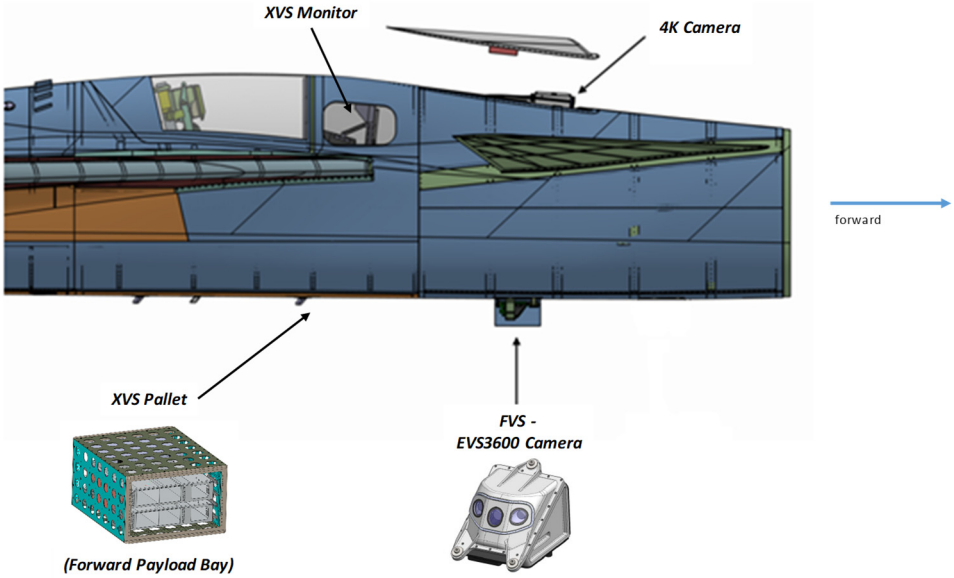


Figure 6 – XVS Equipment

The camera captures 4K (4096 x 3072 pixel) imagery but only a 3840 x 2160 pixel subset is used at 60 frames per second, in a color (Bayer) format. The camera was customized to provide two redundant CoaXPress outputs versus the COTS four CoaXPress outputs. The 4K camera is responsive between 350 and 950 nanometers.

The 4K camera was mechanically bore-sighted, electrically-aligned to within 5 milliradians, and vibration isolated from the fuselage to the extent practical. The X-59 fuselage forward of the camera was fitted with fiducial markers for built-in test.

The 4K camera is housed behind an optically clear, glass window that is heated, using thermostat control, to prevent fogging and ice accumulation. To further minimize fogging, the camera is enclosed in a pressurized Nitrogen-filled bay.

3.2.2 XVS Display

The XVS display is a 24” diagonal Liquid Crystal Display from Viewpoint Systems.

The 4K display is located 41 inches from the pilot DERP, subtending a FOV of 29° H x 17° V. The display includes anti-reflection, anti-glare coatings and has separate luminance settings for day and night operations.

3.2.3 FVS (Lower) Camera

The Collins EVS3600 camera is used as the FVS. The COTS EVS3600 blends three separate cameras (one visual-band and two uncooled InfraRed, IR, cameras) to create a single monochromatic, 640 x 480 pixel resolution video output.

The FVS camera is deployed for taxi, take-off, approach, and landing; otherwise, it is retracted into the nose to prevent adverse effects on the shockwave characteristics of the vehicle.

3.2.4 XVS Pallet

The heart of the X-59 XVS is the XVS pallet which contains the necessary equipment for XVS processing, power, and signal distribution.

Two Trenton System THS2085 HDEC 2U rack-mounted computers are installed in the pallet. The Trentons provide the real-time image processing and camera control that is critical to XVS. A simple camera-to-display system is inadequate for the task [14].

Dual XVS computers are used for redundancy. Health monitoring is active between the two, trading health state data, so the healthiest processor drives the XVS display. A custom-built EON Instrumentation ADV-DP-25 video switching unit accepts the two DisplayPort 2160p60 inputs and actively switches to one healthy DisplayPort 60 Hz 3840x2160 output with mirrored outputs of 30 Hz UHD for telemetry and recording.

The XVS processors operate on the Wind River VxWorks™ real-time operating system.

The Operational Flight Program (OFP) runs on two different execution targets. The first is a standard Intel multi-core Central Processing Unit (CPU) configuration and the second is an AMD Radeon 9171 advanced high-performance Graphical Processing Unit (GPU).

- The Intel CPU-based system has two 2.3 GHz Intel Xeon E5-2658V4 CPUs with 14 cores each for a combined 28 cores.
- The AMD Radeon E9171 GPU has 512, 1.1 GHz GPU cores, 4 gigabytes of memory, 32 texture-mapping units, and 16 raster operators. The GPU cores are custom programmable through small, pipelined executable code units (i.e., ‘shaders’).

Most of the XVS OFP code executes on the CPU, but significant portions of XVS functionality all have components that execute as shaders on the GPU.

The GPU and video capture cards were built specifically by Wolf Advanced Technology to meet XVS requirements as existing COTS at the time could not meet our requirements. The GPU meets MIL-810 specifications and can handle up to five 4K displays using Display Port 1.4 with up to 10-bit color depth.

The frame grabber enables up to four 3G-Serial Digital Interface (SDI) or four 12G-SDI inputs and outputs, two CoaXPress inputs, two DisplayPort inputs, and three analog inputs and outputs.

Custom-tailored Vulkan-based drivers and associated software were designed by CoreAVI to meet rigorous DO-178C standards for mission-critical XVS safety and reliability.

3.2.5 Control Panel and Maintenance Interface

The NASA-built XVS control panel is mounted forward of the pilot on the glareshield. The control panel is the pilot’s XVS interface.

The NASA-built XVS maintenance panel is mounted forward of the pilot and just aft of the monitor on the glareshield. The interface is accessible for ground maintenance only. The panel interface design allows XVS software maintenance without having physical access to the XVS pallet components in the X-59 payload bay.

3.3 Salient XVS Design Features

Several design features are notable:

- The COTS equipment with ruggedization by NASA passed the required environmental qualifications for the X-59, including explosive decompression up to 60K ft for the XVS processors and display.
- All aircraft state data required by the XVS design is provided from the aircraft's Vehicle Management Computers (VMCs) via Ethernet connection. XVS does not communicate back to the VMCs.
- To minimize the design complications, XVS video cannot be shown on the head-down displays (AFDs). However, two ARINC 818 video feeds from the FVS camera can be shown on either AFD in a quarter or full-page format in addition to two analog RS-170 videos that feed FVS video to XVS for display.
- XVS receives approximately 5 Gigabits per second of camera data via CoaXPress with redundant channels from the single 4K camera going to each processor.
- The processors push approximately 12 Gigabits per second of video data to the XVS display. XVS does not apply any video compression for the pilot display as it might compromise image quality.
- The XVS video is, however, compressed for on-board data recording (down to ~20 Megabits/sec) and real-time telemetry (~6 Megabits/sec).

4. X-59 XVS Flight Testing

The X-59 Phase 1 flight testing started 28 Oct 2025 with first flight. First flight kicked off the X-59 Phase 1 testing that will demonstrate airworthiness and systems acceptance. Phase 2 will be used to characterize the vehicles' aerodynamic and acoustic performance. In Phase 3, the X-59 will enter its research phase, flying in the National Air Space (NAS) for data collection, evaluating the public's acceptance of a supersonic "thump".

In Phase 1, XVS flight testing will evaluate that it meets its intended function:

a) Provide the pilot with awareness of other aircraft (airborne and on the surface), vehicles, terrain, and obstacles to avoid collision with these entities;
b) Enable the pilot to identify the required visual landing references;
c) Enable the pilot to maintain position awareness on the airport surface during ground operations; and,
d) Provide the pilot the ability to control the X-59 descent rate, control and maintain the aircraft's trajectory toward the intended touchdown point to achieve a touchdown with acceptable descent rate within the intended touchdown zone and without incurring a tail or empennage strike on the runway.

The Phase 1 flight test data is used to demonstrate this intended function or to modify the performance of XVS so that it does. XVS was designed for ease of software modifications.

This intended function, when met, should satisfy the X-59 XVS goal of providing forward visibility for the pilot to allow the vehicle to meet the requirements of the Phase 3 flight testing; that is, enabling

timely, routine access to and operations within the NAS without a chase aircraft and without special handling by Air Navigation Services Providers (ANSP) above and beyond the special handling that may already be required for a supersonic research aircraft to operate in today's NAS.

The 'proof' for all technologies is always flight – but for XVS operations, the corner cases, many times, occur during surface and taxi operations.

4.1 XVS Design

The 4K camera provides the pilot's primary forward view, while the FVS camera fills in the portion of the image that would otherwise be obscured by the nose (see Figure 7). The 4K imagery is full-color, like a window, but the FVS 'nose-fill' is monochromatic given the choice of the camera. The FVS image luminance is adjusted to match the luminance level of the 4K imagery, but they represent very different aspects of the external environment since the FVS is heavily weighted toward IR. When the FVS camera is retracted, XVS-generated Synthetic Vision (SV) imagery can be used for 'nose fill'.

The disparity of imagery (i.e., resolution, color, etc.) between the 4K and FVS cameras was the consequence of design assurance level requirements. The FVS camera was considered to be a critical element in the flight safety of the aircraft and as such, the FVS camera needed to have a proven design heritage. A COTS camera, approved as an EFVS camera, met this requirement.

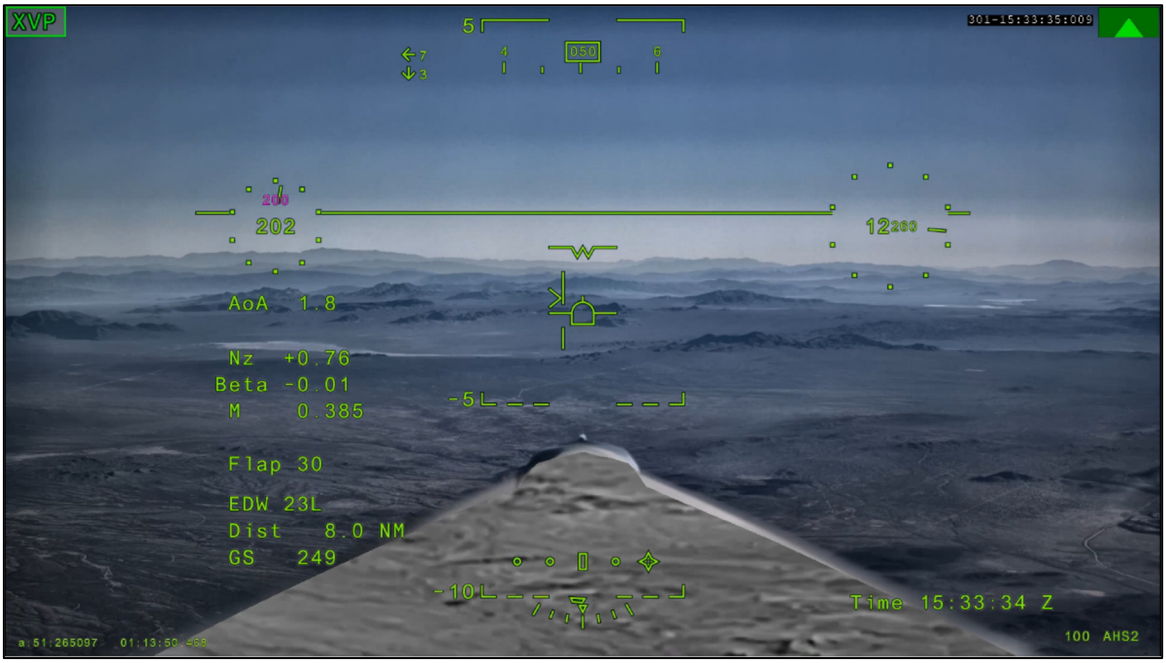


Figure 7 – XVS image from First Flight

Head-up display (HUD)-like symbology is added to aid the pilot.

The HUD symbology set is optimized for flight testing with a plethora of alpha-numeric data in the left-hand stack. For instance, above 37K ft, the alphanumeric HUD information is augmented with the display of "milliMachDot" (the 3rd decimal digit of dM/dt) and "Gamma-Dot" ($d\gamma/dt$) [16] so the pilots can precisely control the aircraft during supersonic testing.

On the XVS control panel, the pilot can adjust the overall image brightness and symbology brightness, the 4K image contrast, and the FVS contrast. The pilot also has controls on the throttle to reject symbology (i.e., remove symbolic elements) as well as to declutter large blocks of symbology if the pilot wants to see what is in the imagery without the clutter or obscuration due to symbology.

A night mode is pilot-selectable which reduces the luminance output of the display and prioritizes

the display of FVS instead of 4K imagery since the IR imagery gives better terrain awareness than the 4K camera.

An XVS control panel switch allows the pilot to override the automatic imagery mode selections and display whatever mode they prefer or to revert back to the auto selection.

4.2 Field-of-View/-Regard

The FOV of a display was established by the installation of the XVS display and the 4K camera lens was selected for a nearly one-to-one FOR (i.e., angular extent of the external world that is represented on the display). As a 'window replacement' technology, the FOV and FOR should be equal.

Also, as a window equivalent technology, the XVS must be conformal and aligned to the external scene, as viewed from the DERP. The XVS display was aligned and positioned to provide a lower FOV of ~-17 deg to match the lower limit of the clear area requirement of AC 25-773. This nose-low clear area of vision (i.e., the view provided by the XVS display or windows) is important to allow the pilot to clearly see the approach end of the runway and the approach lights.

However, the upper viewing angle of XVS is limited by the display size and when positioned for conformality, the pilots cannot see much, if anything, above the waterline of the aircraft.

In simulation and taxi testing, this upper limit of viewing was not well appreciated by the pilots.

Fortunately, a work-around was available. The 4K camera sensor size is 4096 H x 3072 V but the UHD display is only 3840 x 2160 pixels. By having real-time control of the camera, the 'extra' ~900 pixels in the vertical direction allowed a 'look-up/look-down' control feature to be added.

Nominally, the real-time image processing maps the camera pixels to the monitor for conformal viewing, but at the pilot's discretion, a look-up capability was provided, giving almost 6^{o} of nose-up viewing angle in a non-conformal view. The pilots can control the look-up/look-down using the control panel, or they could opt for full-down (conformal) or full-up (non-conformal) viewing using a switch on the throttle quadrant.

The viewing selection is typically obvious to the pilot, but it is also indicated by a split-horizon line on the XVS HUD with one part indicating the true position of the horizon and the other indicating the horizon based on the look-up/look-down angle. When the camera is set to the conformal setting, the true position of the horizon and the horizon based on the look-up/look-down angle are the same and the horizon line is continuous.

4.3 Fuselage Occlusion and Parallax Error

The 4K and FVS cameras are aligned to the vehicle and create a fused image for flight operations. However, since this XVS imagery is derived from cameras located around the nose of the vehicle, parallax (i.e., the displacement or difference in the displayed position of an object compared to its actual position) error is a factor.

The X-59 4K camera location induces very little parallax since it was nicely located with no vertical or lateral displacement from the DERP. On the other hand, the FVS camera induces significant parallax due to its vertical displacement from the DERP, especially in that it is only ~2 feet above the ground during X-59 surface operations.

The FVS camera location, the monochromatic and IR nature of the FVS camera, and the geometry of the X-59 itself (Figure 8) present an initial challenge for taxi operations:

- The pilot sits just about mid-ship with 50 ft of aircraft in front of the pilot and 50 ft aft.
- The pilot is sitting in front of the repurposed F-16 nose gear with a steering point

approximately 19 ft behind the pilot. Oversteering is required with an unusual visual presentation due to the very long nose structure in front of the pilot.

- The FVS camera image exhibits parallax error as it is located approximately 7.5 ft in front of the pilot and 4 ft below the DERP.

Creating a continuous image with this level of parallax error during taxi operations is not a trivial exercise with this design and was not part of the initial Phase 1 test program (Figure 9):

- *"the FVS is not color and produced many shades of grey lines on the FVS displays. This can get a bit confusing when looking at the XVS display, in the upper portion the line to follow is obvious, but the lower FVS picture has multiple lines, many at different angles including lines from the shadow of the aircraft or even left over shadow if you sit in one place too long (since it's an IR camera)."*

However, adaptation by the pilots was quick. They have successfully used their experience and training to overcome the illusions of the XVS imagery and found methods to compensate such as relying on side windows for large turns, not using FVS on the XVS during taxi operations, but using FVS on the head-down displays:

- *the XVS/FVS (is) more challenging on the ground. In the air (including take-off and landing) it's like playing a video game.*
- *To lessen the confusion, I minimized the amount of FVS on the XVS display by biasing the FOV Up.*
- *Since the forward gear is closer to the FVS camera it provides better tracking but still requires a delay to start the turn…I found that I like the Full FVS on the left AFD during taxi to compare to the XVS especially during turns.*

The pilots have also learned that FVS on a highly minified head-down displays with a very low position created the 'go-cart' illusion:

- *During taxi out on taxiway "V" used the Full FVS on the Left-AFD for tracking the taxi line. The higher ground speed produced a "go cart" mode where the aircraft felt like it was taxiing faster than it was. This was particularly noticeable approaching 20 KGS. The XVS seemed normal, but the FVS gave the illusion of faster speed. Below 10 KGS, it was far less noticeable.*

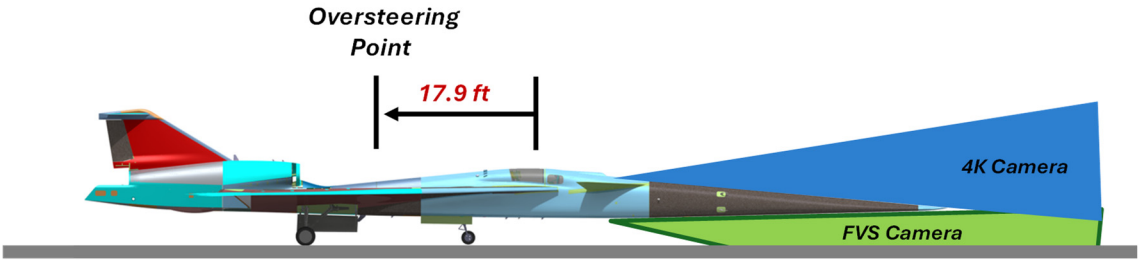


Figure 8 - Geometry of X-59 Taxi Operations

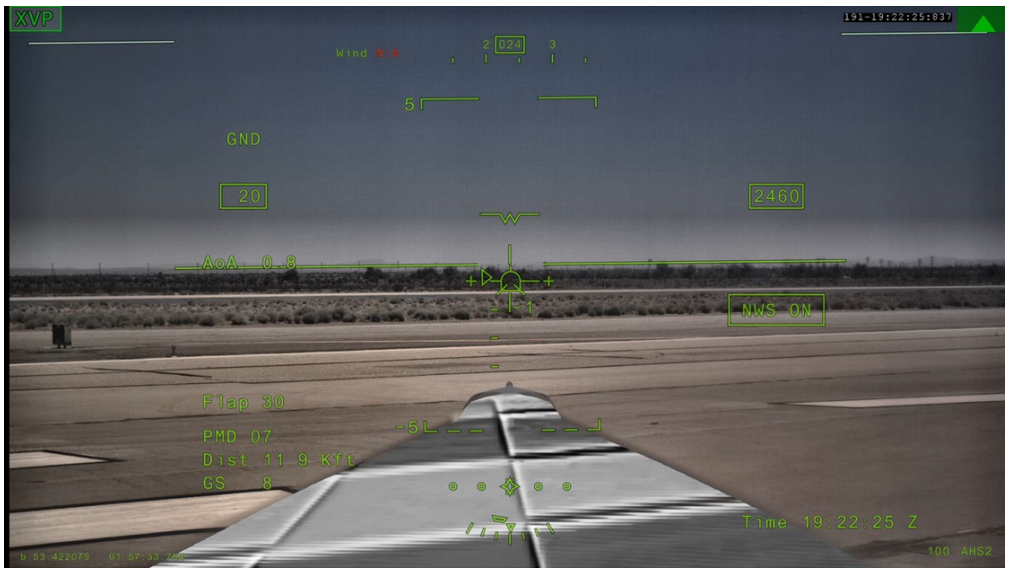


Figure 9 – Imagery during taxi operations

FVS parallax compensation is being developed in the Phase 1 testing phase to ameliorate the taxi illusions (see Figure 10). Perfect unification of the two images will never be possible due to the unique character of the FVS design, but less distortion is possible given the available image processing capabilities of the X-59 XVS.

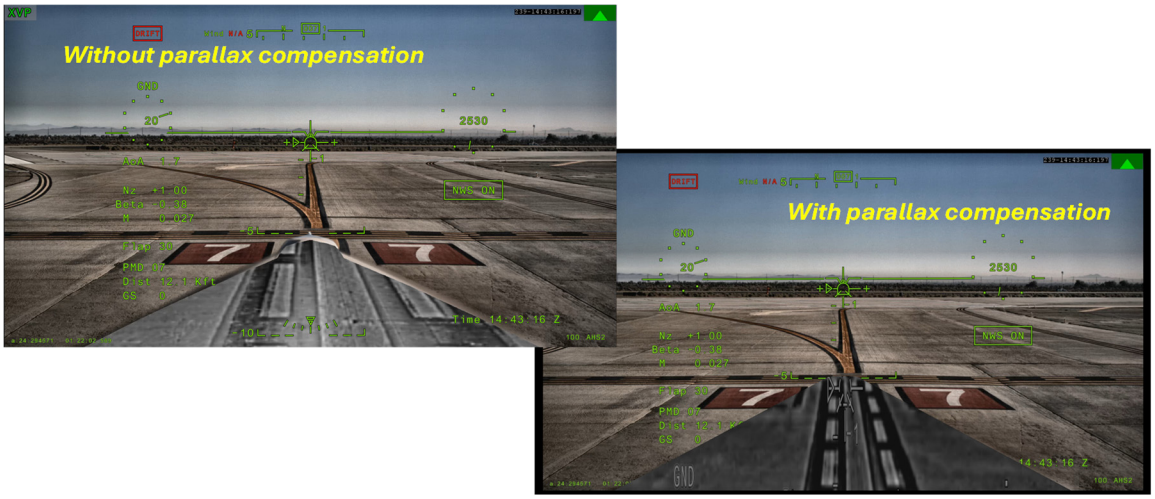


Figure 10 – Example of Planned Parallax Compensation

4.4 Design Assurance Level

The design assurance level of XVS was examined and debated since it significantly impacted both the XVS subsystem design complexity and costs as well as other aircraft subsystems. Ultimately, XVS was built to a mission-critical level.

The primary rationale that supported this argument was:

- The aircraft is going to be piloted only by a select group of extremely well-qualified and well-trained NASA and Lockheed-Martin test pilots.
- The pilots noted that the X-59 outside visibility without an operating XVS was not significantly different than that of flying from the rear seat of many fighter aircraft today (e.g., F-16, F-15, F/A-18) of which they routinely fly.
- A failure of XVS is not a complete loss of forward visibility – the COTS FVS provides

redundant camera outputs to the two fully-flight qualified head-down displays which provides the necessary design assurance and safety for forward visibility. See Figure 11.

- Many other additional technologies and operational procedures are also available to support the pilot, including: judicious selection of weather constraints, mission-rules, minimum equipment lists that include an operable radar altimeter with flare cue, chase aircraft in Phase 1 and Phase 2, the use of electronic path definition via Instrument Landing System and/or Area Navigation, and synthetic vision systems.

Although the design is qualified to a mission-critical level, redundancies were added whenever practical (such as a two processor XVS design). Additional higher-level software requirements were also added recognizing the prominent role that XVS plays in the X-59 pilot-vehicle interface.



Figure 11 – Real-Time Imagery and Symbology Available for X-59 Pilot

During simulation testing, project test pilots evaluated the effects of losing the XVS combined with compounding failures of the FVS, radar altimeter, and AFDs.

The vehicle with a loss of XVS alone was still rated as exhibiting Level 1 handling qualities [17] with low Bedford workload ratings of 2 and 3 [18]. The pilots were able to easily control the aircraft through approach and landing. The head-down presentation of FVS imagery is greatly minified, but the overlay of conformal symbology (pitch ladder, guidance cues, and flight path marker) create a capable display for landing. The pilot workload for roll-out, however, is increased slightly compared to the nominal landing due to the ‘go-cart’ effect (and also due in part to some imperfect modeling of the runway environment and the FVS imagery in the X-59 flight simulator).

The compounding failures worsen performance and workload into Level 2 pilot ratings and Level 2/3 pilot workload ratings but none of them created unsafe operational conditions. The highest workload is principally due to the avionics design architecture using two versus a nominal three AFD architecture. A single AFD failure can cause the loss of significant functionality – such as the loss of the Flight Management System – and simultaneously reduce the available display space to show important flight information.

In Phase 1 and Phase 2 flight testing, the reliability, availability and operational performance of XVS is being scrutinized to assess if it is ready for routine NAS operations in Phase 3.

4.5 Contrast and Dynamic Range

NASA's research experience has shown that camera systems alone do not provide the necessary dynamic range to create adequate imagery across the lighting conditions expected in flight [14]. High dynamic range camera modes are often available but there are tradeoffs such as reduced resolution or non-trivial interface designs.

The XVS design philosophy was that automation should be implemented to create satisfactory imagery across the range of expected environmental conditions with override capabilities and simple manual controls for the pilot to adjust and create better imagery as necessary. As an operational flight subsystem, the pilot should not be expected to become a cinematographer to use XVS.

The X-59 XVS employs a contrast-limited adaptive histogram equalization (CLAHE) method [19] to create the required dynamic range across a broad range of imaging conditions. CLAHE is a local-area contrast enhancement technique using 144 subregions across the imaging area. Local-area enhancement is critical due to the many areas of vastly different illumination in any moment in the flight environment.

The CLAHE contrast technique is also advantageous since a single parameter (clip limit) is used to set the level of enhancement. A fixed clip limit, that was determined as the pilot-selected 'optimum,' is nominally used but the pilot can adjust this value using the control panel to increase or decrease the level of enhancement up or down or off, or return to the nominal selection value.

The challenge of adverse lighting was immediately encountered during X-59 testing when the time-of-year and wind and runway constraints caused taxi testing and 1st flight of the X-59 to be exposed to direct imaging of the sun. This condition is extremely challenging for any camera system to create a usable image for the pilot.

In Figure 12, the 'raw' imagery from the camera is shown as well as the imagery with the contrast setting selected by the pilot.

- *The low sun overwhelmed the XVS display in Auto Contrast, but manual contrast made it acceptable.*
- *(With the Sun directly in 4K camera) I can still pick up runway remaining markers but obviously not as well when they are farther away*
- *I was able to adjust the XVS to create a satisfactory image quality and the XVS symbology was legible and readable*



Figure 12 – Comparison of Raw Camera Imagery vs. Contrast Enhanced

The 'luminance banding' that is visible in the enhanced contrast image of Figure 12 is an artifact of the CLAHE algorithm. Similarly, the colors are washed-out. Although it is not visually pleasing, the

ability to extract the visual references of the runway for the pilot is the critical attribute of the imagery. The key runway references – the centerline, distance remaining markers, painted lines, the lateral and longitudinal confines of the runway - are evident. Additional methods to improve the real-time control of imagery will be tested in Phase 1 but again, the key design challenge is to *not* overwhelm the pilot with controls in the process of creating XVS imagery.

4.6 Display Readability

Although the XVS display features anti-reflective and anti-glare coatings and passed daylight readability evaluations during the design phase, its in-flight performance has fallen short of expectations. While pilots have generally rated the display as 'adequate' or better, sun glare and reflections remain a significant concern. At certain sun angles, glare can make it "*almost impossible to see anything on the monitor behind the reflection*."

The X-59 cockpit environment itself presents challenges. The extensive canopy of the X-59 creates a very bright ambient environment from which to view the XVS display located "*down a relatively dark tunnel*". XVS display design changes are being pursued to improve display readability in Phase 1. The addition of electrochromic canopy/window tinting could be a worthwhile addition to control the ambient lighting environment in a production aircraft.

4.7 Traffic Detection

The resolution of the display and camera system must be equivalent to human acuity measures if XVS is going to meet the standard of having equivalent or better performance than windows. The operational instantiation of this requirement is traffic detection in see-and-avoid operations.

4.7.1 See-to-avoid flight test

The "proof" as to whether the camera and image processing/contrast enhancement method truly meets equivalent or better performance to windows was assessed using a surrogate flight test, flying the identical equipment and processing methods as the X-59. The test was an evaluation of see-and-avoid since this visual task is the driving requirement of imaging performance [12].

The surrogate flight test was necessary to employ a unique test methodology which allowed direct performance comparison of forward-facing windows to XVS.

The test used a between-subjects design with two equally qualified subjects on-board a UC-12 test aircraft, making simultaneous observations, one using the XVS and the other using the forward-facing windows.

See-and-avoid traffic scenarios were flown with one subject occupying the cockpit right seat (i.e., the Out-the-Window (OTW) subject pilot, Figure 13) while the other subject simultaneously used the XVS display in the cabin (i.e., the XVS subject pilot, Figure 13). Midway through the flight, the subjects switched locations and the scenarios were repeated in a different order.

This between-subjects method using the surrogate aircraft eliminated the influence of different times of day, lighting conditions, atmospheric conditions, etc., that might affect the visual search and create potential experimental confounds or disparities for comparison of the two conditions (OTW vs. XVS).

The traffic aircraft in the see-and-avoid scenarios was a Lancair LC-40 aircraft.

All scenarios were flown by the safety pilot in the test aircraft while both subjects were looking for traffic, visually out-the-window and on the XVS display. The OTW subject pilot was not flying and was instructed to use 100% of time scanning for traffic during test runs, just like the XVS subject. Neither of the subjects was aware of the maneuver being flown by the traffic aircraft.



Figure 13 - Comparison of Raw Camera Imagery vs. Contrast

The see-and-avoid scenarios were primarily head-on, level flight encounters – expanding targets with minimal translation - where the test and traffic aircraft flew with altitudes and/or horizontal tracks offset by 500 ft.

Another test scenario had the target aircraft climbing from well-below the test aircraft tracking to a constant bearing, closing range condition, by climbing toward the test aircraft with ground clutter in the background. This scenario represented the case where a traffic aircraft might be in a departure, climbing towards the test aircraft.

The evaluation pilots represented industry, Department of Defense, the Federal Aviation Administration, and NASA, including the X-59 project pilots. Testing details are contained in Reference 20.

The primary evaluation metric was the successful detection of the intruder and the range at which the traffic detection between the intruder and test aircraft occurred.

The test data showed that the ability of the OTW or XVS pilot to detect the traffic intruder was almost identical. The XVS pilot detected the traffic aircraft on 40 out of 64 runs (~63% detection rate) and the OTW pilot 41 of 64 total runs (~64% detection rate).

The key differentiator was the range between the two aircraft when the detection occurred, showing better performance for XVS compared to windows / natural vision.

The distance between the test and intruder aircraft is shown in Figure 14 for all traffic detections using a box plot format. (The box plot shows the median value by the horizontal red line and the top and bottom of the box are the extent of the 75th and 25th percentile. The whiskers extend to the most extreme data points not considered outliers, and statistical outliers are plotted individually using the '+' symbol. Lastly, a notch is shown in the box to indicate the extent of the 95% confidence level of the median value.)

The mean detection range using the XVS was 2.8 nmi with a standard deviation of 0.9 nmi and the mean detection range for the OTW observer was 1.5 nmi with a standard deviation of 0.7 nmi.

At the average closure rate of ~320 kts for the scenarios, this range difference translates to an advantage of ~16 seconds for the user of XVS in see-and-avoid compared to the OTW observer.

The subject's summary assessment was that XVS provided equivalent (or better) performance to the cockpit window for see-and-avoid. One pilot noted that:

Against a small GA representative aircraft under the environmental condition in which we tested, the target (aircraft) was almost impossible to see out the cockpit window but was almost always detected on the XVS display at 3-4 miles range.

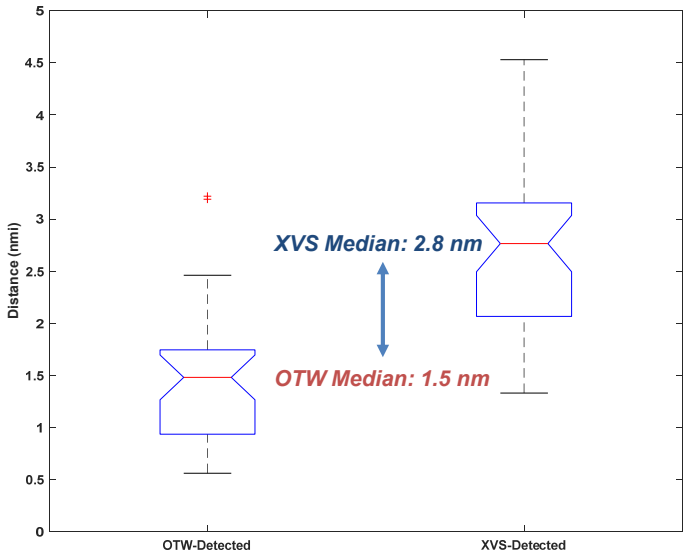


Figure 14 – Separation Distance at Time of Detection When Both XVS and OTW Detected Targets

The surrogate flight test was a “qualified” proof of Technology Readiness Level of 9 - “actual system is flight-proven in operation”; however,

- Speed and altitude test profile was limited especially in comparison to the X-59.
- The weather conditions were limited to the heat, humidity, and haze of Virginia versus the dry desert air of Edwards Air Force Base.

4.7.2 Traffic Symbology

Independent of the ability of the imagery to replicate or even improve upon natural vision for see-and-avoid, the X-59 HUD symbology set includes traffic locator boxes to show the traffic location (in azimuth and elevation) based on the reported surveillance data (i.e., Autonomous Dependent Surveillance-Broadcast, ADS-B In). This capability was demonstrated in surrogate aircraft testing and is now being implemented on the X-59.

One project pilot noted that "*pure XVS was similar or better than naked eye. With the ability to cue with the (ADS-B), it was definitely better*." See-and-avoid, especially as flown under the challenging conditions in this test, is an extremely difficult task. As a project pilot noted "*without target cueing, XVS is better than eyeballs but still inadequate for see-and-avoid*" however, "*with target cueing, XVS is way better than eyeballs and adequate for see-and-avoid*."

The use of traffic surveillance data on XVS is advantageous for two reasons. First, data has shown that an alerted see-and-avoid search provides 8 to 9 times more likelihood of detecting the traffic than without alerting [21, 22]. Second, the display of traffic symbology, positioned in azimuth and elevation, pinpoints the traffic location assuming accurate surveillance data. The X-59 symbology is sized to portray range and ideally, is compensated for the accuracy of the navigational position category. Data tags for relative altitude and climb/descent can also be presented when selected by the pilot using the XVS control panel.

The challenge with depicting traffic in azimuth and elevation on XVS is the accuracy and latency of the ADS-B In data reporting. Latency will cause the traffic boxes to not overlay the traffic. Latency compensation is provided in the X-59; how well this works will be uncovered in subsequent Phase 1 testing.

4.8 Latency and refresh

The latency of the XVS is obviously one of the key performance factors and one of, if not the first issue questioned by all pilots.

XVS operates at 60 Hz in sync with the refresh rate of the XVS display.

The end-to-end latency of the XVS - from photon capture at the 4K camera to photon emission at the display - has been measured at ~85 msec..

To date, the X-59 flight testing has not uncovered any XVS latency issues or defects.

During Phase 1 testing, offset landings, demanding pilot-in-the-loop operations, will be used as a stress-test to assess if this level of latency is satisfactory.

5. Summary

NASA successfully designed and delivered an XVS as government-furnished equipment for the X-59.

XVS technologies have been researched in the past by NASA and others but the X-59 represents the first operational vehicle reliant on an electronic means of vision, in lieu of forward-facing windows, in all phases of flight.

This paper has detailed the design of the X-59 XVS and the findings, to date, of the X-59 XVS and the challenges of flight without forward-facing windows.

Flight testing has revealed the benefits of XVS – equal or better performance in challenging see-and-avoid encounters – as well as the challenges such as creating good imagery especially during direct sunlight viewing and during surface operations in the presence of camera parallax.

Data collection is on-going in the Phase 1 flight test with the plan to continually improve the XVS design as possible and practical and to demonstrate that it is ready to support “file-and-fly” in Phase 3 operations in the NAS.

The X-59 XVS data and experiences are being disseminated for the development of consensus industry and government standards for future XVS designs. This technology represents a possible game-changer whereby aircraft designs that can be developed and approved without the constraints put forth by window requirements to create new and exciting opportunities in aerospace vehicle design and operations, especially supersonic flight over land.

6. Copyright Statement

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