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Panoramic, Large-Screen, 3-D Flight Display System Design

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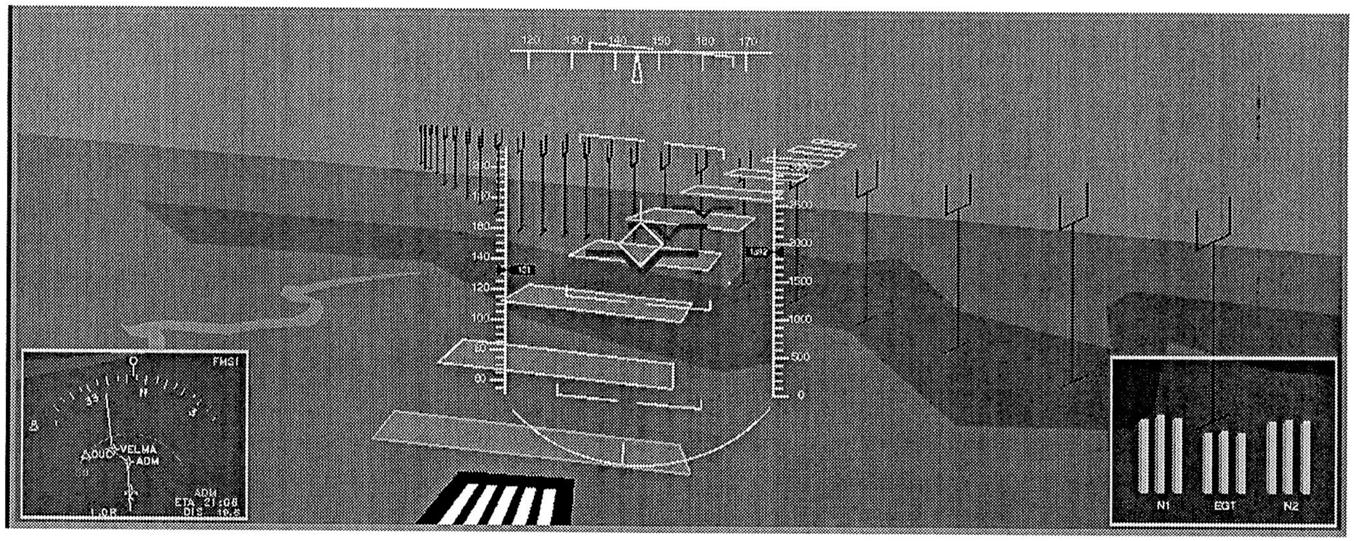

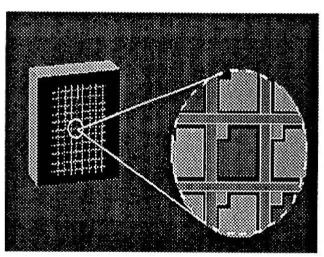

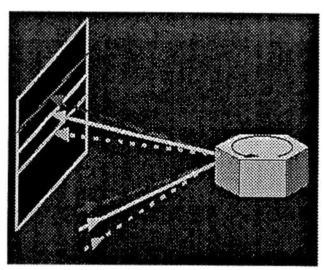

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EXECUTIVE SUMMARY

Honeywell Technology Center (HTC) is pleased to submit this final report (Panoramic, Large-Screen, 3-D Flight Display System Design) to NASA Langley Research Center (LaRC) in fulfillment of the Statement of Work (SOW) of Contract NAS1-20073, of November 8, 1993.

In this report, Honeywell has documented and summarized the results of the contract work, including the results of the required evaluations specified in the SOW and the design specifications for the selected display system hardware. We have also included the proposed development plan and schedule with our estimated ROM (rough-order-of-magnitude) costs to design, fabricate and demonstrate a flyable prototype research flight display system.

The thrust of our effort was in the development of a complete understanding of the user/system requirements for a panoramic, collimated, 3-D flyable avionic display system, and the translation of the requirements into an acceptable system design for fabrication and demonstration of a prototype display in the early 1997 time frame. The display system is intended for research applications in one or both of a motion-base simulator and an aft-compartment airborne simulator. The concepts and technologies described in this report may also show future relevance for panoramic display in next-generation transport aircraft.

Honeywell presented eleven display system design concepts to NASA LaRC during the performance of this program. One of these concepts was down-selected to a preferred display system concept at our January 1995 review meeting with NASA LaRC. Although the concept selected did not currently meet the resolution requirements of the image source, we have shown that the display system is capable of being upgraded to the higher resolution when the image sources become available in late 1997. Anticipating that the higher resolution image sources will become available in a reasonable time frame, the display system collimation optics have been designed to accommodate the higher resolution image sources. A summary discussion of the selected system is provided in Section 3.4. A comprehensive, detailed description of the selected system is available in Section 6.2.

Honeywell's technical approach to determine the preferred display system design concept was divided into the following six tasks that fulfilled the requirements of NASA LaRC's SOW. These six tasks also correspond with the major sections of this report:

Task 1: Display Requirements Analysis
Honeywell formulated a set of preliminary display requirements, including a justification for each requirement. Measurement approaches were also developed for selected requirements. These preliminary requirements were established in consultation with NASA LaRC personnel and with a review of the intended application environments (i.e., motion-base simulation and airborne simulation).

Task 2: Display Techniques and Technology Review
Honeywell performed an in-depth review and evaluation of the state-of-the-art in image source technology, 3-D methods, collimation methods, and interaction methods for a Panoramic, 3-D Flight Display System. Included in this task was a critical analysis of these technologies relative to the preliminary display requirements.

Task 3: Concept Formulation
Honeywell developed eleven candidate conceptual display system designs that could be used in a motion-base simulator and that would be adaptable to flight in a research vehicle. These display system design concepts provide the best technologies and trade-offs for meeting the display system requirements for the Panoramic, 3-D Flight Display System that can be fabricated and demonstrated in the early 1997 time frame. We reviewed these display system design concepts with NASA LaRC at our January 1995 review meeting. At that meeting, a recommended display system concept was selected and approved. In February 1995, several laboratory proof of concept demonstrations were made to NASA LaRC personnel.

Task 4: Required Technology Developments
Honeywell identified display technology improvements and risk reductions which were associated with the maturity of the technologies of the preferred display system design concept.

Task 5: Design Specification

Honeywell prepared a design specification for the preferred display system design concept. The design specification represents the distillation of the analysis and concepts from the preceding four tasks, described in this report, into a concise statement of functional requirements for the preferred display system design concept for the Panoramic, 3-D Flight Display System.

Task 6: Development Plan

Honeywell prepared a development plan which is divided into three phases and contains an outline of the actions necessary for translating the design specifications into a deliverable prototype display system. The development plan provides a road map for final engineering design, risk reduction/assessment, component procurement and fabrication, and integration into the final display system and final acceptance testing. Included is a ROM cost for the three phases of our program for the design, fabrication, integration, testing and demonstration of the Panoramic, 3-D, Fight Display System prototype.

In addition to the six major report sections described above, Honeywell has included the following appendices to the report:

Appendix A- Supplementary Optical Drawings

Honeywell has provided supplementary engineering drawings of optical components/subassemblies for the Panoramic, 3-D Flight Display System prototype design.

Appendix B- Supplementary Electronics Design

Honeywell has provided supplementary design material for the electronics interface for the Panoramic, 3-D Flight Display System prototype.

Appendix C- Bibliography

A general bibliography of cited and related source materials is presented with the citations grouped into major topical areas.

Appendix D- Subject Index

In the interest of avoiding ambiguity, much of the information presented in this report is in tabular rather than prose form. Because the large number of tables and technical terms can make browsing through the document difficult, Honeywell has included a subject index at the end of the report to supplement the table of contents.

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GLOSSARY OF ACRONYMS

AMEL	Active Matrix Electroluminescent
AMLCD	Active Matrix Liquid Crystal Display
ANSI	American National Standards Institute
ARPA	Advanced Research Projects Agency
AVS	Advanced Visionics System
CCD	Cursor Control Device
CGI	Computer-Generated Imagery
CIE	Commission Internationale de L'Eclairage
CRT	Cathode Ray Tube
CSF	Contrast Sensitivity Function
CTF	Contrast Threshold Function
CVCHMD	Combat Vehicle Crew Helmet Mounted Display
DAC	Digital-to-Analog Converter
DOF	Degrees of Freedom
DMD	Digital Micromirror Device (Deformable Mirror Device)
DU	Display Unit
EL	Electroluminescent
ERP	Eye Reference Point
FED	Field Emission Display
FLC	Ferroelectric Liquid Crystal
FLIR	Forward-Looking InfraRed
FOV	Field of View
HDTV	High-Definition TV
HMD	Helmet (Head) Mounted Display
HSCT	High Speed Civil Transport
HTC	Honeywell Technology Center
HUD	Head Up Display
IFOV	Instantaneous Field of View
IPD	Interpupillary Distance
IR	InfraRed
LaRC	Langley Research Center
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MCD	Miniature Color Display
MEDS	Multifunction Electronic Display System
MONARC	Monolithic Afocal Relay Combiner
MTBF	Mean Time Between Failure
MTF	Modulation Transfer Function (or Factor)
NASA	National Aeronautics and Space Administration
NOSC	Naval Ocean System Center
NTSC	National Television Standards Committee
PDLC	Polymer Dispersed Liquid Crystal
PFD	Primary Flight Display
PSD	Power Spectral Density
RGB	Red, Green, Blue
RPM	Revolutions Per Minute
SOW	Statement of Work
STN	Super-Twisted Nematic

GLOSSARY OF ACRONYMS (continued)

TFOV	Total Field of View
TFT	Thin Film Transistor
TN	Twisted Nematic
TSRV	Transport Systems Research Vehicle
UCS	Uniform Color Space
VFD	Vacuum Fluorescent Display
VISIDEP®	Visual Image Depth Enhancement by Parallel Induction
VISTAS	Visual Imaging Simulator for Transport Aircraft Systems

1.0 DISPLAY REQUIREMENTS ANALYSIS

Wide field-of-view (FOV), stereoscopic displays offer the potential to increase head-up time and improve visibility and spatial awareness for flight path guidance following as well as detection of out of tolerance system parameters and obstacles, especially during low-altitude terminal-area flight and in adverse visibility conditions. The effectiveness and acceptance of such displays hinges on the appropriate specification of display attributes such as display resolution, FOV, color, gray scale, stability, and 3-D (stereoscopic and/or volumetric) display parameters. Furthermore, the integration of such display systems into cockpits and airborne simulators imposes further requirements such as low volume, light weight, sunlight readability, and high reliability. A human-centered design approach is vital for the appropriate selection of these parameter levels.

In this section, we present background assumptions and preliminary display requirements for the Panoramic, 3-D Flight Display System. The material is presented comprehensively in the following tables, with supplementary comments provided in the body of this text.

Table	
1-1	Characteristics assumed for three applications of the Panoramic, 3-D Flight Display System
1-2	Definition of terms used in the preliminary display system requirements
1-3	Preliminary display requirements for the Panoramic, 3-D Flight Display System
1-4	Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System
1-5	Calculation/measurement of display parameters referenced in Table 1-3
1-6	General specifications and standards for research electronic equipment installed in NASA LaRC aircraft

Honeywell has viewed the close cooperation of NASA LaRC and Honeywell scientists as critical in developing unique understandings of the requirements for the Panoramic, 3-D Flight Display System design. Therefore, an important element of Honeywell's methodology for defining preliminary display requirements has been consultation with NASA LaRC personnel. NASA LaRC expertise has been drawn on through formal as well as informal contacts with Honeywell to determine context-specific guidelines regarding display system application environments and displayed information content and format. NASA LaRC experience with the VISTAS (Visual Imaging

Simulator for Transport Aircraft Systems) and TSRV (Transport Systems Research Vehicle) aircraft has also played an important role in Honeywell efforts to define contextually specific and relevant requirements, especially with respect to what constitutes a "flyable" display system. NASA LaRC has demonstrated particular experience with stereoscopic imaging parameters, a displays research emphasis also shared at Honeywell. Where possible, this work has been used to establish preliminary display requirements relevant to stereoscopic viewing.

Honeywell assumed that no single system concept was likely to comply fully with all the preliminary requirements (due to either inherent limitations in constituent technologies or technology immaturity). Therefore, these preliminary requirements should not be confused with the display specification, presented in Section 5 of this report. Relevant technology constraints and required technology developments which impact preliminary requirements are identified in intermediate sections.

1.1 Applications

The Panoramic, 3-D Flight Display System will be a testbed for display system concept development, testing, demonstration, and validation. Ultimately, the display concepts exercised with this simulator may find application to the High Speed Civil Transport (HSCT), tentatively scheduled for operation after the year 2005. The simulator is expected to be located in one of two research settings: a motion-base cockpit simulator or the aft-compartment simulator of the NASA TSRV currently a 737 but expected to be upgraded to a 757 by the time the Panoramic, 3-D Flight Display System will be ready for installation. In the future, the technology specified for the simulator may evolve and may be incorporated in the development of a cockpit display system for HSCT. Assumptions made during the display requirements analysis regarding these three environments are summarized in Table 1-1.

Table 1-1. Characteristics assumed for three applications of the Panoramic, 3-D Flight Display System.

Attribute	Motion-Base Simulator	Aft-Compartment TSRV Installation	HSCT
Acceleration	Maximum simulated acceleration as great as that experienced in normal HSCT flight (contingent on the fidelity of the simulator). Assumed to be no greater than 2 g constant (RMS) acceleration on the axis parallel to the fuselage.	Maximum acceleration experienced in normal 757 flight. Assumed to be no greater than 2 g constant (RMS) acceleration on the axis parallel to the fuselage.	Maximum acceleration experienced in normal HSCT flight. Assumed to be no greater than 2 g constant (RMS) acceleration on the axis parallel to the fuselage.
Cooling	Depending on implementation, cooling concerns could include hazard of external heat to operators, noise of active cooling system, capacity of auxiliary air conditioning system, and dust accumulation associated with suction of ambient air.	Depending on implementation, cooling concerns could include hazard of external heat to operators, noise of active cooling system, capacity of aircraft air conditioning system, and dust accumulation associated with suction of ambient air.	Depending on implementation, cooling concerns could include hazard of external heat to operators, noise of active cooling system, capacity of aircraft air conditioning system, and dust accumulation associated with suction of ambient air.
Cost	Development Cost (See Section 6)	Development Cost (See Section 6)	< ~ $100K (estimated production cost goal)
Duration of Use	10 minutes to 10 hours	2 flights/day, 2 to 4 hours per flight	3 to 6 hours per flight (est)
Glare Sources	None normally, but direct and indirect diffuse and specular glare sources are available for simulation testing if desired.	None	Sunlight shafting through side windows may produce direct glare to pilots as well as diffuse and specular glare on the display.
Humidity: Operating	10% to 70% Relative Humidity	5 % to 80% Relative Humidity	5 % to 80% Relative Humidity
Humidity: Storage	10% to 70% Relative Humidity	5 % to 95% Relative Humidity	5 % to 95% Relative Humidity
Illumination: Ambient	Laboratory lighting, controllable from dark to 1000 fc, with diffuse or specular light sources.	No windows within line of sight from the simulator station. Ambient of test aircraft simulator cabin assumed to range from dark to 200 fc.	Sunlight and sunlight shafting through side windows. Ambient of cockpit assumed to vary from dark to 4000 fc, with direct glare sources as high as 8000 fL (assuming windscreen transparency of approximately 80%).
Power	120 V or 240 V, 60 Hz, 20 A max each circuit	Compliant with Mil-Std 704. 400 Hz 115 or 208V AC, 3 phase or 3 single phases. 90 KVA max for each of 2 generators (757). Conversion from 400 Hz to 60 Hz with external power converters is not preferred. 28V DC is available, but of low quality and capacity, requires filtering and regulation if used.	Compliant with Mil-Std 704 (est).
Pressure Altitude	0 to 10000 feet	0 to 15000 feet (maximum equivalent pressure altitude of pressurized cockpit or cabin)	0 to 50000 feet (assumes possible loss of pressurization in cockpit or cabin)

Table 1-1. Characteristics assumed for three applications of the Panoramic, 3-D Flight Display System (continued).

Attribute	Motion-Base Simulator	Aft-Compartment TSRV Installation	HSCT
Redundancy (Failure)	Redundancy not required (delay of experiment is allowable).	Redundancy not required (scrubbed test flight is allowable), unless airborne testing of redundant system is desired.	Redundancy is required to prevent loss of primary flight guidance and navigation display.
Service Date	1Q, 1997	1Q, 1997	2005
Shock	Maximum simulated impulse shock as great as that experienced in normal HSCT flight (contingent on the fidelity of the simulator). Assumed to be ≤3 g impulse (≤20 ms) on the vertical axis and ≤1.5 g impulse on the horizontal axis.	Maximum impulse shock experienced in normal 757 flight. Assumed to be ≤3 g impulse (≤20 ms) on the vertical axis and ≤1.5 g impulse on the horizontal axis.	Maximum acceleration experienced in normal HSCT flight. Assumed to be ≤3 g impulse (≤20 ms) on the vertical axis and ≤1.5 g impulse on the horizontal axis.
Temperature: Operating	15 to 27 deg C	10 to 32 deg C	10 to 32 deg C
Temperature: Storage	12 to 35 deg C	-45 to 65 deg C	-45 to 65 deg C
Users	Users of varied age, flight experience, and visual capability; 1 user.	Experienced commercial aircraft pilots, 30-50 years of age, typically male; 1 user	Experienced commercial aircraft pilots, 30-50 years of age, typically male; 2 users/2 displays
Vibration	Minor exposure to vibration from HVAC system. Possible simulated vibration from Jet Engines and turbulence, contingent on the fidelity of the simulation.	Moderate exposure to vibration from Jet Engines and turbulence through fuselage. Power of vibration is expected to be as much as 100 times greater on the lateral and vertical axes as compared to the fore/aft axis for frequencies below 10 Hz (Boff and Lincoln, 1988). At higher frequencies, power is equally distributed among all three axes. Highest vibration power is expected at frequencies below 15 Hz, with power inversely related to frequency of vibration.	Moderate exposure to vibration from Jet Engines and turbulence through fuselage.
Volume (Dimensions)	Open laboratory space with high ceiling. Volume constraints are contingent on whether a new simulator cab is developed, or retrofit to an existing simulator is required.	Cockpit mockup placed in aft compartment of 757 fuselage, open to rear of cockpit mockup. Installation may require new aft simulator cab, or retrofit of existing 737 TSRV aft-compartment simulator cab.	Forward flight deck installation, likely to be more narrow than contemporary narrow body commercial aircraft.
Weight (Display)	Must be supportable by raised, ventilated flooring (est. maximum of 400 pounds for display system)	Maximum of 100 pounds per separate component to allow manual handling during retrofit installation. Total display system weight maximum of 400 pounds.	Maximum of 100 pounds for one display system, including display processor (estimated production weight goal).

1.2 Preliminary Display Requirements

Discussion of display requirements in a general sense (i.e., prior to detailed concept development) requires a special vocabulary. Toward that end, Table 1-2 presents definitions of four terms used in these preliminary display system requirements.

Table 1-2. Definition of terms used in the preliminary display system requirements.

Term	Definition
Center Line of Sight	The line of sight that originates in the center of the head motion box and intersects the center of the image.
Color Element	The smallest addressable area of the display. Individual color elements may vary in luminance but are limited to a single dominant wavelength, except in cases where color elements are equivalent to pixels (e.g. subtractive color displays or projection displays using optical combination of multiple image sources).
Corner Line of Sight	The four lines of sight that originate in the center of the head motion box and intersect the four points located 10% from the outer corners of the total FOV along the diagonals formed between these corners.
Pixel	A combination of one or more color elements sufficient to display any color within the color gamut of the display system. Color elements are equivalent to pixels for monochrome displays, subtractive color displays, and projection displays using optical combination of multiple image sources.

Table 1-3 is a summary of the preliminary display requirements for the Panoramic, 3-D Flight Display System. A definition is provided for each parameter, and recommended values are given. The justification for selecting each recommended value is given in Table 1-4. Table 1-5 details the calculation and measurement of selected display parameters. These preliminary display requirements were developed using the most demanding assumptions from the two near-term application environments described in Table 1-1. In addition, the assumption was made that a path must be provided for maturity of the display technology to suitability for cockpit integration.

1.2.1 Preliminary Requirements

The preliminary display system requirements included in Table 1-3 are those values which are likely to yield the most satisfactory display system performance from the user's perspective, given an implementation-independent assessment of what may be technologically feasible. All preliminary display requirements in Table 1-3 should be met over the full operating environmental range of the display, over the full usable life of the display. Complex tradeoffs among the many display parameters outlined here must be made in any display system design. System concept development (see Section 3) produced modified requirements for the system specification which account for these tradeoffs.

A sample of the display system parameters addressed in the preliminary requirements are discussed in the text below.

1.2.1.1 General Display Parameters. Display resolution is a major determinant of the availability of task-relevant information to pilots as well as the perceived display image quality. It is important, therefore, that display resolution be selected with regard to characteristics of the human observer, other system (e.g., optical) components, environmental constraints (e.g., vibration), and any sensors which are providing images to the display.

A classic means to characterize human vision is the contrast threshold function (CTF) or its inverse, the contrast sensitivity function (CSF). A typical CTF relates the ability of an observer to detect luminance modulation as a function of spatial frequency. Generally speaking, low spatial frequencies are important for form recognition, while higher spatial frequencies are used to discriminate detail. The human visual system acts as a band-pass filter, with peak sensitivity to spatially modulated light occurring at 3 to 5 cycles per degree (cpd). Spatial frequencies below 0.5 cpd and above 30 to 50 cpd are largely attenuated. The shape of the CTF, as well as the upper and lower spatial frequency limits, varies as a function of various observer and display parameters such as the display luminance, the age of the observer, the size of the visual field, temporal characteristics of the display, the exposure of the observer to vibration and acceleration, and many other factors.

Observer CTFs may be used to estimate the sampling requirements of the display. In consideration of the Nyquist Sampling Theorem, an image must be sampled at the display at a rate of at least 2 samples per cycle to obtain an adequate representation of that image. This theoretical pixel sampling frequency must be modified by a kell factor which represents the difference between the theoretically achievable sampling frequency and that which is practically achievable. The value assigned to the kell factor will vary as a function of the display medium, the image source, and the method of image transmission.

The above analysis technique as well as extensive human factors simulations conducted in Honeywell laboratories (e.g., Reinhart, 1993; Krantz and Silverstein, 1989) have demonstrated that the limiting display resolution under ideal viewing conditions is likely to be approximately 75 to 95 pixels per deg (48 to 38 arcsec per pixel), with the highest limiting resolution for binary displays. That is, while coarser display resolutions will generally be discernible to observers and may impact image quality, artifacts associated with visible pixel structure such as spatial aliasing noise can be attenuated on a display incorporating multiple levels of gray by using a variety of anti-aliasing and noise-reduction techniques.

Perhaps more significantly, other critical sources of resolution reduction exist. Because field conditions in the aircraft (e.g., acceleration and vibration) are not ideal, the limiting resolution for observers of the Panoramic, 3-D Flight Display System is likely to be considerably coarser than the ideal limit. Finally, the effects of other system factors such as sensor or database resolution should be considered to determine the effective resolution of the system as a whole.

Display field of view (FOV) will impact pixel density, vection (illusion of self-motion) and motion perspective perception, situation awareness, and the compellingness of stereoscopic displays. The visual field must be large enough such that the pilot maintains sufficient visual capability during key flight phases such as flare and takeoff rotation as well as on approach where turbulence may induce sizable deviations in pitch and yaw. Typically, a complex tradeoff exists in selecting an appropriate FOV where a fixed resolution image source exists. A narrow FOV allows higher pixel densities to be displayed while a wide FOV promotes the greatest situation awareness and vection. Stimulation of the visual periphery and/or use of a wide FOV display is more likely to produce a compelling vection effect than is the use of a small, foveally presented display. Similarly, wide FOV displays allow more accurate and complete assessments to be made of motion perspective. Motion perspective refers to the perception of the differential flow of points in the visual scene. Both vection and motion perspective perception are important sources of situation awareness, especially for low altitude terminal area maneuvers.

The lighting environments in which the display system is expected to operate will have a significant impact on several display parameters and must therefore be well-characterized. When viewed in full daylight, many displays become impossible to view as both luminance and color contrast are greatly reduced due to reflected ambient light. In addition, pilot adaptation to high forward-scene luminances imposes significant penalties in time required for pilots to adapt to the relatively low display luminance. In general, visual adaptation transients from the display to the surrounding (ground or airborne) visual field should require a change of no more than 10 times in luminance. However, transient factors of as great as 100 are commonly encountered in flight.

Four dimensions of the lighting environment are of particular importance:

- Illumination incident on the display;
- Specular and diffuse reflections from the display surface;
- The ratio of display and forward scene luminances; and
- The presence of direct glare sources, especially the solar disk.

Display luminance contrast is typically optimized for viewing from a design eye reference point (ERP), with off-axis viewing associated with reduced contrast and occasionally contrast reversals for some image source and most collimation technologies. For cockpits where multiple ERPs exist and cross-cockpit viewing is required, the selection of an optimum viewing angle and an envelope of acceptable contrast ranges is usually weighted by consideration of criticality and frequency of use.

The advantages of providing full-color display systems in cockpits have often been debated. The most often cited merits include enhanced realism, improved information segregation or grouping, and greater pilot acceptance. Without a doubt, pilot acceptance has been a dominant criterion for the introduction of color displays into the cockpit. However, significant penalties are also typically incurred when color displays are selected. The most notable color display penalties usually include reduced effective resolution, reduced display luminance, increased complexity of display optics, and the risk of obscuring information by cluttering the display.

The selection of a display color gamut is of great importance because color is typically used as a method of encoding information. It is critically important that pilots and crew be able to correctly identify the colors presented. The colors red, green, blue, yellow, and white are among the most commonly used colors on commercial cockpit displays. Pilots are often trained to assign specific meanings to these colors. Moreover, training manuals and display documentation identify these colors by name. Unfortunately, the "red" specified for avionic displays frequently appears more orange than red while the specified "blue" often appears more cyan or aqua than blue. A second problem that may occur with specified colors is that the white produced using the full intensity red, green, and blue may be too close to yellow and the yellow and white may be confused. Problems with color identification may be exacerbated during low-visibility and high-workload flight. Post et. al. (1986, 1988, 1989) have established establish color naming boundaries that identify regions within the CIE 1976 Uniform Color Space (UCS) where observers reliably call colors by specific names. These boundaries may be used as guidelines to reduce the likelihood that colors will be mis-identified by pilots.

For display systems using digital driver electronics, selection of the number of displayed gray levels as well as the distribution of these gray levels over the display luminance range plays an important role in producing a display with superior image quality. The use of multiple gray scale steps for anti-aliasing is necessary with most matrix displays because the sampling rate of the display is within the pass band of the human visual system. By applying a discrete approximation of a Gaussian point spread function to an image prior to sampling of that image, perceptible spatial artifacts such as stairstepping of lines can be significantly reduced. The elimination of perceptible spatial aliasing in turn leads to improved image quality.

Research conducted at Honeywell (e.g., Silverstein et. al., 1989; Krantz and Silverstein, 1989; Reinhart, 1992a, 1991b) has addressed the identification of an asymptotic gray scale level for subjective image quality: that is, the maximum number of gray steps beyond which no further improvements in subjective image quality may be expected. Generally, for binary, color, graphic line images displayed on color matrix displays (e.g., LCDs) ranging from 150 to 200 dots per inch and viewed at 28 inches, the use of 3 bits of linearly distributed gray scale antialiasing (8 levels of gray, where the first level is the "off" state) produces asymptotic subjective image quality ratings. Comparable Honeywell research indicates that performance and image quality judgments are likely to continue to show improvement beyond 3 bits of gray scale for sensor video and color digital maps, contingent upon the luminance and resolution of the displays and image data source (e.g., sensors, databases).

Several physical display dimensions must be specified in light of the integration of the display system with the installation environment. Some of the important dimensions include: vertical and horizontal extent of the active display area; height, width, and depth of the display system packaging; and weight and approximate center of gravity of the display system.

Design eye reference points must be designated for the optimization of display parameters. Specifically, a determination of display placement with respect to pilot(s) and glare sources must be made, as well as a determination of cross-cockpit viewing requirements. For many collimated displays, specification of a head motion box and head relief are conventional.

Many display technologies may produce undesirable visual phenomena when improperly configured. Examples of visual artifacts include: speckle, misconvergence of image sources, aliasing (spatial, chromatic, and temporal), nonuniformities, highly visible and misaligned seams for tiled displays, image instability, as well as a large number of stereoscopic display artifacts (see below). These artifacts must be well-controlled to maintain a high-quality image.

Speckle is a random interference pattern of intensity which results from the reflection or transmission of highly coherent light (e.g., laser) from (or through) an optically rough surface or turbulent medium. The speckle pattern appears as a three-dimensional pattern of light and dark grains, with the random nature of speckle formation causing the individual speckle grains to be irregularly shaped. Speckle may lead to visual masking, accommodative fatigue, and a general reduction in subjective image quality.

Image instability includes both jitter and flicker. Jitter is present when uncontrolled excursions of display elements occur over time. The major cause of jitter in a scanned display is raster instability. Flicker is influenced principally by display refresh rate, display persistence, FOV, and luminance. A scanned laser display will have no useful persistence. Therefore, its refresh rate must be sufficiently fast to avoid flicker at anticipated room illumination and display luminance levels. The problem is made unfortunately worse by increasing the size of the display to include appreciable peripheral visual content (the eye is most sensitive to flicker at about 20 deg off the optical axis). With no persistence, the refresh rate may have to be well in excess of 80 or 90 Hz to avoid flicker. In the 3-D image case, the presence of flicker may cause the perception of image "breakup" in one or more dimensions, which could be even more disconcerting and unacceptable than flicker in the 2-D case.

For display systems relying on external sensors to provide imagery, the relationship between sensor parameters and display system parameters requires scrutiny. For example, the relationship between field-of-regard of the sensor and FOV will strongly influence the use of the display system. In addition, mismatches in sensor and display resolution introduce the possibility of scan conversion artifacts.

1.2.1.2 Stereoscopic Display Parameters. Stereoscopic displays may offer extra degrees of realism, awareness, and piloting accuracy when properly implemented in pictorial displays as well as providing enhanced display decluttering or alerting value to symbolic displays (e.g., Busquets, Parrish, and Williams, 1990, 1991b; Nataupsky and Crittenden, 1989; Reinhart, 1992b). Honeywell experience with hyperstereoscopic FLIR imagery (e.g., Lippert and Benser, 1987) indicates that stereoscopic displays may also serve to mask independent sensor channel noise. Complementing the pioneering research conducted at NASA LaRC, Honeywell has conducted extensive human factors research to optimize stereoscopic implementations (e.g., Reinhart, 1992a, 1992c, 1991b; Yeh and Silverstein, 1990a, 1990b). Critical system parameters which will impact the successful implementation of a panoramic stereoscopic display include: image source symmetry and stability; the presence of optical crosstalk; apparent depth range; the coordinated overlay of sensor information, computer-generated imagery (CGI), and the outside scene; interactions with basic display performance parameters; and the use of monocular depth cueing.

Synthetic stereoscopic display is accomplished by simulating the spatial retinal disparity present between left and right eyes when viewing objects at different distances from the eyes. While the human visual system is able to detect horizontal image disparities as small as 5 to 10 arcsec under ideal viewing conditions, a number of display system artifacts may be introduced which will jeopardize stereoacuity, reduce apparent image quality, and may even promote viewer discomfort. In order to promote the best visual comfort and stereoscopic image quality, the two image sources should closely match each other in instantaneous luminance, luminance range, chromaticity, and any visible geometric or temporal qualities or artifacts. That is, there should be good symmetry between the visible characteristics of the left and right displays. The effects of stereoscopic asymmetries are generally cumulative until such time as visual discomfort, degraded stereopsis, and even double vision (diplopia) may result.

Honeywell laboratory investigations have been conducted to determine the effects of stereoscopic asymmetries on pilot performance (e.g., Lippert, 1990). Luminance imbalances as small as 15% will be detectable by pilots. Stereoscopic viewing is particularly sensitive to vertical disparities (dipvergence) existing between left and right images. Dipvergence is easily introduced when using a convergent stereo camera geometry or a rotational stereoscopic transformation algorithm. Vertical misregistrations as small as 19 arcminutes may produce immediate eye strain, while diplopia will occur at 45 arcminutes of dipvergence. Sensitivity to dipvergence will increase as a function of time, so lower thresholds should be designed to. For example, dipvergence thresholds as low as 5 arcminutes have been reported. Furthermore, smaller amounts of dipvergence may degrade stereoscopic image quality without producing eye strain. Dipvergence may be minimized through careful control of factors such as field flatness and image stability.

Optical crosstalk in stereoscopic displays gives rise to the perceptual phenomenon known as ghosting, the low-contrast ghost of an image of one element of a stereo pair being superimposed over the other. Crosstalk is a common form of stereoscopic asymmetry and is usually the result of undesired image persistence or leakage of the filter mechanism used for stereoscopic selection. Crosstalk may be exacerbated by screen depolarization in stereoscopic projection displays. The magnitude of crosstalk may also vary as a function of display chrominance.

Effective use of stereoscopic depth mandates the appropriate use of the available range of depth. Generally speaking, the depth viewing volume created by synthetic stereoscopic displays is predicted by the geometry of the two converging optical axes of the eyes and the position of left- and right-eye viewing elements with respect to the imaging medium. When the projected optical axes cross beyond the depth of the plane of accommodation, images are said to be seen in display space with uncrossed disparity, the net perception being that of the object existing within or behind the display. When the projected optical axes cross before the depth of the plane of accommodation, images are said to be seen in viewer space with crossed disparity, the net perception being that of the object existing in front of the display. The theoretical limit for perceived crossed disparity depth is determined by the distance of the viewer to the display or the width of the display image, but the inability of observers to fuse stereo pairs with extreme crossed disparity and accurately interpret fine increments in this perceived space places the practical limit at a much smaller value. The maximum apparent depth in viewer space after which binocular fusion is impossible has been estimated to be approximately 45% of the distance from the observer to the plane of accommodation (Yeh and Silverstein, 1990b). However, Williams and Parrish (1991) recommend 25% as a limit for comfortable viewing. Similarly, as vergence angles approach zero (i.e., as the projected optical axes of the two eyes approach parallel), the theoretical limit for perceived uncrossed disparity depth approaches infinity. Yeh and Silverstein (1990b) report a maximum fusion limit of approximately 250% of the distance from the observer to the plane of accommodation, while Williams and Parrish (1991) recommend a limit of approximately 60% to ensure accurate and comfortable viewing.

Specification of apparent depth limits is best expressed as a function of observer to display distance because it is a well-documented fact that apparent depth increases as a function of viewing distance in synthetic stereoscopic display systems. The range of apparent depth may also be expanded by collimating the display (Busquets, Parrish, and Williams, 1991a).

While many stereoscopic images are presented orthostereoscopically, it is occasionally beneficial to select a hyperstereoscopic presentation. Orthostereoscopic display principles prescribe, in part, that the amount of apparent depth in the stereoscopic image will accurately match that seen by the observer if he or she were to view the scene directly with their own eyes. Hyperstereoscopic displays introduce an exaggerated display of the depth dimension by assuming a larger than normal stereoscopic base (i.e., sensor or eye point separation). For display systems relying entirely on computer-generated imagery, a hyperstereoscopic display may be effectively used to highlight display elements. However, where superimposition of imagery with an outside scene is necessary, hyperstereoscopic presentations could interfere with image superimposition.

For computer-generated stereoscopic imagery, the nature of the transformations used to map the 2-D world into 3-D stereoscopic viewing space will significantly influence the nature of the apparent viewing volume. For example, Williams and Parrish (1991) point out that the use of asymmetric display clipping will increase the effective FOV in the 3-D viewing volume beyond that obtained through symmetric clipping. Similarly, their piece-wise linear approach to mapping the visual scene to the stereo viewing volume can afford greater control over partitioning of the depth viewing volume than traditional asymptotic mapping.

The simultaneous display of sensor video, CGI, and the direct view (either in the view of instruments with the cockpit or the view of the forward scene through the windscreen or canopy) requires a consideration of where and when information should be displayed stereoscopically. Status information displayed stereoscopically should be displayed as close to the plane of convergence as possible to avoid extreme disparities. In addition, displays which appear to project within solid objects in the cockpit may be a cause for concern.

Many of the basic display parameter levels selected will require special consideration for stereoscopic presentations. For example, the presence of unique forms of spatial sampling artifacts in stereoscopic imagery suggests that the gray scale guidelines developed for use with 2-D sampled imagery may not be appropriately applied in the stereoscopic domain. Honeywell laboratory data (e.g., Reinhart, 1992a, 1991b) have demonstrated that stereoscopic display may provide a form of spatial averaging which significantly reduces perceptible spatial and chromatic aliasing and consequently lowers the requirement for the use of gray scale anti-aliasing in stereoscopic imagery. However, extreme aliasing mismatches between left and right images may introduce viewing discomfort.

Narrow FOV stereoscopic displays may produce a highly visible frame effect (i.e., a high-contrast display border). Such borders tend to reduce apparent depth in stereoscopic images, particularly where stereoscopic objects simultaneously extend outward toward the viewer and touch the border of the active area of the display. Consequently, wide FOV displays may further contribute to the compellingness of visual scenes by removing stereoscopic display artifacts from the central area of visual attention.

In addition to the stereopsis cue provided in electro-optical stereoscopic displays, successful 3-D presentations also make use of the various monocular sources of depth information (e.g., Reinhart, 1990a, 1990b). These depth cues include interposition, linear perspective (relative size, texture gradients, elevation), shading, shadows, aerial perspective (luminance contrast, color purity, hue), and motion parallax. While the application of monocular depth cues is not reviewed in this report, it should be noted that the relative impact of these sources of depth information is interactive, with diminishing returns with the addition of greater numbers of depth cue sources. In addition, the misapplication of one or more cues (e.g., motion parallax without control of object interposition) can lead to ambiguous or erroneous perceptions of image depth.

1.2.1.3 Volumetric Display Parameters. Volumetric displays are those having images that occupy three-spatial dimensions. That is, the images have measurable height, width, and depth that may be viewed simultaneously from different ERPs by multiple observers. Volumetric displays require consideration of unique or more stringent display requirements, beyond those basic and stereoscopic display parameters already enumerated.

One stringent volumetric display requirement is bandwidth, which may increase above that required for 2-D or stereoscopic approaches in direct proportion to the addressability of the depth dimension. In light of bandwidth constraints, a unique consideration for volumetric displays is the amount and degree of surface transparency required; large areas with opaque surfaces may help mitigate bandwidth constraints.

Determination of the viewing volume for volumetric displays is more strongly tied to cockpit geometry constraints than conventional stereoscopic approaches, because volumetric displays must occupy a 3-D portion of the cockpit space to use as the active display area.

Specification of appropriate display contrast as a function of viewing angle will be especially challenging for a volumetric display because such displays are typically intended to be viewed simultaneously from multiple ERPs.

Volumetric displays are likely to require that the display medium is bounded on all sides by a transparent material such as glass or plastic. The use of multiple surfaces is likely to compound problems with specular glare in all but the most dimly illuminated environments.

Direct manual interaction with volumetric images is not practically achievable without juxtaposition of a physical pointer with the display medium. This constraint, not present for uncollimated stereoscopic imagery, will require the use of indirect pointing devices (e.g., trackball, mouse, Spaceball) for interaction with volumetric displays.

1.2.1.4 System Electronics Parameters. Carefully designed electronics play a crucial role in any display system. Even the best display technology will not be successful without appropriate interfaces, convenient reconfigurability, and electronic solutions to technology shortcomings. There are at least three primary technology considerations for the Panoramic, 3-D Flight Display System electronics: 1) scan conversion, 2) display specific electronics, and 3) electronic solution of display media limitations (e.g., Hancock and Johnson, 1991). Honeywell has considerable experience in the area of scan conversion for reconfigurable displays, including NTSC, 675, 875, and 1536 line formats, FLIR, weather radar, etc. Our lab units can scan convert PC and workstation outputs and display those on in-test display technologies. The primary electronic ingredients for achieving this capability are an analog to digital converter, a ping-pong image memory, an addressing unit that can be phase locked to the incoming video and an output digital to analog converter. Typically, most of the high speed video components can be obtained commercially off-the-shelf. All of these factors must be considered when analyzing a new display system concept for payoff potential and risk, and these factors need to be considered in light of electronic trends, including ASIC, processor, RAM developments.

The drive electronics are a significant aspect of how crisp the image is, how much detail it has, how uniform it is, how noise free it is, etc. Some of the related criteria most certainly will involve some of the following traditional metrics:

- Signal to noise ratio
- Resolution
- MTF
- Dynamic Range
- Bandwidth
- Refresh Rate
- Update Rate

Traditional compensation and drive circuits include look-up tables for gamma correction, piece-wise linear approximation for complex non-linear distortion pincushion correction, multiplier-accumulator combinations to account for stroke system non-linearities, and response time compensation memories for liquid crystal speed-up.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System.

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Acceleration	Gravities (g)	The maximum acceleration force to which the display system may be exposed, in terms of gravities, during and after which the display is expected to operate normally.	≤2 g constant (RMS) acceleration on the axis parallel to the center line of sight. The display system should withstand the maximum acceleration magnitudes and durations reasonably expected to be encountered in ground-based simulation or TSRV flight, whichever is more extreme. The display should continue to operate normally both during and after such exposure without measurable loss, either temporary or permanent, in performance or MTBF. Temporary losses in image quality during acceleration exposure should neither interfere with image interpretation nor induce pilot control errors.	The failure mode of display components in light of extreme acceleration should also be considered when selecting a *head relief.*
Aliasing	Subjective	Most generally, the presence of visible spatial nonuniformities on the display where such nonuniformities do not exist in the original image. Aliasing may take many forms, including luminance or color banding and spatial discontinuities or "jaggies" in lines and edges. Visibility of spatial aliasing may be determined empirically as indicated in Table 1-5.	No aliasing should be apparent on the display.	Raster displays incorporating mechanical scanners may be vulnerable to aliasing artifacts associated with stepping (discrete approximation of continuous scanning).
Altitude (Pressure)	Feet	The equivalent pressure altitude range over which the display will operate normally, either on ground or in a pressurized cabin or cockpit.	0 - 15000 feet	Assumes 15000 feet is maximum equivalent pressure altitude of pressurized cockpit or cabin per RTCA/DO-160C.
Aspect Ratio: Display Image	Ratio	The ratio of the width of the display image to the height of the display image. Perceptually, the apparent shape of the rectangular display image as viewed from the center of the head motion box.	1.78:1	A 1920 x 1080 pixel count with square pixels will yield an image aspect ratio of 1.78:1.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Aspect Ratio: Pixel	Ratio	The ratio of the width of a pixel to the height of a pixel. Perceptually, the apparent shape of a pixel.	1:1 pixel aspect ratio	Applies only to matrix-addressed displays. A delta-triad arrangement with square color elements has also been demonstrated to offer satisfactory image quality at high pixel densities.
Astigmatism: Oblique	Diopters	A form of optical aberration in which objects located off the optical axis are imaged with differing orientations, depending on the imaging distance. Perceptually, astigmatic display optics require the observer to shift accommodation to bring image features of differing orientation into focus. Unfocused image components will appear blurred.	See *MTF*.	Oblique astigmatism is assumed to be reflected in the requirement for *MTF*.
Chromatic Aberration	Diopters	A form of optical aberration in which objects of different colors have different image distances. Perceptually, display optics with chromatic aberration require the observer to shift accommodation to bring image features of different colors into focus. Unfocused image components will appear blurred.	See *MTF*.	Chromatic aberration is assumed to be reflected in the requirement for *MTF*.
Color Element Failures	Percent, Total	The loss of addressability of individual color elements or clusters of color elements. Color elements may fail either on or off. See Table 1-5 for details on calculation of color element failures.	Maximum of 0.5% total failed blue color elements, 0.25% total failed red and green color elements. Maximum adjacent failed color elements (clusters of the same color) are: (10) clusters of 2 failed elements, (5) clusters of 3 failed elements, (2) clusters of 5 failed elements, and (1) cluster of 10 failed elements. Element cluster restrictions apply to each image source used.	Applies only to matrix-addressed displays.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Color: Maximum Gamut and Uniformity	u', v'	The identification of each color primary (red, green, blue) within the CIE 1976 uniform color space (UCS) when displaying the maximum white luminance and the uniformity of these primaries across the display TFOV. Large-area chromatic uniformity refers to the absence of unintended chromatic differences as measured from the center line of sight and the corner lines of sight. Small area chromatic uniformity refers to the absence of unintended color differences within 0.5 deg of the image TFOV. The measurement of color gamut and uniformity as well as the conversion between 1976 UCS and 1931 color spaces are detailed in Table 1-5.	u' v' red .469 .522 green .127 .560 blue .175 .158 Maximum deviation for each primary is described by a circle with a radius of 0.015 around each primary coordinate. This uniformity requirement also applies to unintended variation in color between or among stereoscopic image fields or image tiles.	These UCS coordinates serve as an example of a commercial, avionic-grade CRT primary flight display.
Coma	No Units	A form of optical aberration in which points viewed off the optical axis appear elongated. Coma contributes to image blur.	See *MTF*.	Coma is assumed to be reflected in the requirement for *MTF*.
Comfort	No Units	The general ease of use of the display system, including 3-D interaction, especially over extended periods of use. Comfort concerns include such subjective phenomenon such as eye strain, disorientation, and hand or arm fatigue.	No muscular (eyes, hands, arms, neck) or visual discomfort should be produced through normal use of the display system.	Some 3-D display methods may be prone to visual discomfort. Some 3-D interaction methods may be prone to hand or arm fatigue.
Convergence Control	No Units	A control should be provided to adjust display color convergence.	Manual control of display color convergence is required. Automatic control, in addition to manual control, is preferred but not required.	A manual control should incorporate physical displacement and resistance as feedback to actuation.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Cooling	No Units	Consideration must be made of the constraints associated with the use of either passive cooling, forced air cooling, or suction of ambient air for cooling.	Passive cooling is acceptable provided heat dissipation does not significantly raise the temperature of the operations environment and the external temperature of the display unit does not present a hazard to operators (see *Temperature: External).* Active cooling is acceptable, provided adequate provision is made for noise isolation, relative to the general noise level of the operations environment. In addition, exhaust air should not cause discomfort to operators. Forced cool air is acceptable provided demand does not exceed the capacity of the available air conditioning system. Suction application of ambient air is acceptable provided dust filtering is used and provision is made in the design of the electronics for dust accumulation.	
Crosstalk	Percent	The amount of light "leakage" from one stereoscopic view to the other, due to imperfect stereoscopic selection or excessive image persistence. Perceptually, the extent to which ghost images are present. See Table 1-5 for details on measurement of crosstalk.	≤5% for white or any primary color.	Screen depolarization may cause crosstalk in projection displays. Crosstalk is typically chromatically dependent.
Dipvergence	Degrees	The presence of disparities between stereoscopic eye points in the vertical direction due to vertical misregistration between stereoscopic fields. This preliminary requirement refers to the maximum dipvergence between stereoscopic fields as measured from two binocular eye points, separated by a nominal IPD such as 2.5", anywhere within the head motion box. See Table 1-5 for a dipvergence measurement procedure.	≤0.08 deg.	Vertical disparities may also be introduced through rotational stereoscopic transformation algorithms.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Distortion	Percent	A form of optical aberration. The net percentage of unintended variation in the position of an image element with respect to an ideal image. Perceptually, the degree to which optical aberrations such as pincushion or barrel distortion are present in the image. See Table 1-5 for details on the calculation of distortion.	≤5% distortion over the total, binocular FOV.	
Drift	No Units	The extent to which display characteristics such as image registration, relative image position, and chromaticity vary over a 24 hour period.	Maximum color gamut drift is 20% of the maximum deviation over 24 hours. Maximum dipvergence drift is 20% of the maximum over 24 hours. Maximum drift in registration accuracy is 20% of the maximum deviation over 24 hours. Where drift is anticipated, controls should be provided for calibration.	Stereoscopic displays may be especially sensitive to drift if the two stereoscopic fields are differentially affected.
Dwell Time	Micro-Seconds	The time required to change a pixel from its minimum luminance to its maximum luminance. See Table 1-5 for calculation of dwell time.	Dwell time should be minimized to meet the requirements for total number of pixels and refresh rate.	
Field Curvature	Diopters	A form of optical aberration in which the image of a flat object does not lie in a plane, with object points falling off optical axis showing the aberration. Perceptually, the presence of variations in the accommodation distance where none should occur. See Table 1-5 for details on measurement and calculation of field curvature.	≤ +/- 0.25 diopters over the total, binocular FOV.	
Field of View: Instantaneous, Monocular	Degrees	The angular subtense, horizontally and vertically, of the image that is visible with one eye from within the head motion box with no head movement. Calculation of monocular IFOV is given in Table 1-5.	Equivalent to the instantaneous binocular FOV.	A smaller instantaneous monocular FOV may be necessary due to optical constraints.
Field of View: Instantaneous, Binocular	Degrees	The angular subtense, horizontally and vertically, of the portion of the image that is visible with both eyes from within the head motion box with no head movement. Calculation of binocular IFOV is given in Table 1-5.	Equivalent to the total binocular FOV.	A smaller instantaneous binocular FOV may be necessary due to optical constraints.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Field of View: Total, Binocular	Degrees	The angular subtense, horizontally and vertically, of the image that is visible with both eyes from within the head motion box. Calculation of binocular TFOV is given in Table 1-5.	≥48 deg (horizontal) x 27 deg (vertical) Preferred is 60 deg x 33.8 deg	Minimum FOV assumes preferred resolution. Preferred FOV assumes minimum resolution.
Field Rate	Hertz	The number of times within a 1-sec interval that all display pixels in a single time-multiplexed field may be addressed. For time-multiplexed displays, a single frame is the sum of all constituent fields (see *Frame Rate*). Time multiplexing includes conventional spatial interlacing techniques as well as time-multiplexed color and time-multiplexed stereoscopic display. Perceptually, field rate is a strong determiner to whether flicker may be perceived in the display.	Minimum of the frame rate multiplied by the total number of fields.	Time-multiplexed stereoscopic displays will have two fields corresponding to the left and right eyes. Time-multiplexed color displays will typically have three fields corresponding to three primary colors.
Flicker	Subjective	The visible and unintended modulation of large area display luminance as a function of time, usually due to inadequate frame rate or short image persistence. Visibility of flicker may be determined empirically as indicated in Table 1-5.	The display should be "flicker free."	Flicker thresholds vary as a function of the age of the observer, as well as display parameters such as ambient and display illumination and display FOV. Display refresh rate may interact with some indoor lighting frequencies to form visible beats.
Frame Rate	Hertz	The number of times within a one-second interval that all display pixels may be addressed. For time-multiplexed displays, a single frame is the sum of all constituent fields (see *Field Rate*). Time multiplexing includes conventional interlacing techniques as well as time-multiplexed color and time-multiplexed stereoscopic display. Perceptually, frame rate is a strong determiner to whether flicker may be perceived in the display.	≥60 Hz. 70 Hz preferred.	Display devices with inherent memory may have special requirements. Frame rate should be compatible with the image data source.
Gray Scale: Shades of Gray per Color Primary	Total	The number of discretely addressable luminance levels for each color primary. Number of gray scale steps may be empirically validated as indicated in Table 1-5.	≥32 linearly distributed shades of gray per color channel, where the first luminance step is equal to the background luminance (If gray shades are nonlinearly distributed, as described below, the minimum requirement may be lower)	Applies to digital display systems only. Assumes display of computer-generated graphics. A larger number of gray shades may be required to display video.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Gray Scale: Distribution of Luminance	Equation	The algorithm describing the linearity of the distribution of available gray scale steps over the luminance range of the display. Validation of this algorithm may be made empirically as detailed in Table 1-5.	Minimum is linear. Nonlinear approaches may be considered, such as: $Luminance_n = [(L_{max}^{1/3} - L_{min}^{1/3}) * n/(steps - 1) + L_{min}^{1/3}]^3$, where n = 0 to (steps - 1), steps is the number of gray scale steps incorporated in the gray scale, and L_{max} and L_{min} define the maximum and minimum display luminance.	Applies to digital display systems only. Equation from McCartney (1992). This advantage of this approach is likely to be context/imagery-dependent and should be empirically validated.
Head Motion Box	Inches	The three-dimensional volume from which the complete binocular image is visible without vignetting. Requirements for distortion, field curvature, and luminance contrast must be met within the entire head motion box.	Horizontal: +/- 4 inches Vertical: +/- 4 inches Depth: +/- 4 inches The center of the head motion box intersects the center line of sight and is located at the on-axis head relief.	The head motion box must be larger than the viewer's interpupillary distance to allow some head motion without binocular image loss. A larger head motion box is desirable. Performance roll-off outside of the head motion box should be gradual rather than abrupt.
Head Relief	Inches	The range of physical clearance between the nearest display system component (on-axis) and the head of the display observer.	≥12 inches on-axis relief in any direction from the center of the head motion box, assuming shoulder and lap belts are used. ≥25 inches relief if shoulder and lap belts are not available. <33 inches in either case. Preferred is 29 inches.	Head relief should be determined through consideration of viewer safety, ease of ingress/egress, visibility of other cockpit displays, and pilot reach envelope to cockpit instruments. Where possible, the use of break-away, fold-away, or padded display components may mitigate the risk of injury.
Humidity: Operating	Relative Humidity	The range of ambient relative humidity over which the display is expected to operate normally.	5 % to 80% Relative Humidity	
Humidity: Storage	Relative Humidity	The range of ambient relative humidity over which the display is expected to be stored without damage.	5 % to 95% Relative Humidity	

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Image Depth	Percent	The range of apparent stereoscopic image depth between the observer and the plane of accommodation (crossed depth) and behind the plane of accommodation (uncrossed depth) achievable by the display device.	System should be capable of displaying crossed depth of up to 25% of the image distance. For large image distances (collimation near infinity), uncrossed disparity will not be effective and should not be used. For closer image distances, system should be capable of displaying uncrossed disparity of up to 60% of the image distance.	See *Justification* for estimate of required disparities expressed in distance units. Applies only to stereoscopic displays. Maximums are derived from testing of uncollimated stereoscopic display and may not generalize to collimated systems.
Image Depth Addressability	Total Depth Planes	Minimum number of discretely addressable depth planes.	Sufficient addressability should be provided such that image features extending or moving through 3-D space appear to do so continuously.	3-D images may be undersampled and produce visible aliasing artifacts.
Image Distance	Inches	The distance from the center of the head motion box to the plane of visual accommodation.	Variable image distance is not required. Preferred image distance is between 48 inches and infinity and must approximate a conformal display. As a minimum, the apparent image distance must be external to the simulated cockpit.	
Image Persistence	Milliseconds	The extent to which a pixel remains active after no longer being addressed. Image persistence is a brief (milliseconds) phenomenon which is a factor in display luminance, flicker, and crosstalk.	Maximum of the inverse of the frame rate. For time-multiplexed displays, maximum should be less than the inverse of the field rate, the exact amount to be determined empirically to ensure compliance with crosstalk requirements. Minimum for all displays to be determined by compliance with the luminance and flicker requirements.	Image persistence interacts with field rate in determining crosstalk in time-multiplexed displays. Special devices, such as the Tektronix split-screen shutter, may be used to mediate crosstalk for longer persistence. Some display media, such as rastered laser light, yield no inherent persistence.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Image Retention	No Units	The visible presence of an image or portion of an image while the display is not active. Image retention is a lasting phenomenon (minutes, hours, or days) with no desirable contribution to display system performance.	No visible image retention should be observed over the usable life of the display.	
Interaction Method	No Units	A display interaction method allows display users to interact with display images. Interaction may include selection of image objects, manipulation of these objects, manipulation of a cursor, and/or rate control.	Display interaction must be possible in real time (i.e., without apparent lag between input and display change) and smoothly and accurately at high-resolution (commensurate with the 3-D resolution of the display). Display interaction should be user-selectable from 1 to 3 degrees of freedom (DOF). The interaction method must be suitable for rate control. The interaction method should allow visual attention to remain on the display. The interaction method should be compatible with arm and/or wrist support to allow stable control under vibration. Multiple methods or devices may be used in combination to accomplish the interaction requirements.	This interaction requirement is assumed to be separate from flight controller requirements. It is assumed that a separate means (e.g., column-mounted yoke or side-stick controller) will be used to control flight in the simulator. No need for rotational control is anticipated.
Interlacing (Spatial)	Ratio	The conservation of display system bandwidth by addressing only a subset of total display pixels during each display refresh cycle. Each subset of pixels addressed comprises a field, with the combined fields in time forming a frame. Interlacing is described by the ratio of fields to frames.	1:1 (spatially noninterlaced)	

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Jitter	Degrees/ Second	The combined vertical and horizontal angular excursion of a pixel location across the display FOV over a one-second period of time due to instability within the display system (not including instability caused by environmental forces such as vibration). Perceptually, the movement of the image or portions of the image with respect to stationary elements of the display system. See Table 1-5 for details on measurement of jitter.	≤0.01 deg per second	Applies to raster displays or displays where jitter may be introduced by a sensor or image generator.
Line Failures	Percent	The temporary or permanent loss of addressability of a complete row or column of color elements or pixels. Lines may fail either on or off. See Table 1-5 for details on definition of line failures.	No line failures are allowable.	Applies only to matrix-addressed displays.
Luminance	Foot Lamberts (fL)	The luminous intensity of a surface in a given direction per unit of projected area. See Table 1-5 for details on measurement of luminance.	≥30 fL (white), measured after the closest optical element to the eye. Preferred is ≥60 fL to allow greater gray scale separation.	A higher luminance will be required at the image source to account for transmission loss in the display system optics and any stereoscopic selection devices such as glasses or shutters.
Luminance Asymmetry	Percent	The percentage difference in luminance between stereoscopic image fields or tiled images when the desired value is identical. See Table 1-5 for details on calculating luminance asymmetry.	≤10%.	
Luminance Contrast	Contrast Ratio	The most common method of expressing display luminance contrast in the display industry. The method for calculating contrast ratio is detailed in Table 1-5.	≥50:1 within the head motion box. Preferred is 100:1	
Luminance Control	No Units	A control, either manual or via computer control, should be provided to adjust display luminance for each stereoscopic image field or tile.	Manual luminance control is required in the form of a balance control between (or among) stereoscopic image fields or image tiles.	Manual controls should incorporate physical displacement and resistance as feedback to actuation, as well as a guard or lockout to prevent inadvertent actuation.
Luminance Half-Life	Hours	The time required for the maximum luminance of the display to be reduced to below 50% of the initial value over the life of the display.	≥1000 hours and the light source(s) must be replaceable.	

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Luminance Nonuniformity	Percent	The percentage of unintended variation in luminance between two areas across the display TFOV. Large-area luminance nonuniformity refers to unintended luminance differences between that measured from the center line of sight and the corner lines of sight. Small area nonuniformity refers to unintended luminance differences within a 0.5 deg area of the display TFOV. See Table 1-5 for details on measurement of luminance nonuniformity.	≤20% for large-area nonuniformity. ≤10% for small-area nonuniformity.	
Misconvergence : Spatial	Percent	The center-to-center misregistration distance between overlapping color elements forming the same pixel, expressed as a percentage of the width of a primary color line. Perceptually, the spatial separation of a color pixel into constituent primary colors. See Table 1-5 for details on measuring spatial misconvergence.	≤33% of line width.	Applies to projection displays, CRTs, and other displays using overlapping color primaries.
Misconvergence : Temporal	Subjective	The degree to which display colors appear to alternate over time, when a single, fused color presentation is intended. Temporal misconvergence may be empirically determined using the procedure detailed in Table 1-5.	No apparent color separation should be visible as a result of using time-multiplexed color mixing.	Applies only to displays using time-multiplexed color.
Modulation Transfer Factor (at display resolution)	MTF	The minimum modulation transmittance of the display optics at the maximum display resolution (frequency). Perceptually, the extent to which the display optics faithfully represent image sharpness.	MTF ≥0.3 at the display resolution (in cycles per deg).	
Packaging	No Units	The mechanical design of the display system packaging (housing) and the means by which the packaged display system is secured to the simulator or aircraft.	Packaging and fastening must be compliant with the mechanical design requirements referenced in Chapter 5 of LHB 7910.1 (see Table 1-6). Packaging must also be compliant with the requirement for overall display system volume (see *Volume*)	
Pixel Count / Line Count	Total	Total number of addressable display pixels or lines in both the horizontal and vertical dimensions.	≥1920 x 1080 pixels.	A 1920 x 1080 pixel count with square pixels will yield an image aspect ratio of 1.78:1.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Power	Amperage, Voltage, Frequency	The total power requirements for the display system, excluding graphics processors.	TSRV-installed unit should be compliant with Mil-Std 704. 400 Hz 115 or 208V AC, 3 phase or 3 single phases. Electrical design should be compliant with Chapter 5 of LHB 7910.1 (see Table 1-6).	AC Power may be available on TSRV aircraft, but of limited quality and capacity. External AC power converters are discouraged for TSRV installation.
Reflectance: Diffuse	Percent	The percentage ratio of the display luminance contribution due to ambient light divided by the illuminance on the display due to that ambient light, where the luminance contribution does not include specularly reflected components of the ambient light. Perceptually, the degree to which display luminance contrast is susceptible to wash out by environmental veiling luminance. See Table 1-5 for details on measurement of diffuse reflectance.	≤0.4% diffuse reflectance.	
Reflectance: Specular	Percent	The sum of the percentages of luminance from equivalent specular light sources reflected by the corresponding display optical elements. Perceptually, the degree to which images of the surrounding environment are mirrored by the display optics (commonly referred to as the "white shirt effect" in commercial cockpits). See Table 1-5 for details on measurement of specular reflectance.	≤4% specular reflectance.	
Refresh Rate	Hertz	A nonspecific term used interchangeably for either Field Rate or Frame Rate.	See *Field Rate* and *Frame Rate.*	
Registration Accuracy	Degrees	Maximum allowable angular deviation of correspondence between the display image and the real-world forward scene.	≤4 deg deviation.	Approximate registration accuracy is needed for correct spatial orientation, but the lack of display transparency to the forward visual scene eliminates the need for precise visual overlay.
Resolution	Pixels /Degree or Lines/Degree	The total number of color elements subtended within one degree at the observer's eye in both the horizontal and vertical directions. See Table 1-5 for details on calculation of resolution.	≥32 pixels/deg (horizontal) x 32 pixels/deg (vertical). Preferred is 40 pixels/deg x 40 pixels/deg.	
Service Date	Year, Quarter	The date on which the display system is expected to begin its useful service life.	1997, 1st quarter.	

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Shock	Gravities (g)	The maximum impulse force to which the installed display system may be exposed, in terms of gravities, after which the display system is expected to operate normally.	≤3 g impulse (≤20 ms) on the vertical axis. ≤1.5 g impulse on the horizontal axis. The display system should withstand the maximum shock magnitudes reasonably expected to be encountered in ground-based simulation or TSRV flight, whichever is more extreme. The display should operate normally after such exposure without measurable loss, either temporary or permanent, in performance or MTBF.	The failure mode of display components in light of extreme shock should also be considered when selecting a *head relief*. This preliminary requirement is for impulse shock generally applied to the system via the aircraft or simulator airframe and does not address impact shock directly applied to any optical elements or other specific display system components.
Smearing	No Units	The apparent blur of display elements between refresh cycles when displaying object motion. Smearing is caused either by mismatches between image persistence and refresh rate or mismatches between update rate and refresh rate.	Smearing should not be observable when moving symbology is displayed.	See *image persistence*, *dwell time*, *refresh rate*, and *update rate*.
Speckle	Subjective	The apparent scintillating or stationary granularity of pixels due to interference patterns of coherent light. Visibility of speckle may be determined empirically as indicated in Table 1-5.	The display should be "speckle free."	Applies only where light sources of relatively high coherence are used, such as laser light. Speckle patterns may appear stationary in collimated displays.
Spherical Aberration	Diopters	A form of optical aberration in which focal length varies as a function of object distance from the optical axis. Perceptually, the presence of blur at the edges of the image.	See *MTF*.	Spherical aberration is assumed to be reflected in the requirement for *MTF*.
Stability	No Units	See *Drift*.	See *Drift*	Stability is assumed to be reflected in the requirement for *Drift*.
Stepping Artifacts	No Units	Raster displays incorporating mechanical scanners may be vulnerable to aliasing artifacts (e.g., luminance banding) associated with stepping (discrete approximation of continuous scanning).	See *Aliasing*	Stepping artifacts are assumed to be reflected in the requirement for *Aliasing*.

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Temperature: External	Degrees	The maximum temperature of any external (unprotected) surface of the display system.	External surfaces intended to be touched during normal operation should not exceed 35 deg C. External surfaces which may be inadvertently touched during display system operation should not exceed 50 deg C.	
Temperature: Operating	Degrees	The range of ambient temperature over which the display is expected to operate normally.	10 to 32 deg C	
Temperature: Storage	Degrees	The range of ambient temperature over which the display is expected to be stored without damage.	-25 to 60 deg C	
Tiling: Pixel Registration	Percent	The center-to-center misregistration distance between adjacent color elements on adjacent, tiled images, expressed as a percentage of the line width. Perceptually, the misalignment of tiled images. See Table 1-5 for details on measuring tiling pixel registration.	≤100% of line width.	Applies only to tiled displays.
Tiling: Luminance Nonuniformity	Percent	The percentage of unintended variation in luminance at seams where two images have been joined to form a larger image. See Table 1-5 for details on measurement of tiling luminance nonuniformity.	≤25% nonuniformity. In addition, tile seams will not intersect the center line of sight.	Applies only to tiled displays.
Transmittance (Head-Mounted Transparencies)	Percent	The percentage of light transmitted by any head-mounted transparencies (e.g., stereoscopic selection eyewear) (if active, in the "on" state). This requirement addresses the visibility of all visual information in the cockpit outside of the Panoramic, 3-D Flight Display System itself, including other head down displays.	≥30% transmittance. Preferred is ≥60%.	Most likely to apply to stereoscopic selection eyewear. Although a 100% transmittance is optimally desirable, reduced transmittance of cockpit light to the eye is acceptable provided there is not a large difference between the net luminance of the Panoramic Display (to the eye) and that of other cockpit displays.
Transparency (See-Through)	Percent	The relative contribution of luminance from the forward scene (outside of the cockpit) to the total display luminance.	No transparency required.	

Table 1-3. Preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Definition	Preliminary Requirement	Comments
Update Rate	Hertz	The number of times within a one-second interval that the display image source (e.g., sensor, graphic generator) may be updated.	Display update rate should match the display refresh rate to preclude temporal aliasing.	
Vibration	Frequency (Hz), Power Spectral Density (PSD), Hours	The maximum ambient vibration to which the display system may be exposed, in terms of both magnitude and duration of exposure, during and after which the display is expected to operate normally.	The display system should withstand the maximum vibration magnitudes and durations reasonably expected to be encountered in aft compartment TSRV flight, including vibration frequencies as high as 2,000 Hz. The display should continue to operate normally both during and after such exposure without measurable loss, either temporary or permanent, in performance or MTBF. Temporary losses in image quality during long-term vibration exposure should be prevented if necessary and possible through vibration isolation measures.	Estimated maximum vibration (based on Boeing 777 DU target) is: Hz PSD (G^2/Hz) 10 0.03 30 0.03 75 0.002 1,000 0.002 2,000 0.0005 Lower PSD values may be suitable for simulator specification.
Volume (Dimensions)	Inches	The physical dimensions of the display system, including power supplies, light sources, and display cooling but not graphics processors.	≤20 inches high ≤30 inches wide ≤40 inches deep	See *Justification* in Table 1-4 for qualification of these dimensions.
Weight	Pounds	The weight of the display system, including power supplies, light sources, and display cooling but not graphics processors.	≤100 pounds per separate component to allow manual handling during retrofit installation. Total display system weight ≤400 pounds.	Excludes Silicon Graphics and other image data sources.

1.2.2 Justification of Preliminary Requirements

Table 1-4 describes the justification for each preliminary display requirement given in Table 1-3. Where possible, direct empirical sources are cited to justify requirements. Some requirements were established on the basis of past display development programs. Some requirements are NASA LaRC requirements established in the SOW for this program.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System.

Display Parameter	Unit	Justification of Selected Value
Acceleration	Gravities (g)	Expected acceleration will depend on specific simulator or airframe design as well as flight profile. However, the preliminary requirement is based on a best estimate of reasonable acceleration tolerance for a large commercial jet aircraft such as the 737 or 757 (used in a research capacity)
Aliasing	Subjective	Visible aliasing is likely to significantly degrade the apparent image quality of the display and could degrade display legibility. Visibility of aliasing will be strongly impacted by apparent pixel/line density and number of and distribution of gray scale steps, with aliasing generally less visible as these other display factors increase.
Altitude (Pressure)	Feet	Assumes 15000 feet is maximum equivalent pressure altitude of pressurized cockpit or cabin per RTCA/DO-160C. Furthermore, assumes all display system components are to be located within a pressurized compartment. Also assumes failure of display system is permissible should loss of cabin pressure occur.
Aspect Ratio: Display Image	Ratio	Minimum NASA LaRC requirement, based on expected display formats. A 1920 x 1080 pixel count with square pixels will yield an image aspect ratio of 1.78:1.
Aspect Ratio: Pixel	Ratio	Based on Burnette (1976), cited in Decker et. al., (1987), p. 44. Using a 5x7 character matrix on a simulated matrix-addressed display, Burnette (1976) demonstrated superior reading speed, search time, and low reading errors for square, monochrome pixels versus vertically rectangular and horizontally rectangular pixels. A delta-triad arrangement (additive color) with square color elements has also been demonstrated to offer satisfactory image quality at high pixel densities.
Astigmatism: Oblique	Diopters	Astigmatism contributes to image blur and is therefore reflected in the requirement for MTF. See *MTF*.
Chromatic Aberration	Diopters	Chromatic aberration contributes to image blur and is therefore reflected in the requirement for MTF. See *MTF*.
Color Element Failures	Percent, Total	Decker at. al., 1987 and Lloyd et. al. 1991 presented performance data that indicate that random monochrome cell failures below 0.5% will not effect search accuracy or speed of reading, regardless of failure polarity. No data are known to exist regarding tolerance to element failures in color displays. However, related Honeywell display programs (i.e., MEDS, B777) have addressed color element failures. To allow for image quality effects, the maximum allowable element failures for red and green elements was taken to be 50% below the performance criteria from Decker and Lloyd. Blue element failures are likely to be more tolerable due to the relative insensitivity of the eye to small blue elements (i.e., small-field tritanopia) and therefore a higher failure rate is allowed. Cluster tolerances are derived from target values in the MEDS program.
Color: Maximum Gamut and Uniformity	u', v'	Primary color coordinates are based on the actual color gamut of the 757/767 cockpit CRTs. The target color gamut for the B777 LCD is more constrained, especially with regards to red, but may represent a more readily obtainable gamut for LCD-based display systems. The uniformity requirement is based on target values from the MEDS program.
Coma	No Units	Coma contributes to image blur and is therefore reflected in the requirement for MTF. See *MTF*.
Comfort	No Units	Discomfort is assumed to jeopardize pilot acceptance and possibly pilot performance.
Convergence Control	No Units	Assuming that display convergence is susceptible to drift, a means is required to calibrate convergence. In the event that automated convergence calibration is provided, the ability to manually control convergence is still required because the resolution of automated control may be insufficient.
Cooling	No Units	Based in part on comments from NASA LaRC EFSS and in part from ANSI/HFS 100-1988.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Crosstalk	Percent	Experience with the Tektronix SGS 620 field-sequential stereoscopic CRT (e.g., Reinhart, 1990) indicates that typical leakage values of 10% to 20% for white images leads to unacceptable levels of ghosting. Ghosting detracts from the stereoscopic presentation by adding a perception of artificiality, and in extreme cases may interfere with stereoscopic fusion. The acceptable limits and performance consequences of ghosting have not been adequately studied, however. A maximum value of 5% was selected by subtracting 3% from the leakage levels typically experienced for the red phosphor in the SGS 620 system, which appeared to be minimally acceptable for wire-frame images. Convergent evidence for selection of this value comes from laboratory measurement of rear projection screens at Honeywell (i.e., Jachimowitz and Trimmier, 1991), where 5% crosstalk was identified as the threshold for subjective acceptability.
Dipvergence	Degrees	Stereoscopic viewing is particularly sensitive to vertical disparities existing between left and right images. Vertical disparities are often the result of using a convergent stereo camera geometry, a rotational stereoscopic transformation algorithm, or misaligned display optics. Vertical misregistrations as small as 19 arcminutes may produce immediate eye strain, while diplopia (double images) will occur at 45 arcminutes of dipvergence. Sensitivity to dipvergence will increase as a function of time, so lower thresholds should be designed to. For example, dipvergence thresholds as low as 5 arcminutes have been reported. Furthermore, smaller amounts of dipvergence may degrade stereoscopic image quality without producing eye strain. Dipvergence in stereoscopic displays may be minimized through careful control of factors such as field curvature and distortion.
Distortion	Percent	Based on typical distortion tolerance allowed in Honeywell optical designs.
Drift	No Units	A 20% maximum drift over 24 hours ensures that no parameter may drift out of the required range in less than 5 days. Specification of drift requirements for image registration and dipvergence ensures control of image position.
Dwell Time	Micro-Seconds	Large dwell times will limit the total number of pixels and the refresh rate.
Field Curvature	Diopters	Based on typical field curvature tolerance allowed in Honeywell optical designs.
Field of View: Instantaneous, Monocular	Degrees	Based on assumption that 100% binocular overlap will lead to superior viewing comfort and stereoscopic performance. Consequently, monocular IFOV is specified as equal to binocular IFOV .
Field of View: Instantaneous, Binocular	Degrees	Based on assumption that a knothole effect is undesirable. Consequently, binocular IFOV is specified as equal to binocular TFOV .
Field of View: Total, Binocular	Degrees	Minimum TFOV based on requirement for preferred resolution. Preferred TFOV based on minimum requirement for resolution.
Field Rate	Hertz	In order to satisfy the minimum requirements for frame rate, time-multiplexed displays (including conventional spatially-interlaced displays) must use field rates faster than the frame rate by a factor of the number of fields composing each frame. As an example, contemporary field-sequential stereoscopic CRTs incorporating 120 Hz stereoscopic field rates (60 Hz frame rate) have been demonstrated to offer "flicker free" performance.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Flicker	Subjective	While flicker has generally not been shown to be associated with specific performance decrements, the presence of flicker is acknowledged to be a distraction and, in general, detracts from overall subjective image quality. Related display design parameters which will influence flicker include frame and field rate, image persistence, FOV, and luminance.
Frame Rate	Hertz	Minimum is NASA LaRC Requirement. Generally, a 60 Hz frame rate is sufficiently high to produce a flickerless display. However, as display luminance and FOV increases, corresponding increases are also seen in the critical flicker frequency.
Gray Scale: Shades of Gray per Color Primary	Total	Prior research at Honeywell (Reinhart, 1992; Silverstein et. al., 1989) has addressed the identification of an asymptotic gray-scale level for subjective image quality; that is, the maximum number of gray steps beyond which no further improvements in subjective image quality may be expected. By in large, for binary, color, graphic line images displayed on LCDs ranging from 150 to 200 dots per inch (dpi) and viewed at 28 inches, the use of 3 bits of linearly distributed gray scale antialiasing per color channel (8 levels of gray, where the first level is the "off" state) produces asymptotic subjective image quality ratings. However, experience both at Honeywell and elsewhere suggests that 32 or more levels of linearly distributed gray scale (per color channel) may be required to display video imagery (see discussion of *resolution*), with the requirement being contingent on application and figure of merit. The use of a power function to distribute gray scale (see below) may lead to more economical use of gray scale and a need for fewer discrete steps.
Gray Scale: Distribution of Luminance	Equation	Minimum requirement is to insure smoothly varied gray scale. Preferred may be a distribution in the form of a power function, because is well known that the perceptual dimension of brightness is not linearly related to luminance (e.g., Carter, 1993). Rather, brightness is best expressed as a Stevens' power function of luminance (e.g., brightness = luminance^a, where $0 < a < 1$). Although values recommended for the exponent in this power function vary (see Hartmann et. al., 1993), values of 0.3 to 0.5 appear to be typical. Although a factor of the square root of 2 is a frequently used guideline for separation of gray scale steps (e.g., Rash et. al., 1990; Farrell and Booth, 1984), this factor tends to exaggerate separation of gray scale steps at all but the lowest levels. A power function of the general form $\Delta L = L^{1/3}$, where ΔL is the minimum change in luminance from the gray scale step with luminance L, provides a more perceptually even distribution of luminance. In either case, it should be noted that the visual threshold to gray scale changes (as measured in controlled laboratory conditions) is likely to be smaller than is suggested by the separation given by these functions. The consequence of the nonlinearity of the luminance-brightness relationship is that linearly spaced gray steps on a display are perceptually inefficient, with gray steps at the high end of the luminance range appearing to be very fine and gray steps at the low end of the luminance range appearing to be very coarse. The practical implementation of such an algorithm is uncertain and must be empirically validated. Preliminary results at Honeywell suggest a strong dependence on image class.
Head Motion Box	Inches	Based on estimate of minimum reasonable tolerance, allowing for imprecision in seat height adjustments, variable posture, and uncontrolled head movements. This parameter is not distance invariant and is therefore not expressed as an angle (i.e., the minimum head motion box should not change in size with changes in the designed head or image position).

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Head Relief	Inches	Minimum based on estimate of minimum head clearance necessary to maintain safety from accidental injury during ingress, egress, and uncontrolled movement of the whole body or head. Although the typical head relief for HUD combiners in military aircraft is 22 inches (F-14A) to 33 inches (F-15) (Egan and Goodson, 1978, p. 23), the head relief for the Flight Dynamics HUD combiners in transport aircraft is only 12 inches at the design eye reference point (Aarons, 1991). Use of a smaller head relief will allow greater freedom in selection of a collimation method, but should only be allowed if involuntary upper body movements are restricted through the use of conventional aircraft lap and shoulder belts. Maximum head relief based on typical design eye reference distance for conventional primary flight display (e.g., Boeing 777). Use of larger head reliefs could jeopardize the visibility of such displays as well as pilot reach to cockpit instruments. Preferred head relief is based on the range from the average military HUD head relief and the maximum head relief, assuming a larger head relief will enhance operational safety. The use of fold-away, break-away, or padded components may also improve safety.
Humidity: Operating	Relative Humidity	Based on estimate of ambient humidity range in aft compartment during normal operation.
Humidity: Storage	Relative Humidity	Based on estimate of ambient humidity range in aft compartment during storage.
Image Depth	Inches	The depth viewing volume created by synthetic stereoscopic displays is predicted by the geometry of the two converging optical axes of the eyes and the position of left- and right-eye viewing elements. When the projected optical axes cross beyond the plane of accommodation, images are said to be seen in display space with uncrossed disparity, the net perception being that of the object existing behind the plane of accommodation. When the projected optical axes cross before the plane of accommodation, images are said to be seen in viewer space with crossed disparity, the net perception being that of the object existing in front of the plane of accommodation. The theoretical limit for perceived crossed disparity depth is determined by the distance of the viewer to the plane of accommodation, but the inability of observers to fuse stereo pairs with extreme crossed disparity and accurately interpret fine increments in this perceived space places the practical limit at a much smaller value. For uncollimated displays, the maximum apparent depth in viewer space after which binocular fusion is impossible has been estimated to be approximately 45% of the image distance from the observer (Yeh and Silverstein, 1990b). However, Williams and Parrish (1991) recommend 25% as a limit for comfortable viewing. As vergence angles approach zero (i.e., as the projected optical axes of the two eyes approach parallel), the theoretical limit for perceived uncrossed disparity depth approaches infinity. Yeh and Silverstein (1990b) report a maximum fusion limit for uncollimated displays of approximately 250% of the image distance, while Williams and Parrish (1991) recommend a limit of approximately 60% to ensure accurate and comfortable viewing. For collimated displays, Parrish et. al. (1993) demonstrated that uncrossed depth is unusable when large image distances are used (collimation near infinity). As the degree of collimation is reduced, the utility of uncrossed depth is likely to increase.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
		The above guidelines can be translated to approximate distance units for maximum crossed and uncrossed disparity using the following equation: $D_a = D_v S_d/(I_{pd}-S_d)$, where D_a is the apparent depth of the stereoscopic form relative to the accommodation distance, D_v is the image distance, I_{pd} is the interpupillary distance, and S_d is the horizontal disparity, all expressed in distance units (Cormack and Fox, 1985). For uncrossed disparities, values of D_a and S_d are expressed as positive numbers. For crossed disparities, S_d and D_a are negative numbers. Values of D_a increase to infinity for crossed disparities when I_{pd} is equal to S_d. The value of D_a is 50% of D_v when the absolute value of S_d is equal to I_{pd}. To calculate the maximum disparity as percentages of D_v, a general form of the equation can be derived as follows: S_d=percent/100(I_{pd}-S_d). Using a value of 72 mm to represent the largest expected I_{pd}, the crossed disparity requirement is calculated to 24 mm for 25% of the image distance (remembering to express S_d as a negative number for crossed disparity). For positive disparity, the requirement is calculated to be 56 mm for 60% of the image distance. Note that the extent to which these guidelines, developed for uncollimated displays, will generalize to collimated displays is untested.
Image: Depth Addressability	Percent	Depth aliasing is likely to significantly degrade the apparent image quality of the display and could degrade display legibility and control. The depth addressability of contemporary stereoscopic displays does not come close to approaching the limits of human stereoscopic acuity, and jagged image features as well as discontinuous object motion are commonly seen in 3-D images. Subpixel addressing (e.g., Diner and Sydow, 1991) may be used to reduce depth aliasing.
Image Distance	Inches	Accommodation distances as close as 12 inches would be minimally tolerable for comfortable accommodation (ANSI (HFS 100-1988)), but a larger distance is likely desired to approximate conformal display.
Image Persistence	Milliseconds	To avoid smearing of images, no visual evidence of a display image should remain on the display longer than one frame cycle after the image has been commanded to be removed. Image persistence should be based on field rate for time-multiplexed color displays and time-multiplexed stereoscopic displays to minimize crosstalk. NASA LaRC experience with time-multiplexed projection CRTs (120 Hz field rate) indicates that green phosphor persistence must be less than 2 ms to prevent excessive crosstalk; this corresponds to a persistence of approximately 24% of the inverse of the field rate (8.3 ms/cycle). Tektronix CRT-mounted LC stereoscopic shutters use a horizontal split (two shutters, one above the other) to allow longer phosphor decay times with less crosstalk. Selection of minimum persistence should allow compliance with display luminance, display flicker, and crosstalk requirements.
Image Retention	No Units	Retained images can reduce display contrast and introduce visual artifacts in images currently displayed.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Interaction Method	No Units	Devices for 3-D interaction may be generally viewed as operating linearly (e.g., thumbwheel), on a plane (e.g., trackball), or in a volume (e.g., magnetic or inertial sensor for hand position). Beaton et. al. (1986;1987) have demonstrated the accuracy advantages of manipulating 3-D images with an array of linear controls and Reinhart (1990;1991) has demonstrated the effective use of a combined thumbwheel-trackball approach. Both of these approaches allow selective isolation of control to discrete lines and planes within the 3-D volume, a possible advantage in an airborne environment due to vibration and acceleration. The penalty for these approaches is a reduced speed of control. Volumetric techniques (e.g., Reising et. al.) have shown positive laboratory performance and allow a more natural and rapid interaction with 3-D images but may be prone to acceleration, vibration, and calibration problems.
Interlacing	Ratio	NASA LaRC requirement.
Jitter	Degrees/ Second	Derived from maximum ANSI (HFS 100-1988) jitter for workstation displays.
Line Failures	Percent	Decker at. al., 1987 and Lloyd et. al. 1991 presented performance data that indicate that random monochrome line failures below 0.5% will not effect search accuracy or speed of reading, regardless of failure polarity. No data are known to exist regarding tolerance to line failures in color displays. However, line failures are likely to degrade subjective image quality and may lead to inadvertent errors in displayed color. A randomly occurring line failure could also interfere with display legibility if it is coincident with small characters or symbols. Related Honeywell display programs (i.e., MEDS, B777) have target values of zero line failures for these reasons.
Luminance	Foot Lamberts (fL)	NASA LaRC minimum requirement for luminance. A higher luminance at the display will be required if a reduction in luminance due to transmission loss as a function of stereoscopic selection devices is anticipated.
Luminance Asymmetry	Percent	Honeywell laboratory investigations have been conducted to determine the effects of stereoscopic HMD asymmetries on helicopter pilot performance (e.g., Lippert, 1990). Luminance imbalances as small as 15% will be detectable by pilots.
Luminance Contrast	Contrast Ratio	Preferred ANSI (HFS 100-1988) contrast ratio for workstation displays is 7:1. Although there appears to be little performance benefit associated with higher contrast ratios on binary displays, a higher value will be required in order to achieve meaningful separation of gray scale steps. The value of 50:1 is derived from the MEDS program. A more demanding target CR (100:1) is found in the B777 program, but the lack of high levels of ambient illumination in the aft flight deck and motion-base simulation environments should allow selection of a lower display contrast.
Luminance Control	No Units	Periodic calibration of luminance symmetry requires provision of luminance balance control.
Luminance Half-Life	Hours	Based on estimate of tolerance to interruptions for servicing the display. For comparison, a typical LCD cold cathode fluorescent backlight has a luminance half-life of approximately 10,000 hours.
Luminance Nonuniformity	Percent	Maximum ANSI (HFS 100-1988) large and small area luminance variations for workstation displays are 50%. However, more conservative values were derived from the transmittance uniformity target in the MEDS program (20% and 10%) as more consistent with the requirement for symmetry between stereoscopic image sources.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Misconvergence : Spatial	Percent	Data cited in Silverstein at. al. (1985) indicate that noticeable decrements in performance and image quality will occur for misconvergence values beyond 1 arcminutes (0.0167 deg) or 33% of line width. Since apparent misconvergence is sensitive to line width, the line width figure of merit was selected.
Misconvergence : Temporal	Subjective	A generally recognized problem with time-multiplexed color displays is the potential for perceptual color separation associated with relative head/display movements. It is assumed that such color separation is not acceptable for this display application.
Modulation Transfer Factor (at display resolution)	MTF	This general expression of optical quality is assumed to encompass optical aberrations such as coma, spherical aberration, chromatic aberration, and astigmatism. A modulation transfer factor of 0.3 at the limiting resolution of the display has been used at Honeywell to represent the threshold ability of observers to see modulation. In theory, however, a more complete characterization of usable display modulation is obtained by comparing a complete modulation transfer *function* with an observer contrast threshold function.
Packaging	No Units	NASA LaRC requirement for research aircraft.
Pixel Count / Line Count	Total	NASA LaRC requires a minimum 1280 x 1024 pixel format. To meet the minimum required image aspect ratio and wide horizontal binocular TFOV, either an alternative high definition format is required or tiling of multiple displays (introduces risk of tiling artifacts).
Power	Amperage, Voltage, Frequency	NASA LaRC estimate of 757 TSRV capabilities. Use of external power converters to provide 60 Hz power for TSRV installation is discouraged by NASA for reliability and ease of handling reasons.
Reflectance: Diffuse	Percent	Based on twice the target value used in the MEDS program, because glare sources are expected to be considerably less common in the simulation environments being designed for.
Reflectance: Specular	Percent	Based on twice the target value used in the MEDS program, because glare sources are expected to be considerably less common in the simulation environments being designed for.
Refresh Rate	Hertz	See *Field Rate* and *Frame Rate.*
Registration Accuracy	Degrees	Based on approximately 10 times the accuracy achievable in precision-mounted HUDs (e.g., Wood, 1991, p. 349). It is estimated but not tested that this value will be sufficient for spatial orientation and control.
Resolution	Pixels/Deg or Lines/Deg	A recent Honeywell display simulation (32 linear gray scale levels, stereoscopic viewing, subtractive color, 40 fL max white, 40:1 CR, and 70% aperture ratio) demonstrated excellent image quality for video images at as low as 32 pixels/deg. Given the similarities between the requirements of the Panoramic, 3-D Flight Display System and the display simulation referenced, 32 pixels/deg was specified as a minimum resolution. To allow for variance between the simulation and the display system being designed (e.g., the possible use of additive rather than subtractive color, the possibility of a lower aperture ratio), a preferred resolution is specified as 25% higher than the minimum resolution. Note that for additive color displays, the number of rows or columns of color elements must be converted to pixels to calculate resolution. For example, for a delta triad arrangement of three color primaries, the number of rows is multiplied by $1/\sqrt{3}$ (approximately 0.577) to obtain an equivalent number of pixels. The equivalent image quality of additive and subtractive color displays with equal resolutions calculated in this fashion is only estimated and should be tested. Note also that aperture ratio will have a significant impact on required resolution due to its effect on the visibility of line structure in the image. Simulations are currently being conducted at Honeywell to address these issues.
Service Date	Year, Quarter	NASA LaRC estimate.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Shock	Gravities (g)	Expected shock will depend on specific simulator or airframe design as well as flight profile. However, the preliminary requirement is based on a best estimate of reasonable shock tolerance for a large commercial jet aircraft such as the 737 or 757 (used in a research capacity). This preliminary requirement for impulse shock generally applied to the system via the aircraft or simulator airframe and does not address impact shock directly applied to any optical elements or other specific display system components.
Smearing	No Units	Smearing degrades image quality and the effective display system MTF for moving objects. Smearing can be a significant problem with LCDs, especially at low temperatures.
Speckle	Subjective	In addition to detracting from the overall subjective image quality, speckle has been demonstrated to degrade the effective modulation transfer function of the display.
Spherical Aberration	Diopters	Spherical aberration contributes to image blur and is therefore reflected in the requirement for MTF. See *MTF*.
Stability	No Units	See *Drift*.
Stepping Artifacts	No Units	Stepping artifacts such as luminance banding are assumed to be a specific case of aliasing. See *Aliasing*.
Temperature: External	Degrees	Based on recommendations for maximum external display unit temperatures found in ANSI/HFS 100-1988.
Temperature: Operating	Degrees	Based on estimate of ambient temperature range in aft compartment during normal operation.
Temperature: Storage	Degrees	Based on estimate of ambient temperature range in aft compartment during storage.
Tiling: Pixel Registration	Percent	Based on the estimated maximum tolerable misregistration. While smaller values are desirable, technology constraints will make this unlikely.
Tiling: Luminance Nonuniformity	Percent	Visible tile seams in the form of abrupt changes in display luminance are assumed to be unacceptable distractions which may interfere with display legibility as well as stereoscopic fusion. The luminance uniformity requirement for tiled displays is assumed to be a special case of the general requirement for large-area luminance uniformity. Visible tile seams intersecting the center of the image are assumed to be especially undesirable.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Transmittance (Head-Mounted Transparencies)	Percent	The transmittance of head-mounted transparencies such as stereoscopic selection eyewear will impact both the net display luminance at the eye and the luminance of other cockpit instrumentation. It is important to note that this requirement applies to the transmittance of the transparency itself, irrespective of any other display selection devices incorporated (e.g., display-mounted shutters) and therefore is principally directed at controlling the visibility of cockpit objects other than the Panoramic, 3-D Flight Display System (e.g., head down displays). Although a 100% transmittance is optimally desirable, reduced transmittance of cockpit light to the eye is acceptable provided there is not a large difference between the net luminance of the display (to the eye) and that of other cockpit displays. Assuming that a typical maximum luminance of self-luminous head-down cockpit displays is 100 fL white (e.g., Boeing 777, MEDS), a head-mounted transparency transmittance as low as 30% will yield a luminance of 30 fL (to the eye) for such displays, which matches the minimum required luminance of the Panoramic, 3-D Flight Display System. Convergent evidence that a 30% transmittance will be acceptable is that conventional sunglasses (typically 20%-30% transmittance) are currently allowed in the cockpit. A 60% transmittance is preferred to allow a luminance match if the preferred luminance for the display is used (i.e., 60 fL). Note that transparencies with low transmittance may not allow visibility of reflective cockpit displays unless supplementary instrument lighting is provided.
Transparency (See-Through)	Percent	The display system is assumed to incorporate synthetic image generation, with no forward scene available for viewing through a transparent display in either the aft cockpit or the motion-base simulator. Consequently, no display transparency is required.
Update Rate	Hertz	The effects of mismatches between update rate and refresh rate on moving objects will depend on the velocity and duration of movement (see Lindholm, 1992). For very short durations and steady eye fixations, jerky movement will be seen. For longer durations and smooth pursuit eye movement, images will appear blurred and have reduced contrast, the magnitude of degradation depending on the extent of the mismatch. A similar but separate perceptual phenomenon is *smearing*.
Vibration	Frequency (Hz), Power Spectral Density (PSD), Hours	Expected vibration exposure will depend on specific airframe and engine design as well as flight profile. However, the values given are representative of those included as target test requirements for the B777 DU Program. It is possible, and perhaps likely, that a more relaxed requirement will be suitable for the Panoramic, 3-D Flight Display System when used for simulation.

Table 1-4. Justification of preliminary display requirements for the Panoramic, 3-D Flight Display System (continued).

Display Parameter	Unit	Justification of Selected Value
Volume (Dimensions)	Inches	Several possible installation concepts are possible, each with implications for the volume constraints on the display system. The display could be installed at eye height, essentially presenting a synthetic window. Alternatively, the display could be installed in the location of contemporary head down displays (i.e., PFD, NAV, EICAS, etc.). The maximum display height was selected to be compatible with either installation. In either installation, there is also question as to whether a new aft cockpit simulator cab or ground-based simulator cab will be developed, or whether retrofit of the existing 737 TSRV simulator cab will be selected. The maximum display depth is likely to be compatible with an upper installation in either a new or retrofit cab. However, a lower installation assuming retrofit will be complicated by existing compartment equipment such as rudder pedal linkage. If a limited retrofit is desired, significantly greater detail must be considered regarding the existing equipment dimensions. Finally, assuming the display is to be used by a single viewer, and that it may be desirable to make side-by-side comparisons of the Panoramic display with conventional displays, a maximum display width was selected which occupies approximately 50% of the width of the 737 TSRV aft-compartment simulator instrument panel.
Weight	Pounds	Based on estimated manual handling requirements for retrofit installation in TSRV. TSRV is assumed to have moveable ballast to accommodate introduction of relatively heavy test equipment without perturbations of center of gravity.

1.2.3 Calculation/Measurement of Display Parameters

The value of most display parameters is contingent on the operational definition of the parameter as well as the measurement technique applied. Therefore, those display parameters cited in the display requirements which have potential for ambiguity have been reduced to operational definitions in Table 1-5. While no such table can be complete, Table 1-5 may be used in conjunction with Tables 1-3 and 1-4 to establish more clearly what is meant by each requirement, and the extent to which the requirement is a reasonable one.

Table 1-5. Calculation/measurement of display parameters referenced in Table 1-3.

Display Parameter	Unit	Calculation/Measurement
Aliasing	Subjective	Eight viewers should serve as subjects in a test of aliasing visibility. Subjects should be between 18 and 35 years old including both males and females, or a representative sample of the target population who will use the display. If visual acuity or color normalcy are important attributes of the target population, these should be tested as well. The display should contain representative imagery normally encountered during simulator use, with display luminance set as high as would normally be used. The display used for testing should be of a representative apparent pixel density and images should be used with representative amounts and distributions of gray scale. Subjects should view the display from the center of the head motion box and move their visual attention across the binocular TFOV of the display. For each class of imagery, subjects should indicate whether they see aliasing, in the form of spatial discontinuities, jagged lines, or color banding. To be considered "aliasing free," at least 90% of subjects should report no aliasing for the conditions tested.
Color Element Failures	Percent, Total	Percentage color element failures may be calculated as follows: $(\text{Elements}_{failed} / \text{Elements}_{total})100$, where Elements_{failed} is the total number of failed color elements for red, green, or blue and Elements_{total} is the total number of active pixels. Color elements may fail "on" or "off." Allowable clusters are total allowable clustered failures, where a cluster is defined as two or more adjacent color elements of the same color.
Color: Maximum Gamut and Uniformity	u', v'	Large area chromatic uniformity is determined by measuring u', v' coordinates from the center and corner lines of sight. Small area chromatic uniformity is calculated using the points of largest difference within a 0.5 deg portion of the display TFOV. Uniformity measurements should be made for all three color primaries (red, green, blue) as well as white. The conversion to 1931 CIE x, y from 1976 CIE u'v' is as follows: x = 27u'/4/[(9u'/2)-12v'+9], y = 3v'/[(9u'/2)-12v'+9]. The conversion from 1931 CIE x, y to 1976 CIE u'v' is as follows: u' = 4x/(-2x+12y+3), v' = 9y/(-2x+12y+3).
Crosstalk	Percent	Crosstalk may be measured by presenting a white image to one stereoscopic channel but not the other. The luminance of the image should be measured as seen from each channel (e.g., through each lens of stereoscopic glasses). The selection leakage is defined as follows: leakage = $(\text{Luminance}_{off} / \text{Luminance}_{on})100$, where Luminance_{off} is the luminance as measured through the nonselected channel and Luminance_{on} is the luminance as measured through the selected channel. This measurement should be performed from the center line of sight, as well as the four corner lines of sight. This procedure should be repeated for red, green, and blue. This procedure should be repeated with the image being sent to the other stereoscopic channel.
Dipvergence	Degrees	Dipvergence may be measured in the following way. A calibration image constructed of numbered horizontal lines should be presented to each display channel, with the vertical position of selected lines noted with respect to a fixed reference (e.g., a viewing reticle). Samples should be taken at multiple positions on the lines and for multiple lines because image rotation or other image distortions may exist. The physical vertical separation of equivalent test image lines can be converted to degrees of visual subtense as: $2 \tan^{-1}(V/2F)$, where V is the vertical separation of equivalent test lines and F is the focal length of the display optics.
Distortion	Percent	Distortion is commonly measured by displaying a uniform grid pattern and measuring the maximum deviation in the displayed grid positions from the expected distance from the center of the grid. Distortion is then calculated as: $2(\lvert h_2-h_1\rvert)/(h_2+h_1)100$ or $2(\lvert v_2-v_1\rvert)/(v_2+v_1)100$, where h_1 and h_2 correspond to the expected and measured horizontal distance from the center of the grid and v_1 and v_2 correspond to the expected and measured vertical distance from the center of the grid. These calculations should be made as a minimum with respect to the four corner lines of sight.

Table 1-5. Calculation / measurement of display parameters referenced in Table 1-3 (continued).

Display Parameter	Unit	Calculation/Measurement
Dwell Time	Micro-Seconds	Dwell time is calculated as: (Duty Factor) (Frame Rate^{-1}), where duty factor is the time spent addressing each pixel. Duty factor is the inverse of the smallest number of display units (pixels or lines) which must be addressed within each frame (e.g., line-addressed displays have a significantly higher duty factor than scanned displays with an equal number of pixels).
Field Curvature	Diopters	Field curvature should be measured, as a minimum, from the center line of sight, as well as the four corner lines of sight. There are several measurement methods, and the most appropriate for the design will be selected.
Field of View: Instantaneous, Monocular	Degrees	Instantaneous, monocular FOV is calculated as a percentage of the instantaneous, binocular FOV.
Field of View: Instantaneous, Binocular	Degrees	Instantaneous, binocular FOV is calculated as a percentage of the total binocular FOV.
Field of View: Total, Binocular	Degrees	Total, binocular FOV is calculated as: Pixels/Resolution, where Pixels is the total number of pixels either horizontally or vertically and Resolution is the number of pixels per deg either horizontally or vertically. Alternatively, FOV may be calculated as: $2 \tan^{-1}(I/2F)$, where I is the horizontal or vertical extent of the image source and F is the focal length of the display optics.
Flicker	Subjective	Twenty viewers should serve as subjects in a test of flicker visibility, each viewer allowed to adapt to the normal light levels of the simulator environment for ten minutes prior to testing. Subjects should be between 18 and 35 years old including both males and females, or a representative sample of the target population who will use the display. If visual acuity or color normalcy are important attributes of the target population, these should be tested as well. The display should contain representative imagery normally encountered during simulator use, with display luminance set as high as would normally be used. Subjects should view the display from the center of the head motion box and alternatively fixate at the center of the binocular TFOV and 20 deg to the right of the right edge of the binocular TFOV for 15 seconds each. At each fixation point, subjects should indicate whether they see flicker. To be considered "flicker free," at least 90% of subjects should report no flicker for the conditions tested.
Gray Scale: Shades of Gray per Color Primary	Total	To verify the total number of gray shades available per color channel, the luminance of the display should be measured in a dark room while each primary color channel is addressed from zero in the smallest increments possible.
Gray Scale: Distribution of Luminance	Equation	To verify the nature of the gray scale luminance distribution, the values recorded from the above procedure should be plotted against their digitally-commanded values and a regression equation fit to the data.
Jitter	Degrees/ Second	Jitter of characters or arbitrary symbols should be measured from the center line of sight, as well as the four corner lines of sight. The maximum horizontal and vertical excursion of each character (expressed in degrees) is recorded over a one-second period. Jitter is calculated for each point as: $(H^2 + V^2)^{0.5}$, where H is the horizontal excursion and V is the vertical excursion.
Line Failures	Percent	Percentage line failures may be calculated as follows: $(\text{Lines}_{\text{failed}} / \text{Lines}_{\text{total}})100$, where $\text{Lines}_{\text{failed}}$ is the total number of failed rows or columns and $\text{Lines}_{\text{total}}$ is the total number of display rows or columns. Lines may fail on or off.

Table 1-5. Calculation / measurement of display parameters referenced in Table 1-3 (continued).

Display Parameter	Unit	Calculation/Measurement
Luminance	Foot Lamberts (fL)	Luminance should be measured from the center line of sight, as well as the four corner lines of sight. A solid white image should be used for measuring foreground luminance. A solid black image should be used for measuring background luminance. A photometer with a one deg acceptance angle is appropriate for these measurements. Photometers should be periodically checked against an NIST-traceable luminance standard.
Luminance Asymmetry	Percent	The procedure described under *Luminance* is used to measure each stereoscopic image field or image tile. Luminance asymmetry is calculated for each of the pairs of measured luminance values as: $(\lvert Luminance_{low} - Luminance_{high} \rvert / Luminance_{high})100$, where $Luminance_{low}$ represents the lowest luminance of the pair and $Luminance_{high}$ represents the highest luminance of the pair.
Luminance Contrast	Contrast Ratio	The luminance and background luminance should be measured from the center line of sight, as well as the four corner lines of sight. Contrast ratio is calculated as: $C_R = L_{max} / L_{min}$, where L_{max} is the higher of the two luminance measurements and L_{min} is the lower of the two luminance measurements.
Luminance Nonuniformity	Percent	Large area luminance nonuniformity is calculated as: $(\lvert Luminance_A - Luminance_C \rvert / Luminance_C)100$, where $Luminance_C$ is the luminance of the image measured from the center line of sight and $Luminance_A$ is the luminance of the image measured from each of the corner lines of sight. Small area luminance uniformity is calculated as: $(\lvert Luminance_{B1} - Luminance_{B2} \rvert / Luminance_C)100$, where $Luminance_C$ is the luminance of the image measured from the center line of sight and $Luminance_{B1}$ and $Luminance_{B2}$ represent the image luminance measured anywhere within a 0.5 deg circle within the TFOV. A photometer with a one deg acceptance angle is appropriate for measuring large-area luminance nonuniformity. However, an acceptance angle of no larger than 0.25 deg must be used for measuring small-area nonuniformity.
Misconvergence : Spatial	Percent	Line profiles should be measured using a scanning radiometer on a positioning stage. Misconvergence is measured as the separation of red, green, and blue primaries in a white line, vertically for a horizontal line and horizontally for a vertical line. Misconvergence of white cross-hair targets should be measured in the image from center and corner lines of sight. Misconvergence is defined as: $(line_{white} - line_{primary})/line_{primary})100$, where $line_{white}$ is the half-amplitude width of the luminance profile of the white line and $line_{primary}$ is the half-amplitude width of the luminance profile of the widest of the three primary color component lines.
Misconvergence : Temporal	Subjective	Eight viewers should serve as subjects in a test of temporal misconvergence. Subjects should be between 18 and 35 years old including both males and females, or a representative sample of the target population who will use the display. If visual acuity or color normalcy are important attributes of the target population, these should be tested as well. The display should contain representative imagery normally encountered during simulator use, with display luminance set as high as would normally be used. Subjects should view the display from the center of the head motion box and move their visual attention across the entire binocular TFOV of the display. Rapid head movement or vibration and jolting of the display system should be included in the test conditions if they are likely to be encountered in normal use of the display. For each class of imagery, subjects should indicate whether they see temporal misconvergence, in the form of color separation. To be considered "free of temporal misconvergence," at least 90% of subjects should report no color separation for the conditions tested.

Table 1-5. Calculation / measurement of display parameters referenced in Table 1-3 (continued).

Display Parameter	Unit	Calculation/Measurement
Modulation Transfer Factor (at display resolution)	MTF	Luminance modulation, M, is defined as: $(L_{max} - L_{min}) / (L_{max} + L_{min})$, where L_{max} is the higher luminance of the foreground or background, and L_{min} is the lower luminance of the two. The modulation transfer factor, MTF, is calculated for any given spatial frequency as: M_{out} / M_{in}, where M_{out} is the modulation of the image after transmission through the optical system and M_{in} is the modulation of the image prior to transmission through the optical system.
Reflectance: Diffuse	Percent	Diffuse reflectance is measured by placing a small non-directional light source (simulating a point source) in the center of the head motion box. A small white reference surface having approximately 100% Lambertian reflectance is placed at the first optical element along and normal to the center line of sight. Reflectance is given by $(Luminance_R / Luminance_{WH})/100$, where $Luminance_{WH}$ is the reflected luminance of the white reference surface and $Luminance_R$ is measured from a second point in the head box and at an angle of 10 degrees from the center line of sight, and aligned such that no specular reflection is included in the luminance measurement. The measurements are made in an otherwise dark room and with the display lamps turned off.
Reflectance: Specular	Percent	Specular reflectance is measured by aiming a photometer along the center line of sight. For each surface contributing significant, noticeable specular reflectance (where a clear image of a light source can be seen), the specular reflectance contribution from that surface is measured by placing a light source with a white diffusing filter in a location such that the corresponding specular image is sampled by the collection angle of the photometer. The reflectance contribution is given by $(Luminance_R / Luminance_S)/100$, where $Luminance_S$ is the luminance of the diffuse source and $Luminance_R$ is the luminance of the reflected image of the diffuse source. Specular reflectance is the sum the contributions from the collimating mirror, the beamsplitter, and all additional significant specular reflections. The measurements are made in an otherwise dark room and with the display lamps turned off.
Resolution	Pixels/Deg or Lines/Deg	Resolution is calculated for horizontal or vertical image directions as: pixels / FOV, where pixels is the total number of addressable pixels, either horizontally or vertically, and FOV is the binocular, total FOV. Note the distinction between color element and pixel (Table 1-2).
Speckle	Subjective	Eight viewers should serve as subjects in a test of speckle visibility. Subjects should be between 18 and 35 years old including both males and females, or a representative sample of the target population who will use the display. If visual acuity or color normalcy are important attributes of the target population, these should be tested as well. The display should contain representative imagery normally encountered during simulator use, with display luminance set as high as would normally be used. Subjects should view the display from the center of the head motion box and move their visual attention across the binocular TFOV of the display. For each class of imagery, subjects should indicate whether they see speckle, in the form of scintillating or stationary, granular alternations of light and dark. To be considered "speckle free," at least 90% of subjects should report no speckle for the conditions tested.
Tiling: Pixel Registration	Percent	Tiling registration should be measured using a scanning radiometer on a positioning stage. Tiling registration is defined as: $(\text{separation} - line_{width})/line_{width})100$, where separation is the center-to-center separation of two abutting white lines on adjacent image tiles and $line_{width}$ is the average half-amplitude width of the luminance profile of the two lines. Measurements should be made with 8 test points falling within 10% of the TFOV of the tile seam.

Table 1-5. Calculation / measurement of display parameters referenced in Table 1-3 (continued).

Display Parameter	Unit	Calculation/Measurement
Tiling: Luminance Nonuniformity	Percent	To measure tiling luminance nonuniformity, the procedure detailed for measurement of large-area luminance nonuniformity should be followed, with the exception that comparisons to image center measurements should be made with 8 test points falling within 10% of the TFOV of the tile seam.
Transmittance (Head-Mounted Transparencies)	Percent	To measure transmittance, the luminance of a white light source (nonpolarized) should be measured with a photometer both directly and through the transparency. Transmittance of the transparency is calculated as follows: transmittance = $(Luminance_{transparency} / Luminance_{direct})100$, where $Luminance_{transparency}$ is the source luminance measured through the transparency (e.g., stereoscopic selection glasses) and $Luminance_{direct}$ is the luminance of the source measured directly.

1.3 Additional NASA Display Guidelines

Additional guidelines for flight research equipment are referenced in NASA LHB 7910.1 and are presented here in Table 1-6.

Table 1-6. General specifications and standards for research electronic equipment installed in NASA LaRC research aircraft.

Reference	Title/Description
LHB 7910.1	NASA Flight Research Program Management.
MIL-C-172	Cases; Bases, Mounting; and Mounts, Vibration for Use with Electronic Equipment in Aircraft.
MIL-E-5400	Electronic Equipment, Aerospace, General Specification for.
MIL-B-5087	Bonding, Electrical and Lightning Protection, for Aerospace Systems.
MIL-W-5088	Wiring, Aerospace Vehicle.
MIL-E-7080	Electric Equipment, Aircraft Selection and Installation of.
MIL-T-8700	Installation and Test of Electronic Equipment in Aircraft.
MIL-W-22759	Wire, Electric, Fluoropolymer Insulated Copper or Copper Alloy.
MIL-SPEC-C-27500	Cable, Electrical Shielded and Unshielded, Aerospace.
MIL-P-27733	Procedures for Installation of Equipment in Aircraft for Test Purposes.
MIL-W-81044	Wire, Electric, Crosslinked Polyalkene, Crosslinked Alkene-Imide Polymer, or Polyarylene Insulated, Copper or Copper Alloy.
MIL-STD-202	Test Methods for Electronic and Electrical Component Parts.
MIL-STD-454	Standard General Requirements for Electronic Equipment.
MIL-STD-810	Environmental Test Methods.
RTCA DO-160A-80	Environmental Conditions and Test Procedures for Airborne Equipment.
T.O. 1-1A-8	Structural Hardware.
T.O. 1-1A-9	Aerospace Metals- General Data and Usage Factors.
T.O. 1-1A-14	Aircraft Electric and Electronic Wiring.

2.0 DISPLAY TECHNIQUES AND TECHNOLOGY REVIEW

This section of the report presents a summary of technologies and methods available for potential use in the Panoramic, 3-D Flight Display System. A general review is presented first, followed by a rating of technologies and methods relative to the preliminary display requirements. The review and rating material are organized by the following four technology areas:

- Image Source Technology
- 3-D Methods
- Collimation Methods
- 3-D Interaction Methods

For the purposes of the techniques and technologies review, these four areas are treated independently. The interactions among these groups are considered in Section 3 of this report. The material is presented comprehensively in the following tables, with supplementary comments provided in the body of this text.

Table	
2-1	Definition of terms used in the technology review
2-2	Survey of image source technologies
2-3	Survey of 3-D methods
2-4	Survey of collimation methods
2-5	Survey of 3-D interaction methods
2-6	Strawman requirements for rate and compare analysis
2-7	Rating of image source technologies
2-8	Rating of 3-D methods
2-9	Rating of collimation methods
2-10	Rating of 3-D interaction methods

2.1 Technology Survey

The technology survey is a summary of the candidate methods and technologies reviewed for potential use in the Panoramic, 3-D Flight Display System. The tables include a description of each method or technology, along with general discussion of major benefits and considerations for each. General categories and methods are discussed at the beginning of each table, with subsequent sections describing implementations of these categories. As described, each implementation clearly encompasses a wide variety of detailed configurational possibilities, many of which can be readily found in the relevant literature. In certain cases, the nonorthogonal nature of these methods implies that there will be some overlap among the various implementations. Additional combinations of the listed methods are possible.

The tables also list attributes and comments about the methods or technologies. While resembling a list of advantages and disadvantages, a more general interpretation is implied. No comparisons against a specific baseline are being made at this point, and an attribute which leads to a significant advantage or disadvantage in one configuration may be inconsequential in another. The headings "Benefits" and "Limitations/Considerations" were selected to be consistent with this general nature of the remarks at this stage.

Technical terminology is sometimes imprecise. In common usage, many terms take on a range of meanings, depending upon the specific context in which they are used as well as the background of the author or reader. To aid in the interpretation of the associated matrix discussions, some guidelines are given below (Table 2-1) with respect to certain terms used in those discussions. The terminology should still be interpreted based upon the context in which it is used, including any additional qualifiers.

Table 2-1. Definition of terms used in the technology review.

Term	Definition
Bandwidth	The time-averaged rate of information flow through a system or system component. For example, "channel bandwidth" refers to the bandwidth for one image source and the data path (including image data generators or sensors, image data processing and interface means) associated with it. "System bandwidth" includes the total average rate of information flow to meet the image quality objective for all displayed perspectives (e.g. both eyes for stereo) using the 3-D methods and configurations under consideration. Used without a qualifier, "bandwidth" refers to both the system and its individual components. Assumed throughout the comments in these tables is a consistent image quality objective to each eye for the various methods. Thus, for example, a stereoscopic display is assumed to provide two perspective views of image quality equal to a that of a comparable non-stereo display (i.e. would not rely on reducing the vertical resolution of each field or on changing the frame rate). Hence, the system bandwidth for the stereo display is assumed to be twice the system bandwidth of a non-stereo display. As a further example, a generic, ideal time-multiplexed single-channel system would not sacrifice resolution or frame rate as compared to a system incorporating two separate channels, one for each eye or perspective. Hence, the "channel bandwidth" for the time-multiplexed single-channel image source and data path would be twice that of the individual channel bandwidths in the two-channel system, although the display systems would have equivalent system bandwidths.
Image Source	An electro-optical display element or display device which converts image data from electrical to optical form. An image source can be either monochrome or color. Some color image sources, such as a subtractive color AMLCD image source, may be made up of multiple monochrome image sources.
Resolution	The term "resolution" typically has many connotations, including the total number of pixels, the pixel density on the display device, or the pixel density in the final image (versus angle or position). It can also be taken to include tonal resolution or grayscale, temporal resolution, or a number of other image quality or optical metrics. For the purposes of this program, we prefer to keep this term general and defined by the context. Resolution in terms of pixel density can be readily related to total number of pixels by knowing the intended image dimensions or angular FOV.
Temporal Artifacts	Temporal artifacts are any time-related anomalies which are introduced by the display (and possibly sensor or processing) components. Examples of such artifacts include image smear, lag, flicker, persistence-induced stereo crosstalk, strobe effects, discontinuous motion, and multiple images associated with interlaced/non-interlaced scanning or sensor/display refresh rate mismatch in the presence of motion. There may be instances in which motion-related artifacts could introduce spurious stereoscopic depth cues in a 3-D system.
Tiling	In both conventional displays and 3-D displays, it may be advantageous to subdivide the image source and/or the data path. This opportunity is assumed to be present in all cases, and carries with it obvious implications on the channel bandwidth of each "image source tile".

2.1.1 Image Source Technologies

This portion of the technology survey identifies and categorizes the primary image source candidates for the Panoramic, 3-D Flight Display System (Table 2-2). While no such list of display technologies can be complete, the major categories are included. With the exception of certain CRT-based displays, the candidate technologies are not currently routinely available with sufficient pixel counts to meet anticipated resolution and FOV requirements (Table 1-3) without a tiled or mosaic approach. For the technologies being most actively extended to high information content, examples of recently reported laboratory prototypes are given. It should be recognized that neither large nor small formats are favored in this survey, since the applicability of each is strongly dependent upon the collimation and 3-D methods to be considered, and both projection and direct collimation are possible.

Artifacts such as image retention and non-uniformity can occur in all of the display technologies listed. These are not explicitly discussed below, as they are quite dependent upon the details of the implementation. It is reasonable to expect that the suppression of these effects can be correlated with the maturity of the technology. Significant progress is continuing in many of these technology areas.

The key attributes for identifying a successful candidate image source technology for panoramic displays are versatility, availability, maturity and the perceived ability to meet the needs of the program. As part of the technology survey, Honeywell has reviewed a broad range of image source methods.

Out of the many possible known display technologies for panoramic systems, Honeywell has concentrated its internal development efforts on light valve projection and laser projection. A fundamental advantage of the laser and light valve approaches is the effective decoupling of resolution and luminance as competing objectives. This greatly increases the flexibility for covering large display area or functioning in high ambient illuminations. As with the projection display industry in general, Honeywell's primary interest is in development and application of Active Matrix Liquid Crystal Display (AMLCD) light valves. The laser display approach is seen, at this time, as offering potential advantages to meet special needs, with broad applicability coming later.

Alternate light valve technologies exist, but lie outside the mainstream of light valve development. One such device which deserves consideration is the deformable mirror light modulator (DMD). Research and development on this approach has been ongoing for a considerable period of time, but has been limited to a comparatively small number of companies, most notably Texas Instruments. Reported and demonstrated results have been quite promising, but are often difficult to assess in terms of real performance, reliability and path to commercialization. Because its implementation as a light valve is in many ways comparable to the use of an AMLCD light valve, AMLCD light valve conceptual designs will in many ways exhibit a reasonable physical compatibility with designs using the DMD (or other light valve).

2.1.1.1 AMLCD Light Valves. The most established light valve approach for high resolution, speed and contrast is clearly the twisted nematic (TN) AMLCD. The AMLCD is widely accepted as a highly capable technology on a strong evolutionary path. The capability of these devices continues to be improved at a rapid pace, and the cost promises to remain competitive due to the application of established processing methods and the size of the markets which can use such a device. AMLCDs provide excellent performance for both direct view and projection applications. Both of these modes have been explored for compatibility with the preliminary display requirements.

Due to practical size limitations in current fabrication methods for direct view AMLCDs, projection of these electrically addressed light valves is very appealing. Light valve projection displays are commercially available, but most current devices have insufficient resolution for use in a panoramic display. Resolution is limited by materials, processing capabilities, fabrication techniques and device bandwidth. Current AMLCD devices are well-suited for projection of television images and presentation graphics. Other LCD systems, such as laser addressed thermal smectic LCDs, provide superb resolution and gray scale, but are slow when compared with the requirements for real time displays.

A light valve, for this discussion, is a multichannel light modulator which does not produce light but rather controls light generated by an external source. Typical advantages of light valve projection systems include:

- Light valve technology is being driven by the television and computer markets to continually higher resolution and gray scale capability, although the resolution at this time still falls short of that needed for a high-resolution panoramic display.

- Light valve systems generally have no moving parts.
- Lifetime can be very long, with the possible exception of the lamp.
- The luminance and chromaticity can be made quite high through prudent lamp and optics selection.
- The lamp can be physically separated from the deflection apparatus, where heat can be more easily dissipated.
- Display luminance and resolution are less interrelated than in certain other display technologies.
- Color gamut can be large, and color matching is simplified.
- No speckle problems are expected, unless a laser or other long coherence length source is used.
- Systems can be relatively compact and light.
- Optics are generally more straightforward than in approaches requiring wider collection angles, such as high-luminance CRT projection.

Some current limitations of light valves should be stated as well:

- Current light valves leave room for improvement in one or more areas: resolution, gray scale, transmission, contrast or speed.
- System design is less straightforward if extreme luminance levels are required or if the area of coverage is large. The challenges of high source luminance, high collection efficiency and thermal effects begin to play an important role under these conditions.
- Lamp lifetime and operating considerations are generally not ideal.
- The imaging characteristics are somewhat different from those of a CRT, e.g. pixel versus raster, hence direct comparison can be difficult.
- Typically, current light valves have environmental constraints, such as temperature range, which must be checked relative to the intended application.

The general goals in selecting a light valve for a projection avionics display include:

- High transmittance in the chromatic regions of interest
- High resolution

- Good gray scale capability
- Video rate switching speed
- Compact
- Good environmental performance
- Rugged
- Long life
- Acceptable cost

The AMLCD was selected as the preferred high performance light valve for other display development efforts. While much of the current work in AMLCDs is directed toward relatively large displays such as the display unit (DU) for the Boeing 777, there is considerable interest in the miniaturization and resolution enhancement of small active matrix displays. In particular, Honeywell has been actively pursuing development of a high-resolution, small format AMLCD light valve well suited for projection displays. Key to this development is the incorporation of integrated drivers using single crystal silicon, allowing resolution of 1000 lines per inch or more. In addition to panoramic displays, this technology is also directed toward a new generation of light-weight, high-resolution, high-luminance and low-voltage head mounted displays.

Honeywell has completed a contract for developing a Miniature Color Display (MCD Final Report, 1993; Sarma et.al., 1993), based upon subtractive color LCD technology. Under this program, full-color AMLCD image sources have been fabricated at a resolution of 300 lines per inch (lpi). For applications not requiring the compact image source afforded by the subtractive color approach, more conventional additive methods have also been evaluated.

Honeywell has completed the subtractive color AMLCD portion of the ARPA-funded Kopin AMEL/AMLCD program. One of the goals of this program was to provide 1280 x 1024 monochrome AMLCD displays for integration into the CVCHMD (Combat Vehicle Crew Helmet-Mounted Display). Honeywell demonstrated a monochrome, 1280 x 1024 AMLCD at the ARPA Joint Services Working Group meeting in Washington, D.C. in June, 1994. The video rate monochrome light valves are approximately 1000 lpi, contain integrated drivers and provide 6-8 bits of tonal resolution. The light valves resulting from this program are prime candidates for use in a panoramic display system. The results of the Kopin team effort on the ARPA and Advanced Visionics System (AVS) will be essential in assessing the risk, cost and performance of an AMLCD light valve approach for the Panoramic, 3-D Flight Display System.

Use of 1280 x 1024 light valves will minimize the amount of display tiling required as compared with commercially available light valves, although some tiling may still be necessary. One option for managing the tiled segments is overlapping the segments slightly, with the smoothing of the seam adjusted electronically. A key benefit of the AMLCD approach, however, is the potential for even greater pixel densities. Considerable interest has been shown in developing even higher resolution devices, and ARPA has funded a program to develop a 2560 x 2048 AMLCD using 12-micron pixels.

2.1.1.2 Laser Projection. Laser projection offers dramatic potential advantages, such as resolution, luminance, efficiency, color gamut, reliability and flexibility. New developments and applications continually spur additional interest in this area. Recent examples include High-Definition TV, frequency-doubled diode-pumped solid state lasers, and visible laser diodes.

The components and tools for these display systems have evolved as well. Applications ranging from military systems to laser printers and optical storage have driven the technology of lasers, scanners and laser optics beyond the laboratory into markets measured in millions of units per year. Honeywell has developed a compact monochrome laser projection system for the purpose of identifying appropriate applications and addressing each of these four aspects. This "hands-on" experience provides extra insight into the questions to be asked when considering a laser display.

Unlike the AMLCD, laser projection has not yet been put into broad, routine use throughout the display industry, with the exception of large format laser entertainment displays. Several aspects of the technology remain which have thus far limited the widespread applicability of this approach. These include:

- Deflection bandwidth
- Laser speckle
- Availability of "reasonable" lasers (output power, efficiency, cost)

- Packaging (size, stability, etc.)

The relative importance of these limitations varies strongly with the nature of the application requirements.

In a typical raster-mode laser projector, the laser and modulator provide conversion from electrically encoded image data to optical form. This is directed to and focused on a screen by a pair of deflectors and an imaging lens, often an f-theta lens. The screen can be either a very simple surface or can be tailored to provide additional control of the viewing geometry or polarization. The key components to be analyzed for the Panoramic, 3-D Flight Display System are the laser(s), the fast axis deflection method, and the screen (in the context of 3-D methods).

Some of the goals in selecting a compact visible laser source are:

- Appropriate spectral (RGB) outputs (either directly or with conversion)
- High output power, for the desired luminance over the FOV and exit pupil
- Single spatial mode (TEM_{OO}) output is generally required
- Compact
- Efficient (low power consumption/heat generation)
- Good environmental performance
- Rugged
- Long life
- Acceptable cost
- Short temporal coherence length may be beneficial

Candidate lasers include gas lasers, solid state lasers, and semiconductor (diode) lasers. While gas lasers provide higher output power and a broader selection of wavelengths than visible diode or solid state lasers, the size and power requirements may be prohibitive, especially for a high luminance, flyable display scenario. Diode-pumped solid state lasers with green output have become routinely used, and several techniques can be used to create both red and blue systems. Red laser diodes have become commodity items, and shorter wavelength devices have been demonstrated. A bonus with the diode lasers is the capability for direct modulation, whereas the other types require external modulators, usually based upon acousto-optic principles.

As an alternative to a direct multi-color laser display, a laser-excited phosphor or fluorescent screen approach may also be considered. This configuration retains many of the advantages of the direct display, but yields full color with a monochrome scan engine while eliminating the potential for laser speckle. Laser speckle is a diffraction-related artifact resulting from the use of a highly coherent source with a diffusing screen and a small collection aperture (e.g. the pupil of the eye). In addition to the use of a phosphor screen, speckle can be reduced by averaging techniques and by screen selection. There is generally a trade-off, however, between speckle and such parameters as resolution, efficiency, size or weight.

Many laser scanning methods and variations are described in the literature. Four major approaches are used:

- Acousto-optic deflection
- Polygon (moving mirror) scanning
- Hologon scanning
- Galvanometer deflection

Each of these approaches has a variety of options and variations. At least three quite different acousto-optic deflection methods are well known. The first is Bragg angle deflection, where an incident beam is deflected by a refractive index grating formed by acoustically driving the deflector medium. In the second case, a frequency-chirped acoustic pulse is applied to one end of the deflector. This acts like a Bragg angle deflector as well, with the added effect of focusing action due to the frequency chirp. A portion of the incoming beam is deflected and focused to form an image spot. As the acoustic wave propagates down the length of the deflector, the focused spot sweeps out the scan line. With a third method, best suited for pulsed lasers having repetition rates in the tens of kHz, an entire line of video-modulated acoustic signal is loaded into the device. The laser pulses then read the video out, one line at a time.

The lack of moving parts in the acousto-optic approach is very appealing. Disadvantages, however, are a complex and somewhat inefficient optical layout and a strong wavelength sensitivity, which complicates matters further in achieving full color.

Polygon scanners are rotating mirror assemblies with a number of flat facets around the perimeter. These are routinely used in laser printing engines and are capable of extremely high resolution. At video rates, however, a large number of facets and quite high rotation speeds are required.

Hologon scanners are holographic analogs to the polygon scanner. One implementation is a flat disk containing transmissive holographic or diffractive gratings. The laser light is diffracted to a new angle by the grating, that angle changing with the rotation of the disk. An advantage of the transmissive hologon approach is a reduced sensitivity to wobble in the rotational assembly. Disadvantages, especially for high bandwidth applications such as real time video, include a smaller angle amplification factor and lower practical limiting speeds than for a comparable polygon.

Current galvanometer scanners fall far short of the scan rate required for the fast axis, but are the best general option for the slow scan axis. From a simplified perspective, the line scan rate for a single 1280 x 1024, 60 Hz display can be estimated to be 1024 * 60 = 61.44 kHz, whereas the slow scan axis rate is on the order of 60 Hz.

This line rate also presents a major challenge for each of the other approaches. As an example, a polygon scanner with 32 facets would have to turn at 115200 RPM to achieve this linescan rate. Although this is possible, lower speeds are much more desirable and practical. Significantly increasing the number of facets while maintaining an in-line resolution of 1280 "pixels" brings the RPM down but leads to an impractically large polygon diameter. A numerical model is in place which incorporates the beam size, facet size, duty cycle, angle amplification factor, number of facets, horizontal and vertical resolution, and motor speed to predict the diffraction limited performance of such a scan system. The analysis quickly reveals that the use of multiple laser beams provides the most fruitful path to achieving high resolution performance. Additional techniques can be implemented to improve bandwidth without additional beams, but these add optical complexity and can significantly reduce the optical efficiency of the system.

For a reasonable 1280 x 1024, 60 Hz, full-color display, each of the candidate scanning technologies will require multiple beams, perhaps a minimum of 2 to 4 per color, to keep the size and mechanical speeds within reason. The concept analysis must thus consider the complexity and configurational options of generating, deflecting, and maintaining the stability of 6 to 12 laser beams per 1280 x 1024 segment of the display. For higher resolutions, the number of beams should scale approximately with the number of pixels.

2.1.1.3 Light Sources. An advantage of the light valve approach, whether direct view or projection, is that image luminance can generally be increased without sacrificing resolution. While the increase will of course come at the expense of power dissipation, viewing angle, or other parameters, this is quite an advantage over many emissive technologies. With CRTs, for example, increasing the luminance typically leads to a resolution loss.

Selection of the light source for a light valve configuration should be based upon a number of parameters such as luminance, power, lifetime, spectrum, reliability and ease of maintenance. The candidates are quite different for direct view and projection modes. Requirements are also strongly driven by the viewing angle distribution. For example, figuring screen gain or limited exit pupil into the optical throughput greatly affects the amount of lamp output required to achieve a given luminance.

Candidate light sources might include:

- Incandescent (tungsten halogen). Direct and fiber coupled illumination are possible. Lamps are essentially instant on, and are relatively insensitive to power dropouts. Lifetimes are limited, but replacement is straightforward.

- Arc lamps (xenon, metal halide or others). Direct or fiber coupling are again options. Efficiencies are significantly higher than incandescent sources, but warm-up times apply, and special measures may be required to restart the lamps if they go out. The small arc is well suited to efficient projection without large aperture optics. Lifetimes are typically short to moderate, although certain compromises in custom lamp design can increase this. Replacement can be less straightforward due to high pressures in the lamps, and lamp orientation can be important unless special design precautions are taken.

- Fluorescent lamps. Lifetime, efficiency, and power consumption are advantages, but obtaining high luminance can be difficult. Fluorescent lamps are best suited for direct view applications due to their extended source nature.

For high output applications, the arc lamps have the highest capability. Tradeoffs may be necessary if luminance and viewing angle requirements are high and power is limited. A tri-band form of the metal halide arc lamp is currently being developed under ARPA funding. This approach offers the potential for increasing luminance further or reducing the input power and cooling requirements.

2.1.1.4 Projection Screens. The projection screen is a very important component of a projection display. Even in a collimated display, it may be necessary to include a projection screen prior to the collimation element(s). Screen gain, size, and transmission/reflection characteristics must be considered when selecting a screen for a particular application. In some stereoscopic configurations involving polarization methods, image depolarization may lead to unacceptable stereo crosstalk. Other competing attributes may be desirable, such as high or low screen gain. These parameters are often interrelated and involve tradeoffs in the screen selection process. Special screen techniques, such as diffractive and surface relief structures, offer unique design capabilities which can be applied to system designs. For example, low gain and low image depolarization can be provided simultaneously.

Screen gain characteristics, as a function of bend angle, determine the relative luminance and viewing zone of a particular screen. In panoramic display applications requiring a large horizontal FOV, projecting images on the edges of the screen result in a large bend angle to get to the viewer. Many screens exhibit a falloff beyond a bend angle of 20 deg. Hot spots can be eliminated through the use of a low gain screen or additional structures such as a Fresnel field lens. A large head motion box also dictates the screen gain required. Often, the head motion box requirements can be different for horizontal and vertical axes. Several screen techniques allow discrimination in this way.

Screen transmission/reflection can strongly affect the performance of a projection display in the presence of ambient light. Reflection or backscattering can lead to lower image contrast and even make the image unviewable. With conventional diffusing screens, those with the widest viewing angle generally have the highest reflection. Again, certain special screen techniques can help in this regard. Contrast enhancement techniques, both conventional and unconventional, can be applied to further minimize backscattering on rear projection screens. Front projection screens pose a particularly difficult challenge in rejecting ambient light, although there are methods available to overcome this problem.

Diffractive and refractive microstructures can be incorporated into the screen design to improve the screen gain (luminance) and uniformity across a large field. The microstructures serve to scatter the light at the display surface into a controlled, modest solid angle for the viewer. The goal is a better match between the cone angle of the light coming from the projector and the viewing angle of the eye, with the diffusion envelope of the display matching the viewer's head motion box volume. To further assist in matching the illumination profile with the viewing zone, many screen types can be designed to incorporate field lens functionality as well as diffusion.

Effects on image quality must be considered when selecting the screen configuration. Screen microstructure can both limit resolution and interfere to generate Moiré artifacts. The microstructures or microlenses in the screen should preferably be at least two or three times smaller than the resolution limit of the projected image.

Microlens arrays can also be useful in one-to-one correspondence with source pixels, depending upon the source chosen, in order to modify the cone angle leaving the pixel. This makes a better match between the luminance envelope of the emitter and the numerical aperture of the projection optics. Diffractive optics may also be used in the projection optics. For a rotationally symmetric wide FOV system with full color, the chief functions of added diffractive surfaces are aspheric correction and chromatic correction. This can reduce the number of elements, and hence the size, of projection systems. This has been demonstrated by Honeywell's work with binary optics, which are a class of diffractive elements fabricated by microlithographic techniques. These binary optics have been used in both visual and IR applications.

For a panoramic display with special screen requirements, conventional screen elements form a good starting point. These can be augmented as necessary with special screen techniques such as diffractive binary optics, other surface relief microstructures or alternatively with analogous volume holographic optics in some cases. These methods enable the realization of high performance screen concepts.

Table 2-2. Survey of image source technologies.

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
Device Categories				
(General, Emissive)	Display image source which generates light locally at each pixel, where the amount or nature of such light is controllable via the data path.	No additional light source is required. Intrinsic viewing angle is often better than with light valves. High peak luminance can be achieved in many cases.	Emissive technologies are prone to resolution vs. luminance tradeoffs. Image source lifetime may be problematic in high luminance and high resolution applications.	
(General, Light Valve)	Display image source generates no light intrinsically, but provides an image-wise modulation to a generally uniform applied light source.	Reduced interaction of luminance and resolution.	Separate light source is required, and consumes power whether individual pixels are on or off. Peak luminance is generally the same as the full, large-area white luminance.	
Scanning Methods				
Electrical Matrix Scanning	An array or matrix of addressable elements is multiplexed by sequential selection signals, most typically in the form of row and column addressing lines. Examples include active or passive matrix LCDs, electroluminescent (EL) displays and field emission displays (FEDs).	These systems are generally more compact and more stable than the other scanned systems.	Restricted to format of the packaged source device. Fabrication and yield issues must be overcome.	
Electrostatic / Magnetic	Electromagnetic fields are applied to vary the trajectory of one or more electron beams. This is the primary scanning method in most CRTs.	CRT scanning is well developed and supports high bandwidth scanning. No moving parts.	Can be bulky. Possible convergence or image position drift.	
Opto-Mechanical	Scanning of an addressable point or line of display elements is achieved with moving mirrors or other moving optical components. Examples include rotating polygons and galvanometers, often used for laser scanning.	Moving mirror optical scanners provide significant configurational flexibility. Can have high efficiency, and be achromatic. Well suited for low and moderate deflection rates.	Multiple beams may be required for high resolutions, due to practical limitations on mechanical speeds. High speed moving parts may not be suitable for certain operating environments.	

Table 2-2. Survey of image source technologies (continued).

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
Electro-Optical / Acousto-Optical	Scanning is achieved without traditional moving parts, most commonly by induced density gradients or refractive index variations. Example is an acousto-optic deflector, such as for laser scanning.	Laser scanning is provided without moving parts, with possible benefits in reliability and display environment compatibility.	High information content display can be difficult. Wavelength sensitive. Generally lower efficiency than opto-mechanical systems.	
Color Methods				
Monochrome	Only a single color component, although it may include broad spectral bands.	Serves as a basis for many color methods.	Limited color information.	
Color: Integrated Additive	Side-by-side elements with different color spectra. Examples include shadow mask CRT, and LCD with a triad-pattern color filter array. Quite common in direct view applications.	Yields full color with only a single image source. Short persistence is not a requirement as with the other single image source approach, time-sequential color. Common approach. Stable and easily viewed or projected. Can be implemented with nearly all image source technologies.	The image source must have approximately three times as many addressable elements as the monochrome image sources used in the other approaches. Lower optical efficiency than some approaches. Pixel substructure may be detrimental if visible.	
Color: Combined Additive	Optical merging of multiple monochrome image sources, one for each color band. This is typically done with colored beamsplitters or by projecting onto a common screen. This approach is not generally used for direct view.	Yields full color at the intrinsic device pitch. Potentially the highest optical efficiency. Can be implemented with all image source technologies.	Can be bulky and heavy, especially with large monochrome image sources. Requires 3 monochrome image sources for full color.	
Color: Subtractive	Each light valve in a stack of light valves controls or removes a particular color band. System configuration is such that the three images are adequately combined. This approach is not generally used for direct view. Analogous method could also be used for stacked emissive devices.	Yields full color at the intrinsic device pitch. Very compact and stable method for utilizing multiple display devices. High efficiency possible.	Increased potential for optical artifacts if parameters and design are not selected appropriately. Requires 3 monochrome image sources for full color.	

Table 2-2. Survey of image source technologies (continued).

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
Color: Time-Sequential	A single image source generates separate images in the separate spectral bands, one after the other. A color filter wheel, electro-optic switchable color filter, or set of pulsed light sources may be used.	Requires the fewest addressable elements of all color methods.	Lower optical efficiency than some approaches. Requires high switching speed (e.g. field rate may be three times that of the other approaches). Even with fast switching and appropriate high bandwidth data path, potential for temporal artifacts (e.g. color breakup with motion) is increased.	
Emissive Devices				
Cathode Ray Tube (CRT)	Electron beam(s) excite a phosphor screen. Magnetic or electrostatic deflection (scanning) is generally internal to the tube.	No backlight required. Wide viewing angle. Common, low-cost approach. Mainstream display technology. High resolution commercially available. Time-sequential color possible.	Bulky. Luminance vs. resolution constraints. High voltage requirements problematic in some applications.	Approximately 2K x 2K, full color
Electroluminescent, (EL) Passive Matrix or Active Matrix (AMEL)	Moderately high voltage signals are applied to special phosphors, resulting in electroluminescence. Several variations exist, such as AC thin film EL and DC powder EL. Passive matrix implies multiplexing with relatively low switching frequency for each pixel. Active matrix allows higher multiplexibility and increased luminance.	No backlight required. Wide viewing angle.	Current technology is quite limited in the blue spectral band, making full color EL problematic. Luminance vs. resolution and pixel count constraints. Drive voltages complicate driver and active matrix design.	
Field Emission Display (FED)	Electrons are generated locally and accelerated into a nearby phosphor screen. Several variations exist, both for electron emission structures and phosphor type.	No backlight required. Wide viewing angles. Thin, light-weight displays anticipated. Lower voltage operation possible, compared with CRTs. Time-sequential color should be possible.	Technology in development stage. Low voltage phosphors have lower efficiency than standard HV phosphors.	6" diagonal color system (LETI)

Table 2-2. Survey of image source technologies (continued).

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
Laser (scanned)	One or more laser beams are scanned in two axes to sweep out an image. Scanning mechanisms can be either electromechanical, acousto-optical or electro-optical. The laser light may be viewed directly, or indirectly via the use of fluorescent screens.	Spectrally pure color bands Reduced resolution vs. luminance constraints.	Potential for coherence artifacts (e.g. speckle). Scanning system complexity for a high bandwidth display. Laser availability for practical full color system.	
Light Emitting Diode (LED)	Photon emission from diode junctions. Arrays and displays can be made and multiplexed.	Good switching speed. Candidate for scanned linear source (used in print heads).	Efficiency is comparatively low, especially for blue. Rarely used for high resolution displays.	
Plasma	Photon emission is achieved by voltage induced gas discharge (AC or DC). Spectral bands are either generated directly by the discharge, or indirectly by phosphor excitation. Matrix methods are typically passive, with good multiplexibility.	Active matrix not required. Well suited to relatively large formats. Rapid progress being made.	Though relatively thin (as compared to CRT or projection systems), these displays are typically heavy. Luminance is more limited than with most other technologies. Technology in development stage.	1024 x 768, full color, 30", 20 fL, prototype (Photonics Systems, Inc.)
Vacuum Fluorescent Display(VFD)	A phosphor is excited by electron emission from filament cathodes.	Mainstream display technology for low resolution displays.	Not generally used for high resolution displays.	
Light Valves				
Digital Micromirror Device (DMD)	An array of small micromirrors is controlled by an underlying integrated circuit addressing array. The mirrors are tilted selectively to control the direction of reflected light. Used as a reflection mode light valve for projection displays. (also known as deformable mirror)	High switching speed, can be used with sequential color. High optical efficiency possible due to high aperture reflection mode and no polarizers. Good gray-scale with pulse width modulation. Does not require liquid crystal or similar material.	Generally restricted to projection due to small format and use of dark-field illumination methods. Still at proof-of-concept stage, though with encouraging results. Both time-sequential color and combined additive color demonstrated.	2048 x 1152 combined, additive color (Texas Instruments)

Table 2-2. Survey of image source technologies (continued).

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
LCD: Ferroelectric (FLC)	A non-twisted LCD geometry, again using polarizers, where switching speed and a degree of bistability are achieved by using a different type of liquid crystal material. Several variations exist.	Higher switching speed. Bistability advantageous in some configurations. Potentially lower cost than AMLCD. Both time-sequential and subtractive color are feasible.	Not as well established as TN devices. Promising technology, but products have been slow in coming, however vendors claim to be overcoming traditional trouble areas (e.g. grayscale, uniformity, stability).	1280 x 1024, 16 colors, 15" Prototype (Canon), 2560 x 2048 B & W prototype (Canon)
LCD: CRT Addressed	A reflective mode LCD projector, addressed by a high resolution CRT image coupled to a photoconductor in the LC panel.	Commercial projection systems are available. High optical efficiency and high luminance.	Color is most readily achieved by combined additive color. This leads to a rather bulky system.	
LCD: Polymer Dispersed (PDLC or NCAP)	Microscopic LC droplets are embedded in a polymer. Field switchable alignment controls the amount of scattering due to refractive index mismatch. Also can be operated in absorbing modes by adding dichroic dyes.	Easy to fabricate PDLC layer. In most common modes, higher efficiency is achieved as polarizers are not used. Wide direct view viewing angle. Time-sequential color is feasible.	Voltage and contrast requirements make active matrix versions more difficult. Not yet competitive with TN devices in high resolution applications.	
LCD: STN Passive Matrix (STN)	Polarization based light valve where the non-linear response of the liquid crystal is emphasized to increase multiplexibility without adding additional non-linear elements. There are several other variations in addition to Super-twisted nematic (STN).	Lower cost and easier to produce than AMLCD. Mainstream display technology, with further development anticipated. Subtractive color possible.	Generally lower image quality than AMLCD (e.g. grayscale, viewing angle, switching speed, contrast, multiplexibility), although development in these areas continues.	

Table 2-2. Survey of image source technologies (continued).

Image Source Technology	Description	Benefits	Limitations/Considerations	Comments/ Examples
LCD: TN Active Matrix (AMLCD)	A light valve where field-switchable twisted nematic (TN) liquid crystal material is used to selectively rotate the polarization of light between a set of polarizers. In the active matrix approaches, a non-linear element (e.g. thin film transistor, or TFT) is placed at each pixel to increase multiplexibility of the matrix.	High multiplexibility. Many formats possible. Mainstream display technology, with further development anticipated. Very good performance. High luminance is possible. Subtractive color possible.	Optical efficiency and luminance can be limited. More costly to produce than certain other technologies. Viewing angle is more limited than with emissive displays. Switching speed slower than some other display technologies, but generally video rate compatible.	1280 x 1024 mono, 1.5", int. driver, prototype (Kopin); 1472 x 1024 mono, 1.9", int. driver, prototype (Sharp); 3072 x 2048 mono, 13", prototype (Xerox / Standish)
LCD, various other types	A large variety of other LCD operating modes have been developed. Examples include dynamic scattering, thermal smectic, OMI, ECB, cholesteric, phase change, guest host, plasma addressed, e-beam addressed, photo-addressed, etc.	Each has special advantages for certain applications.	While possibly meeting special performance requirements, these do not in general have the overall performance of the TN and STN types.	
PLZT	Ceramic-based polarization control light valve. Several variations have been developed.	Higher switching speed than many alternative light valves.	High voltage requirements.	
LCD: Reflective, Matrix Addressed	While most TN liquid crystal devices have been made in transmissive mode, certain of the LCD geometries can support reflection mode devices. Here, the optical efficiency can be significantly higher than in the traditional high performance TN AMLCD.	Higher aperture efficiency.	Optical geometries are generally more complicated. Limited compatibility with the preferred AMLCD geometry (TN).	
Various Other Technologies	Examples include electrochromic, photochromic, electrophoretic, magnetic, electromechanical, deformable membrane, oil, e-beam addressed laser, piezo-electric actuated mirror, etc.		In general, these lack the performance and development support of the prevailing methods.	

2.1.2 3-D Methods

This portion of the technology survey identifies and categorizes the major methods for 3-D displays (Table 2-3). By 3-D, we mean the presentation of depth information by perspective disparity and/or accommodation disparity. While a sense of depth can also be conveyed or enhanced by graphical methods such as shading or linear perspective, these are not included here.

The many display technologies that have been proposed for the presentation of 3-D images can generally be categorized as either stereoscopic (stereo pair), autostereoscopic, or volumetric. Autostereoscopic displays differ from stereoscopic displays in that they require no special viewing mechanisms to be worn on the head such as polarized glasses. Volumetric displays are characterized by their use of a real 3-D volume as the display medium. These classes of 3-D display may also be distinguished by the amount of information required to construct images. While stereoscopic displays require presentation of two times the amount of information of a comparable monocular display, volumetric displays require the encoding of much greater amounts of information, since bandwidth will increase roughly as a function of the number of display elements in depth. This bandwidth constraint will force tradeoffs among display size, resolution, addressability, and image luminance.

2.1.2.1 Stereoscopic Displays. Perhaps the most critical aspect of the development of stereoscopic displays is the design of the stereoscopic selection mechanism. The stereoscopic selection mechanism is responsible for delivering the left image to the left eye and the right image to the right eye, with perfect image separation being the ideal. Stereoscopic selection is either space-multiplexing or time-multiplexing. In the space multiplexing strategy, multiple image sources are used (one for each eye) or a single image source is divided into two display areas. Time-multiplexing approaches sequentially present horizontally offset images to the left and right eyes. Time-multiplexing systems produce satisfactory stereoscopic images provided that sufficient display refresh and selection device switching rates are used such that the eye integrates the images over time and flicker is not perceived.

The anaglyph stereogram separates left- and right-eye images by using colored images (usually red and green) in conjunction with colored filter glasses. Anaglyph stereograms have a number of severe limitations compared to other stereo technologies. First, since colored filters are used, it is not possible to present original images in their full and true colors. Additionally, some blurring of the image may occur and observers may experience binocular rivalry and visual discomfort.

The unsatisfactory performance of the anaglyph technique as well as early mechanical stuttering approaches gave rise to the use of linear polarization to control presentation of horizontally disparate images to the left and right eyes. The primary difficulty with the use of linear polarization to view stereograms is the sensitivity to head position. For example, if the left and right images were polarized vertically and horizontally, respectively, with a corresponding polarization of a viewer's glasses, then a tilt of the head in the transverse plane relative to the direction of propagation would alter the acceptance and rejection of the filters and the eyes would not see the proper image channels. The failure of the stereoscopic selection device to adequately separate the left and right eye views will prevent the proper perception of stereoscopic images (e.g., ghosting will be visible). The problem of head position sensitivity associated with linear polarization has been overcome by using circular polarization. Circular polarization is achieved by first passing light through a linear polarizer and then a quarter-wave linear retarder. The net effect is the passage of light which is propagated not in a single plane, but rather in a clockwise or counter-clockwise helix. The chief advantage is that the absorption of a circular polarizer is largely insensitive to rotations in the transverse plane of the direction of light propagation. Consequently, changes of head position will not jeopardize the quality of stereoscopic images when circular polarizers are used.

Several schemes have been described which employ flat panel displays as the image source for a stereoscopic display. Honeywell has devised such an approach ("Full-color Three Dimensional Flat Panel Display", U.S. Patent #5,113,285, May 12, 1992). This approach to generating full-color 3-D imagery uses a full-color AMLCD, and a separate liquid crystal cell, capable of providing alternating lines of fixed retardation varying in phase by one-half wave. This retardation cell is aligned and superimposed over the image forming AMLCD. Light exiting the AMLCD is normally plane polarized (i.e., polarization vector in one specific direction). By presenting alternating (spatially) left eye/right eye views on the corresponding alternating lines (rows or columns) of the display, and then passing the light through a retarder which alternates (to match the alternating display lines) between one-quarter-wave and three-quarter-wave phase retardation, the two views (left and right) are circularly polarized in opposite directions. With the viewer wearing circularly polarized glasses or visor, the correct view is presented to the appropriate eye.

The Visual Image Depth Enhancement by Parallax Induction (VISIDEP®) technique produces apparent depth though dynamic vertical disparity. Two images are separated by a rotation on the horizontal axis by 1 or 2 deg and are alternated at approximately 10 Hz. The VISIDEP® technique provides a sense of real-time color depth while requiring no special glasses or shutters. The image is not entirely satisfactory, however, since a slight vertical rocking motion is induced by the low frequency alternation of views and the magnitude of apparent depth is small. Attempts to increase the frequency of alternation result in the loss of the depth sensation.

A typical chromostereoscopic display involves viewing colored images through a double set of low and high dispersion prisms placed before each eye. The prism arrangement may be used to augment the otherwise weak chromatic dispersion effect of the human crystalline lens. Alternatively, by reversing the prisms the relative depth ordering of the chromatic spectrum can be reversed (i.e., blues closer and reds farther away). The amount of chromatic dispersion is controllable by changing the relative orientation of the two prisms in relation to one another. The chromostereoscopic display medium remains limited in the use of image color coding. The relative depth seen in the display will follow the relative spectral ordering of the colors used in the display. Furthermore, colors with high spectral purity are necessary to yield the sharpest chromostereoscopic images and the total apparent depth in the display is typically limited to approximately 10 cm.

2.1.2.2 Autostereoscopic Displays. Autostereoscopic displays perform the stereoscopic selection function (i.e., present disparate images to the left and eight eyes) without the use of glasses worn by the observer. A large number of autostereoscopic display technologies have been demonstrated, most with significant limitations in their current state of development. Perhaps the most familiar autostereoscopic display techniques are those developed by Dimension Technologies (DTI). DTI has demonstrated at least two variations of a raster-barrier technique. In the first embodiment, left- and right-eye portions of the LCD image are interleaved and a raster barrier (e.g., a Ronchi grid) is placed in front of the image. The raster barrier successfully performs the stereoscopic selection, provided that the observer's head position does not change. Moving the head from side to side creates an uncomfortable sensation as the image channels cross to their unintended eye and the apparent image depth appears to reverse. At a minimum, a reliable head tracking system is required to overcome this limitation. In DTI's second embodiment, luminance limitations of the raster barrier technique are offset by controlling presentation of the interleaved eye views with directional backlight columns. Many other autostereoscopic techniques exist, including a very common approach which incorporates vertical half-cylinder lenses for stereoscopic selection.

2.1.2.3 Volumetric Displays. Volumetric displays do not require synthetic generation of the stereo perspective and are a promising display approach for situations where large numbers of observers are present or multiple and simultaneous viewing angles are required. A major obstacle in the development of large, dynamic volumetric displays is the very high bandwidth which is required, especially if the display of complex, real-world imagery is to be achieved.

One common volumetric display concept is based on the construction of a virtual image volume with a vibrating mirror. This usually involves the linking of a light-weight, deformable mirror to a modulator such as a loudspeaker woofer. The system is called *vari-focal* because the focal length of the mirror surface changes as a function of the amplitude and frequency of the driving modulator. By reflecting the image of a CRT (or other image source) off the mirror and driving the loudspeaker in synchrony with the display rate, a display volume may be created as a collection of depth planes in time. The vari-focal mirror concept is seriously limited by bandwidth and phosphor decay constraints, such that only monochrome, wireframe images can realistically be displayed.

A similar display concept makes use of a stack of fixed, electrically switchable liquid crystal mirrors rather than vibrating a single mirror surface. An image is projected onto the front of the mirror stack, which is viewed through a dielectric mirror. The depth of the image at any given moment in time is determined by which of the mirrors are in a transmissive state and which are in a reflective state. For example, in a five-mirror display, an object would be projected to the middle depth by placing the first two mirrors in a transmissive state and the third mirror in a reflective state.

Another volumetric display concept is based on laser excitation of a volume of transparent gas. Display elements are addressed by creating fluorescent spots at the intersection of two laser beams. This display could be easily viewable by multiple display operators from multiple perspectives. This class of volumetric display technology, however, is entirely immature, with many unsolved technical obstacles.

One volumetric approach (developed by Texas Instruments under contract to ARPA) uses a rotating surface (e.g., disk) on which a synchronized light (laser) beam is used to create a three-dimensional image. Two of the dimensions are obtained through the scanning of the laser beam, while the third is provided by synchronization of the beam location with the beam-disk distance, which is varied by the offset of the disk from normal to the laser beam central axis. A similar approach has been studied by the Naval Ocean System Center (NOSC).

In another use of a laser beam for volumetric presentation (not yet developed) the beam might be scanned in two dimensions by an array of small reflective light valves, while the third dimension is obtained by oscillation of a plane at which the laser beam becomes visible through interference with a third (oscillating) laser plane. In the absence of the interference of the two beams, both laser sources would be invisible to the human eye.

Table 2-3. Survey of 3-D methods.

3-D Method	Class	Description	Benefits	Limitations/Considerations
3-D Categories				
(General, Stereoscopic)	Stereoscopic	Provide left and right eye perspective views to generate a 3-D effect.	Most commonly used approach.	Viewer comfort is quite sensitive to details of the implementation. Attenuation of the non-display environment by eyewear (if used). Lateral perspective is generally limited (in comparison with volumetric) unless tracking features added.
(General, Auto-stereoscopic)	Autostereo	Stereoscopic methods where special eyewear is not required.	Glasses not required.	Viewing envelope generally restricted unless head-tracked. Lateral perspective is generally limited (in comparison with volumetric) unless tracking features added. In some configurations, tracking can yield at best a discontinuous perspective view.
(General, Volumetric)	Volumetric	In a full implementation, an actual 3-D image is generated, including accommodation (focus) depth and variable perspective with head movement.	Change of perspective with head motion. Agreement of lateral disparity and focus cues.	System bandwidth requirements can be extreme due to the increased information content associated with the third axis. More technology-limited than stereo. Generally yields translucent imagery unless hidden content is removed. Not consistent with established two-perspective methods. May require larger physical volume for display system.
General Methods				
(General, Time Multiplexing)	Time Multiplexing	Assumes use of shutter-based (or equivalent) selection mechanism to alternately pass a right or left image to the respective eye. Head mounted portion can be active or passive. Most commonly, a single display device generates both perspectives, but this is also a possible method for separate image sources (with shutters added if necessary to reduce crosstalk).	Simple approach if a single high bandwidth image source (and associated data path) is available for providing both stereo perspectives. Fairly common method. Flexible technique.	Requires high channel bandwidth if a single image source is to be used without sacrificing spatial resolution. Similarly, short persistence may be required. Increased potential for temporal artifacts. Attenuation of non-display environment due to polarizers and/or duty cycle.

Table 2-3. Survey of 3-D methods (continued).

3-D Method	Class	Description	Benefits	Limitations/Considerations
(General, Spatial Multiplexing)	Spatial Multiplexing	Separate image source elements provide left and right perspectives. Left/right image sources may be completely separate, or may be interleaved in some manner. Sometimes combined with other multi-plexing selection methods, such as polarization.	Reduced constraints on switching speed, persistence, etc. when compared with time multiplexing with a single image source.	Requires twice as many image elements than a single time-multiplexed source, as well as a geometrical separation mechanism.
(General, Color Separation)	Color Separation	Spectral filtering to select left and right eye images. Used alone or in combination with time multiplexing (see color multiplexing, below).	Can be used to relax requirements on other selection mechanisms.	Possibility of spectral crosstalk. Color imbalance to eyes a potential concern
(General, Polarization)	Polarization	Polarized glasses are used to select left and right eye images. Circular polarization is commonly preferred over linear polarization, reducing sensitivity to head angle. Polarization methods are generally used in combination with other separation mechanisms.	Fairly common approach. Implies light-weight glasses.	Attenuation of non-display environment. Full color requires careful polarization rotation to minimize crosstalk.
Eyewear-Based Stereo Methods		Two-perspective approaches requiring the user to wear special glasses or similar eyewear. The glasses typically include polarizers or electro-optic shutter mechanisms.		
Single Channel, Time-Multiplexed Stereo	Time Multiplexing, possibly Polarization	Single image source generates two stereo fields per frame, with alternate fields providing the left and right perspectives. Special eyewear is generally used in the stereo selection mechanism, and may include shutters or polarizers.	Single image source suggests straightforward configuration.	Channel bandwidth and response time (or persistence) requirements are high. Data path bandwidth may also be an issue. Increased potential for temporal artifacts.
Dual Channel, Time-Multiplexed Stereo, Spatially Combined	Time Multiplexing, Spatial Multiplexing, possibly Polarization	Two image sources generate separate left and right eye perspectives. Displayed images are spatially combined, such as with beamsplitters or by projection onto a common screen. Time multiplexing with shutters is used to control left/right viewability.	Channel bandwidth and response time constraints may be relaxed due to the use of two sources. May be feasible to boost the left/right switching rate, especially for a long persistence image source.	Can be bulky in some configurations, especially if individual image source devices are large. Increased potential for temporal artifacts such as strobe effects in shuttering the images.
Dual Channel, Spatially Combined Stereo with Polarization	Spatial Multiplexing, others possible	Two image sources generate separate left and right eye perspectives. Displayed images are spatially combined, such as with beamsplitters or by projection onto a common screen. Polarizers or other non-temporal mechanisms are used to control left/right viewability.	Robust. Straightforward. No special persistence constraints.	Can be bulky in some configurations, especially if individual image source devices are large.

Table 2-3. Survey of 3-D methods (continued).

3-D Method	Class	Description	Benefits	Limitations/Considerations
Color Multiplexing	Polarization, Color Separation, Time Multiplexing	Hybrid method involving both time multiplexing and color separation. While right eye sees one spectral field, the other eye sees the complementary spectrum. Spectral fields are alternated at the time multiplexing rate.	Reduced flicker possible. May allow a reduction in frame rate.	General considerations of time-multiplexed systems. The degree of flicker reduction is expected to be luminance dependent.
Microretarder / Micropolarizer Display	Spatial Multiplexing, Polarization	Individual display elements include micro polarizer (or retarder) elements inside or near the display. Can also be autostereo, related to the parallax barrier approach.	Direct view stereo display possible.	Parallax. Best performance is expected with micro elements closely coupled to the image elements. Unless tiled, image source resolution and channel bandwidth requirements are high, since a single image source is implied for both perspectives.
Prism or Mirror Stereoscope	Spatial Multiplexing	Prismatic or mirror based glasses merge two side by side or over/under displayed images (e.g. Mirror Stereoscope, ca. 1833). May also use polarizers.	Simple, effective method.	Half resolution (picture size), visual distortion for non-display world. Sensitive to head position and angle.
Two-Color Glasses (Anaglyph)	Color Separation	Colored glasses are used, to select left and right eye images	Very low cost. Direct view.	Full color a problem. Crosstalk difficult to control. Color balance and comfort concerns.
Binocular Head Mounted Display (HMD)	Spatial Multiplexing	Separate image sources are provided for the left and right eyes, mounted on the head and collimated.	Straightforward two-channel stereo system. Moves with head.	Traditional considerations for head mounted devices, e.g. head supported weight, center of gravity.
Auto-stereoscopic Methods		Two stereo perspectives are provided without the use of special glasses.		
Dual Channel, Dual Projection System Combined Stereo with Directional Optics (e.g. Fresnel)	Spatial Multiplexing, Autostereo	Two projectors combined onto a single screen. Typically uses Fresnel or lenticular optics to control left/right viewability.	Excellent stereo separation. No special eyewear.	Limited viewing zone. Parallax corrections, if implemented, may be discontinuous.

Table 2-3. Survey of 3-D methods (continued).

3-D Method	Class	Description	Benefits	Limitations/Considerations
Parallax Barrier (also called Raster Barrier)	Autostereo, Spatial Multiplexing	Side by side pixels for left/right views, grid determines which eyes see the pixels. May also vibrate grid, use multiple grids, or add directional backlighting to define viewing volume.	No special eyewear. Direct view configuration possible.	Limited head motion, although can be increased by head tracking. Parallax corrections, if implemented, may be discontinuous. Possible FOV limits. Unless tiled, image source resolution and channel bandwidth requirements are high., since a single image source is implied for both perspectives.
Sequential Frame Moving Slit (Dynamic Parallax Barrier)	Time Multiplexing, Autostereo	A moving slit and high speed source is used to define two or more perspective views. Related to parallax barrier. Slit aperture can optionally be located in the Fourier plane of an optical system.	No special eyewear. Capable of a number of perspective views (i.e., more than two).	Channel bandwidth and persistence demands are high, as a single image source is most easily used. Moving slit approach difficult if needing a large viewing volume
Vertical Cylindrical Lenticular (e.g. "Panoram-agram")	Autostereo, Spatial Multiplexing	Vertical cylinder lens (usually a lenticular array) selects pixels for each eye. Related to parallax barrier methods.	No special eyewear.	Limited head motion. Parallax corrections, if implemented, may be discontinuous. Possible FOV limits. Unless tiled, image source resolution and channel bandwidth requirements are high., since a single image source is implied for both perspectives.
Retroreflector Array	Autostereo	Uses a retroreflective array and beamsplitter element to simplify tracking of viewing volume. Collimated imagery is retroreflected back toward the projector by the array. A beamsplitter redirects some or all of this light to form a new viewing envelope. Autostereo suggests two side-by-side projectors. Compatible with spatial multiplexing and eyewear-based selection mechanisms as well.	Special eyewear not required Head following feasible with collimated system.	Not mature. Potential concerns about optics resolution, FOV and array structure artifacts.
Volumetric Methods		Methods with true 3-D image generation capability.		
Vari-Focal Mirror	Volumetric	Driving a relay mirror (or lens) to view an image source with variable focal length and hence varying depth planes	Provides focus cues as well as stereoscopic cues.	Severely limited by channel bandwidth & persistence constraints. Lack of obscuration.
Static Stacked Mirrors (switchable)	Volumetric	Related to Vari-focal, selectable mirrors are used to provide multiple depth planes	Depth (focus) dimension optically scanned with no moving parts.	Severe channel bandwidth constraints, discrete depth resolution. Lack of obscuration.

Table 2-3. Survey of 3-D methods (continued).

3-D Method	Class	Description	Benefits	Limitations/Considerations
Moving Screen	Volumetric	Examples include rotating disk or screw, or otherwise oscillating screen. Imagery is projected onto it in synchronization with its z position.	Straightforward opto-mechanical method for sweeping third image dimension.	Severe bandwidth constraints, size constraints. Lack of obscuration.
Holograms	Volumetric	Holographic display, where appropriate image is generated for a variety of viewing angles, including those for the two eyes.	True 3-D theoretically possible.	Practical limitations on color, bandwidths, etc. Current technology constraints.
Gas Excitation	Volumetric	Multiple wavelength (simultaneous) excitation of a gas or other material, scanned.	Full, projected 3-D "real image" possible.	Severe bandwidth constraints, full color an unknown. Technology constraints. Lack of obscuration.
Multiple Plane Modulators	Volumetric	Multiple image sources (e.g. light valves, maybe also a CRT) are used at different physical locations (e.g. planes) to allow a 3-D image to be formed.	Capable of focus depth range as well as perspective depth.	Transparency, discrete depth resolution.
Other 3-D Methods		Not categorized as stereoscopic or volumetric.		
Chromo-stereoscopic	Other	Image focus position dependent upon spectral wavelength. The small misalignment (5 deg) of the foveal axis and the optical axis of the eye leads to a slight prismatic deviation. Because the effect is mirror-imaged from left-eye to right-eye, a binocular disparity can be produced which results in a stereoscopic (3-D) separation when adjacent saturated primary colors are presented.	Can be achieved without special glasses. Low cost.	Not a general technique for full color. Limited depth volume in some forms. Limited utility. Chromostereopsis is generally uncomfortable
VISIDEP®	Other	Alternating perspective views provided to viewer, but with no selection mechanism. Dynamic disparity on the order of 1-2 deg at a rate of 10 Hz or so.	No special glasses or other hardware required. May give added sense of depth.	Vertical rocking artifact, Small depth magnitude. Uncertain performance.
Time Delay Glasses (e.g. Pulfrich Pendulum Effect)	Other	Dark neutral filter over one eye, clear filter over the other, special signal processing	Low cost. Added perception of depth.	Requires motion cues, gives limited depth, uncomfortable viewing. Uncertain performance.

2.1.3 Collimation Methods

This portion of the technology survey identifies a number of display collimation methods and categorizes them by the type of optical elements that are used. Table 2-4 includes a description of each collimation method, along with a general discussion of the major benefits and considerations for each. This table is as inclusive as possible and serves as the starting point for identifying candidate collimation methods capable of meeting the Panoramic, 3-D Flight Display System requirements. The collimation methods presented have been collected from the head-up display, helmet-mounted display, and direct view display technologies. They have not been specifically reconfigured to match the Panoramic Display form and function requirements. Therefore, some of the methods show optical combiners for see through capabilities (not required for the Panoramic Display).

In creating a stereoscopic display, the depth-viewing volume (the amount of apparent viewing depth created by the use of a stereoscopic technique) is an important measure of the potential usefulness of the display. Greater depth-viewing volume provides a potentially greater information range, and allows distant objects to actually appear distant. Unfortunately, the depth-viewing volume achieved when the surface of the display is within a few feet of the viewer is limited to several feet around where the eyes are focused (i.e., the display screen surface). By moving the focus (accommodation) distance out, the maximum stereoscopic image depth also increases. This can be achieved by adding display optics to present a virtual image, where the apparent focus distance to the display is larger than the actual distance.

Traditional examples of virtual image displays are Helmet Mounted Displays (HMDs) and Head Up Displays (HUDs). These displays offer advantages such as compactness, see-through, and reduction of parallax considerations (e.g., Droessler, 1990, 1989). The image is normally collimated to allow registration of the image with the real world scene.

To provide a collimated virtual image an optical element is needed between the observer and the image source. For collimation, the image source is placed at the focal length of the lens. For the observer to see the full image, the exit pupil of the lens must be located at the observer. The eye piece of a telescope is an excellent example of a collimation lens. For many flight applications a see-through system requirement is also necessary. This means a combiner fold is then required so the collimating lens doesn't distort the real world see-through scene. This increases the distance from the exit pupil to the collimating lens which makes the lens larger for the same FOV. To minimize this lens size some optical power is sometimes put in the combiner. This, however, can complicate the system and may require additional collimation and even relay lenses.

Relay optics are needed in most display systems to match the physical dimensions of the display source with the needed image format of the collimation optics. The two primary functions of the relay optics are to relay the image from one position to another and usually to provide image magnification. The relay function is usually necessary to provide a convenient position for the mounting of the typically bulky display source. The magnification function is necessary to match the needed system resolution with the display source resolution as well as provide the correct projection image format size. For maximum luminance the outer diameter of the relay optics is equal to the dimensions of the display source.

The incorporation of collimation into the Panoramic, 3-D Flight Display System will add considerable complexity to the system. For example, a screen size requirement of 10 x 20 inches would require the first element to be at least that size. Elimination of see-through requirements allows some simplification, and enables the use of on-axis catadioptric options. An unfolded, completely refractive system would likely be the smallest, with its size determined by the FOV, its distance to the observer (eye relief), exit pupil size, and the size of the image source.

The potentially large FOV requirements for the current program suggest a need to consider non-traditional approaches in addition to traditional configurations. Potential tradeoff areas are FOV, exit pupil, optical complexity, size, weight and cost. The Panoramic, 3-D Flight Display System requires high FOV coverage, and non-traditional methods appear to offer significant potential advantages.

It may be possible to reduce size, weight and cost by replacing some or all of the refractive elements with powered Fresnel or diffractive elements. Fresnel lens quality and methods continue to be advanced, and the use of Fresnel elements in imaging optical systems continues to increase. This technology gives the optical designer a powerful new set of tools for tasks such as aspheric correction and chromatic correction.

One limitation of collimated displays is the head motion box, or exit pupil size. Whereas a real image display can be designed to be viewed from nearly any angle, practical collimating optics dictate a reduced head motion box for the viewer, outside of which performance is significantly degraded. The degradation may take the form of image distortion, loss of resolution, vignetting of the image, or complete loss of the displayed image. If necessary, certain collimation approaches may be amenable to extension of the head motion box by some form of head tracking or following. In the event that a restrictive head location is acceptable, or if head tracking is incorporated, interesting stereoscopic possibilities emerge. Because limited head motion box is a consideration shared by both collimated displays and autostereoscopic methods, accepting this attribute for one can enable the other as well.

Table 2-4. Survey of collimation methods.

Collimation Methods	Description	Benefits	Limitations/Considerations
General Methods			
(General, Refractive)	Systems that provide collimation with traditional refractive lenses. Traditional refractive lens systems provide excellent performing collimation systems. Refractive eyepieces are the standard for most visible telescope and microscope systems.	Most commonly used and inexpensive.	Lenses are heavy. Lenses need chromatic aberration correction.
(General, Reflective)	Systems that provide collimation with optically powered reflective mirrors. Reflective elements provide compact folded collimation systems. To avoid obscurations, the system must be tilted or have a partially reflecting beamsplitter.	Compact system size. Light-weight elements. Have no chromatic aberrations.	Difficult optical correction for tilted elements. Untilted systems have reduced display transmissions.
(General, Catadioptric)	Systems that provide collimation using both refractive and reflective elements. Catadioptric systems combine the compactness of the reflective elements with the excellent performance of the refractive collimation or relay systems.	Can design a balance of refractive and reflective system benefits.	The refractive and reflective considerations apply proportionately to the level of their use.
(General, Holographic)	Systems that use holograms to provide collimation and/or beam combination. Holographic systems provide highly efficient monochromatic combiner elements.	Holograms have high reflectances for the designed wavelengths. Holograms can provide nonsymmetric optical correction on a symmetrically aligned element.	Holograms have some environmental susceptibility and bright background flaring considerations. Secondary images can also be a problem.
(General, Supplementary)	Other methods that supplement any of the already mentioned methods. These are used to improve the performance of any of the collimation methods.	Vary with each method.	Vary with each method.
Refractive Methods			
Symmetric (Figure 2-1)	A traditional symmetric refractive eyepiece type lens system collimates the source image into the pupil defined by the head motion box.	Inexpensive lenses. Large head relief.	Large glass systems are heavy.
Symmetric Combiner (Figure 2-2)	A traditional symmetric refractive collimation lens system with a combiner fold and an additional fold for compact placement of the CRT.	Folding system changes the system package dimensions.	Smaller head relief with the combiner fold. Lower display transmission with combiner.
Symmetric Relayed Virtual Image (Figure 2-3)	Traditional symmetric refractive collimation lens system with added relay lenses for correct image size and good center of gravity position for the CRT source.	Can use smaller high resolution image sources for more compact overall system.	Must trade the benefits of a smaller image source with the additional lens size and weight concerns. Virtual relay lenses can be large.

Table 2-4. Survey of collimation methods (continued).

Collimation Methods	Description	Benefits	Limitations/Considerations
Symmetric Relayed Real Image (Figure 2-4)	Traditional symmetric refractive collimation lens system with added projection lens system with screen to project the correct real image size from the image source.	Can use smaller high resolution image sources with small projection lenses for more compact overall system.	Additional screen element size, weight, and transmission loss considerations. Projection lenses can be small.
Fresnel (Figure 2-5)	Three Fresnel lenses can be combined with a small conventional refractive lens to provide a compact and light-weight collimation system. A Fresnel lens resembles a flat plate that has the curved surface approximated by narrow right circular cylindrical rings intersected by conical portions called grooves.	Light-weight systems.	Fresnel lens performance limitations must be considered. VIDS has large Distortion 30%. WAVIDS relay optics with screen is heavier and larger.
Reflective Methods			
Symmetric Beamsplitter (Figure 2-6)	A single reflective mirror has excellent symmetric optical performance when a beamsplitter fold permits an on axis collimation system use.	Folds make the system more compact.	Lower display transmissions with beamsplitter. Reduced head relief with fold.
Tilted (Figure 2-7)	Two tilted reflective elements collimate and fold the image source to form and unobscured collimated display.	Higher display transmissions with no beamsplitter. Large head relief.	Elements with tilt introduce increased levels of astigmatism and distortion which either limits the useful FOV, or requires additional compensating optical elements for good system performance.
Tilted Relayed Real Image (Figure 2-8)	A tilted reflective element collimates a projected real image from a screen to form an unobscured collimated display.	Higher display transmissions with no beamsplitter. Large head relief.	Elements with tilt introduce increased levels of astigmatism and distortion which either limits the useful FOV, or requires additional compensating optical elements for good system performance. Single element optically powered reflector systems have small tilt angles which force the image source and relay optics to intrude into pilot's cockpit space.

Table 2-4. Survey of collimation methods (continued).

Collimation Methods	Description	Benefits	Limitations/Considerations
Tilted Relayed Virtual Image (Figure 2-9)	A tilted reflective element collimates a relayed virtual image from two reflective mirrors.	Good display transmissions with no beamsplitter and no screen losses. Large head relief.	Elements with tilt introduce increased levels of astigmatism and distortion which either limits the useful FOV, or requires additional compensating optical elements for good system performance.
Pancake Window® (Figure 2-10)	A concave mirror along with straight through crossed linear polarizers and quarter wave plates collimate the source within a very compact volume.	Most compact system.	Lowest display transmissions.
Catadioptric Methods			
Symmetric Beamsplitter & Relayed Image (Figure 2-11)	Adding a relay lens to the single mirror and beamsplitter collimator of Figure 2-6 permits smaller sources to be located in more optimal positions.	Can use smaller high resolution image sources.	Additional optical elements are required for relay.
Tilted Catadioptric (Figure 2-12)	A optically powered reflective combiner with a flat beamsplitter and refractive relay lens system with prism fold gives a wide FOV collimated display using a small high resolution CRT positioned in the optimum center of gravity position.	An angularly selective reflective beamsplitter coating provides excellent display transmissions. Excellent performance for wide FOVs.	Elements with tilt introduce increased levels of astigmatism and distortion which either limits the useful FOV, or requires additional compensating optical elements for good system performance.
Mangin Mirror (Figure 2-13)	Two decentered Mangin mirrors refract and reflect to collimate the image source.	Mangin mirror performance is better than that of a single mirror.	Mangin mirrors are heavier than regular mirrors.
Polarizing Prism (Figure 2-14)	A beamsplitter coating with quarter wave plates transmits and reflects the light in sequence to allow the collimating optical path to be folded within the beamsplitting prism. Two reflecting mirrors and lens then collimate the source.	Compact with high display transmission.	Prisms are heavy.
MONARC (Figure 2-15)	A Monolithic Afocal Relay Combiner is used with a refractive collimation lens. The MONARC relays the pupil to that of the refractive collimation lens.	Acrylic combiner allows relay optics and image source placement to the side of the line of sight.	Acrylic combiner can be heavy.
Parabolic Afocal Relay Visor (Figure 2-16)	A parabolic reflective afocal relay is used with a refractive collimation lens. The confocal parabolic reflectors relay the pupil to the refractive collimation lens.	The refractive collimation optics and image source can be placed a good distance from the viewers line of sight.	The afocal mirror relay can become quite large.

Table 2-4. Survey of collimation methods (continued).

Collimation Methods	Description	Benefits	Limitations/Considerations
Refractive, Reflective and Fresnel Display (Figure 2-17)	An asymmetric refractive and Fresnel lens system is folded with a prism and reflective elements to make a very compact collimation system.	Very compact display system.	Some asymmetric lenses are required.
Holographic Methods			
Edge Combiner (Figure 2-18)	An edge illuminated hologram combined with a cylindrical collimation lens provide a very compact collimation system.	Very compact system. Has no sunlight flare problems.	Concept works for only small FOVs and a static image only.
Single-Collimator /Combiner with Relay (Figure 2-19)	A reflective holographic element collimates the image relayed by a refractive relay lens.	High display and see through transmissions.	Single element optically powered reflector systems have small tilt angles which force the image source and relay optics to intrude into pilot's cockpit space.
Double Collimator with Combiner (Figure 2-20)	A spherical holographic collimator is combined with a flat holographic plate to form a clear holographic visor to collimate the image source.	High display transmissions.	Present system has only a 20 deg FOV.
Lenticular Screen (Figure 2-21)	A holographic lenticular lenslet array uses small spatial filters to provide a stereoscopic display.	Has compact and simple optics.	Needs a large image source with interlaced left and right images. Head motion box or view zone is small and stereo drifts with small head movements.
Supplement-ary Methods			
Retroreflecting Combiner (Figure 2-22)	A retroreflecting combiner with a flat beamsplitter reduces the size of the collimating lens aperture for same sized head motion boxes.	Large head motion box sizes.	Retroreflecting screens are still in development.
Diffractive Optical Elements (Figure 2-23)	Diffractive optical elements can be used in the collimation or relay lens systems to improve the system.	Reduces system size. Improves resolution. Increases head motion box size.	Diffractive elements are expensive if only a small number of systems are needed.
Double Combiner (Figure 2-24)	Two parallel partially reflecting combiners increase the systems vertical FOV.	Increased vertical FOV.	Lower display transmissions.

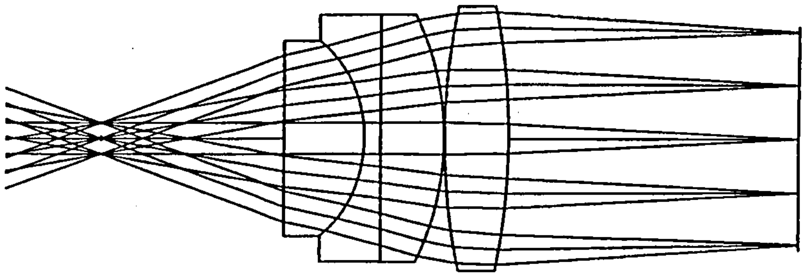


Figure 2-1. Symmetric Refractive Collimator.

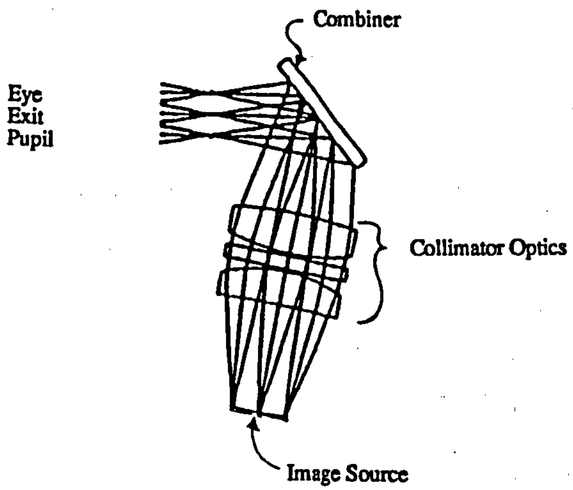


Figure 2-2. Symmetric Refractive Collimator with Combiner.

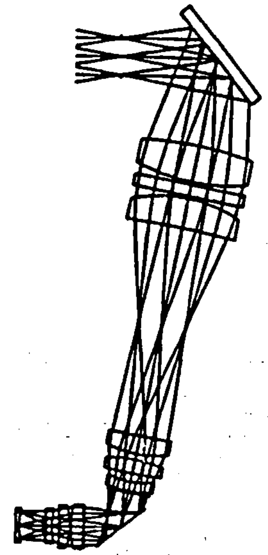


Figure 2-3. Symmetric Refractive Collimator with Virtual Relayed Image.

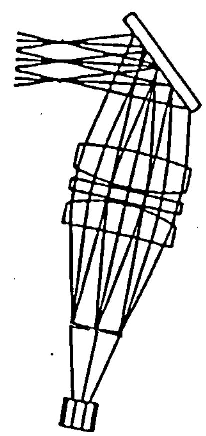


Figure 2-4. Symmetric Refractive Collimator with Relayed Real Image.

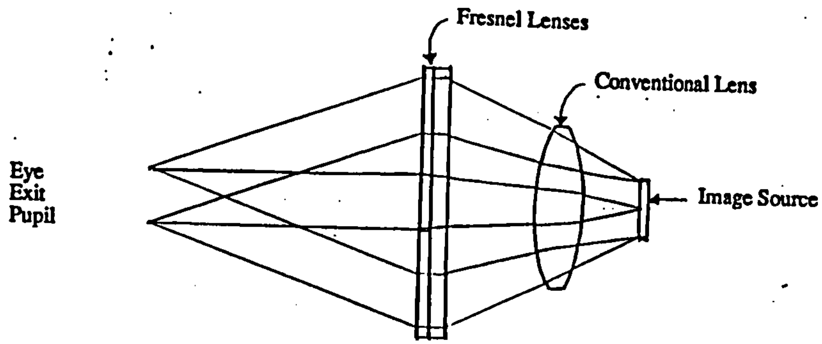


Figure 2-5. Fresnel Lens Collimator

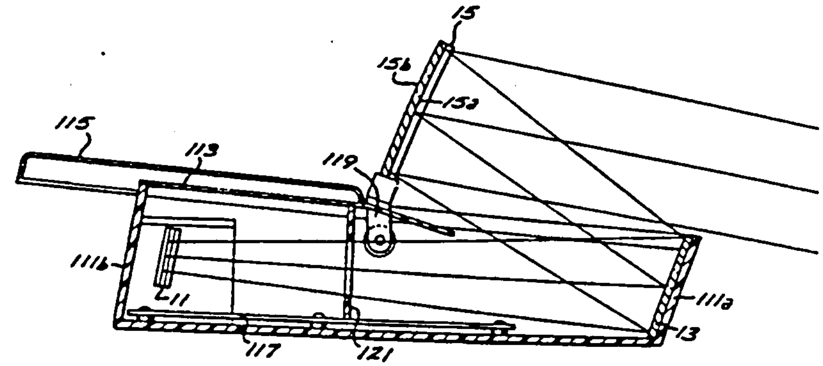


Figure 2-7. Tilted Reflective Collimator (Patent #5028119).

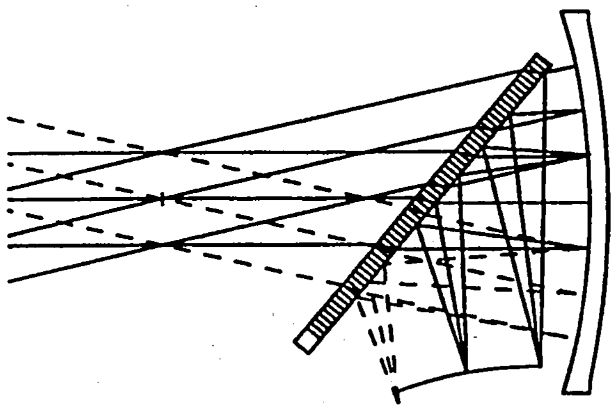


Figure 2-6. Symmetric Reflective Collimator with Beamsplitter.

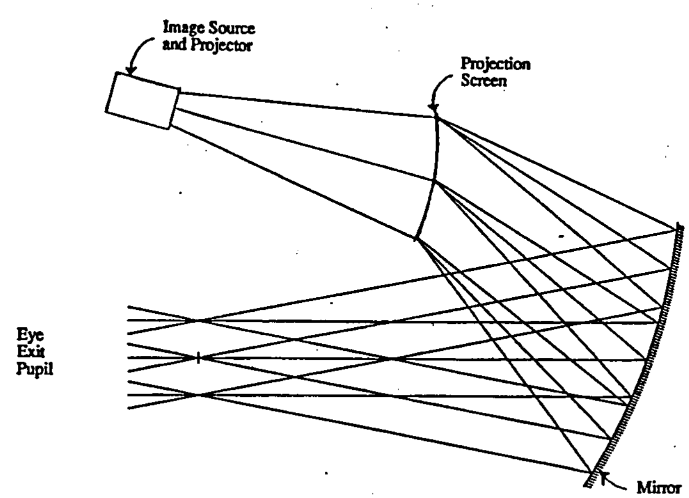


Figure 2-8. Tilted Reflective Collimator with Relayed Real Image

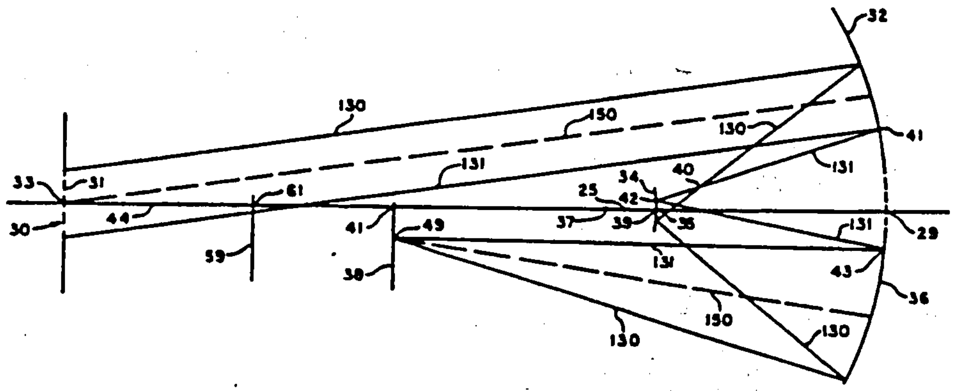


Figure 2-9. Tilted Reflective Collimator with Relayed Virtual Image (Patent #4737021).

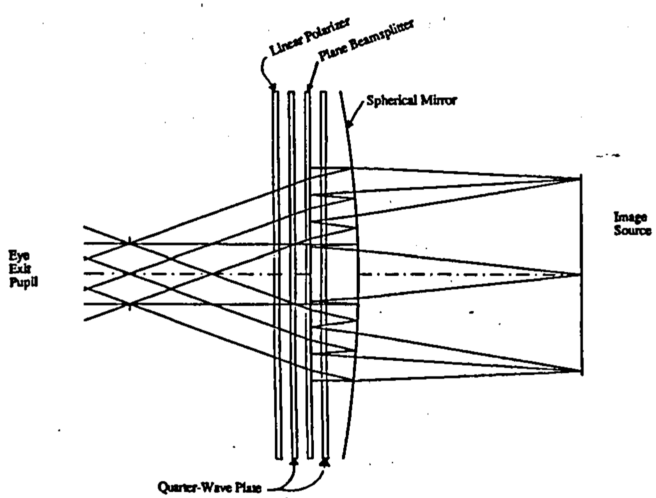


Figure 2-10. Pancake Window® Collimator (After LaRussia and Gill, 1978).

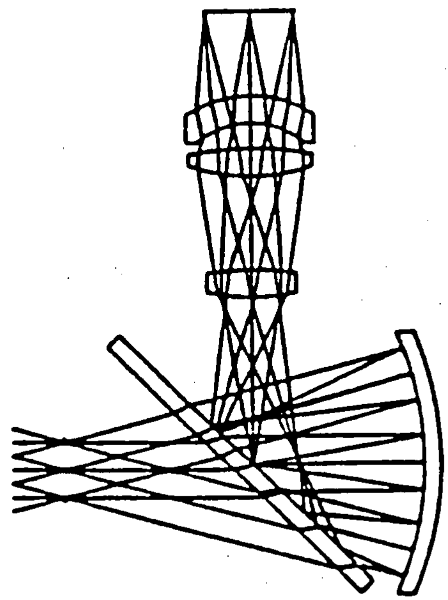


Figure 2-11. Symmetric Reflective Collimator with Beamsplitter and Relayed Virtual Image.

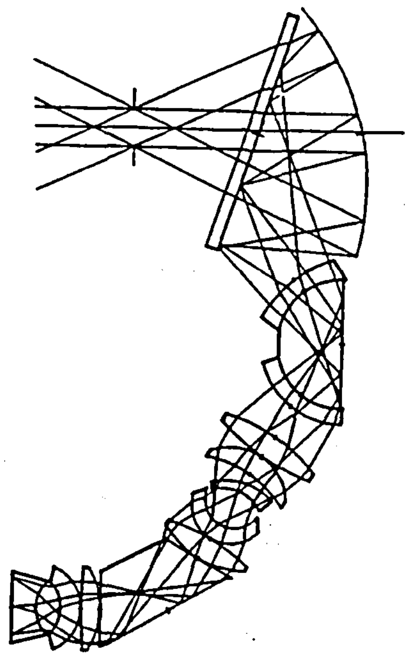


Figure 2-12. Tilted Catadioptric with Beamsplitter and Relayed Virtual Image

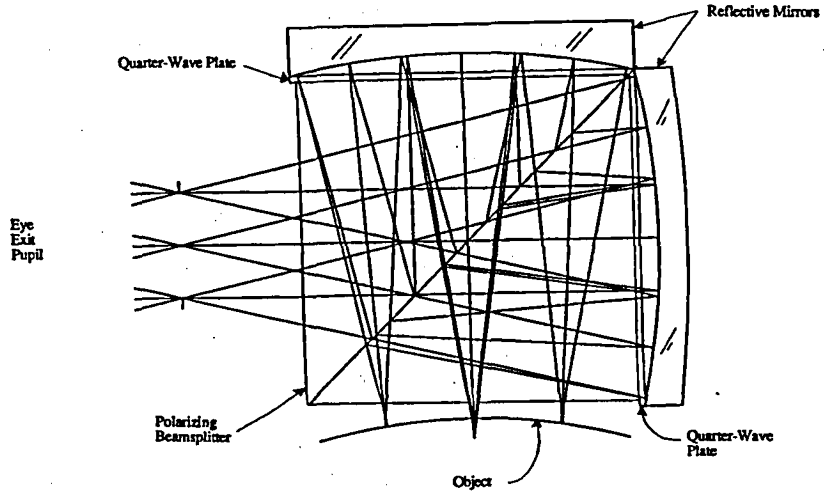


Figure 2-14. Polarizing Prism Catadioptric Collimator

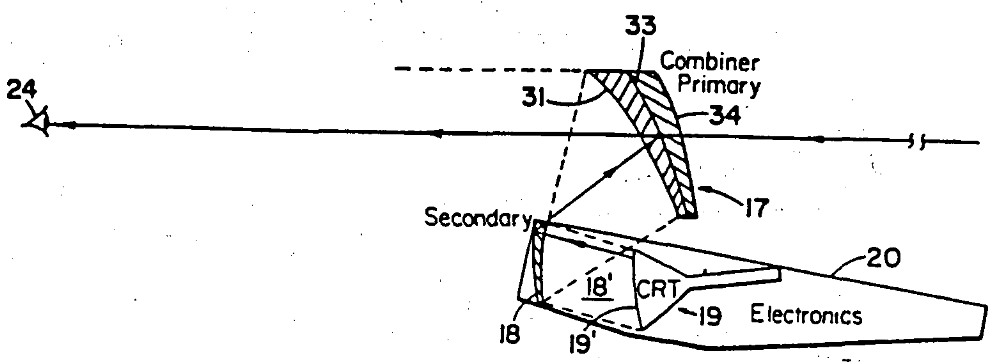


Figure 2-13. Mangin Mirror Catadioptric Collimator (Patent #4729634)).

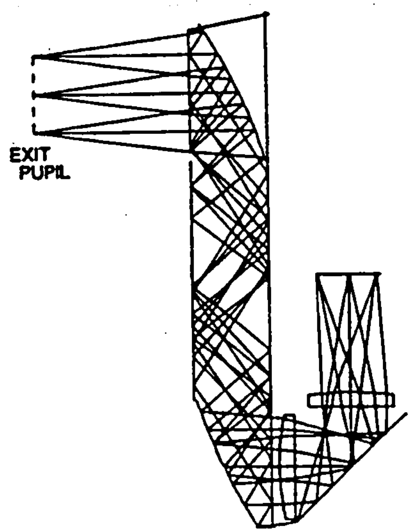


Figure 2-15. Monolithic Afocal Relay Combiner with Refractive Collimator.

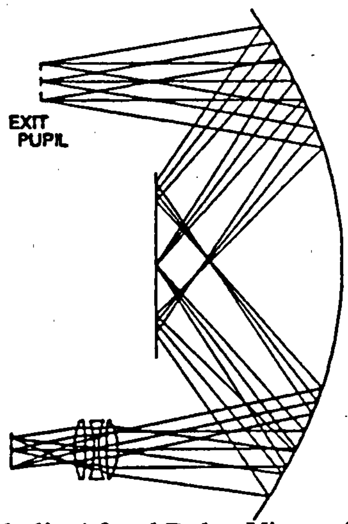


Figure 2-16. Parabolic Afocal Relay Visor with Refractive Collimator.

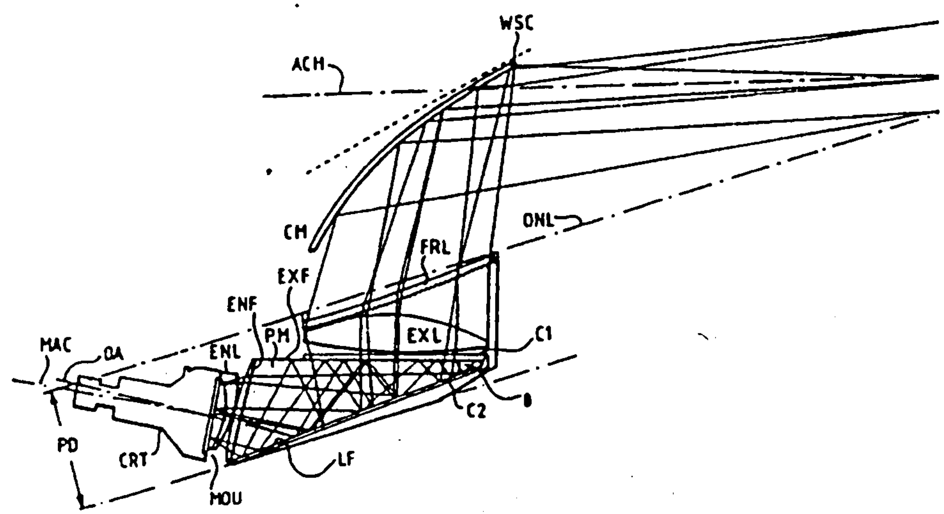


Figure 2-17. Refractive, Reflective and Fresnel Display (Patent #5249081)).

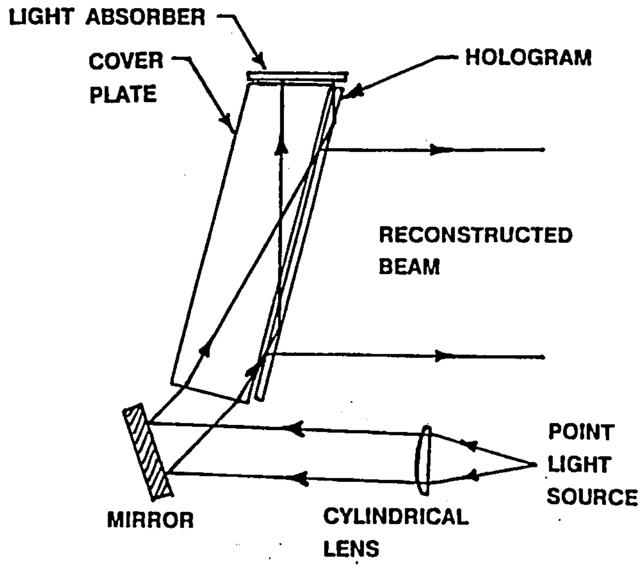


Figure 2-18. Edge-Illuminated Holographic Collimator (Patent #4643515)).

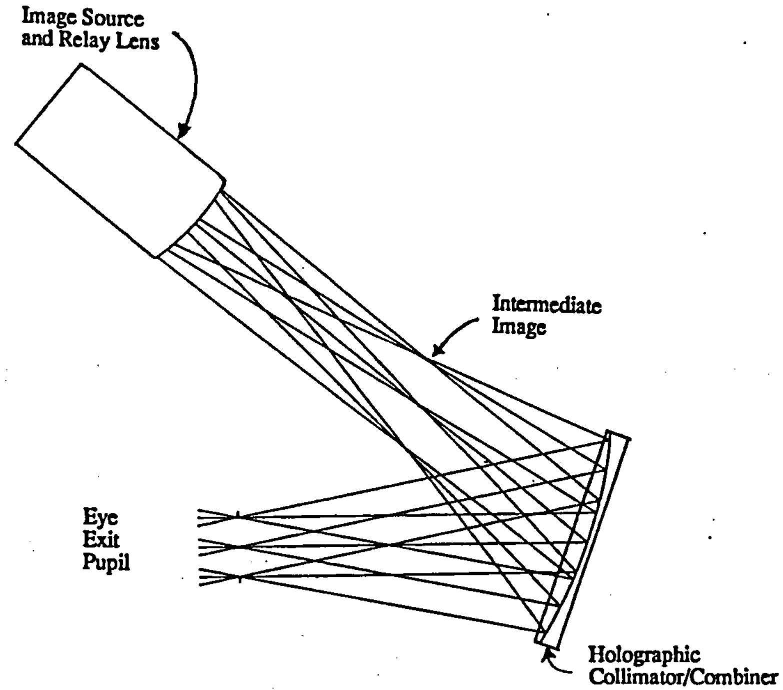


Figure 2-19. Single Holographic Collimator/Combiner with Relayed Image

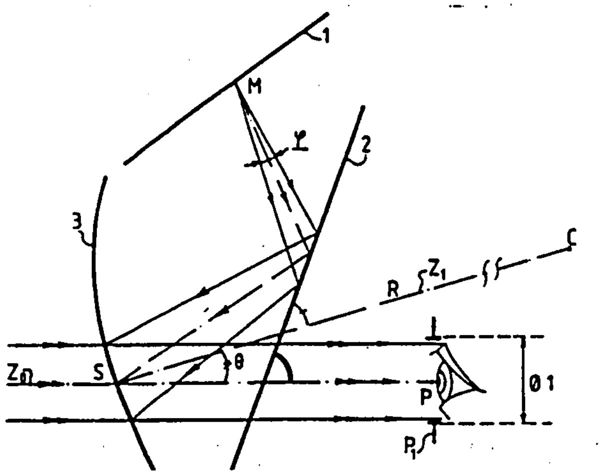


Figure 2-20. Double Holographic Collimator/Combiner (Patent #4874214)).

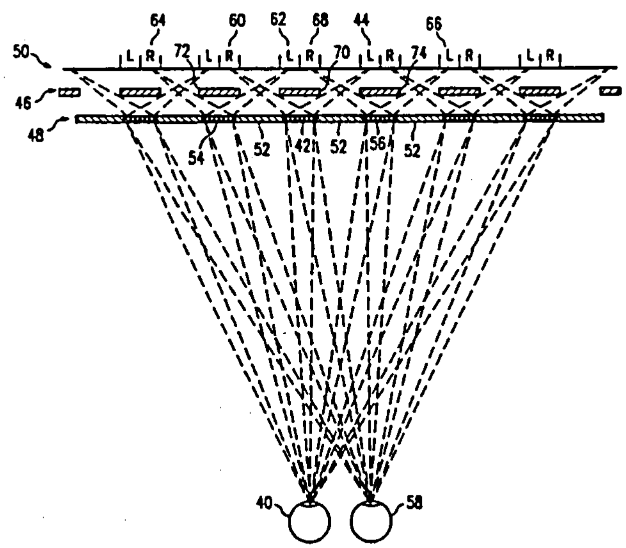


Figure 2-21. Holographic Lenticular Screen Collimator (Patent #4993790)).

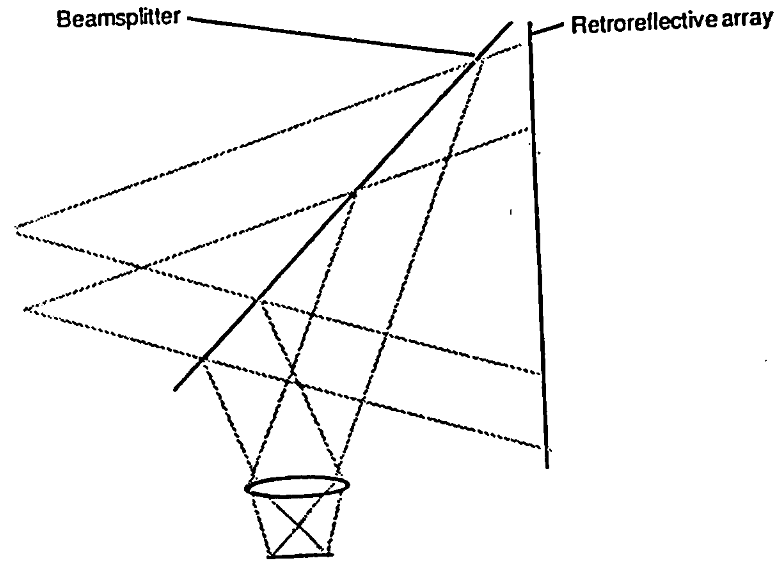


Figure 2-22. Retroreflecting Combiner.

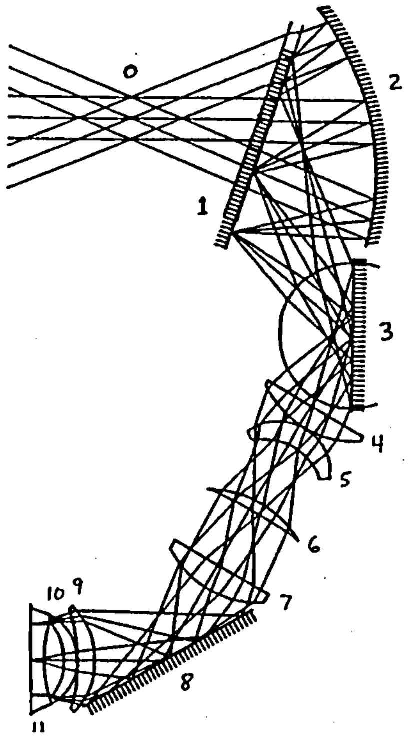


Figure 2-23. Diffractive Optics Display with Tilted Catadioptric Performance.

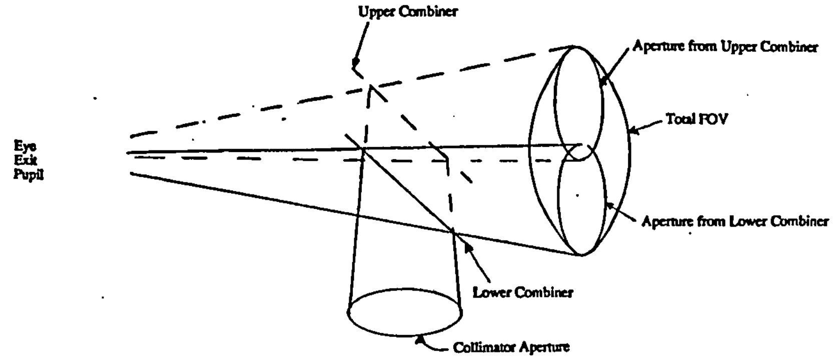


Figure 2-24. Double Combiner for Increased FOV.

2.1.4 3-D Interaction Methods

The effective visual display of information in 3-D brings with it unique questions regarding user input and 3-D image manipulation (e.g., Reinhart, 1991a). Traditional pointing devices that might be used for 3-D manipulations include direct manipulation devices such as light pens and touch screens, and indirect pointing devices such as the mouse, trackball, joystick, and graphics tablet. In addition, head or eye tracking solutions as well as several novel selection devices such as the Spaceball have been developed in recent years which bear consideration for this application. Many of these devices may be inappropriately applied to collimated, stereoscopic, or volumetric images unless the user's interaction with the complete display system is well-defined.

This portion of the technology survey identifies and categorizes the major methods for user interaction with the 3-D display. The survey is limited to those methods and technologies suited to selecting 3-D display areas or targets, positioning or tracking a 3-D cursor, and rate control; the survey does not address methods for the entry of alphanumeric data. Table 2-5 includes a description of each method, along with an indication of which methods are generally suitable for rate control. In addition, the maximum number of degrees of freedom (DOF) for translational and rotational control for each method is given. A general discussion of major benefits and limitations/considerations is provided for each method.

Interaction methods are described here relative to their conventional use. Novel adaptations of the methods may also be made for unconventional use in 3-D environments. For example, a "flying mouse" may be made by combining the mechanical mouse with one of the tracking methods. Degrees of freedom for translational and rotational control are maximums: that is, implementations of many of the interaction methods incorporate fewer DOF. For example, joysticks are available in a range from one to six total DOF. Similarly, a six DOF controller may be operated with fewer DOF through adjustment of software drivers. In addition, many devices may be selectable between translational and rotational control through switch (button) activation or context-sensitive software drivers.

Table 2-5. Survey of 3-D interaction methods.

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
General Interaction Categories					
(General, Direct Interaction)	Direct	User input is accomplished by operating directly on or at the display image.	No	Allows intuitive integration of input device with display device. Operation of direct interaction devices is usually easy to understand.	May not allow high precision in cursor placement or target selection. Some direct interaction methods may be incompatible with collimated images.
(General, Indirect Interaction)	Indirect	User input is accomplished by operating with a device remote from the display image.	Yes (generally)	Allows physical separation of input device and display device.	Ease of use is dependent on control properties such as control/display relationship (i.e., gain), backlash, deadspace, and resistance.
General Interaction Methods					
(General, Translation: Linear)	1 DOF Translation	User input is limited to a single spatial axis for positioning (zone of operation is described by a line) or a single rate variable at any given time. Switches may be used, however, to toggle between or among multiple axes or rate variables in a serial fashion.	Yes	High precision of position and rate control. Rapid selection of linearly arranged targets.	Multiple 1 DOF input devices may be used to effect a 2 or 3 DOF input. However, coordination of multiple input devices may be more time consuming than the use of a single, higher DOF input device.
(General, Translation: Planar)	2 DOF Translation	User input is limited to combinations of two orthogonal spatial axes for positioning (zone of operation is described by a plane) or two rate variables at any given time. Switches may be used, however, to toggle between or among multiple planes or combinations of rate variables in a serial fashion.	Contingent on specific method.	Rapid 2 DOF input relative to the use of two 1 DOF input devices. Rapid selection of targets arranged on a single plane.	Multiple 1 DOF input devices may be used to effect a 2 or 3 DOF input. However, coordination of multiple input devices may be more time consuming than the use of a single, higher DOF input device.
(General, Translation: Volumetric)	3 DOF Translation	User input is limited to combinations of three orthogonal spatial axes for positioning (zone of operation is described by a volume) or three rate variables.	Contingent on specific method.	Rapid 3 DOF input relative to the use of combinations of lower DOF devices. Rapid selection of targets distributed within a volume.	May not allow high precision with simultaneous 3 DOF control due to cross-coupling of control axes.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
(General, Rotation: Single Axis)	1 DOF Rotation	User input is limited to a single axis of spatial rotation or a single rate variable at any given time. Switches may be used, however, to toggle between or among multiple axes of rotation or rate variables in a serial fashion.	Yes	High precision of rotation and rate control.	Multiple 1 DOF input devices may be used to effect a 2 or 3 DOF input. However, coordination of multiple input devices may be more time consuming than the use of a single, higher DOF input device.
(General, Rotation: Dual Axis)	2 DOF Rotation	User input is limited to combinations of two orthogonal axes of spatial rotation or two rate variables. Switches may be used, however, to toggle between or among multiple axes of rotation or combinations of rate variables in a serial fashion.	Contingent on specific method.	Rapid 2 DOF input relative to the use of two 1 DOF input devices.	Multiple 1 DOF input devices may be used to effect a 2 or 3 DOF input. However, coordination of multiple input devices may be more time consuming than the use of a single, higher DOF input device.
(General, Rotation: Triple Axis)	3 DOF Rotation	User input is limited to combinations of three orthogonal axes of spatial rotation or three rate variables.	Contingent on specific method.	Rapid 3 DOF input relative to the use of combinations of lower DOF devices.	May not allow high precision with simultaneous 3 DOF control due to cross-coupling of control axes.
Indirect Interaction Methods					
Glove	Planar Translation AND Dual Axis Rotation	A glove fits over the user's hand and flex sensors translate movements of the hand's joints into digital control signals. This method is usually used in conjunction with one of the tracking methods described below to track hand position.	Yes	Interaction device stays with user.	Limited resolution. Potential for inadvertent control inputs. Inputs are relative to null position of hand; requires additional method (tracking) for third DOF in translation or rotation.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Joystick: Isometric	Volumetric Translation AND Triple Axis Rotation	A lever mounted vertically to a fixed base, with the size and shape of the lever being variable. Pressure applied to the lever is proportionately translated to a digital signal via a strain gauge. Little or no displacement of the lever occurs, and output returns to zero when force is removed. Isometric joysticks may use small levers covered with a finger-actuated key or larger, hand-manipulated levers, knobs, pistol grips, or balls. One or more buttons or triggers may be embedded in the joystick base or on the top or side of the lever.	Yes	Lack of moving parts may increase reliability. Option for small size.	Lack of lever displacement reduces feedback to user. Depending on size, lever may be vulnerable to damage or inadvertent actuation. 2 DOF devices are most common, with 3 DOF devices incorporating lever twist action for a single degree of rotational control or (less commonly) lever push-pull action for a third translational degree of freedom. 4 and 6 DOF joysticks exist, but are less common (see Spaceball, below).
Joystick: Binary	Planar Translation OR Dual Axis Rotation	A lever mounted vertically to a fixed base, with the size and shape of the lever being variable, including knobs, pistol grips, or balls. Pressure applied to the lever is translated to a digital signal via displacement of the lever to contact one of an array of switches (commonly eight) located around the circumference of the base of the lever. The input is binary and not proportional to lever force or displacement. A spring is used to return the lever to the center position when force is removed. One or more buttons or triggers may be embedded in the joystick base or on the top or side of the lever.	Yes (assumes momentary activation of joystick to increase or decrease rate)	Restricted resolution simplifies control options. May be especially suitable for matrix input operations.	Coarse output is unsuitable for fine, continuous input tasks. Depending on size, lever may be vulnerable to damage or inadvertent actuation. Rate control is possible, but not smoothly and rapidly.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Joystick: Isotonic	Volumetric Translation OR Triple Axis Rotation	A lever mounted vertically to a fixed base, with the size and shape of the lever being variable, including knobs, pistol grips, or balls. Pressure applied to the lever causes the lever to be deflected and is translated to a digital signal via a potentiometer. When an isotonic joystick is used as a rate control, a spring is used to return the lever to the center position when force is removed. A spring-return to center is not used when an isotonic joystick is used as a position control. One or more buttons or triggers may be embedded in the joystick base or on the top or side of the lever.	Yes	Lever displacement provides an additional visual feedback as to the magnitude of the input.	Depending on size, lever may be vulnerable to damage or inadvertent actuation. 2 DOF devices are most common, with 3 DOF devices incorporating lever twist action for a single degree of rotational control or (less commonly) lever push-pull action for a third translational degree of freedom. 4 and 6 DOF joysticks exist, but are less common (see Spaceball, below).
Keypad: Displacement	Linear Translation * OR Single Axis Rotation *	Individual keys (e.g., arrow keys) are used to input positional changes, rate changes, or designate targets. Pressure applied to the keypad causes a spring-loaded key to descend, completing an electrical connection.	Yes (assumes momentary activation of key to increase or decrease rate)	Use of keys can be obvious if appropriately arranged and labeled. Force and auditory feedback is provided. Very accurate for small positional changes or small changes in rate.	May be noisy. Difficult to operate with gloves. * Minimum of 2 keys required for full degree of freedom.
Keypad: Membrane	Linear Translation * OR Single Axis Rotation *	Individual keys (e.g., arrow keys) are used to input positional changes, rate changes, or designate targets. Pressure applied to the keypad causes two conductive layers to be joined, completing an electrical connection.	Yes (assumes momentary activation of key to increase or decrease rate)	Use of keys can be obvious if appropriately arranged and labeled. Sealed against environmental contaminants. Very accurate for small positional changes or small changes in rate. Very thin profile.	Low level of force feedback. No inherent auditory feedback. Difficult to operate with gloves. * Minimum of 2 keys required for full degree of freedom.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Mouse: Gyroscopic	Volumetric Translation OR Triple Axis Rotation	Two miniature optical gyroscopes are embedded in a hand-held housing, with buttons located on top of the device. The gyroscopes allow simultaneous control of three DOF, with button selection between translational control (left-right, up-down, forward-backward) and rotational control (pitch, yaw, roll).	Yes	Can be used as a conventional 2 DOF mouse on a flat surface or as a 3 DOF controller.	More fault modes than conventional mouse device (e.g., gimbal-lock). 3 DOF operation could lead to arm fatigue.
Mouse: Mechanical	Planar Translation OR Dual Axis Rotation	A small hand held device with one to three buttons for target selection. Movement of the mouse across a flat surface causes a ball located on the bottom of the mouse to rotate. Rotation of the ball is translated to a digital signal via rotating wheels and potentiometers or optical encoders.	Yes		Requires flat surface area for operation. Dust and dirt may interfere with operation.
Mouse: Optical	Planar Translation OR Dual Axis Rotation	A small hand held device with one to three buttons for target selection. Movement of the mouse across a reflective grid causes the LED light emitted from the bottom of the mouse to be interrupted. Interruption of the LED light is translated to a digital signal via photosensors in the bottom of the mouse.	Yes	Lack of moving parts may increase reliability.	Requires flat surface area for operation. Requires special optical mouse pad. Sensitive to orientation of the mouse pad grid relative to the mouse. Has limited resolution.
Spaceball	Volumetric Translation AND Triple Axis Rotation	A special case of the isometric joystick. A spherical controller intended to be grasped by a single hand, mounted to a fixed base with forearm support and multiple buttons located on a platform opposite of the forearm support. Pressure applied to the ball is proportionately translated to a digital signal via LEDs and photodiodes located inside the sphere. Little or no displacement of the sphere occurs, and output returns to zero when force is removed. Software/button control allows use as a linear positioning control.	Yes	Allows intuitive mapping of 3-D control actions to 3-D display actions. No physical displacement of control device required. Full 6 DOF control available, with software drivers available to reduce cross-coupling.	

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Tablet: Acoustic	Planar Translation	Electric pulses are generated at the tip of a stylus and detected by microphones located on the sides of the tablet. Alternately, the pulses can be generated on the tablet with the stylus serving as the detector. Another version of the acoustic tablet operates in the same way as the acoustic touch screen, with high-frequency waves transmitted over a surface.	Yes	Allows tracing of templates. Lack of moving parts may increase reliability.	Requires the use of a special stylus. May be sensitive to environmental noise.
Tablet: Electrical/ Magnetic	Planar Translation	A sensor in a stylus or puck detects magnetic or electrical signals generated by a grid of conductors on the tablet.	Yes	Lack of moving parts may increase reliability.	Requires the use of a special stylus. Voltage-gradient version does not allow tracing of templates because stylus must contact the tablet.
Tablet: Touch-Sensitive	Planar Translation	Any of the three touch-sensitive touch screen technologies (capacitive, conductive, cross-wire) may also be applied as touch-sensitive tablets. See *Touch Screens* below.	Yes	Allows tracing of templates. No special stylus required.	Inadvertent touches to tablet can generate inadvertent inputs.
Thumbball	Planar Translation	A small trackball mounted on the end of a joystick, intended to be operated with the thumb of the same hand used to control the joystick.	No (cross-coupling of rate and position)	Allows simultaneous control of two planar devices (thumbball and joystick), with maximum of 5 DOF.	
Thumbwheel, Slider switch, or Dial	Linear Translation OR Single Axis Rotation	A small wheel mounted in a fixed base. Movement of the wheel with respect to its housing is translated to a digital signal via potentiometers or optical encoders. Alternately, a small lever or key mounted on a lever with similar principal of operation.	Yes	Precise means of controlling inputs to a single spatial dimension. Precise control of a single rate variable.	May not be suitable for tracking tasks or tasks requiring rapid, continuous input. Other linear devices, such as slider switches, are also available.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Trackball	Planar Translation AND Single Axis Rotation	Movement of a ball with respect to its housing is translated to a digital signal via rotating wheels and potentiometers or optical encoders. One or more buttons are usually embedded in the trackball housing, although depression of the trackball itself may also serve a control function.	No (cross-coupling of rate and position)	Does not require movement of unit over surface.	Dust and dirt may interfere with operation. 3 DOF trackballs usually provide one DOF of rotation through rotation of the ball. 2 DOF trackballs are most common.
Voice Recognition	Linear Translation OR Single Axis Rotation	A complex series of processes are applied to transform speech input to a useful display interaction method. The raw speech signal detected via microphone is digitized, compressed, and normalized to remove variability such as rate of speech. A variety of techniques may be used to extract features from the normalized, digitized signal.	Yes	Hands are free for other actions. Lack of moving parts may increase reliability.	Not well-suited for complex control. Limited vocabulary. Susceptible to environmental noise. Speaker-dependent systems may be susceptible to user voice changes. Most systems do not recognize continuous speech.
Direct Interaction Methods					
Light Pen	Planar Translation	Signals from a light detector embedded in the end of a stylus are coordinated with the display refresh to provide an indication of pen position.	Yes	Allows obvious mapping of input to display.	Possible user arm fatigue. Hand and pen obscure display during operation. Requires additional method for target selection.
Touch Screen: Acoustic	Planar Translation	The finger interrupts a matrix of ultrasonic waves generated on the display surface by transducers on the edge of the display. Transducers serve as both wave generators and detectors.	Yes	Allows obvious mapping of input to display. Does not require user to touch a surface.	Poor resolution. Prone to dirty and scratched surfaces. False activations from scratches and dirt possible. Hand and finger obscure display during operation. Possible user arm fatigue. Requires spacing between edge of display active area and transducers.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Touch Screen: Capacitive	Planar Translation	Capacitance of finger generates an electrical impulse on a conductive film deposited on the back of a glass overlay.	Yes	Allows obvious mapping of input to display.	Poor resolution. Reduced display transmittance. Touch screen accumulated grease and dirt. Gloves interrupt capacitance. Hand and finger obscure display during operation. Possible user arm fatigue.
Touch Screen: Conductive	Planar Translation	Pressure applied to the touchscreen causes two conductive layers to be joined, completing an electrical circuit.	Yes	Allows obvious mapping of input to display. Highest resolution touch screen technology.	Reduced display transmittance. Prone to dirty and scratched surfaces. Hand and finger obscure display during operation. Possible user arm fatigue.
Touch Screen: Cross-Wire	Planar Translation	Pressure applied to the touchscreen cause two overlaid grids of wires (one grid carrying a voltage) to touch, completing an electrical circuit.	Yes	Allows obvious mapping of input to display.	Poor resolution. Reduced display transmittance. Prone to dirty and scratched surfaces. Hand and finger obscure display during operation. Possible user arm fatigue.
Touch Screen: Infrared	Planar Translation	The finger interrupts a matrix of LED beams placed above the display surface and paired with photodetectors.	Yes	Allows obvious mapping of input to display. Does not require user to touch a surface.	Poor resolution. Parallax associated with separation of display and light beams. False activations from smoke and dirt possible. Hand and finger obscure display during operation. Possible user arm fatigue. Sensitive to ambient illumination.
Tracker: Eye	Planar Translation	An IR beam is directed to the eye of the user and produces multiple reflections from the cornea. One of these reflections is tracked by a motorized mirror system which also records relative eye movements from a calibrated reference position. Monocular direction of gaze is used to compute direction of pointing.	No (insufficient resolution, cross-coupling of rate and position)	Hands are free for other actions.	Frequent calibrations to individuals may be necessary. Questionable reliability in airborne environment due to vibration and acceleration. Limited resolution due to involuntary eye movements. Requires additional method for target selection.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Tracker: IR	Volumetric Translation AND Triple Axis Rotation	IR sensors are placed on the body (head or hand via a helmet, headband, or glove). Alternatively, the sensors may be attached to a hand-held device such as a mouse or pistol grip. The sensors are illuminated with rotating IR beams, the IR beam sources located in fixed positions. The distances between the IR beams and the IR sensors are used to derive angles and compute direction of pointing or volumetric position.	Yes	Allows natural pointing. When mounted on head, hands are free for other actions. When mounted on hand, likely to leave fingers and thumb free for other actions.	Possible sunlight interference. Calculation of derived direction or position in real time may introduce lag. Volumetric IR tracking requires a larger number of sensors and beam sources than direction of pointing (planar) IR tracking.
Tracker: LED	Volumetric Translation AND Triple Axis Rotation	LEDs are placed on the body (head or hand via a helmet, headband, or glove). Alternatively, the LEDs may be attached to a hand-held device such as a mouse or pistol grip. The sequentially energized LEDs are recorded by one or more cameras, the cameras located in fixed positions. The vectors from the camera focal plane to each LED segment are used to compute direction of pointing or volumetric position.	Yes	Minimal added weight to body. Allows natural pointing. When mounted on head, hands are free for other actions. When mounted on hand, likely to leave fingers and thumb free for other actions.	Possible interference from reflections. Calculation of derived direction or position in real time may introduce lag. Volumetric LED tracking requires a larger number of cameras and LEDs than direction of pointing (planar) LED tracking.
Tracker: Magnetic	Volumetric Translation AND Triple Axis Rotation	A two- or three-axis magnetic sensor is placed on the body (head or hand via a helmet, headband, or glove). Alternatively, the sensor may be attached to a hand-held device such as a mouse or pistol grip. The sensor detects the relative position of a multi-axis magnetic transmitter, the transmitter located in a fixed position. Magnetic field vectors are used to compute direction of pointing or volumetric position.	Yes	Allows natural pointing. When mounted on head, hands are free for other actions. When mounted on hand, likely to leave fingers and thumb free for other actions.	Calculation of derived direction or position in real time may introduce lag. EMI and cockpit metal may limit resolution of magnetic system. Magnetic tracker may cause EMI with other cockpit devices.

Table 2-5. Survey of 3-D interaction methods (continued).

Interaction Method	Class	Description	Rate Control?	Benefits	Limitations/Considerations
Tracker: Ultrasonic	Volumetric Translation AND Triple Axis Rotation	Ultrasonic transmitters are placed on the body (head or hand via a helmet, headband, or glove). Alternatively, the transmitters may be attached to a hand-held device such as a mouse or pistol grip. The ultrasonic transmissions are detected by ultrasonic receivers, the receivers located in fixed positions. The distances and orientation among the receivers as well as the distances between the receivers and the transmitters are used to compute direction of pointing or volumetric position.	Yes	Allows natural pointing. When mounted on head, hands are free for other actions. When mounted on hand, likely to leave fingers and thumb free for other actions.	Possible interference from air turbulence. Calculation of derived direction or position in real time may introduce lag. Volumetric ultrasonic tracking requires a larger number of transmitters and receivers than direction of pointing (planar) ultrasonic tracking.
Tracker: Video	Volumetric Translation AND Triple Axis Rotation	An array of visual patterns is placed on the body (head or hand via a helmet, headband, or glove). Alternatively, the patterns may be drawn on a hand-held device such as a mouse or pistol grip. The visual patterns are illuminated and recorded by one or more paired camera and light systems, the cameras and lights located in fixed positions. The vectors from the camera focal plane to each pattern feature are used to compute direction of pointing. or volumetric position.	Yes	Negligible added body weight. Allows natural pointing. When mounted on head, hands are free for other actions. When mounted on hand, likely to leave fingers and thumb free for other actions.	Possible interference from reflections. Calculation of derived direction or position in real time may introduce lag. Volumetric video tracking requires a larger number of cameras and visual patterns than direction of pointing (planar) video tracking.

2.2 Rate and Compare

For the rate and compare analysis, the techniques and technologies identified in Section 2.1 are considered in the context of the preliminary display requirements identified in Section 1.2. A primary goal of the rate and compare effort is to identify key risk areas for each of the technologies and to select a subset of preferred candidates for further consideration. A subset of the preliminary display requirements from Table 1-3 was selected. This set of "strawman" requirements is shown in Table 2-6 below, and includes those parameters with the greatest potential impact during this technology downselection phase.

Table 2-6. Strawman requirements for rate and compare analysis, based on Preliminary Display Requirements (Table 1-3).

Parameter	Minimum	Comments
Field of View (FOV)	48 H x 27 V	60 x 33.8 preferred
Pixel Density (Resolution)	40 pixels / deg	At minimum FOV. 32 pixels/deg okay at larger FOV.
Pixel Count	1920 x 1080	Can be tiled, but not in center of FOV. Implicitly includes such considerations as drivers, interconnect and interfacing.
Gray Shades	32 linear steps	Non-linear distribution may be considered if advantageous.
Head Motion Box	+/- 4 inches in all 3 axes.	With no vignetting. Both the collimation and 3-D methods can impact the head motion box. The center of the head motion box intersects the center line of sight and is located at the on-axis head relief.
Luminance	30 fL	As seen from head motion box. 60 fL is preferred.
Luminance: Contrast Ratio	50:1	100:1 is preferred.
Eyewear Transmittance	30%	Higher transmittance is preferred (e.g. 60%). This requirement is highly relevant to the use of polarizing eyewear.
Physical Constraints	max of 20"H x 30"W x 40" deep, 100 lbs. per component, 400 lbs. total	Volume and weight
Head Relief	12" minimum 33" maximum	Use of shoulder and lap belts is assumed.
Service Date	1Q, 1997	Need reasonable path to this date.
Other requirements	(numerous)	See Table 1-3. Examples include chromaticity constraints, power, tile seam visibility, speckle and other artifacts.

In the tables which follow, the candidate methods and technologies are comparatively rated with respect to these preliminary strawman requirements. The ratings shown do not at this point consider specific interactions with the other system components. For example, the ratings with respect to head motion box for the 3-D Methods consider only the stereo selection mechanism, and do not include collimation head motion box considerations (which are assessed separately). As another example, the rated luminance compatibility of the image sources (e.g. plasma) can be further reduced if a low transmittance 3-D method or collimation method is used. Such system interactions are considered in Section 3. Assessments here are based upon current technology and reasonable anticipated development within the time frame of the strawman requirements, not upon ultimate capability of the candidate technologies. The ratings shown can be interpreted as follows.

Rating	Meaning
++	Favorable, probably not limiting in terms of preliminary requirements
+	Challenging, but see a reasonable path
–	Some concern, but still warrants consideration.
– –	Major concern. Perceived as introducing significantly more risk than alternatives in meeting the strawman requirements.
?	Not known without further clarification of the method (e.g. if multiple approaches are grouped together)

Ratings are provided only for those requirements for which there is a direct impact. This ratings allow an effective, early elimination of many of the initial candidates from further consideration based upon the strawman requirements.

The first level of downselection was made by recognizing the significant risk associated with the "Major concern" (– –) items. As such, the preferred candidates for further consideration in later program phases are those marked as Preferred (**P**), having received no "Major concern" ratings relative to any of the strawman requirement entries.

2.2.1 Image Source Technologies

Table 2-7 contains the ratings of image source technologies against a subset of the strawman display system requirements. The rating scale described on the previous page is adopted here, and preferred methods (designated in the first column with a "P") are those receiving no double minus ratings. Although image source technologies are rated here individually, appropriate system concepts incorporating combinations of technologies, as well as further down selection of preferred image source technologies, are reviewed in Section 3 of this report.

Of the 17 display technologies presented in Table 2-7, four were rated as preferred methods. These include three light valves, namely: the DMD; the TN AMLCD; and the reflective matrix-addressed LCD. Plasma display technology was the only emissive type to gain the preferred status in this rate and compare phase of the program.

CRT technology was eliminated from consideration due to physical incompatibility with the strawman requirements, in particular due to the size required, although the CRT compared favorably to other types in most other respects. Other emissive display types, such as EL, FED, LED and VFD, were eliminated from consideration for a variety of technical shortcomings or undemonstrated performance relative to the strawman requirements, coupled with the assessment that those shortcomings would not be overcome in the comparatively short strawman time frame. Scanned laser display methods were also eliminated, due to lack of well-suited laser sources, the risk of speckle artifacts, and the complexity associated with achieving the required high scanning bandwidths.

The remaining light valve technologies which were not preferred all had technical shortcomings as well, as discussed in Table 2-7. Most of these approaches are based upon alternate liquid crystal operating modes. In addition to the technology developments required to achieve adequate performance, the preferred TN AMLCD was recognized as being more capable or more developed in nearly all respects. Therefore, these alternate non-emissive technologies were eliminated from further consideration.

Table 2-7. Ratings of image source technologies.

Image Source Technology	Preferred Candidate?	Pixel Count	Gray Shades	Luminance	Luminance Contrast Ratio	Physical (Size, Weight)	Service Date	Other Rqts.	Comments
									Technical risk due to schedule is likely with many approaches, in light of current development path and trends. Tiling is likely to be necessary in many cases.
Emissive Devices									Luminance requirements are not particularly high, but certain technologies may experience difficulties due to attenuation by collimation and stereo selection methods.
Cathode Ray Tube (CRT)		++	++	+	+	− −	++		Physical parameters (e.g. size, weight) are a major concern. Use of smaller CRTs leads to difficulties in meeting resolution or luminance requirements. Otherwise, the CRT is a relatively mature technology.
Electroluminescent (EL)		+	−	−	+		− −	− −	Although full color is under development (blue phosphors in particular), achieving a suitable color gamut at the required luminance is not anticipated in the strawman time frame.
Field Emission Display (FED)		−	?	+	?		− −		While development activities are increasing, this technology is still in a relatively early development stage.
Laser (scanned)		−	+	+	+	− −	− −	−	Current practical laser technology and the high scanning bandwidth (e.g. requiring multiple scanning channels) contribute a high risk factor of implementing this technology in the required time frame, especially with respect to size and power. The risk of speckle artifacts is also a concern, although relatively low luminance helps.
Light Emitting Diode (LED)		− −	−	−	?		− −	−	Not readily compatible with developed or near-term LED sources.

Table 2-7. Ratings of image source technologies (continued).

Image Source Technology	Preferred Candidate?	Pixel Count	Gray Shades	Luminance	Luminance Contrast Ratio	Physical (Size, Weight)	Service Date	Other Rqts.	Comments
Plasma	P	–	+	–	+		+	–	Early prototypes are promising, although format is rather large, tiling and dual channel stereo are likely to be required, and luminance may not support requirements, especially with optics losses. Color gamut may also be a concern.
Vacuum Fluorescent Display (VFD)		– –	–	+	+		– –		Not readily compatible with developed or near-term sources.
Light Valves									Luminance is closely tied to light source selection and power consumption. High luminance may require undesirable tradeoffs in that area (e.g. high power, cooling, lifetime of light source).
Digital Micromirror Device (DMD)	P	+	++	+	+		+	?	Promising technology, significant recent progress. Combined additive color may be necessary to eliminate color breakup. Limited data available on producibility and reliability, although prototypes have been demonstrated.
LCD: Ferroelectric (FLC)		–	– –	+	+		–	?	Gray scale difficult. Limited data available on suitability for this application.
LCD: CRT Addressed		–	+	+	+	– –	+		As with other CRT system, bulkiness is a concern.
LCD: Polymer Dispersed		–	+	+	+		– –		Schedule risk. While possibly forthcoming, pixel counts are expected to remain below AMLCD during this time frame.
LCD: STN Passive Matrix		–	–	+	–		+	– –	While available, a very high level of tiling will be required and optical/temporal performance are lower than AMLCD. In particular, video rate performance of near term technology is not adequate.

Table 2-7. Ratings of image source technologies (continued).

Image Source Technology	Preferred Candidate?	Pixel Count	Gray Shades	Luminance	Luminance Contrast Ratio	Physical (Size, Weight)	Service Date	Other Rqts.	Comments
LCD: TN Active Matrix (AMLCD)	P	+	+	+	+		+		Considered to be the most capable LCD technology, although also higher cost. Uncertainty as to how soon pixel counts will be sufficient to eliminate need for tiling.
LCD, various other types		– –	?	+	?		– –		Generally reduced performance and less developed than AMLCD.
PLZT		– –	+	+	+		– –		Not readily compatible with developed or near-term sources.
LCD: Reflective, Matrix Addressed	P	+	?	+	?		–		Limited development momentum. Performance generally lower than TN LCD.
Various other technologies (see Section 2.1)							– –		Limited development momentum and generally insufficient performance for each included technology.

2.2.2 3-D Methods

Table 2-8 contains the ratings of 3-D methods against a subset of the strawman display system requirements. The rating scale used in previous rate and compare tables is adopted here, and preferred methods (designated in the first column with a "P") are those receiving no double minus ratings. Although 3-D methods are rated here individually, appropriate system concepts incorporating combinations of methods, as well as further down selection of preferred 3-D methods, are reviewed in Section 3 of this report.

Of the 25 3-D methods presented in Table 2-8, 10 were rated as preferred methods. Of the eyewear-based stereo methods, the prism or mirror stereoscope approach was judged to be inadequate relative to the head motion box requirement, while the anaglyph approach will not deliver the required color gamut. The HMD approach was removed as a contending 3-D method at the requirement of NASA LaRC. All of the autostereoscopic methods reviewed here were selected as preferred methods, although all pose significant challenges regarding head motion box. None of the volumetric or alternative 3-D methods were rated as preferred methods, largely due to problems reaching the pixel count requirement.

Table 2-8. Ratings of 3-D methods.

3-D Method	Preferred Candidate?	Pixel Count	Head Box	Luminance	Eye Wear	Service Date	Other Rqts.	Comments
Eyewear-Based Stereo Methods								Polarization/shutter eyewear based methods generally do not constrain the head motion box beyond that imposed by the collimation method. Polarizing eyewear introduce substantial attenuation, hence the upgrade path for eyewear transmittance is limited.
Single Channel, Time-Multiplexed Stereo	P		++		+			
Dual Channel, Time-Multiplexed Stereo, Spatially Combined	P		++		+			
Dual Channel, Spatially Combined Stereo with Polarization	P		++		++			
Color Multiplexing	P		++		+			
Microretarder / Micropolarizer Display	P		++		++			
Prism or Mirror Stereoscope			– –					Not polarization based. Head motion box too limited if directional optics are on head (see related autostereo methods, however).
Two-Color Glasses (Anaglyph)			++		– –		– –	Non-symmetric left/right transmittance. Incompatible with color requirements.
Binocular Head Mounted Display (HMD)			++		++		– –	NASA LaRC requirement to eliminate HMD approach from consideration.
Auto-stereoscopic Methods								Head tracking generally required due to geometrical relationships involving inter-pupillary distance (IPD) and FOV .
Dual Channel, Dual Projection, Combined Stereo with Directional Optics (e.g. Fresnel)	P		–		++			
Parallax Barrier	P		–		++			
Sequential Frame Moving Slit (Dynamic Parallax Barrier)	P		–		++			
Vertical Cylindrical Lenticular (e.g. Panoramagrams)	P		–		++			

Table 2-8. Ratings of 3-D methods (continued).

3-D Method	Preferred Candidate?	Pixel Count	Head Box	Luminance	Eye Wear	Service Date	Other Rqts.	Comments
Retroreflector Array	P		–		+ +			
Volumetric Methods								In general, volumetric approaches do not directly limit the head motion box, although special collimation considerations may apply. Luminance is reduced in many cases by sharing of the image source(s) over multiple depth planes.
Vari-Focal Mirror		– –	+ +	–	+ +			Limited depth addressability due to practical image source bandwidth constraints.
Static Stacked Mirrors (switchable)		– –	+ +	–	+ +			Limited, discrete depth addressability.
Moving Screen		– –	+ +	–	+ +			Limited depth addressability due to practical image source bandwidth constraints.
Holograms		– –	+ +		+ +	– –	– –	Development status implies schedule risk. Limited depth addressability due to practical image source bandwidth constraints. Chromaticity gamut a concern.
Gas Excitation		– –	+ +	–	+ +	– –	– –	Development status implies schedule risk. Limited depth addressability due to practical image source bandwidth constraints. Chromaticity gamut a concern.
Multiple Plane Modulators		– –	+ +	–	+ +			Limited, discrete depth addressability.
Other 3-D Methods								Generally limited depth addressability.
Chromostereoscopic		– –	+ +		+ +		– –	Performance uncertain in many areas. Limited depth addressability, tied to chromaticity content.
VISIDEP®		– –	?		+ +		– –	Performance uncertain in many areas. Limited depth addressability.
Time Delay Glasses (e.g. Pulfrich Pendulum Effect)		– –	?		– –		– –	Eyewear attenuates and is non-symmetric. Performance uncertain in many areas. Depth addressability is dependent on other image content.

2.2.3 Collimation Methods

Table 2-9 contains the ratings of collimation methods against a subset of the strawman display system requirements. The rating scale used in previous rate and compare tables is adopted here, and preferred methods (designated in the first column with a "P") are those receiving no double minus ratings. Supplementary methods presented in the previous survey of collimation methods are not complete collimation methods per se, and are not included in Table 2-9.

The requirements for the optical collimation methods are not independent of each other, but rather are inter-related. The maximum FOV of a system is dependent on the acceptable resolution of the system. High resolution systems have smaller FOV maximums and low resolution systems can have a large FOV. For the FOV evaluation the required resolution of 40 pixels/deg was assumed necessary and each method's maximum FOV providing this resolution was then estimated. The level of effort in the current program did not support an optical design optimization task for the evaluation of each method's performance. However, what information was available and the designer's experience with each method was used for an estimate. Additionally, some interpretation of the literature's performance claims was required. Specifically, the available information on some concepts indicated large FOVs with a lower resolution than the required 40 pixels/deg. In these cases, an educated estimate of the required reduction in FOV for the finer resolution was made. The resultant FOV estimate was then compared with the required 48 deg H x 27 deg V FOV and the appropriate rating was then placed in the table.

To obtain numbers for the head motion box, the head relief, and the physical size estimates, one requirement had to be selected so the other two could be calculated. The physical size of a system is a direct function of the required head relief and FOV of the system. The size of an optical system is directly scalable, with the angular resolution of the system being preserved (however the pixel size scales with the same factor as the rest of the system). Therefore, if the system size is available, one need only scale the system for the requirements. Starting with the head motion box size, the collimation method system is then scaled to give the head motion box. From this scaling, the head relief and the physical system size is calculated. The head relief times the tangent of the FOV plus the head motion box size gives the necessary size of the first element for a system with no vignetting over the full FOV.

Once the size of the first element is determined, the complete system can be scaled. However, if the size information for the method is not available, it is necessary to do some first order design calculations for the smallest lens size estimate. The practical lens F-number limitation of f/1 can be used to determine the smallest reasonable focal length for the collimation system. This focal length is then multiplied by the tangent of the FOV to give the required image source size. If the required image source size is not available, the collimation system will then need to have a reimaging relay system to magnify the available image source to the size needed by the collimation optics. For the purpose of Table 2-9, no assumptions were made regarding the image source size available (consequently, the non-relayed image collimation methods were not eliminated). Using the f/1 limitation criterion for system size estimation results in an optimistically small system estimate. This will give all systems the benefit of any doubt. No weight estimates were made for this table. Weight estimates were subsequently calculated for the preferred collimation systems only at a later stage in the analysis (see Section 3.1).

Summing up Table 2-9, the preferred candidates can be regrouped into five smaller groups. The first one is the refractive group which can meet the requirements in any of the arrangements (symmetric, symmetric with virtual relay, and symmetric with real relay). The second group is the tilted reflective with real relay system which has a large FOV but presently a questionable resolution match. The third group is the symmetric catadioptric with beamsplitter and virtual relay and the tilted catadioptric. These two concepts are quite similar, with the exception that one is symmetric with low transmissions and one is non-symmetric with higher transmission. The fourth system is the Pancake Window® which by itself cannot meet the requirements, but with some additional optical elements can meet the requirements. The last preferred system is the polarizing beamsplitter which can meet the requirements only if the prism is replaced by a thin beamsplitter plate (plate not depicted in Figure 2-10).

Noteworthy is that no holographic collimation concepts were preferred. However, holographic elements will be considered supplementary methods and could be used in other concepts that are preferred. This is true for all the supplementary methods which can contribute improved performance or size/weight advantages for most concepts.

Table 2-9. Ratings of collimation methods.

Collimation Method	Preferred Candidate?	FOV	Head Motion Box	Head Relief	Physical (excluding weight)	Comments
Symmetric Refractive	P	++	+	++	++	Performance and size looks acceptable.
Symmetric Refractive with Fold		++	+	– –	– –	With no see-through requirements this system is redundant.
Symmetric Refractive with Virtual Relay	P	++	+	++	+	An unfolded version looked acceptable.
Symmetric Refractive with Real Relay	P	++	+	++	+	An unfolded version looks acceptable.
Fresnel (VIDS) WAVIDS		– – – –	+ +	++ ++	++ –	VIDS Fresnel lenses had an image swimming problem. WAVIDS improved performance still not acceptable.
Symmetric Reflective with Beamsplitter		– –	+	–	++	The FOV will not meet the limit with only one reflective element; and more elements add obscurations. Low transmission of optics will require high luminance image source.
Tilted Reflective (Two Mirror System)		– –	+	–	–	With only two mirrors, acceptable performance restricts system to too small a FOV.
Tilted Reflective with Real Relay	P	++	+	++	–	System has optics intruding into observer's space. Folds will be needed to reposition the optics into the available space.
Tilted Reflective with Virtual Relay		–	+	–	– –	Some three mirror systems may meet the FOV limit. However, they will exceed the size limit.
Pancake Window®	P	+	+	++	++	The low transmission optics will require a very high luminance image source. Additional elements are needed to meet the FOV requirements.
Symmetric Catadioptric with Beamsplitter and Virtual Relay	P	++	+	–	++	Low transmission of optics will require high luminance image source.
Tilted Catadioptric	P	++	+	+	+	The system has acceptable performance with increased transmission.
Mangin Mirror		– –	+	++	+	The performance of a two mangin mirror system is limited to too small a FOV.
Polarizing Prism	P	++	+	+	–	The polarizing beamsplitter prism is large and heavy. A lighter weight polarizing beamsplitter warrants consideration.
MONARC		– –	+	++	– –	The large head relief makes the acrylic combiner too large and heavy. The FOV is too small.
Parabolic Afocal Relay		– –	+	++	– –	The FOV is too small. The reflective afocal relay becomes too large with the required head relief.

Table 2-9. Ratings of collimation methods (continued).

Collimation Method	Preferred Candidate?	FOV	Head Motion Box	Head Relief	Physical (excluding weight)	Comments
Refractive Reflective & Fresnel		– –	+	++	++	The FOV is too small.
Holographic Edge Combiner		– –	+	++	++	The FOV is too small. The present combiner is an illuminated hologram (target pattern). For our application the concept would only work if a real time hologram was available.
Holographic Collimator/Combiner		– –	+	+	+	The collimator/combiner needs to perform for color. The FOV is too small.
Holographic Collimator with Combiner		– –	+	+	+	More optical elements will be needed to meet the FOV limit. Multiholograms will be needed for color.
Lenticular Screen		++	– –	++	++	The head motion box size is too small. Stereo drift with head movement needs correction.

2.2.4 3-D Interaction Methods

Table 2-10 contains the ratings of 3-D interaction methods against a subset of the strawman display system requirements. The rating scale used in previous rate and compare tables is adopted here, and preferred methods (designated in the first column with a "P") are those receiving no double minus ratings. Although interaction methods are rated here individually, appropriate system concepts incorporating combinations of methods, as well as further down selection of preferred 3-D interaction methods, are reviewed in Section 3 of this report.

Of the direct interaction methods reviewed, five of the fifteen general approaches were rated as preferred methods. The variations of the joystick (including the Spaceball) are all generally suitable and have historical precedence for use as cockpit controllers. The suitability of these methods depends strongly on the particular configuration and control properties (e.g., amount of displacement, control deadspace) selected. Thumbwheels, slider switches, and dials were also judged to be acceptable means to augment 2 DOF controllers. Those indirect devices not given preferred status generally had limitations associated with excessive user fatigue, instability under vibration, or inadequate resolution.

Touchscreens and light pens were rated as preferred direct interaction methods, although neither method is suitable to provide 3 DOF without a supplementary interaction method. Tracker technologies, although used effectively for some helmet-mounted sight applications, were judged to be inadequate for the interaction needs of the Panoramic Display System; instability under vibration and inadequate resolution were identified as two limiting factors.

Table 2-10. Ratings of 3-D interaction methods.

3-D Interaction Method	Preferred Candidate?	Comfort	Resol-ution	Service Date	Update Rate	Other Reqs.	Comments
Indirect Interaction Methods							
Glove		–	– –	+	+		Limited comfort, including hand fatigue. Inherently limited resolution.
Joystick: Isometric	P	+ +	+ +	+ +	+ +	+	May require additional method for desired DOF, although 3 and 6 DOF devices are available. Isometric control may be nonoptimal for vibratory environments.
Joystick: Binary		+ +	+ +	+ +	+ +	– –	Although high-resolution control is possible with this method, it cannot be achieved smoothly and rapidly.
Joystick: Isotonic	P	+ +	+ +	+ +	+ +	+	May require additional method for desired DOF.
Keypad: Displacement		+	+ +	+ +	+ +	– –	Although high-resolution control is possible with this method, it cannot be achieved smoothly and rapidly.
Keypad: Membrane		+	+ +	+ +	+ +	– –	Although high-resolution control is possible with this method, it cannot be achieved smoothly and rapidly.
Mouse: Gyroscopic		– –	–	+	+ +	– –	Continuous use for 3 DOF control would lead to hand, wrist, or arm fatigue. Inherently instability of method under vibration and loads.
Mouse: Mechanical		+ +	+ +	+ +	+ +	– –	Inherent instability of device under vibration and loads.
Mouse: Optical		+ +	+	+ +	+ +	– –	Inherent instability of device under vibration and loads.
Spaceball	P	+ +	+ +	+ +	+ +	+	Essentially, a 6 DOF isometric joystick. Capable of all modes of interaction indicated in preliminary requirements. Isometric control may be nonoptimal for vibratory environments.
Tablet (Acoustic, Electrical/ Magnetic, Touch-Sensitive))	P	+ +	+	+ +	+ +	–	Requires additional method for 3 DOF control. Rate control possible, but not optimal.

Table 2-10. Ratings of 3-D interaction methods (continued).

3-D Interaction Method	Preferred Candidate?	Comfort	Resol-ution	Service Date	Update Rate	Other Reqs.	Comments
Thumbball		+	+	+ +	+ +	– –	Not suitable for simultaneous position and rate control due to high degree of cross-coupling between control axes. Requires additional method for 3 DOF control.
Thumbwheel, Slider switch, or Dial	P	+ +	+ +	+	+ +	–	Requires one or more additional methods for greater than 1 DOF control
Trackball		+ +	+ +	+ +	+ +	– –	Not suitable for simultaneous position and rate control due to high degree of cross-coupling between control axes. Requires additional method for 3 DOF control.
Voice Recognition		+	– –	–	–	– –	Resolution of volumetric position or rate control inherently limited by vocabulary. Questionable reliability.
Direct Interaction Methods							
Light Pen	P	–	+	+ +	+ +	–	Intermittent use may produce arm fatigue. Requires additional method for 3 DOF control.
Touch Screen (Acoustic, Capacitive, Cross-Wire, Infrared)	P	–	–	+ +	+ +	–	Intermittent use may produce arm fatigue. Requires additional method for 3 DOF control.
Tracker: Eye		+	– –	–	–	– –	Resolution of control limited by involuntary eye movements and requirement of frequent calibrations Questionable reliability in airborne environment due to vibration and load. Requires additional method for 3 DOF control.
Tracker (IR, LED, Magnetic, Ultrasonic, Video)		– –	–	+	–	– –	Extended use would produce arm fatigue. Calculation of derived volumetric direction or position from multiple sensors in real time would likely introduce lag. Inherent instability of method under vibration and loads.

3.0 CONCEPT FORMULATION

In this section of the report, the preferred technologies and methods identified in Section 2.2 are further downselected. This downselection occurs through a detailed performance analysis of collimation methods (Section 3.1) and a pair-wise compatibility analysis of image source options, 3-D methods, collimation methods, and 3-D interaction methods (Section 3.2). Those technologies and methods which are most compatible are then assembled in general system concepts (Section 3.3). Finally, the general concepts are downselected to a single system concept, presented in greater detail than the general concept definitions (Section 3.4).

The material is presented comprehensively in the following tables, with supplementary comments provided in the body of this text.

The preferred constituent technologies and methods were previously identified in Section 2.2 and are summarized in Table 3-1 below.

Table 3-1. Summary of preferred technologies and methods from rate and compare analysis (Section 2.2).

Technology Area	Preferred Methods
Image Source Technologies	Large Displays • Plasma (Emissive) • AMLCD Projection Light Valves • Transmissive (AMLCD) • Reflective (DMD, Reflective LC)
3-D Methods	Eyewear Methods: • Time Multiplexing (single or dual channel, possibly with color multiplexing) • Spatially Combined with Polarization (dual channel) • Microretarder/Micropolarizer Auto-stereoscopic methods: • Dual Channel, Dual Projection Combined Stereo (directional optics, e.g. Fresnel, or two pupil retroreflector method) • Parallax Barrier (single channel, bi-directional approach -- includes cylindrical lenticular and dynamic barrier approaches)
Collimation Methods	• Refractive (including relay methods) • Reflective (with real relay) • Catadioptric (symmetric and tilted, with beamsplitter or polarizing beamsplitter) • Pancake Window® (special case of reflective or catadioptric) • Retroreflector Array Relay Method (also considered as a separate 3-D method)
3-D Interaction Methods	Indirect Interaction Methods • Joystick (includes Spaceball) • Tablet • Thumbwheel, Slider Switch, or Dial Direct Interaction Methods • Light Pen • Touchscreen

3.1 Estimates of Collimation Method Performance

The preferred collimation methods (see Table 3-1) were modeled with optical design software to provide a more accurate estimate of expected performance. Such modeling provides estimates of the expected size and weight of each collimation approach as a function of head motion box size, FOV, and head relief. The results of the collimation modeling are presented in Table 3-2. For the purposes of this modeling effort, we assumed the strawman requirements for the head motion box size (±4" in 3-D), the FOV (48 deg x 27 deg), and the maximum physical volume (20" x 30" x 40"). These constraints in turn limit the maximum possible head relief to 25", at which point the first optical element reaches the 20" x 30" size maximum.

To summarize Table 3-2, all the preferred collimation methods exceed the preliminary display requirement ceiling of 100 lbs, even without including the projection screen and projection optics for the small image sources. The smallest and lightest candidates are the Pancake Window®, the symmetric catadioptric, and the retroreflector. Results for each of the preferred methods modeled are discussed in detail below.

Table 3-2. Preferred collimation method modeling comparison.

Preferred Collimation Method	Volume (HxWxD)	Weight (Optics Estimate Only)	Image Source Size	Max Head Relief
Refractive (Figure 3-1)	20" x 30" x 37"	450 lbs plastic (1500 lbs glass)	20" x 30"	15"
Refractive Real Relayed Image (Figure 2-3)	> the above refractive	> the above refractive system	Depends on projection magnification.	15"
Refractive Virtual Relayed Image (Figure 2-4)	>> the above refractive	>> the above refractive system	Depends on relay magnification.	15"
Tilted Reflective with Real Relayed Image (Figure 2-8)	40" x 40" x 50"	140 lbs for light mirror, screen, and projection optics	Depends on projection magnification.	12"
Pancake Window® (Figure 3-2)	20" x 30" x 23"	110 lbs plastic (220 lbs glass)	22" diagonal	15"
Pancake Window® with Projection Optics	20" x 30" x 40"	150 lbs plastic with screen & projection lens	Depends on projection magnification.	15"
Symmetric Catadioptric (Figure 3-3)	30" x 44" x 30"	100 lbs (light mirror & pellicle beamsplitter (BS))	19" x 33"	12"
Symmetric Catadioptric with Projection Optics	40" x 44" x 30"	140 lbs for light mirror, pellicle BS, screen, & projection lens	Depends on projection magnification.	12"
Tilted Catadioptric (Figure 3-4)	50" x 46" x 100"	300 lbs (100 lbs for light mirror & pellicle BS, plus 200 lbs for relay lenses)	Depends on relay magnification.	17"
Polarizing Combiner (Figure 3-5)	30" x 44" x 30"	180 lbs for light mirror & polarizing coated pellicle BS	19" x 33"	12"
Retroreflector (Figure 2-22)	40" x 44" x 30"	160 lbs for light retroreflector, pellicle BS, & collimation lens	Depends on relay magnification.	12"

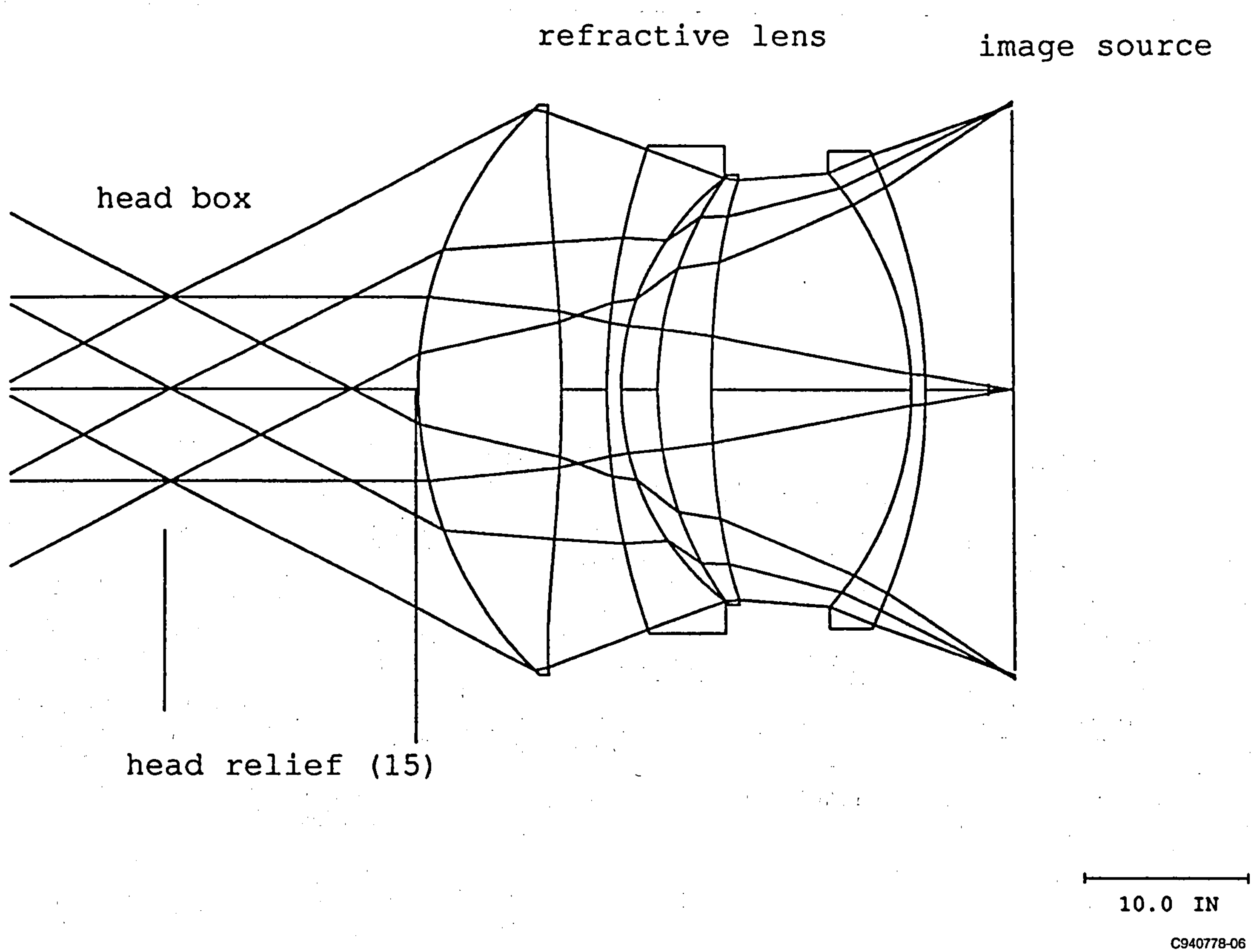


Figure 3-1. Refractive Collimator.

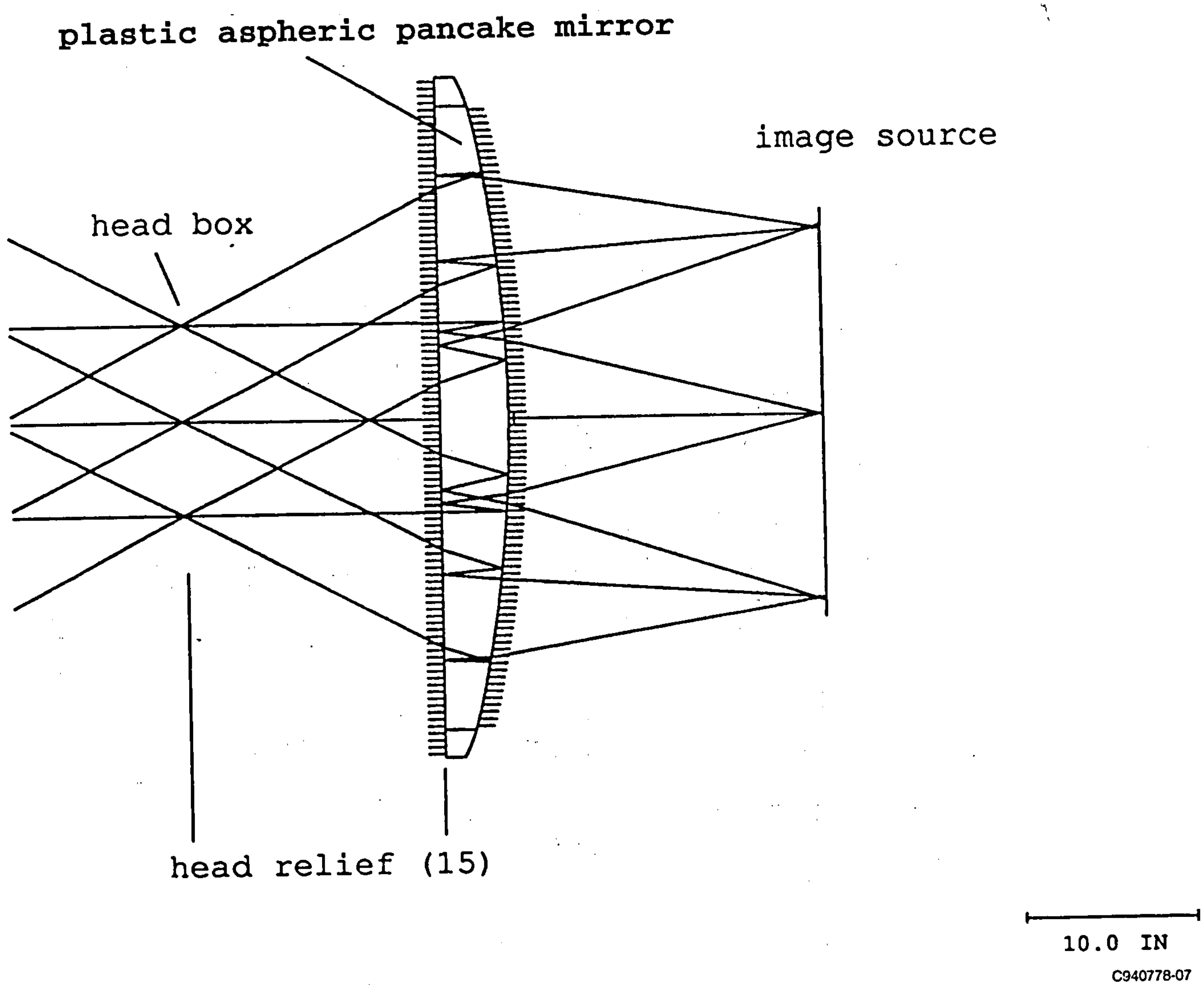


Figure 3-2. Pancake Window® Collimator.

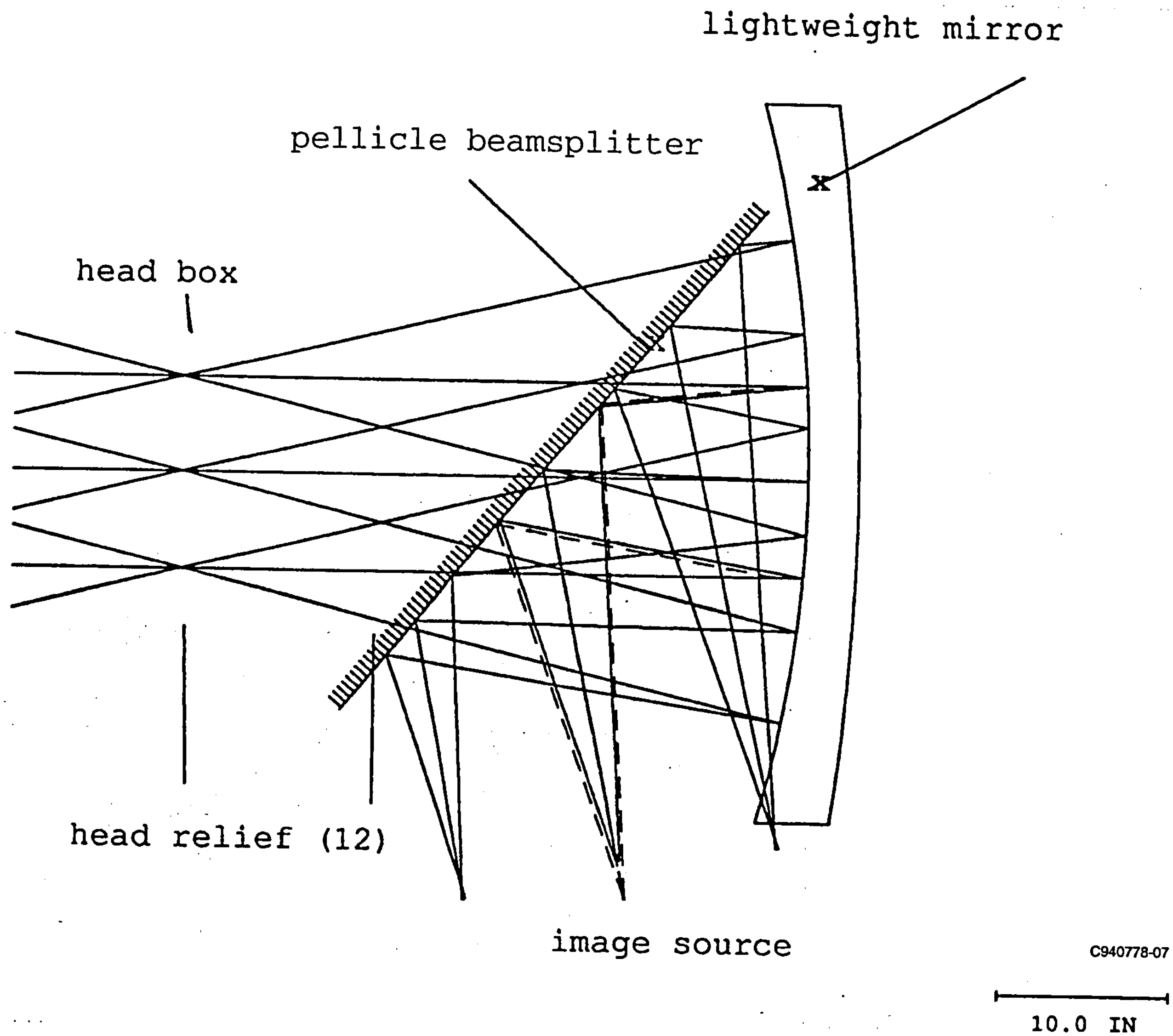


Figure 3-3. Symmetric Catadioptric Collimator.

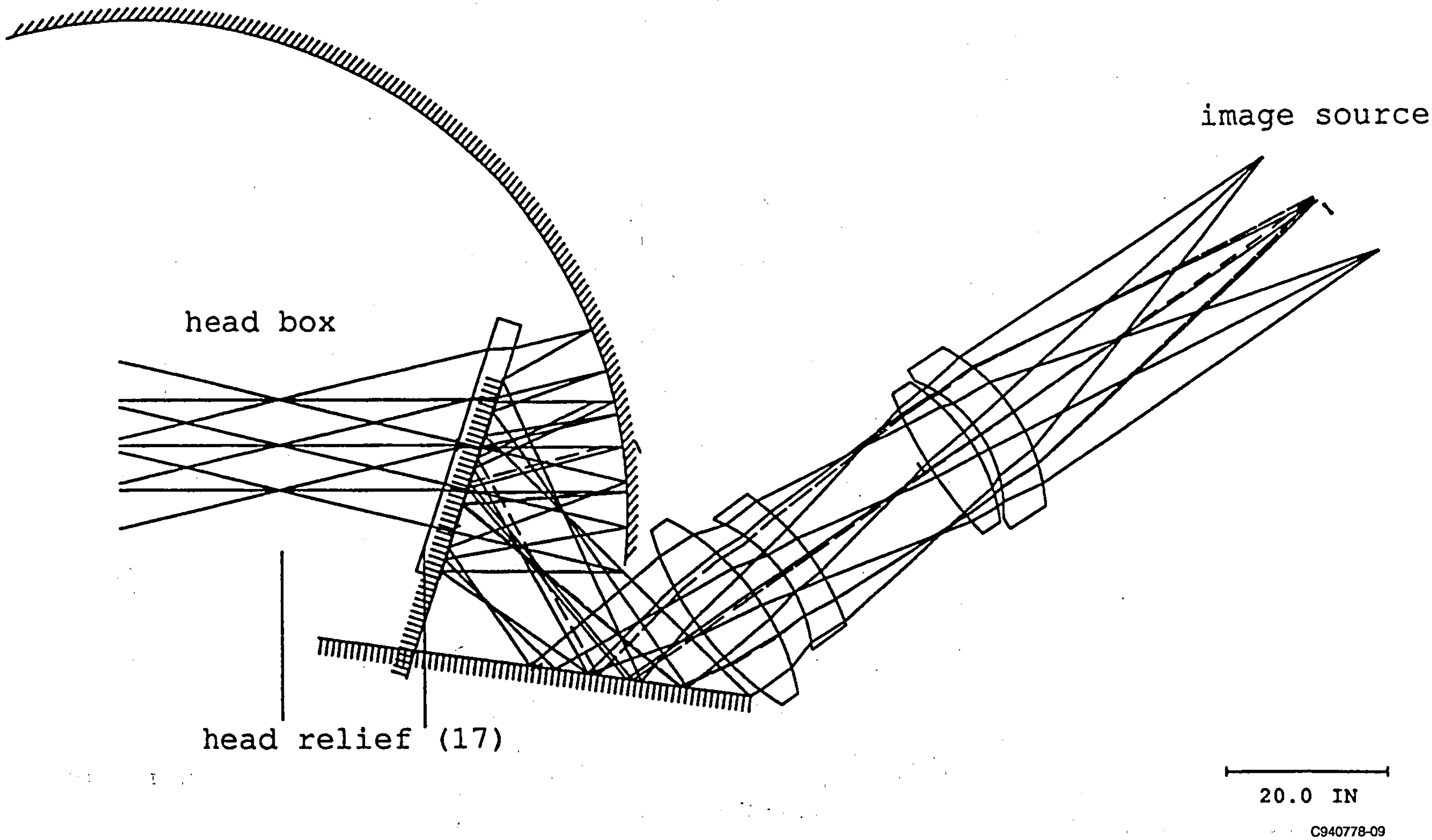


Figure 3-4. Tilted Catadioptric Collimator.

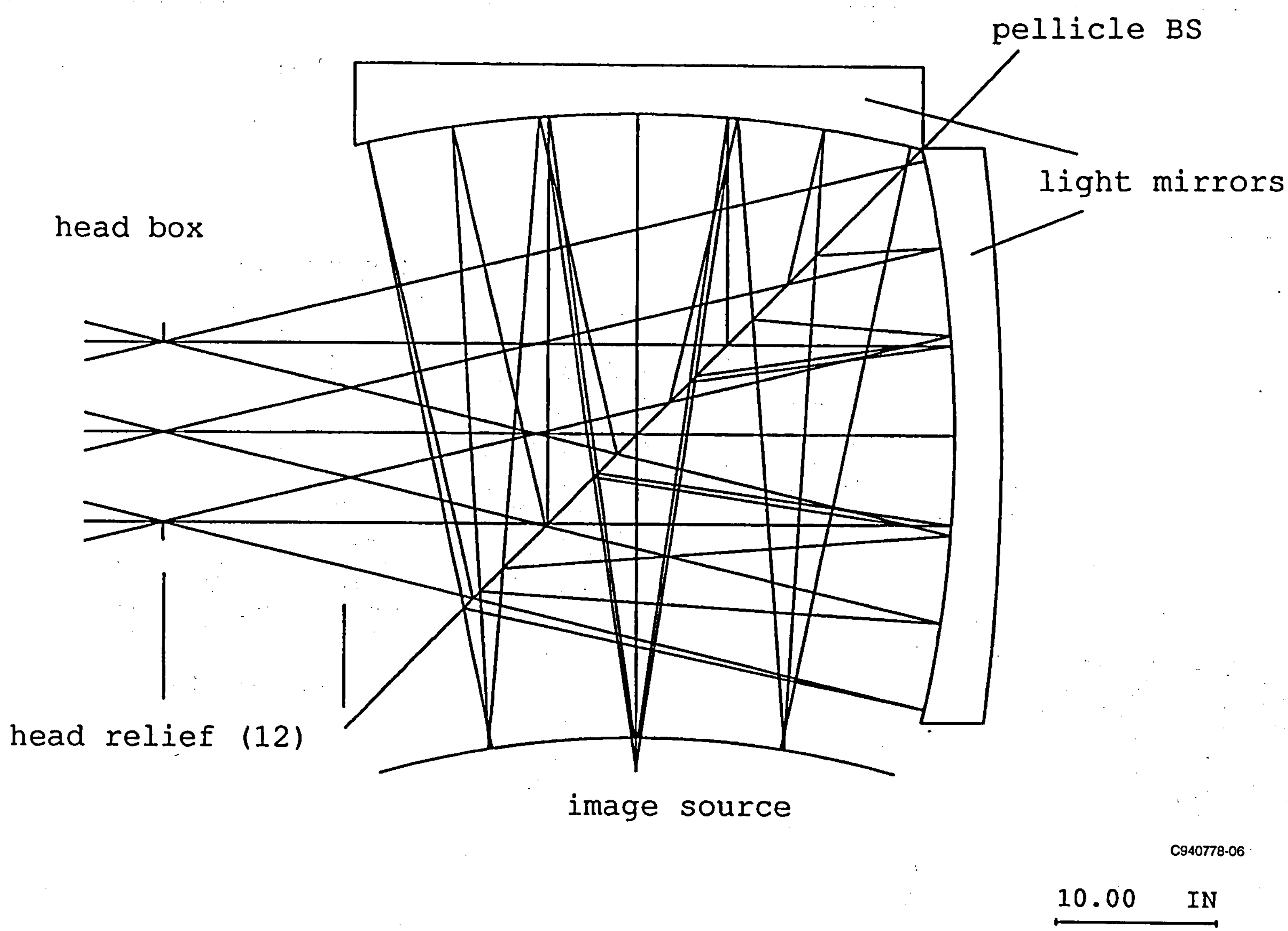


Figure 3-5. Polarizing Combiner Collimator.

3.1.1 Detailed Results from Collimation Modeling

The smallest of the refractive preferred collimation methods is the non-reimaging refractive approach (Figure 3-1). This approach will meet the volume requirement with a head relief maximum of 15", provided an image source size of 20" x 30" is available. However, the weight of the four-element refractive lens system modeled, if made from glass, is 1500 pounds. If plastic is used the weight can be reduced to approximately 450 pounds, but this still exceeds the required 100 pound maximum. If an image relay system is added to this refractive system (Figures 2-3, 2-4), the weight will only grow. Therefore, the refractive with virtual method and the real image relay method were not modeled. These later methods are, however, included in Table 3-2 with comments.

The tilted reflective with real relayed image approach (Figure 2-8) has a volume larger than the strawman requirement, even with the 12-inch minimum head relief. Furthermore, the weight of this method exceeds 100 lbs when the projection screen and projection optics are added. The poor performance of the tilted first mirror will also require a complex projection optical system.

The Pancake Window® (Figure 3-2) with a head relief of 15 inches has the smallest volume of all the preferred methods. However, the resolution of this approach is marginal and may need some additional correction. The weight estimate for plastic elements is near 100 pounds. If a preferred image source as large as the 21-inch diagonal cannot be found, an image relay or image projection system will need to be added. The projection system adds approximately 17 inches to the depth of the system and approximately 40 lbs for the screen and projection lens.

The symmetric catadioptric method (Figure 3-3) exceeds the strawman maximum volume, even using the smallest head relief of 12 inches. However, with an ultralight-weight composite mirror and a mylar pellicle beamsplitter, a weight of near 100 lbs can be achieved. If a preferred image source as large as the 19" x 33" cannot be found, an image relay or image projection system will need to be added. The projection system adds approximately 10 inches to the height of the system and approximately 40 lbs for the screen and projection lens.

The tilted catadioptric system (Figure 3-4) requires a large volume because of the image relay lens size. The image relay lens size can be reduced if optimized or even changed to a smaller projection system. However, the optical correction will be more complicated than for the symmetric catadioptric approach. Additionally, the combiner fold will be heavier than the symmetric approach due to the addition of one mirror.

The polarizing combiner method (Figure 3-5) will have a volume equal to that of the symmetric catadioptric method. However, the polarizing combiner approach will be heavier than the symmetric catadioptric approach due to the addition of one mirror. As with the other concepts with large image sizes, if a screen and projection optics are needed the size and weight will also grow.

The retroreflector method (Figure 2-22) exceeds the maximum strawman volume even with the 12-inch minimum head relief, but only weighs 160 lbs with the relay lenses included. However, retroreflecting screens are still in development.

The large volumes and weights of these collimation methods are an area of concern. Therefore, a tradeoff analysis was performed to determine the impact of relaxing the strawman requirements. The volume of each system is a function of the head relief, the FOV, and the head motion box size. This general relationship is represented in Figures 3-6 and 3-7, where volume is presented in relative units only. Figure 3-6 is a plot of relative physical volume vs FOV half angle (the strawman half field angle is 27.5 deg diagonal), with each curve representing a different combination of head relief and head motion box size. Curve 1 of Figure 3-6 is for a head relief of 33 inches and a head motion box size of 8 inches. Curve 2 is for a head relief of 33 inches and a head motion box size of 4 inches. Curve 3 is for a head relief of 12 inches and a head motion box size of 8 inches. Curve 4 is for a head relief of 12 inches and a head motion box of 4 inches. Figure 3-6 shows an 8 to 11 fold increase in physical volume with an increase in head relief from 12 to 33 inches.

Figure 3-7 illustrates the impact of head relief on relative physical volume for a constant half FOV (27.5 deg) and a constant head motion box size (8 inches). From this figure, the volume is shown to double for a head relief change from 13 to 18 inches. Volume doubles again as head relief increase from 18 to 25 inches.

The size and weight estimates discussed here and in Table 3-2 are based upon a given set of assumptions. Altering the assumptions such as depicted in Figures 3-6 and 3-7, or for example by implementing a more conventional and potentially stable beamsplitter element where indicated, would clearly impact these estimates. Even so, the size and weight estimates tabulated serve their intended purpose as excellent indicators of the approximate magnitudes and comparisons of the configurations relative to the strawman requirements.

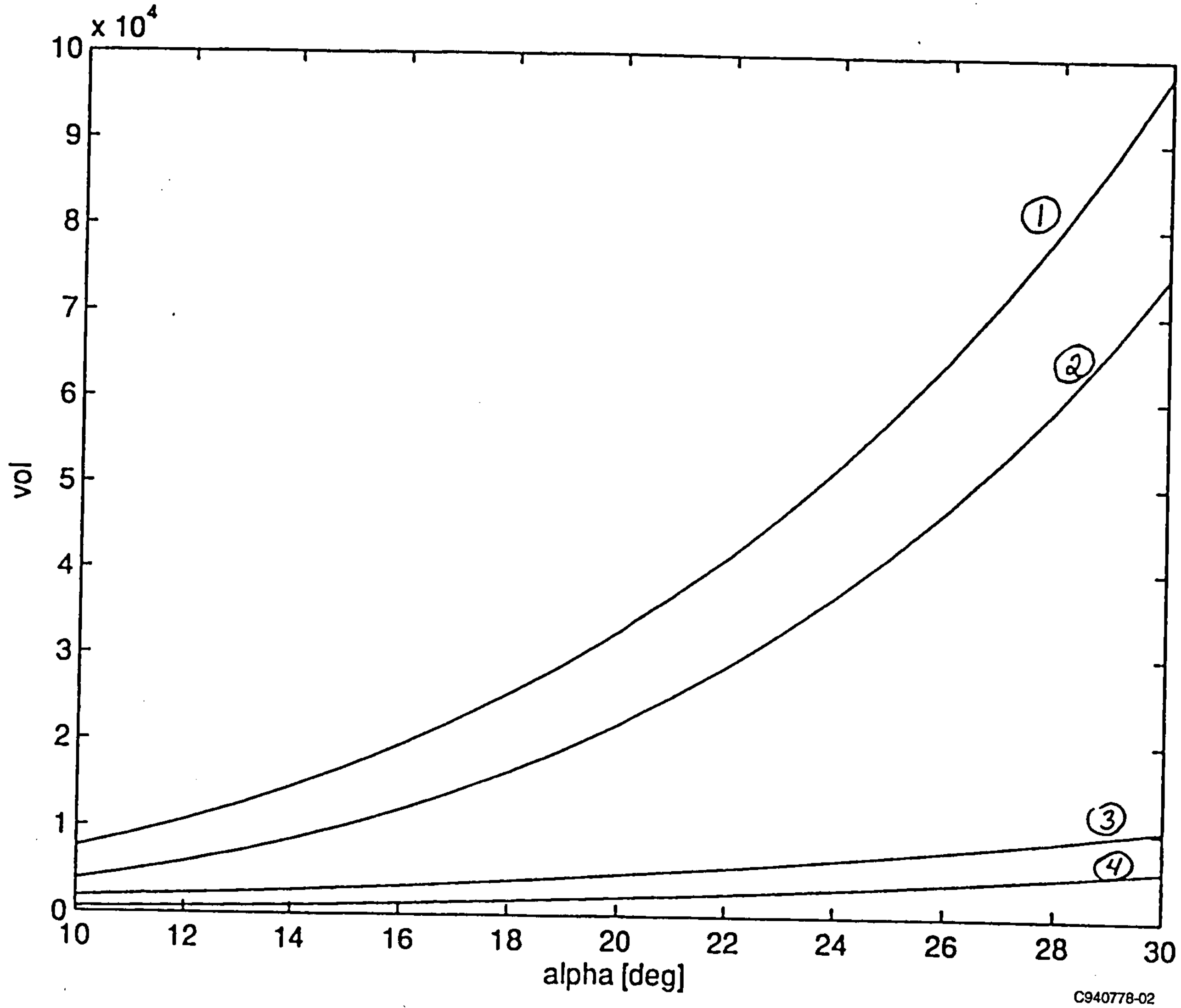


Figure 3-6. Volume (relative units) vs Half FOV.
1 head relief=33", head box=8". 2 head relief=33", head box=4". 3 head relief=12", head box=8". 4 head relief=12", head box=4".

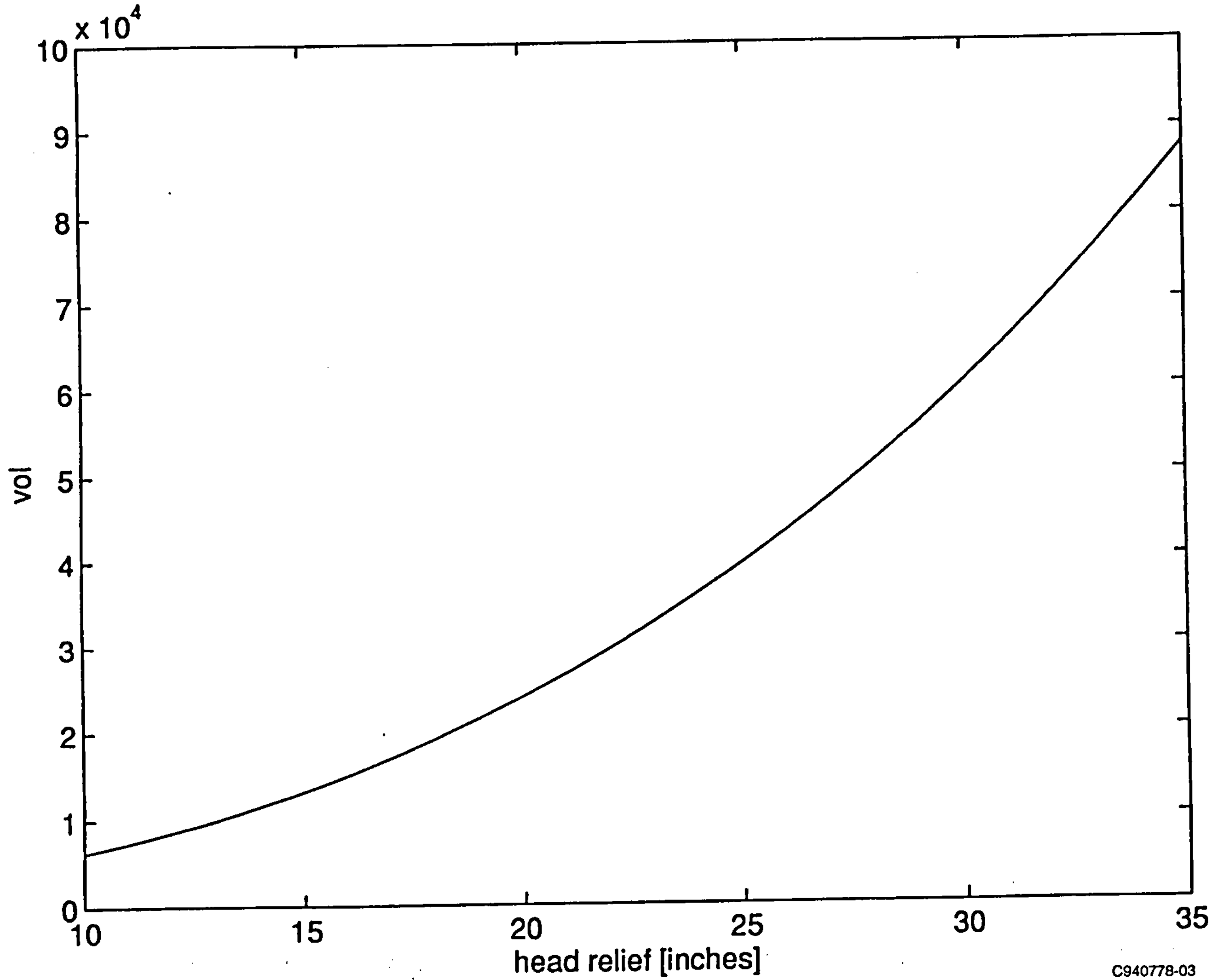


Figure 3-7. Volume (relative units) vs Head Relief: Half FOV=27.5 deg, Head motion box=8".

3.2 Compatibility of Methods

The following three tables (Table 3-3 to 3-5) illustrate the compatibility of preferred technologies and methods for image source technology, 3-D method, collimation method, and 3-D interaction method. These tables are used to further downselect the preferred technologies and methods selected in the rate and compare task (summarized in Table 3-1). Ratings signify favorable (+) or unfavorable (-).

3.2.1 Image Source Technologies vs 3-D Methods

Table 3-3 describes the relative compatibility of four classes of preferred image source technology with seven preferred 3-D methods.

Table 3-3. Compatibility of preferred image sources and preferred 3-D methods (independent of collimation method).

3-D Methods	Plasma	AMLCD ("large")	Projection AMLCD	DMD / Reflective LC
Eyewear Methods				
Time Multiplexing, Single Channel	+ At this time, although there is some question about adequacy of persistence and driver bandwidth.	- Switching speed limitation for TN.	- Switching speed limitation for TN.	+ Should be possible.
Time Multiplexing, Dual Channel	- Image source size, low luminance, and less desirable than single channel.	+ Possible, although size is a concern. Difficult to tile.	+ Possible, although temporal aliasing must be avoided.	+ Should be possible for reflective LC, but not preferred for DMD.
Dual Channel, Spatially Combined Stereo with Polarization	- Image source size.	+ Possible, although size is a potential concern.	+ Possible.	+ Possible.
Microretarder / Micropolarizer Display	- Not easily implemented, non-standard, low luminance.	- Not suitably implemented.	- Not suitably implemented.	- Not suitably implemented.
Autostereo Methods				
Dual Channel, Dual Projection Combined Stereo with Directional Optics (e.g. Fresnel, Retroreflector)	+ Possible, although size is a concern. Difficult to tile.	+ Possible, although size is a concern. Difficult to tile.	+ Possible.	+ Possible.
Parallax Barrier (including Cylindrical Lenticular)	+ Possible, but more difficult at high resolution. Available pixel count is inadequate.	+ Possible, but more difficult at high resolution. Available pixel count is inadequate.	+ Possible, but probably difficult to apply to projected image.	+ Possible, but probably difficult to apply to projected image.
Sequential Frame Moving Slit (Dynamic Parallax Barrier)	- Luminance.	- Switching speed.	- (A special case of time-multiplexed and directional).	- (A special case of time-multiplexed and directional).

+/- ratings signify favorable/unfavorable.

3.2.2 3-D Methods vs Collimation Methods

As noted in the detailed estimate of collimation method performance, a relatively large image (image source or intermediate image) is required in nearly all cases, unless the head motion box is to be filled by head following of the source and collimator. This can take the form of a large panel, a medium size panel (in some cases) or a real image projection. The conclusions presented in Table 3-4 are based in part upon results from optical modeling analysis with respect to size and weight of large FOV, high resolution systems.

Some explanation is required for the retroreflector array concept. It is unique in that it can either be a 3-D method in its own right (subset of dual channel, directional stereo), or alternately serve as a supplemental collimated relay method for other stereo methods. As such, it is included in both a row and a column.

Table 3-4. Compatibility of preferred 3-D methods and preferred collimation methods.

3-D Method	Refractive	Pancake Window®	Symmetric Catadioptric, Beamsplitter	Tilted Catadioptric	Retroreflector Array Collimated Relay Method
(General comments on performance of collimation method)	Generally too heavy.	Has rather low transmittance, and may require some performance tradeoffs.	Heavy, and may require performance tradeoffs.	Generally too large and too heavy.	Has potential advantages, but resolution and artifacts are concerns. Can use most stereo methods.
Time multiplexed	- Too heavy, but otherwise possible (dual channel).	+ Compatible, in dual channel configuration, but luminance is a concern.	+ Possible, in dual channel projection mode, but may be bulky and too heavy.	- Too heavy and large.	+ Compatible.
Dual Channel, Spatially Combined, with Polarization	- Too heavy, but otherwise possible, especially with projected source.	- Not compatible due to Pancake Window® polarization scheme.	+ Compatible if projection. Can tile sources, but need to verify low crosstalk. May be bulky and too heavy.	- Too heavy and large.	+ Compatible if appropriate elements are used.
Dual Channel, Directional Projection	- Possibly compatible if projection, but difficult to expand head motion box. Even head tracking leaves no easy way to move pupil. Still too heavy.	+ Compatible if projection, though difficult to expand head motion box.	+ Compatible if projection, but difficult to expand head motion box. Bulky & heavy.	- Too heavy and large.	+ Compatible (listed separately in bottom row of table).
Parallax Barrier/Lenticular	- Too heavy. May be compatible otherwise, but no practical image source.	+ Compatible, in principle, although current image sources will require tiling. Seamless tiling requires projection mode (difficult registration) or multiple beamsplitters. Latter option is limited if head motion box is large. Low transmittance.	+ Compatible, in principle, although current image sources will require tiling. Seamless tiling requires projection mode (difficult registration) or multiple beamsplitters (may be too large).	- Too heavy and large.	+ Possible.
Retroreflector (as Directional Autostereo 3-D Method)	+ Compatible, but resolution and artifacts are concerns.	- Not justifiable due to low transmittance.	+ Compatible, but resolution and artifacts are concerns.	- Could be used, but other options probably better.	(Relay method implied here, by definition).

+/- ratings signify favorable/unfavorable.

3.2.3 3-D Interaction Methods vs Collimation

Table 3-5 describes the relative compatibility of five classes of preferred 3-D interaction methods with collimated display. The direct interaction methods require direct, manual operation on the image and are therefore incompatible with collimated presentation of the image at infinity.

Table 3-5. Compatibility of preferred 3-D interaction methods with collimated display.

3-D Interaction Method	**Compatibility with Collimated Display**
Indirect Interaction Methods	
Joystick (includes Spaceball)	+
Tablet	+
Thumbwheel, Slider Switch, or Dial	+
Direct Interaction Methods	
Light Pen	- Direct interaction of light pen and image is incompatible with presentation of image at infinity.
Touch Screen	- Direct interaction of finger or stylus and image is incompatible with presentation of image at infinity.

+/- ratings signify favorable/unfavorable.

3.3 General System Concepts

Presented in the following tables and figures are general conceptual systems, based upon the results of the detailed collimation method modeling (Section 3.1) and the pairwise compatibility comparisons (Section 3.2). Basic conceptual layouts are defined, with options listed. These options are secondary in terms of downselection.

3.3.1 General Display Concepts

This portion of the report documents the preferred combinations of image source, 3-D method, and collimation method. Some combinations have been eliminated, due to perceived risk or due to existence of a similar but preferable configuration. Note that no concepts are listed using the refractive or tilted catadioptric configurations due to optics weight and/or size. Also, at this point DMD is taken to also include reflective LCDs. The general display concepts described are:

A	Symmetric catadioptric with time multiplexing
B	Symmetric catadioptric with polarization
C	Pancake Window® with time multiplexing
D	Pancake Window®, dual channel with directional projection (autostereo)
E	Retroreflective relay method with dual collimating projectors
F	Symmetric catadioptric, dual channel directional projection (autostereo)
G	Symmetric catadioptric, parallax barrier applied to projected tiled image
H	Unfolded catadioptric with time multiplexing
I	Pancake Window® with time multiplexing of non-tiled, beamsplitter-combined large image sources
J	Pancake Window®, parallax barrier applied to projected tiled image
K	Pancake Window®, parallax barrier using tiled, direct-view displays

Table 3-6. General Display Concept A: Symmetric catadioptric with time multiplexing.

3-D Method	Time multiplexed Stereo.
Image Source	Light valve: • Option 1: Single channel, DMDs, tiled if necessary. • Option 2: Dual channel, multiple projection AMLCDs, tiled if necessary (initially).
Optical Configuration	• Folded, symmetric catadioptric system. • Single beamsplitter. • "Light-weight" front surface mirror. • Curved real image screen. • Separate projection modules for each light valve. • "Injected", or reverse path projection, using collimating optics and supplemental optics to create appropriate image on screen.
Eyewear	• Circular polarizer glasses. • Display-mounted polarizing means. • Variable retarder mechanism, either on eyewear or display system.
Secondary Options	• Polarizing beamsplitter for improved efficiency. • Xenon or metal halide lamp, possibly fiber coupled. • Optional directional properties on real screen. • Optional rear projection onto screen (non-injected). • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color at 120 Hz, but this is not anticipated). Configuration supports tiling/overlay of multiple projectors to extent necessary. • Light-weight and compact optics. • Suppression of AMLCD/shutter aliasing.
Features/Discussion	• Simple symmetric configuration provides excellent central performance and reasonable performance near edges of field and head motion box. • Image somewhat visible outside of design head motion box although may be degraded. • This "injected" projection scheme provides several potential advantages. • Large reflectors are achromatic.
Potential Trouble Areas	• Optics weight, size and form factor. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Temporal artifacts associated with time multiplexing. • Tiling seams.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV, and allowable obscuration by projectors.

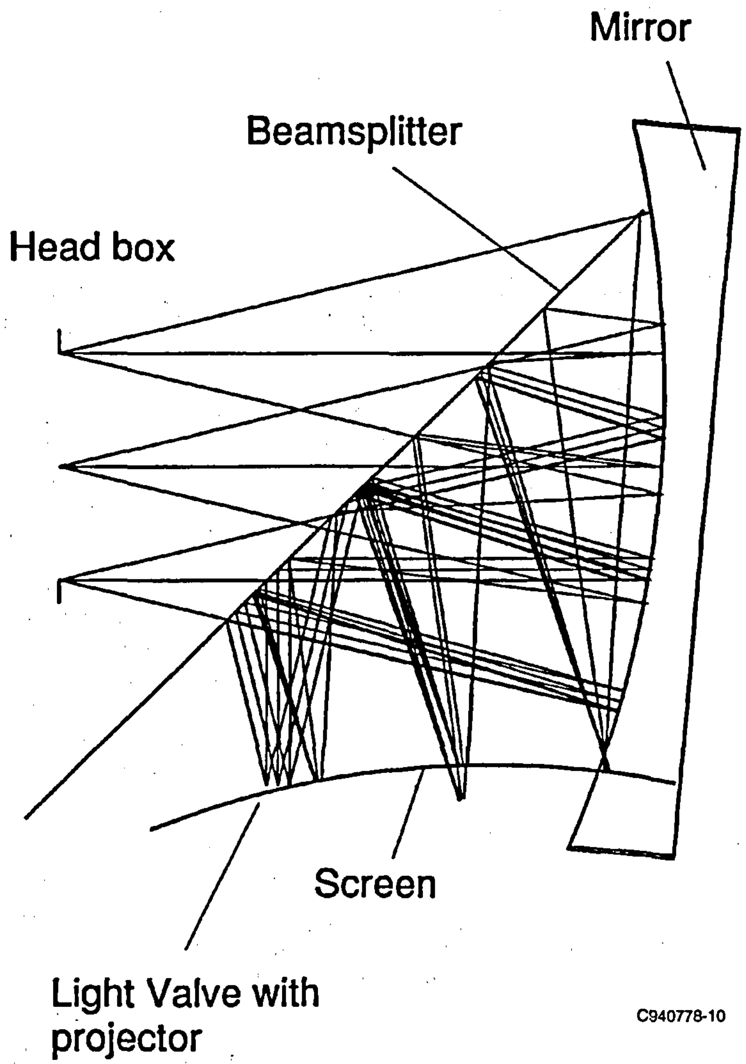


Figure 3-8. General Display Concepts A and B: Symmetric Catadioptric with Time Multiplexing or Polarization.

Table 3-7 General Display Concept B: Symmetric catadioptric with polarization.

3-D Method	Polarization .
Image Source	Light valves, tiled as necessary: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Folded, symmetric catadioptric system. • Single beamsplitter. • "Light-weight" front surface mirror. • Curved real image screen, polarization preserving. • Separate polarizing projection modules for each light valve. • "Injected", or reverse path projection, using collimating optics and supplemental optics to create appropriate image on screen.
Eyewear	• Circular polarizer glasses
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional directional properties on real screen. • Optional rear projection onto screen (non-injected). • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color). Configuration supports tiling/overlay of multiple projectors to extent necessary. • Light-weight and compact optics.
Features/Discussion	• Simple symmetric configuration provides excellent central performance and reasonable performance near edges of field and head motion box. • Image somewhat visible outside of design head motion box although may be degraded. • This "injected" projection scheme provides several potential advantages. • Large reflectors are achromatic.
Potential Trouble Areas	• Optics weight, size and form factor. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Tiling seams. • Polarization crosstalk in the optics.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV, and allowable obscuration by projectors.

Table 3-8. General Display Concept C: Pancake Window® with time multiplexing.

3-D Method	Time multiplexed stereo.
Image Source	Light valve: • Option 1: Single channel, DMDs, tiled if necessary. • Option 2: Dual channel, multiple projection AMLCDs, tiled if necessary (initially).
Optical Configuration	• Pancake Window®, with associated polarization control elements. • Light valves projected onto real image screen to match size and tiling requirements.
Eyewear	• Circular polarizer glasses. • Display-mounted polarizing means. • Variable retarder mechanism, either on eyewear or display system.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional directional properties on real screen. • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color). Projection configuration supports tiling/overlay of multiple projectors to extent necessary. • Light-weight and compact optics. • High efficiency Pancake Window® optics. • Suppression of AMLCD/shutter aliasing.
Features/Discussion	• Pancake Window® is compact but generally very inefficient. • Image somewhat visible outside of design head motion box although may be degraded.
Potential Trouble Areas	• Luminance. • Optics weight, size and form factor. • Extra volume and weight associated with the projector. • Meeting requirements without additional elements. • Tiling seams.
Helpful Tradeoff Areas	• Luminance requirements. • Resolution fall-off at edges of head motion box.

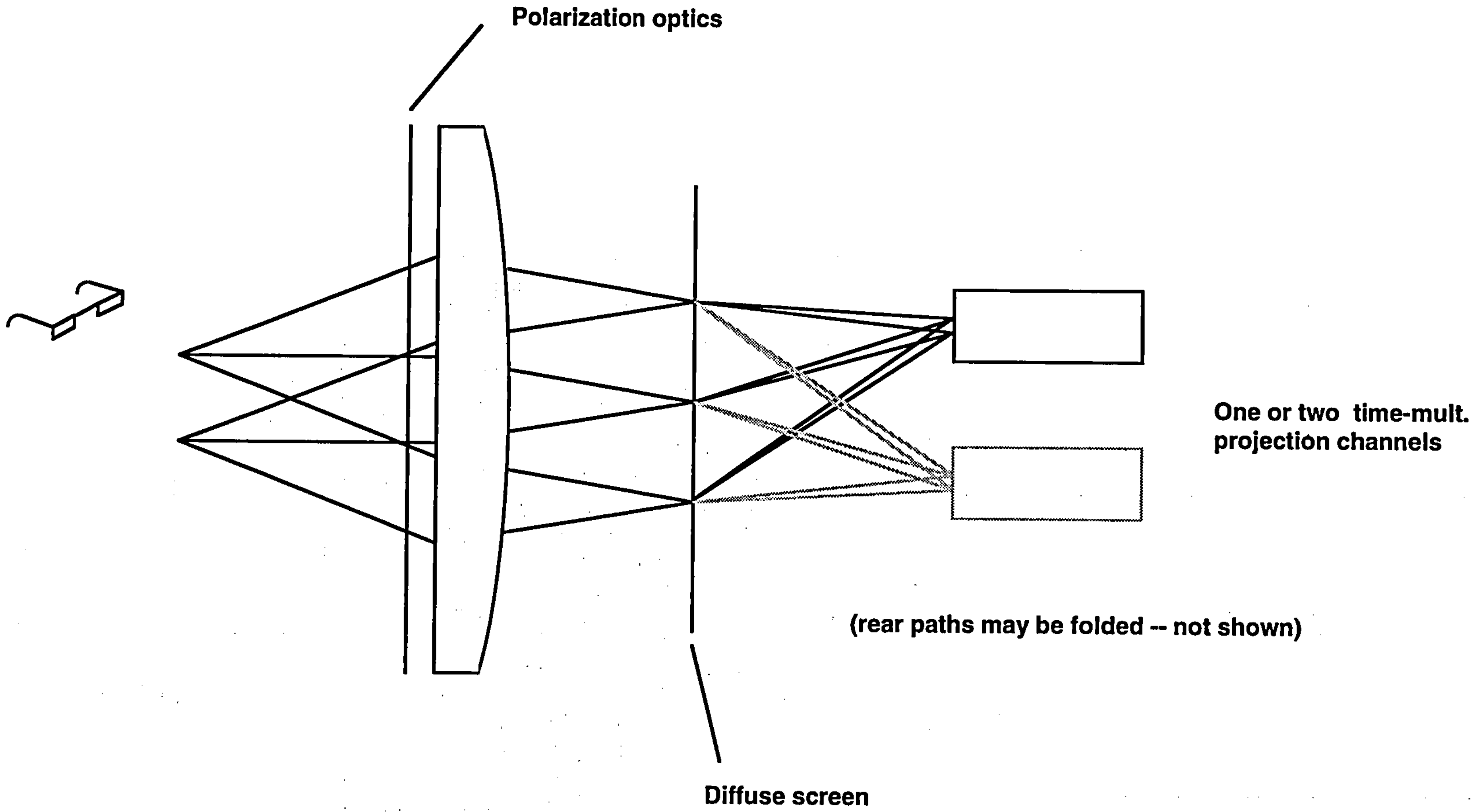


Figure 3-9. General Display Concept C: Pancake Window® with Time Multiplexing.

Table 3-9. General Display Concept D: Pancake Window®, dual channel with directional projection (autostereo).

3-D Method	Dual channel directional projection (autostereo).
Image Source	Light valve: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Pancake Window®, with associated polarization control elements. • Relayed optical system, with field lens type of arrangement. • Dual ("combined") image source arrangement, e.g. beamsplitter or projection onto additional screen. • Dynamically movable pupil in relay optics (e.g. polarizer and spatially switchable retarder). • Coarse head following to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional forms of "combined" projector. • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color). • Light-weight and compact optics. • High efficiency Pancake Window® optics.
Features/Discussion	• Pancake Window® is compact but generally very inefficient. • Use of multiple image relays raises significant concern about size and other issues. Relay optics will be large and projector unit will scale with head motion box dimensions.
Potential Trouble Areas	• Luminance. • Optics weight, size and form factor. • Extra volume and weight associated with the projector and relay optics. • Meeting requirements without additional elements. • Tiling seams. • Degradation if multiple relays are used.
Helpful Tradeoff Areas	• Luminance requirements. • Resolution fall-off at edges of head motion box.

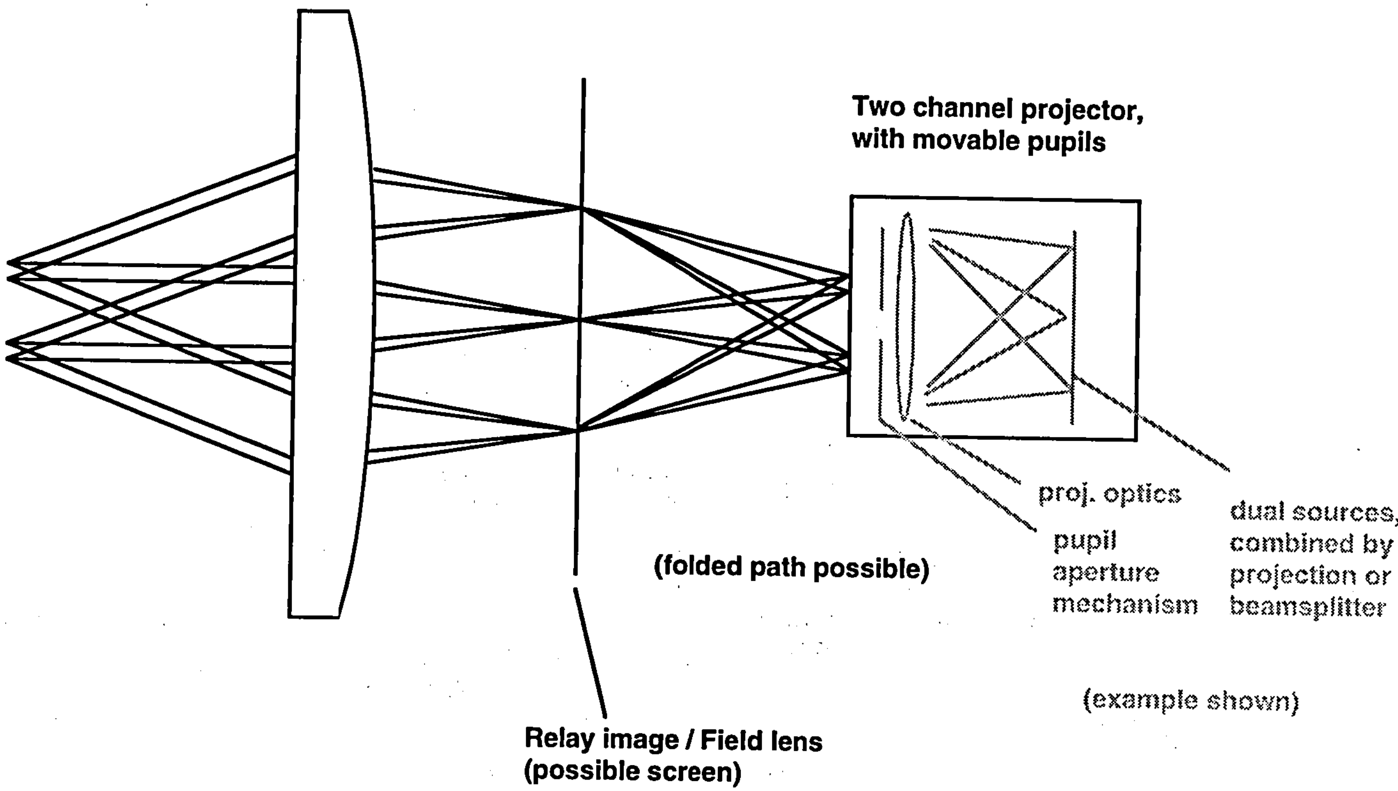


Figure 3-10. General Display Concept D: Pancake Window®, Dual Channel with Directional Projection (Autostereoscopic).

Table 3-10. General Display Concept E: Retroreflective relay method with dual collimating projectors.

3-D Method	Dual channel directional projection (autostereo). (Other methods possible in similar relay configuration)
Image Source	Light valve: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Image sources are collimated by "compact" optics, to give eye-sized pupils, but with no head relief requirements. • Beamsplitters used to "tile" collimated projectors if required, for each eye. • Dynamic physical translation of compact projectors (in 3 axes for full functionality). • Collimated rays are relayed to actual head motion box location by beamsplitter and retroreflective array screen (e.g. molded corner cube array). • Coarse head tracking controls translation mechanism to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional forms of autostereo projector (e.g. with no moving mechanical parts). • Implementation of various collimation configurations. • Implementation of other 3-D methods (e.g. polarization or time multiplexing, no moving parts).
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color). • Verification and effective implementation of suitable retroreflector array. • Light-weight and compact optical arrangement. • Projector translation mechanism.
Features/Discussion	• While offering unique potential advantages, such as vibration tolerance and reduced weight, the method has not been fully demonstrated at high resolution and wide FOV. • Biggest concerns involve effective resolution (including fabrication precision) and artifacts associated with the boundaries between retroreflective elements, especially at non-normal angles of incidence. • Physical translation of the projectors provides autostereo over the full head motion box (including depth), but may be undesirable for reliability or other reasons. Alternate methods involve tradeoffs as well.
Potential Trouble Areas	• Effective resolution of optical relay. • Artifacts associated with boundaries between retroreflective elements. • Fabrication complexity of suitable array. • Optics weight, size and form factor. • Tiling seams. • Luminance, due to use of beamsplitter. • Acceptability (e.g. reliability) of mechanical translators if used.
Helpful Tradeoff Areas	• Luminance requirements. • Resolution. • Artifacts.

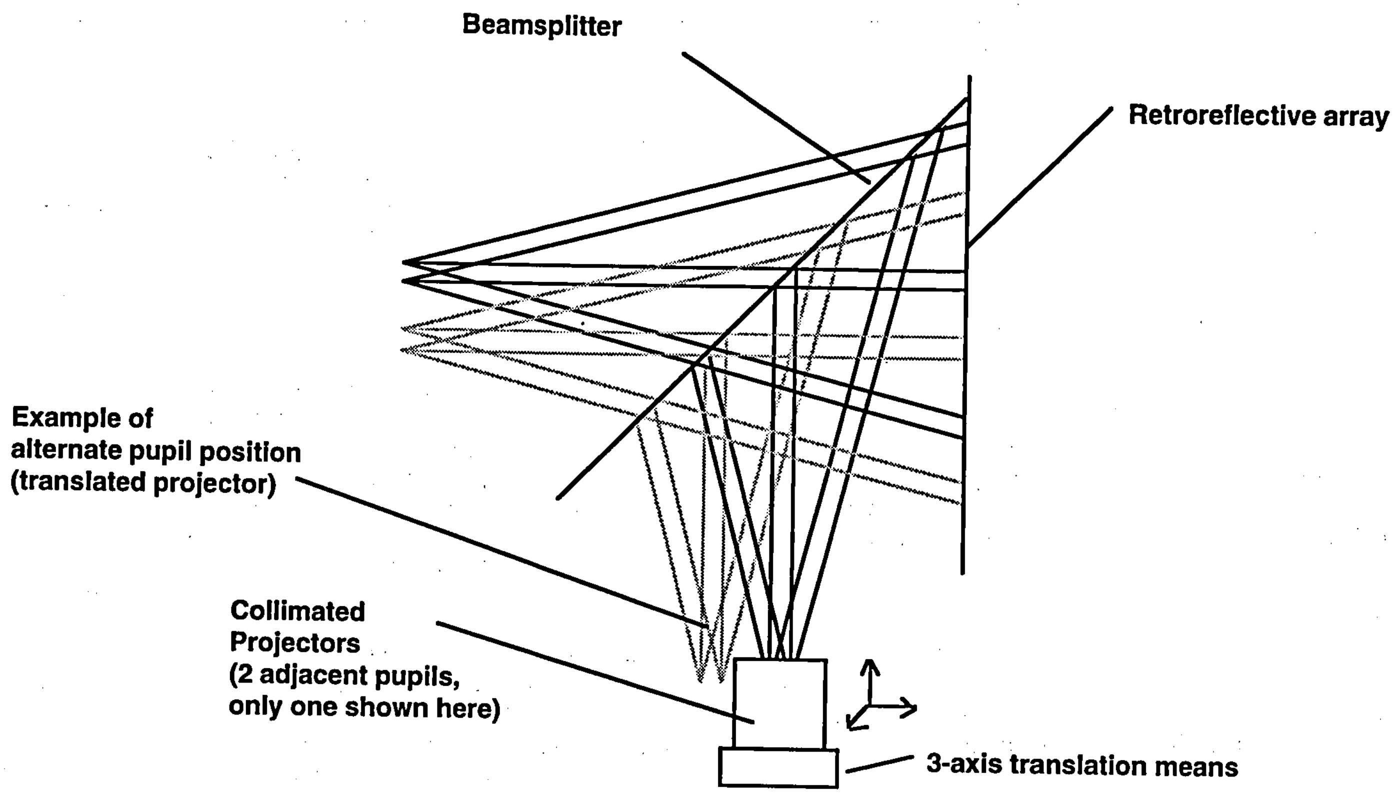


Figure 3-11. General Display Concept E: Retroreflective Relay Method with Dual Collimating Projectors.

Table 3-11. General Display Concept F: Symmetric catadioptric, dual channel directional projection (autostereoscopic).

3-D Method	Dual channel directional projection (autostereo).
Image Source	Light valves: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Folded, symmetric catadioptric system. • Single beamsplitter. • "Light-weight" front surface mirror. • Relayed optical system, with field lens type of arrangement. • Dual ("combined") image source arrangement, e.g. beamsplitter or projection onto additional screen. • Dynamically movable pupil in relay optics (e.g. polarizer and spatially switchable retarder). • Coarse head following to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional forms of "combined" projector. • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color). • Light-weight and compact optics.
Features/Discussion	• Use of multiple image relays raises significant concern about size and other issues. Relay optics will be large and projector unit will scale with head motion box dimensions.
Potential Trouble Areas	• Optics weight, size and form factor. • Extra volume and weight associated with the projector and relay optics. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Tiling seams. • Degradation if multiple relays are used.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV. • Size and form factor, to accommodate projectors.

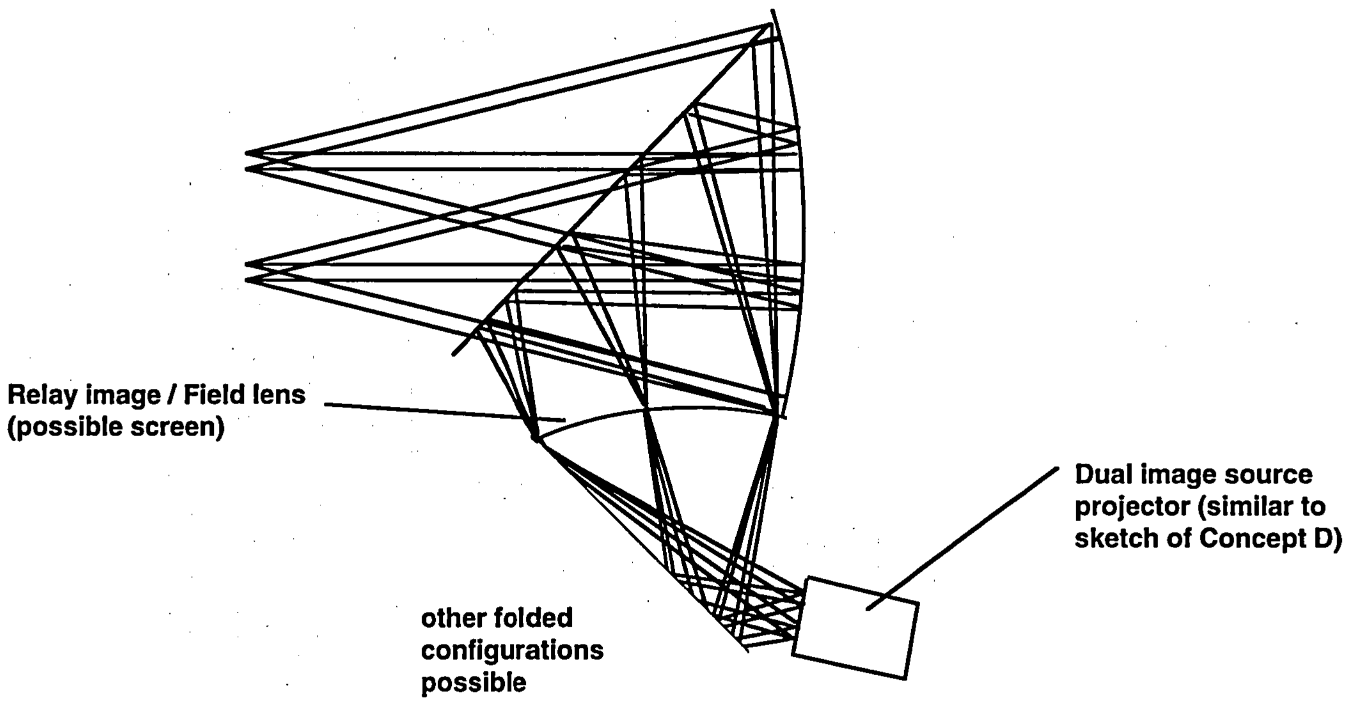


Figure 3-12. General Display Concept F: Symmetric Catadioptric, Dual Channel Directional Projection (autostereoscopic). (Vertical pupil separation shown for clarity. Actual separation of pupils would be in horizontal axis for autostereo.)

Table 3-12. General Display Concept G: Symmetric catadioptric, parallax barrier applied to projected tiled image.

3-D Method	Parallax barrier (autostereo, related to dual channel directional projection).
Image Source	Light valves: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Folded, symmetric catadioptric system. • Single beamsplitter. • "Light-weight" front surface mirror. • Tiled image source arrangement, with double resolution in horizontal axis to provide compatibility with parallax barrier method. • Dynamically movable projected image (e.g. translation or deflection). • Matching parallax barrier mask to define left/right illumination profiles. • Coarse head following to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional curved screen and barrier mask. • Additional large elements for reduction of aberrations. • Possibility of dynamic parallax barrier rather than (or in addition to) image translation. • Addition of real-time image position feedback to partially compensate for vibration or drift.
Required Technology Developments	• Practical and available image source (ideal is 3840 x 1080 full color). • Light-weight and compact optics. • Dynamic image position control for smooth translation of autostereoscopic pupils. • High stability, high resolution projector, with tight distortion control, and matched barrier mask.
Features/Discussion	• Rear projection arrangement raises concern about size. • Resolution/stability requirements on real image relay projector are severe, since drift relative to the barrier mask can reverse stereo effect or cause image loss. • Image translation alone may not provide desired head motion box depth, although a dynamic mask with adequate degrees of freedom may allow this.
Potential Trouble Areas	• Relative vibration between the barrier mask and the projected image. • Projector resolution. • Luminance due to attenuation by barrier. • Optics weight, size and form factor. • Extra volume and weight associated with the projector. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Tiling seams.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV. • Size and form factor, to accommodate projector. • Lower horizontal pixel density, to improve vibration tolerance.

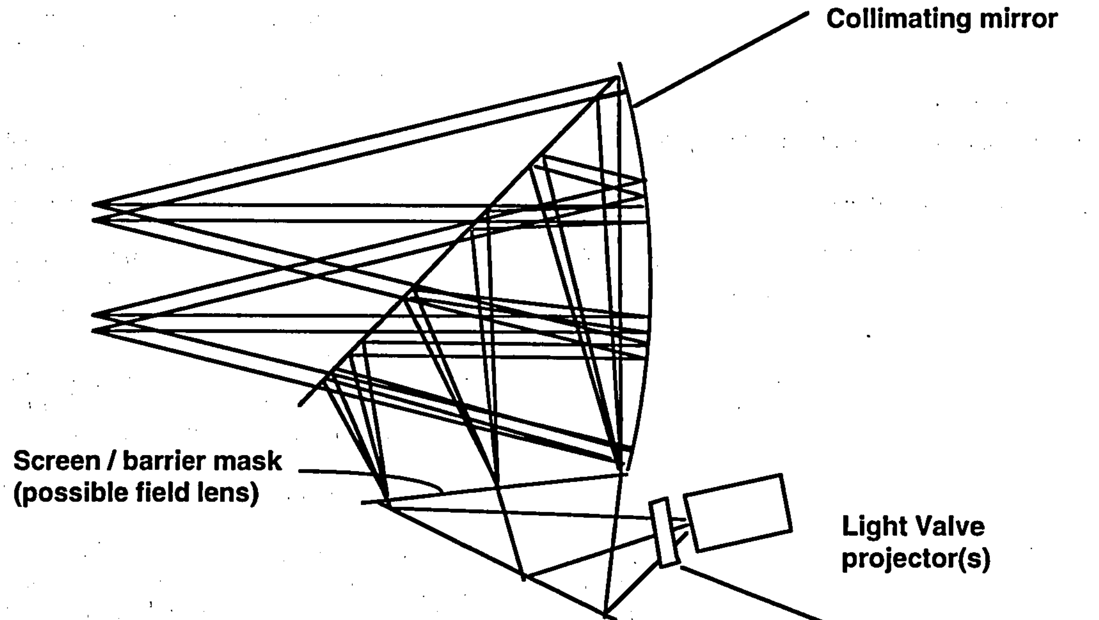


Figure 3-13. General Display Concept G: Symmetric Catadioptric, Parallax Barrier Applied to Projected Tiled Image. (Vertical pupil separation shown for clarity. Actual separation of pupils would be in horizontal axis for autostereo.)

Table 3-13. General Display Concept H: Unfolded catadioptric with time multiplexing.

3-D Method	Time multiplexed stereo.
Image Source	Light valve: • Option 1: Single channel, DMDs, tiled if necessary. • Option 2: Dual channel, multiple projection AMLCDs, tiled if necessary (initially).
Optical Configuration	• Unfolded, symmetric catadioptric system. • "Light-weight" front surface mirror. • Polarization-selective real image screen (transparent or diffuse, depending upon polarization). • Separate projection modules for each light valve. • "Injected", or reverse path projection, using collimating optics and supplemental optics to create appropriate image on screen.
Eyewear	• Circular polarizer glasses. • Display-mounted polarizing means. • Variable retarder mechanism, either on eyewear or display system.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Additional large elements for reduction of aberrations.
Required Technology Developments	• Practical and available image source (ideal is 1920 x 1080 full color at 120 Hz, but this is not anticipated). Configuration supports tiling/overlay of multiple projectors to extent necessary. • Light-weight and compact optics. • Polarization-selective screen under development. • Suppression of AMLCD/shutter aliasing.
Features/Discussion	• Novel, polarization selective screen allows use of no-beamsplitter, on-axis reflective geometry. Image is projected onto the screen (diffuse) using one polarization, and is viewed through the screen (transparent) after collimation and polarization rotation. • Image somewhat visible outside of design head motion box although may be degraded. • This "injected" projection scheme provides several potential advantages. • Large reflectors are achromatic.
Potential Trouble Areas	• Optics weight, size and form factor. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Temporal artifacts associated with time multiplexing. • Tiling seams. • Possible haze due to incomplete polarization effects. • Screen fabrication issues, especially if curved screen is required.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV, and allowable obscuration by projectors.

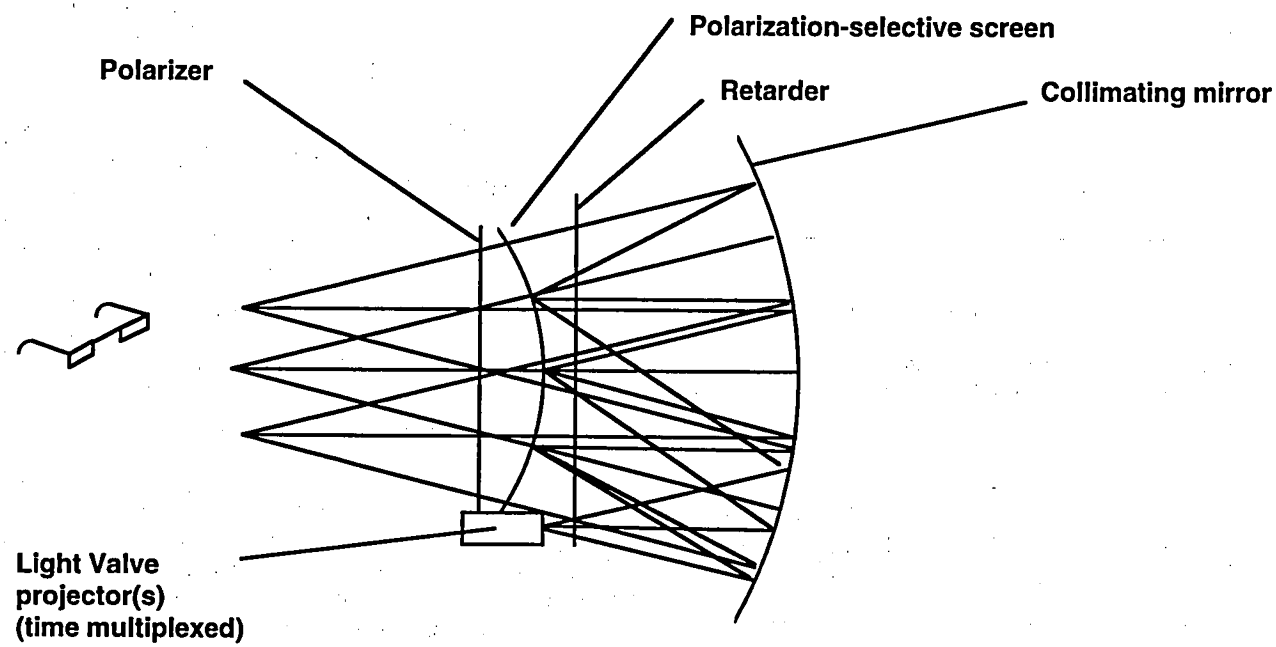


Figure 3-14. General Display Concept H: Unfolded Catadioptric with Time Multiplexing.

Table 3-14. General Display Concept I: Pancake Window® w/ time multiplexing of non-tiled, BS-combined large image sources.

3-D Method	Time multiplexed stereo .
Image Source	Two "large" full-color AMLCD image sources (i.e. direct view type).
Optical Configuration	• Pancake Window®, with associated polarization control elements. • Backlighted image sources combined using polarizing beamsplitter element, behind Pancake Window®. • Variable retarder(s) used to switch between image sources, in conjunction with polarization selectivity of Pancake Window® elements.
Eyewear	• Circular polarizer glasses. • Display-mounted polarizing means. • Variable retarder mechanism, either on eyewear or display system.
Secondary Options	• Additional large elements for reduction of aberrations. • Non-polarizing beamsplitter arrangement also feasible, but lower efficiency expected.
Required Technology Developments	• Practical and available image sources (ideal is 1920 x 1080 full color) in size compatible with optical geometry. • Light-weight and compact optics. • High efficiency Pancake Window® optics. • Suppression of AMLCD/shutter aliasing.
Features/Discussion	• Pancake Window® is compact but generally very inefficient. Coupling this with the low efficiency of direct view color AMLCDs raises concerns over the practicality of a suitable backlight. • Image somewhat visible outside of design head motion box although may be degraded. • System is not readily tiled seamlessly, so may be limited in pixel count to available color AMLCD formats.
Potential Trouble Areas	• Luminance. • Optics weight, size and form factor. • Optical aberrations associated with a beamsplitter having thickness suitable for stability. • Meeting requirements without additional elements. • Adequate space for dual image source configuration.
Helpful Tradeoff Areas	• Luminance requirements. • Resolution fall-off at edges of head motion box.

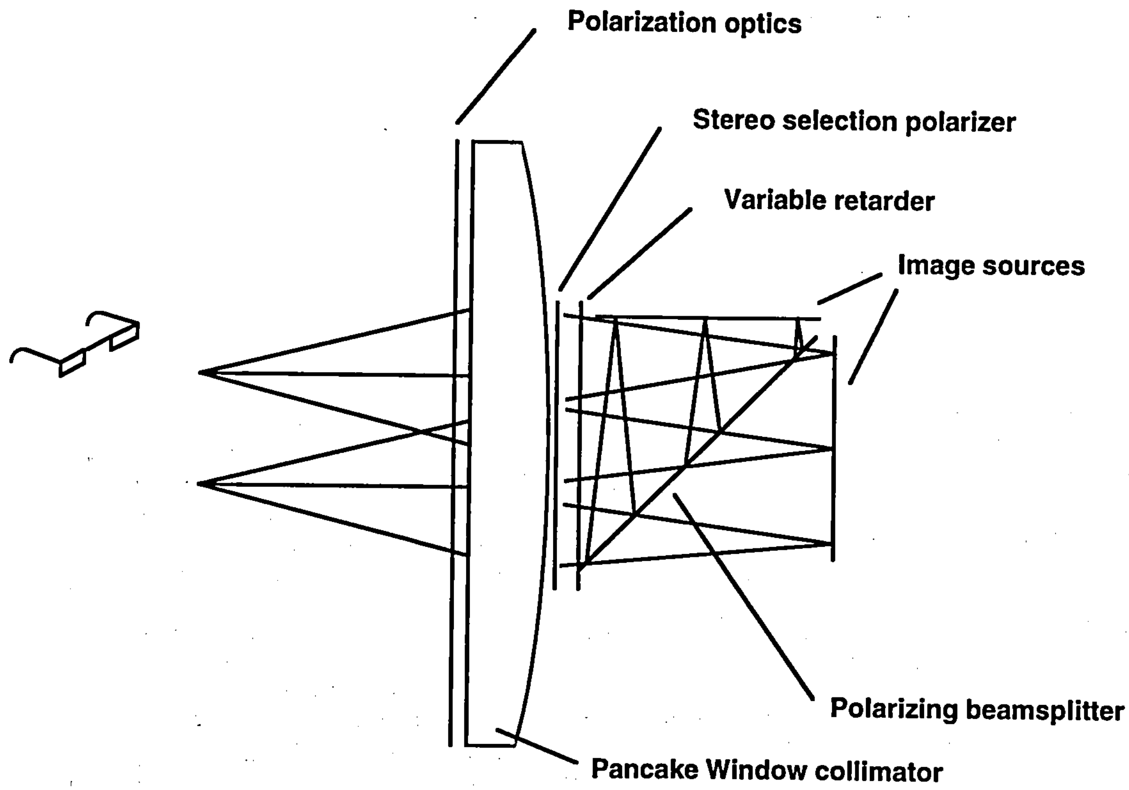


Figure 3-15. General Display Concept I: Pancake Window® w/ Time multiplexing of Non-Tiled, BS-Combined Large Image Sources.

Table 3-15. General Display Concept J: Pancake Window®, parallax barrier applied to projected tiled image.

3-D Method	Parallax barrier (autostereo, related to dual channel directional projection).
Image Source	Light valves: • Option 1: DMDs. • Option 2: AMLCDs.
Optical Configuration	• Pancake Window®, with associated polarization control elements. • Tiled, projected image source arrangement, with double resolution in horizontal axis to provide compatibility with parallax barrier method. • Dynamically movable projected image (e.g. translation or deflection). • Matching parallax barrier mask to define left/right illumination profiles. • Coarse head following to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Xenon or metal halide lamp, possibly fiber coupled. • Optional curved screen and barrier mask. • Additional large elements for reduction of aberrations. • Possibility of dynamic parallax barrier rather than (or in addition to) image translation. • Addition of real-time image position feedback to partially compensate for vibration or drift.
Required Technology Developments	• Practical and available image source (ideal is 3840 x 1080 full color). • Light-weight and compact optics. • Dynamic image position control for smooth translation of autostereoscopic pupils. • High stability, high resolution projector, with tight distortion control, and matched barrier mask.
Features/Discussion	• Rear projection arrangement raises concern about size. • Resolution/stability requirements on real image relay projector are severe, since drift relative to the barrier mask can reverse stereo effect or cause image loss. • Image translation alone may not provide desired head motion box depth, although a dynamic mask with adequate degrees of freedom may allow this.
Potential Trouble Areas	• Relative vibration between the barrier mask and the projected image. • Projector resolution. • Luminance due to attenuation by Pancake Window® as well as barrier mask. • Optics weight, size and form factor. • Extra volume and weight associated with the projector. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Tiling seams.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Rounded corners on FOV. • Size and form factor, to accommodate projector. • Lower horizontal pixel density, to improve vibration tolerance.

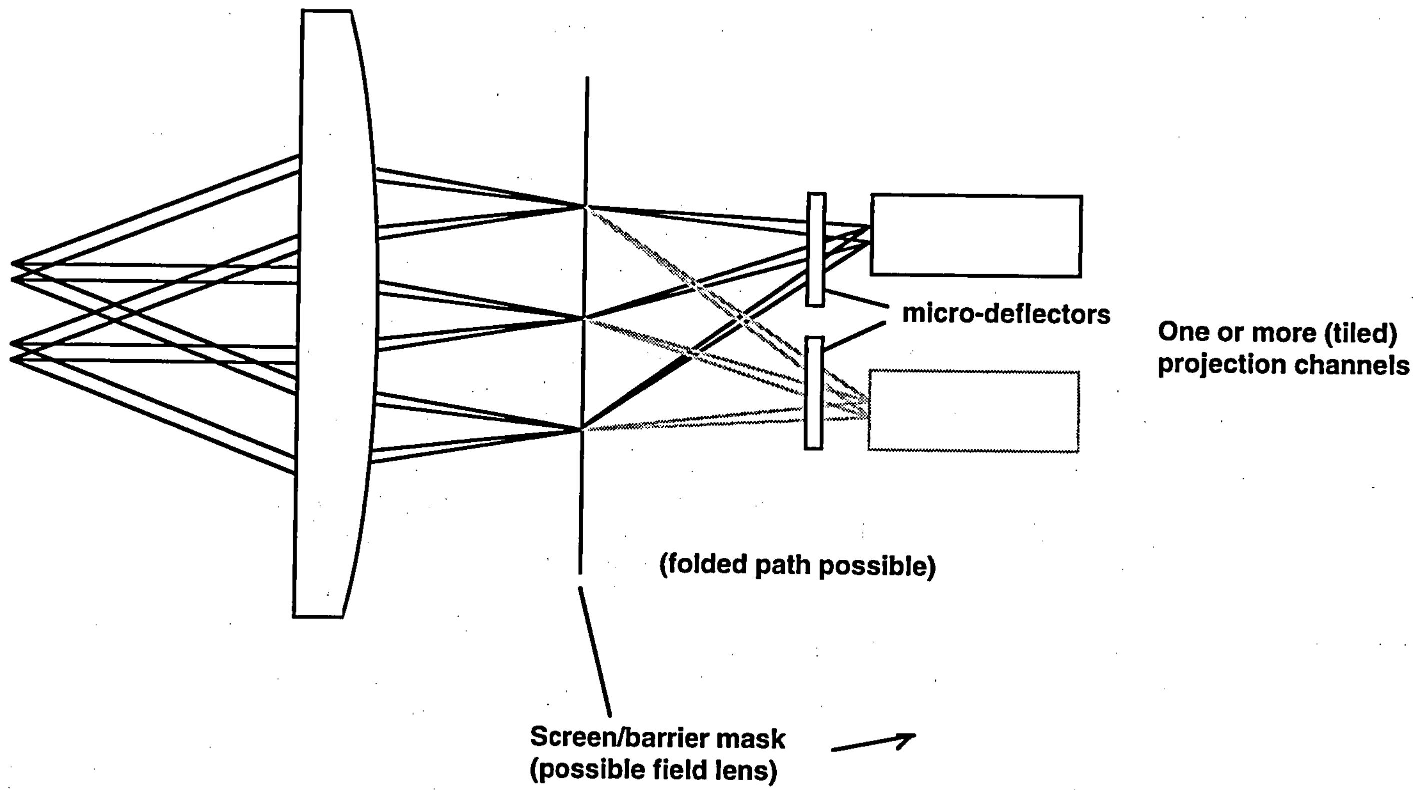


Figure 3-16. General Display Concept J: Pancake Window®, Parallax Barrier Applied to Projected Tiled Image.

Table 3-16. General Display Concept K: Pancake Window®, parallax barrier using tiled, direct-view displays.

3-D Method	Parallax barrier (autostereo, related to dual channel directional projection).
Image Source	Multiple full-color direct view AMLCDs.
Optical Configuration	• Tiled Pancake Windows®, with associated polarization control elements, multiple contiguous flat beamsplitters, and a single large (or segmented) curved beamsplitter. • Dynamic parallax barrier masks (effective translation by mechanical or electro-optic means). • Coarse head following to position autostereo pupils in head motion box.
Eyewear	• None required.
Secondary Options	• Additional large elements for reduction of aberrations. • Backlight profile steering rather than (or in addition to) barrier mask translation.
Required Technology Developments	• Practical and available image source(s) (ideal is 3840 x 1080 full color), having appropriate size. Tiling is supported, although large head motion box and compact size serve to reduce the effectiveness of tiling. • Light-weight and compact optics. • Dynamic barrier mask control for smooth translation of autostereoscopic pupils.
Features/Discussion	• Pancake Window® sections are readily tiled, although seams are still troublesome as with other tiling approaches. Large head motion box requires that pixels in the overlap regions be duplicated in adjacent panels, reducing (or eliminating, in some cases) the benefit of tiling. • Barrier mask translation alone may not provide desired head motion box depth, although a dynamic mask with adequate degrees of freedom may allow this. • Dynamic barrier control is required to eliminate discontinuities in the head-tracked pupils.
Potential Trouble Areas	• Luminance due to attenuation by Pancake Window®, color AMLCD and barrier mask. Backlight requirements may be impractical. • Optics weight, size and form factor. • Meeting requirements without additional elements. • Ambient light reflection due to mirrors. • Tiling seams. • Ineffectiveness of tiling due to compact size and large head motion box.
Helpful Tradeoff Areas	• Resolution fall-off at edges of head motion box. • Smaller head motion box. • Reduced luminance.

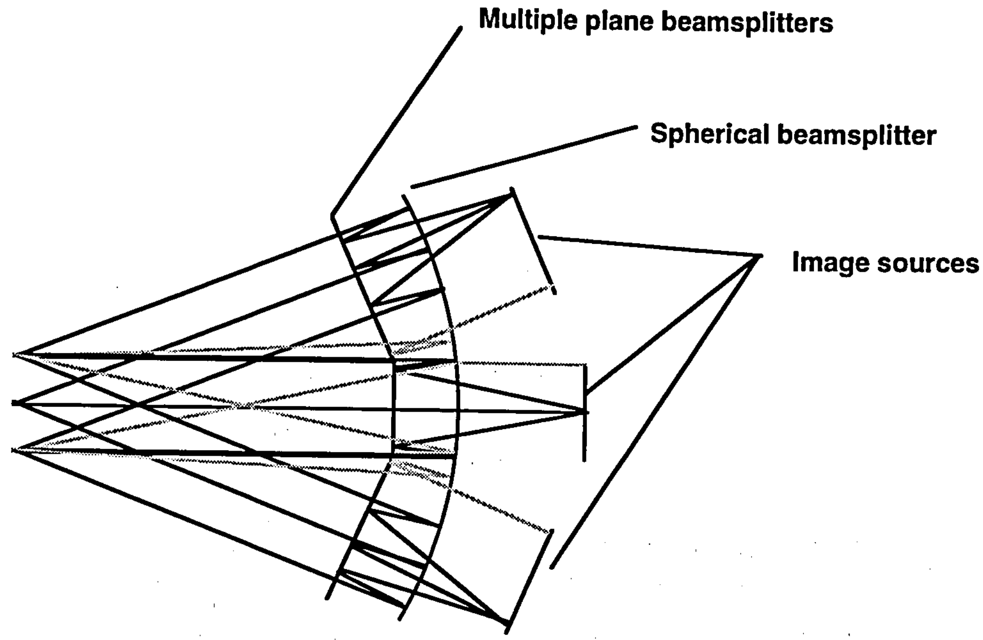


Figure 3-17. General Display Concept K: Pancake Window®, Parallax Barrier Using Tiled, Direct-View Displays. (Example tiling arrangement is depicted. Parallax barrier implementation is not shown in sketch.)

3.3.2 Analysis of General Display Concepts

The general display concepts discussed in Section 3.3.1 resulted from consideration of individual technologies and methods as well as an assessment of compatibilities among collimation and other system components. To further select a preferred configuration, additional analysis of each of these concepts was performed relative to the strawman requirements. The subsequent concept downselections and reasons for rejection of methods are summarized in Tables 3-17 and 3-18, and are discussed below.

Table 3-17. Selected methods from analysis of General Display Concepts A-K.

Selected	Rejected	Reason for Rejection (risk areas)
Light valves • AMLCD • DMD	**Direct view devices** • AMLCD • Plasma	• Development time frame / trends • Resolution / availability • Luminance • Form factor/flexibility
3-D eyewear • Time multiplexed • Polarization	**Autostereo** • Parallax barrier • Dual channel • Retroreflector array	• Development time frame • Smooth pupil motion • Vibration environment • Head tracking • Optical complexity
Folded, symmetric catadioptric • Rear projection of light valve • Front projection of light valve	**Pancake Window®**	• Luminance
	Other symmetric catadioptric	• Development time frame

Table 3-18. Further selection of methods from analysis of General Display Concepts A-K.

Candidate	Final Selection	Reason for Rejection (risk areas)
Light valves • AMLCD • DMD	**AMLCD Light valves** • Two stereo channels • Combined additive color	• Development time frame / trends • Availability • Configurational flexibility
3-D eyewear • Time multiplexed • Polarization	**3-D eyewear** • Time multiplexed • Shutter in eyewear	• Development time frame • Ambient light issues • Stereo channel crosstalk
Folded, symmetric catadioptric • Rear projection of light valve • Front projection of light valve	**Folded, symmetric catadioptric** • Rear projection of light valve	• Development time frame • Luminance • Ambient light issues

3.3.2.1 Image Source. As shown in Table 3-17, light valve projection was selected as the image source method. There were two primary considerations for the rejection of direct view devices such as plasma displays and large AMLCDs. The first is luminance capability. Emissive devices such as plasma displays are presently limited in luminance output. While this might be acceptable if a high transmission refractive collimator were used, such a system is unacceptable from a physical perspective, particularly in terms of weight as discussed earlier. Luminance is also a concern for direct view AMLCD concepts for similar reasons, although directional backlighting schemes could possibly help.

The second consideration for any of the large displays concerns the availability, format, and the associated lack of design flexibility. Considerable risk is anticipated in obtaining actual devices having suitable resolution and size in the strawman time frame, especially in light of the stereo requirement. Current trends in the development of these displays do not appear to support the needs of this program directly, and the collimated stereo designs are not readily adapted to make use of these devices to meet the strawman requirements in an effective manner.

Table 3-18 further identifies the AMLCD as the selected light valve for this display. This selection is based upon the anticipated availability of suitable devices. While DMD technology has been demonstrated at the strawman resolution, the technology has yet to be commercialized and availability cannot be ensured in the strawman time frame. In contrast, the broad industry-wide activity and trends in AMLCD technology raise the possibility of multiple light valve suppliers.

3.3.2.2 3-D Method. The general display concepts A through K include both autostereoscopic and eyewear-based methods. While both are considered viable (and autostereo does provide certain desirable attributes), our analysis suggests that implementation of any of the autostereoscopic methods considered introduces significantly higher risk in achieving the desired performance in the relatively short strawman time frame.

Several factors contribute to this increased risk, as identified in Table 3-17. Perhaps most important is our implicit assumption in each of these concepts that smooth pupil motion is required over the full three-dimensional range of head motion. This means that relatively fine, dynamic directional control of the illumination apertures (eye boxes) is required. While each of the listed concepts provides for this, some concepts (e.g. G and J) are put at risk by likely vibration in the intended display environment. Others (e.g. K) require the development of dynamically adjustable parallax barrier mechanisms, and still others (e.g. D and F) involve increased optical relay complexity and the potential for degradation of the projected image. Autostereoscopic concept E includes a relay approach for which high resolution capability has not yet been demonstrated without the potential of visual artifacts. Coupled with all of these autostereoscopic methods is the requirement for head tracking, which further impacts the system complexity.

The analysis therefore supports the initial implementation of an eyewear-based 3-D method such as time multiplexing or polarization multiplexing. Further comparison of these two eyewear methods provides a justification for the selection of time multiplexing as shown in Table 3-18. This selection arises from analysis of ambient light suppression, especially since both of the remaining candidate collimation methods involve beamsplitters and large on-axis mirrors. Without effective contrast enhancement measures, the resulting reflections could easily overwhelm the displayed imagery. The best reflection suppression method in this case involves polarization optics, effectively eliminating polarization multiplexing as an option. While time multiplexing could of course be implemented such that simple polarizing glasses could be worn, placement of the shutter mechanism in the eyewear is considered to be the lowest risk approach due to the large size of the collimating optics.

3.3.2.3 Collimation Method. As discussed earlier, the most promising candidates for providing high performance collimation in a large but relatively light-weight system are symmetric catadioptric configurations, including both the folded catadioptric with beamsplitter and the unfolded catadioptric, along with the related Pancake Window® approach. Performance is enhanced in the projection light valve case by incorporating an appropriately curved screen.

Some advantages of the Pancake Window® (see Figure 3-2) include intrinsic wide FOV capability, light weight, large head relief and a compact form factor. The primary disadvantage is that it is typically very inefficient, being several times less transmissive than a comparable conventional folded system such as is shown in Figure 3-3 (which itself is potentially several times less efficient than a straight-through refractive system). Based upon analysis of the luminance capabilities and efficiencies of the various system components, use of the Pancake Window® introduces unacceptable risk in meeting the strawman luminance requirements in the absence of further development and optimization of the system. While possibilities exist for improving the efficiency of this configuration, the time frame again makes this development less desirable, especially in light of the large element sizes involved. For these reasons, the symmetric, folded catadioptric collimator, with beamsplitter, was selected for the final system recommendation as shown in Table 3-17. The remaining catadioptric approach (H) was rejected due to the development required to achieve adequate performance via the special projection screen/diffuser.

As indicated in Table 3-18, the optical configuration is further specified to use a rear projection real image relay screen. While front projection approaches such as that shown in Figure 3-8 have certain potential advantages, they would in the present system result in unacceptable efficiency losses as well as increased concerns regarding ambient light.

3.3.3 General Interaction Concepts

This portion of the report documents the preferred combinations of 3-D interaction methods. The interaction method is intended not for conventional flight control, but rather simulator display functions such as 3-D object selection and manipulation and continuous 3-D rate and/or cursor position control.

For the three general interaction concepts evaluated below (Tables 3-19 to 3-21), it is assumed that software drivers will be available with which the input methods may be exercised with reduced degrees of control freedom where desired (preferably user selectable). It is further assumed, per the preliminary display requirements (Table 1-3), that the interaction method must be compatible with arm and/or wrist support to allow stable control under vibration. The general interaction concepts described are:

A 3 DOF joystick (isometric or isotonic)
B 2 DOF joystick (with optional 1 DOF controller)
C 2 DOF tablet (with optional 1 DOF controller)

Table 3-19. General Interaction Concept A: 3 DOF joystick (isometric or isotonic).

3-D Interaction Method	Single isometric or isotonic joystick with 3 simultaneous DOF.
Grip/Packaging	• Option 1: Pistol grip. • Option 2: Ball (e.g., Spaceball). • Option 3: T grip.
Mode Control/Selection	• Option 1: base-mounted buttons. • Option 2: grip-mounted buttons or trigger.
Assignment of DOF	• Option 1: Force applied to two orthogonal axes, perpendicular to stick, with 3rd axis parallel to length of stick. • Option 2: Force applied to two orthogonal axes, perpendicular to stick, with 3rd axis from rotation of stick. • Option 3: Force applied to grip for desired translation (isometric).
Integration	• Fully integrated in one control device.
Secondary Options	• Software gain adjustment. • Software control of control deadspace.
Required Technology Developments	• Flexibility of software drivers. • Silicon Graphics interface (hardware, software).
Features/Discussion	• Available as COTS device. • Can be operated as a 3-n DOF controller through software isolation of control inputs.
Potential Trouble Areas	• None anticipated.
Helpful Tradeoff Areas	• None.

Table 3-20. General Interaction Concept B: 2 DOF joystick with 1 DOF controller.

3-D Interaction Method	Single isometric or isotonic joystick with 2 simultaneous DOF AND Thumbwheel, dial, or slider switch (1 DOF).
Grip/Packaging	• Option 1: Pistol grip. • Option 2: Ball (e.g., Spaceball). • Option 3: T grip.
Mode Control/Selection	• Option 1: base-mounted buttons. • Option 2: grip-mounted buttons or trigger.
Assignment of DOF	• Option 1: Force applied to two orthogonal axes, perpendicular to stick, with 3rd DOF from thumbwheel. • Option 2: Force applied to two orthogonal axes, perpendicular to stick, with 3rd DOF from dial. • Option 3: Force applied to two orthogonal axes, perpendicular to stick, with 3rd DOF from slider switch.
Integration	• Option 1: Thumbwheel integrated with grip. • Option 2: Thumbwheel, dial, or slider switch integrated with base. • Option 3: Thumbwheel, dial, or slider switch on separate base (for use by alternate hand).
Secondary Options	• Software gain adjustment. • Software control of control deadspace.
Required Technology Developments	• Limited COTS devices: May require custom development. • Flexibility of software drivers. • Silicon Graphics interface (hardware, software).
Features/Discussion	• Can be operated as a 3-n DOF controller through software isolation of control inputs. • Separation of control to 2 DOF and 1 DOF inputs may be desirable for novice users and may enhance accuracy.
Potential Trouble Areas	• May require custom integration.
Helpful Tradeoff Areas	• None.

Table 3-21. General Interaction Concept C: 2 DOF tablet with 1 DOF controller.

3-D Interaction Method	Single tablet with 2 simultaneous DOF AND Thumbwheel, dial, or slider switch (1 DOF).
Grip/Packaging	• N/A
Mode Control/Selection	• Option 1: Buttons mounted on face of base. • Option 2: Buttons mounted on side of base. • Option 3: Tablet selection of virtual buttons. • Option 4: Buttons mounted on stylus.
Assignment of DOF	• Option 1: Finger or stylus selection on two orthogonal axes, with 3rd DOF from thumbwheel. • Option 2: Finger or stylus selection on two orthogonal axes, with 3rd DOF from dial. • Option 3: Finger or stylus selection on two orthogonal axes, with 3rd DOF from slider switch.
Integration	• Option 1: Thumbwheel, dial or slider switch integrated with base. • Option 2: Thumbwheel, dial or slider switch integrated with stylus. • Option 3: Thumbwheel, dial or slider switch on separate base (for use by alternate hand).
Secondary Options	• Software gain adjustment.
Required Technology Developments	• No known integrated COTS devices: Will require custom development. • Flexibility of software drivers. • Silicon Graphics interface (hardware, software).
Features/Discussion	• Can be operated as a 3-n DOF controller through software isolation of control inputs. • Separation of control to 2 DOF and 1 DOF inputs may be desirable for novice users and may enhance accuracy.
Potential Trouble Areas	• Will most likely require custom integration.
Helpful Tradeoff Areas	• None.

3.3.4 Analysis of General Interaction Concepts

All three general interaction concepts are technically viable and of relatively low cost. The joystick concepts in particular (concepts A and B) are widely available as COTS devices. The specific selection of configuration options for all concepts will be highly dependent on the specific software applications used within the Panoramic, 3-D Flight Display System environment. Because of the current uncertainty in usage, as well as the low cost and COTS availability of these devices, there is neither need nor ability to downselect further among these two concepts at this time. It was recommended that NASA purchase multiple COTS implementations of Concepts A and B for trial once the software interaction requirements for the Panoramic, 3-D Flight Display System are better defined. One implementation of interaction Concept C, the cursor control device (CCD) from the Boeing 777 cockpit, is uniquely suited for cursor control with avionic displays but is not available as a COTS device with an RS-232 interface. Further discussion of this device is presented in the final system concept (Section 3.4), the display specification (Section 5), and the development plan (Section 6).

3.4 Selection of Final System Concept

3.4.1 Display System

Based upon the discussion of concepts in Section 3.3, a final display system recommendation was made and subsequently selected with NASA concurrence. The baseline configuration is shown in Figure 3-18.

Image Source
- Dual channel AMLCD projectors

3-D Method
- Dual channel time-multiplexing
- LCD shutter glasses

Optical Configuration
- Folded symmetric catadioptric with beamsplitter
- Front surface collimating mirror
- Curved real image relay screen
- Shuttered and combined LCD projectors
- Means for suppression of ambient reflection

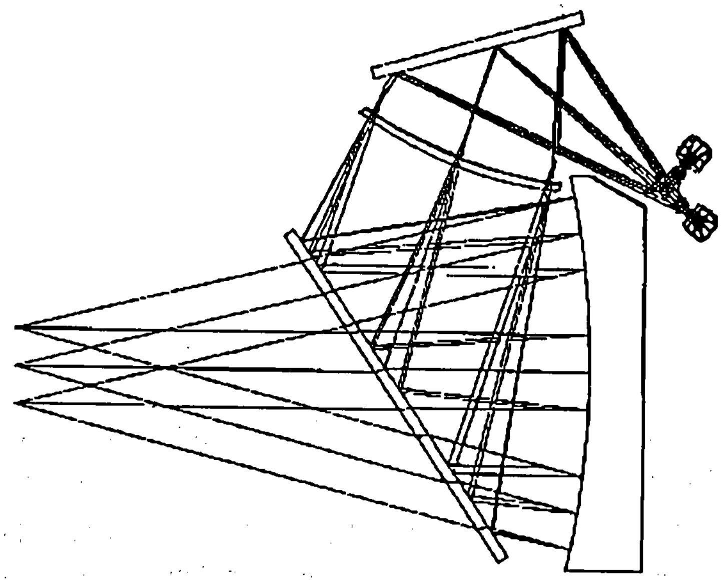


Figure 3-18. Selected Display System Concept (Symmetric Catadioptric with Time Multiplexing).

3.4.1.1 Image Source. The image source subsystem will consist of two full-color AMLCD light valve projectors. Each projector will use three monochrome light valves in an optically-combined additive color mode. In the baseline system, a color combiner prism will be used in conjunction with the projector optics such that each light valve modulates one color (R, G or B) of the light projected onto the curved screen by that projector. To maximize performance, the projector will be centered on the axis of symmetry for the screen. Curvature in the image plane is accounted for in the lens design.

The two projectors correspond to the two eye perspectives, left and right. A polarizing beamsplitter will be used to efficiently combine the output of the two projectors, such that identical lenses can be used and both are effectively on-axis with respect to the screen.

Illumination of the light valves will be provided by two metal halide arc lamps. Metal halide lamps provide the best available trade-off between efficiency, luminance, reliability, safety and lifetime. As an option, a single lamp could be used, although the use of two is preferred for redundancy reasons. Condensing optics (not shown) will be provided between the lamps and the light valves, serving several purposes. The condensing system must efficiently collect light from the lamps, partially collimate that light, split it into component colors and direct the light uniformly onto the light valves. Conventional collimating and color splitting designs are envisioned, although the detailed design of such a system involves numerous trade-offs between uniformity, collection efficiency and other parameters. This topic is addressed further in Section 4.

The system concept includes interface electronics to allow driving the image sources by two synchronized stereoscopic Silicon Graphics output channels. Image source calibration and adjustment such as gamma correction is assumed to take place within the Silicon Graphics, although these capabilities could optionally be provided in the interface unit.

3.4.1.2 3-D Method. The selected 3-D method is time-multiplexed stereo. A dual channel image source configuration will be used in order to avoid the response time and persistence issues which would otherwise be encountered with a single channel AMLCD time-multiplexed system. Synchronized pairs of shutters will be used to ensure that each eye sees only its appropriate perspective.

As shown in Figure 3-19, each color LCD projector module will be followed by a corresponding pi-cell variable retarder. The variable retarders will selectively rotate the polarization of the LCD output, and the resulting images will be subsequently passed or blocked by the polarizing beamsplitter or other supplemental polarizer in the system.

These shutters will be alternately opened such that each perspective is projected onto the screen for a fraction of a frame, for example 1/120th of a second, and at any given time only one perspective will be present. Corresponding shutters in the stereo eyewear will be synchronized with the earlier ones such that correct perspectives are viewed. The remaining variable retarder in Figure 3-19 will be situated between the polarizing combiner and the screen and will serve to ensure that polarization of the light reaching the screen is compatible with maximum transmittance through the collimation optics.

Luminance balance between the two stereoscopic channels will be achieved via adjustment of the relative duty cycles of the left/right shuttering mechanisms. Supplemental control may also be provided by adjusting the Silicon Graphics video signal to the display. Additional, optional complexity in the illumination path can provide other adjustment methods or even largely eliminate the need for subsequent adjustment after an initial calibration.

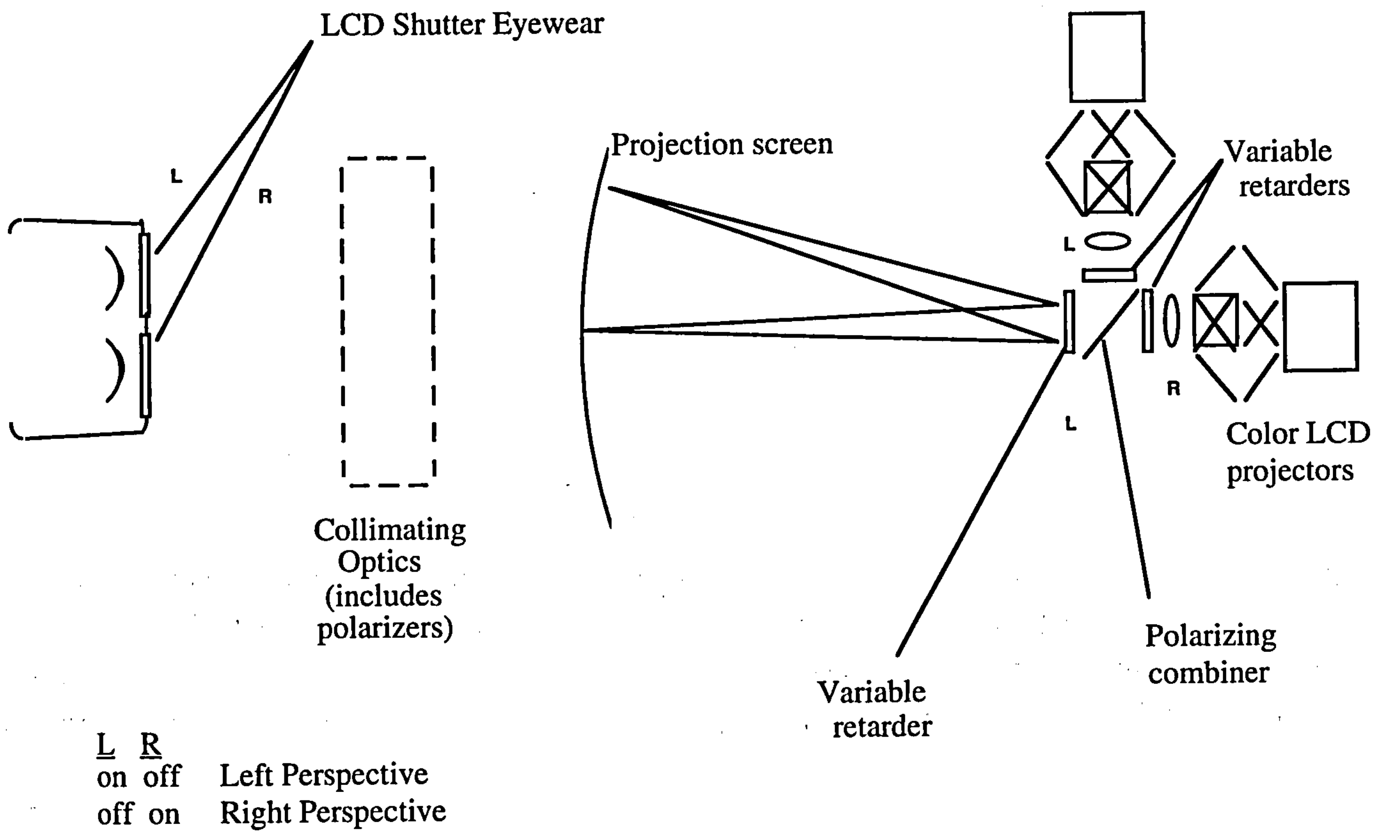


Figure 3-19. Selected Display System Concept (Dual Channel Time-Multiplexed Stereo 3-D Method).

3.1.4.3 Collimation Optics. The selected optical collimation method is shown in Figure 3-20. (Additional drawings can be found in Section 6 as well as Appendix A). After being relayed to the curved projection screen, the scattered light will be reflected by the beamsplitter and subsequently collimated by the front surface curved mirror. A portion of the collimated light will then pass through the beamsplitter to the head motion box. The large elements are of a construction and size which will provide both ample stability and reasonable weight.

Optical performance of such a system having a curved image screen will meet or exceed the strawman optical performance, and allow for additional viewing (albeit with some vignetting and increasing aberrations) beyond the specified head motion box. With the dimensions as shown, an unvignetted pupil (head motion box) of approximately 6" x 4" will be provided at an on-axis head relief of 20 inches. Reducing the head relief will increase the unvignetted pupil accordingly. The optics were in this case scaled from a maximum width dimension of 30 inches.

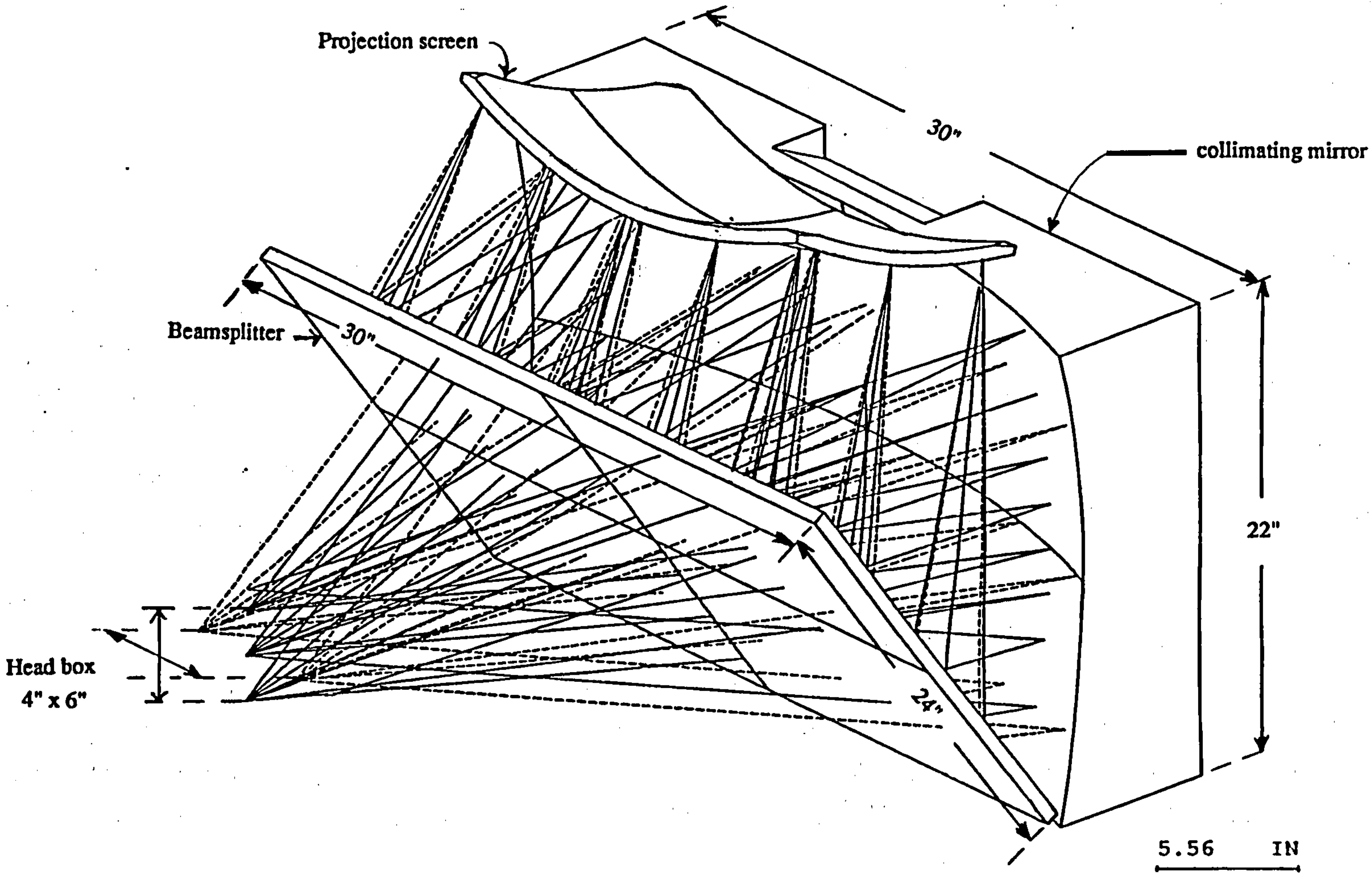


Figure 3-20. Selected Collimation Method.

3.4.1 3-D Interaction Method

Based upon the discussion of interaction method concepts in Section 3.3, the cursor control device (CCD) provided by Honeywell to the Boeing 777 cockpit was selected for modification to the requirements of the Panoramic, 3-D Flight Display System. Other COTS interaction devices were recommended for NASA procurement, independent of the specification and development plan included in this report (see Section 3.3.3).

The base CCD configuration, standard to the Boeing 777, is sketched in Figure 3-21. Two CCDs are mounted in the Boeing 777 cockpit, one to either side of the aisle stand. The touch pad is mounted in a raised, angled housing to provide wrist support. All buttons are dual-position switches. Annunciator lights are included above each button to indicate the currently selected display for control. The top three buttons as well as a single side-mounted thumb switch are configured for either left (Captain) or right (First Officer) installation; the button configurations are mirror-imaged between the two configurations. Figure 3-21 is configured for the First Officer position (the thumb switch is not shown in Figure 3-21).

When interfaced with other Boeing 777 software (i.e., the AIMS cabinet), the CCD accepts touch pad inputs for either absolute or relative cursor positioning, including a "hot corner" concept for quickly moving the cursor to the corner of a display. The touchpad is capacitive, consisting of a non-reflective conductive coating with an active area of 2.5 x 2.5 inches (excluding the rounded corner areas). The resolution of the touchpad is 882 x 882 resolvable touch points. The touchpad's four corners are driven by an alternating voltage. When a human finger comes in contact with the conductive surface, a small capacitance is introduced. This causes current to flow through the corners to the capacitance. The magnitude of the current is proportional to the magnitude of the leakage capacitance and the proximity of the capacitance to the corner. The touch position calculations are based on the magnitude of the currents flowing through each of the four corners, and yield rectangular X and Y coordinates.

The CCD communicates with the AIMS cabinet via an ARINC 429 interface. Five unique circuit card assemblies (CCA) are used to accomplish the ARINC 429 interface, convert power, and convert analog signals to digital signals. A digital signal processor is used in one CCA to execute touchpad position calculation algorithms. Provisional designs have been made for an RS-232 transceiver to be included in one of the CCAs, but the transceiver is not included in the standard CCD configuration.

The CCD requires 28 volt DC power, and the maximum power consumption of the CCD and associated CCAs is a total to 9.3 watts.

The Boeing 777 CCD is a fully-developed interaction device, and as such no development requirements are given in Section 4. However, several aspects of the Boeing 777 CCD require engineering design to make this device suitable for use in the Panoramic, 3-D Flight Display System. These engineering requirements are outlined in the development plan (Section 6).

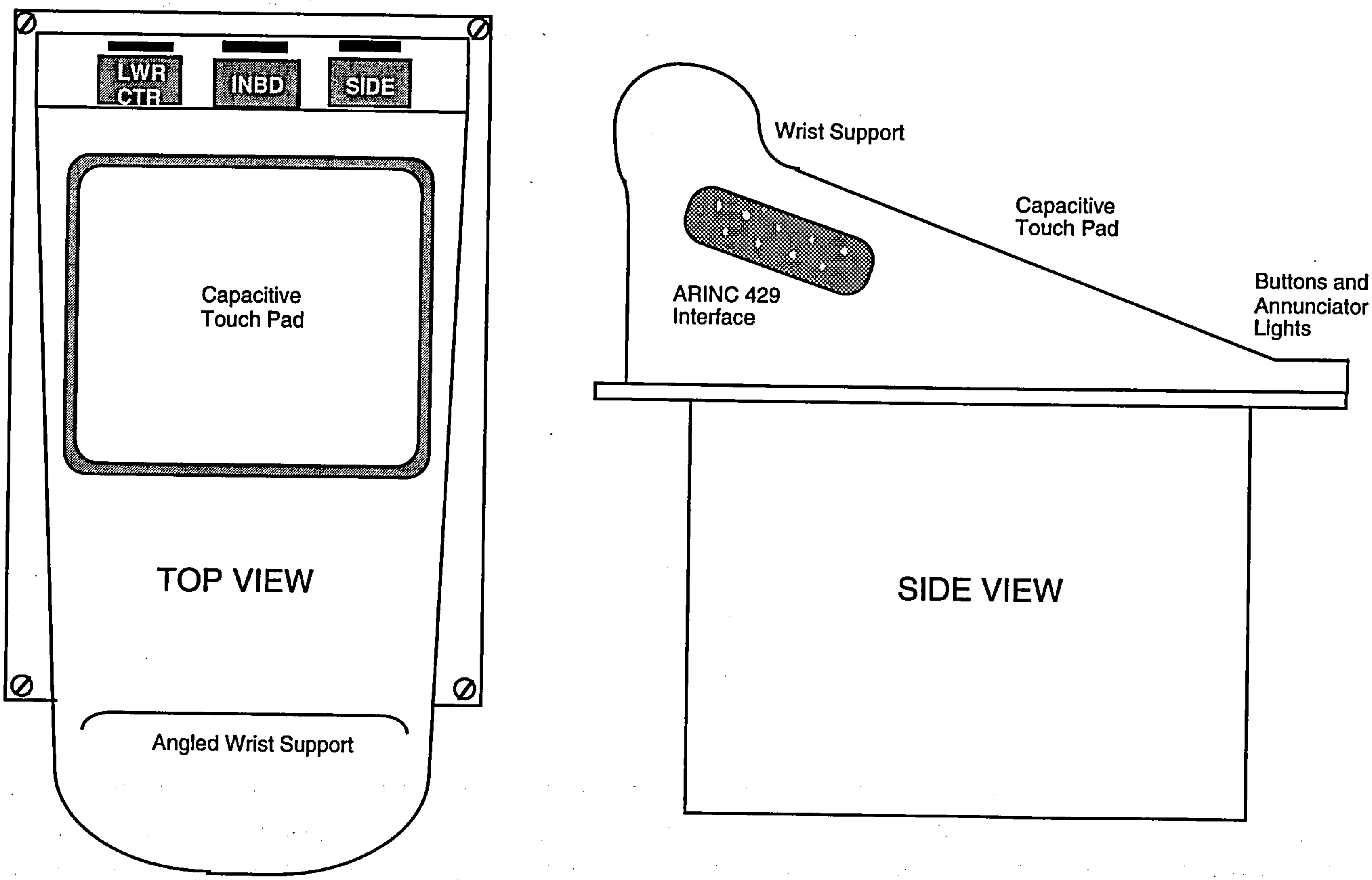


Figure 3-21. Sketch of Capacitive Touch Pad Cursor Control Device (not to scale) (Side thumb switch not shown)

4.0 REQUIRED TECHNOLOGY DEVELOPMENTS

Throughout the technology review and concept analysis phases of this program, discussions of the relevant strengths and limitations of the methods have been presented. These discussions in themselves serve as indicators of developments necessary to make those methods or technologies more suitable for the Panoramic, 3-D Flight Display System. In this section, however, we address specifically any perceived limitations or shortcomings in the technologies and methods selected for the final configuration. The conclusions and supporting discussions are grouped into four categories as presented and summarized in Table 4-1.

Table 4-1. Required developments and activities for the final display system configuration.

Required Technology Developments	Technologies in which significant development is needed to meet the strawman requirements. • Image source technology -- development and availability of large pixel count AMLCDs
Risk Reduction Areas	These are areas in addition to the required fundamental technology developments which present potential risks in meeting the strawman requirements, but which can be addressed within the context of the proposed development plan. These include • Display luminance • Eyewear transmittance
Detailed Engineering Design Activity	Numerous areas which require engineering activity throughout the design and implementation of the selected concept, but in which no fundamental technology gaps are apparent. • Final optical design • Detailed mechanical design • Detailed electronics design
Upgrade Path	Potential paths to improving the performance capabilities of the display concept • Planned subsystem upgrades (e.g. image source) • Concept modifications (given additional development, time frame, or requirements)

4.1 Discussion of Required Developments

4.1.1 Required Technology Developments

Throughout the analysis portions of this program, it has been evident that the time frame for fabrication of the display system is short relative to typical technology development time scales. As such, the downselection process has repeatedly favored approaches requiring a minimum of technology development. For the most part, the selected system concept is largely conventional in nature. One subsystem, however, clearly falls short of the strawman requirements in its present state of development.

This area requiring development is the image source technology. Simply put, no readily available image source can provide the strawman resolution and other desired performance attributes with an appropriate form factor. While resolution requirements could be met with CRTs, their size is prohibitive for the collimated display concepts. Alternate devices such as AMLCDs, plasma displays and DMDs fall short in at least one area such as number of pixels, luminance, or form factor.

In the case of the selected image source technology, AMLCD light valve projection, the major shortcoming for this design is the number of pixels. While laboratory prototypes have been demonstrated with higher information content, the apparent upper limit on number of pixels in the strawman time frame is around 1280 x 1024 rather than 1920 x 1080 or more. A number of methods to address this shortcoming have been considered. These are:

1) Incorporate development of higher pixel count displays into the Panoramic, 3-D Flight Display System development plan
2) Incorporate image mosaic tiling (or similar methods such as interleaving) to achieve higher pixel count
3) Reduce the performance requirement to match available devices without tiling
4) Use available devices without tiling, but with an upgrade path to higher performance when the technology is available

Option 1 is readily ruled out as being beyond the intended scope of the Panoramic, 3-D Flight Display System development plan, both in terms of time frame and estimated resource availability. Such development activity is currently underway at several companies, and includes ARPA-funded activity.

Image tiling, as suggested by option 2, certainly provides a means for meeting the resolution requirement in a relatively timely manner, but introduces other risks and considerations. To be most effective, tiling is ideally seamless in appearance. While a number of methods can be used to approach this level of performance, high-resolution seamless tiling is at best extremely difficult, even under ideal environments. The intended application environments for the Panoramic, 3-D Flight Display System include both motion base and aircraft mounting, making alignment and stability of the tiled approaches a significant concern. Included in early requirements discussions was the desire to avoid seam placement near the center of the FOV, implying that at least three projectors (each providing full color as well as stereo) would be needed. Besides increasing the required precision and repeatability of the optics, this would greatly impact the optical complexity due to the loss of projector/screen symmetry. The implementation and optimization of such a tiling approach would increase the risk, duration, and cost of the display development plan.

Option 3 eliminates the problem by ignoring it completely and fails to satisfy the intended purpose of the display system, which is to provide a vehicle for assessing the benefits and issues associated with use of a high-resolution, panoramic display.

Option 4 represents the recommended compromise approach. In this approach, delays associated with the complexity and risk of implementing tiling are eliminated by constructing the initial image projector with lower information content images sources. The large optical elements and 3-D method are implemented, however, in a way which supports the strawman resolution requirement, including FOV as well as pixel count. In this way, straightforward upgrade compatibility is provided. Since appropriate higher pixel count devices are anticipated to be available relatively soon after the strawman time frame, this option is considered to be the best way of meeting program goals in light of the technology constraints.

While the strawman requirements call for 1920 x 1080 image sources, the most suitable devices anticipated in the strawman time frame (with relatively low risk) are 1280 x 1024 monochrome AMLCDs. These devices can be matched up with the panoramic, high resolution collimator in a number of configurations, as shown in Figure 4-1. In particular, the interim solution can sacrifice FOV or resolution, or strike a compromise between the two. The need to make these trades is brought about by the difference in aspect ratio between the interim (1280 x 1024) image source (1.25:1) and the upgrade (1920 x 1080) image source (1.78:1), the latter for which the collimation optics are designed.

The upper configurations in Figure 4-1 show various ways of trading resolution and FOV. The shaded rectangles represent the full active area of the projected image source, while the wire-frame rectangles represent the available FOV of the collimation optics. Where the two rectangular areas overlap perfectly, the full active image source area is visible to the observer. Where unfilled area is presented (top left and top center), unused FOV in the collimation optics is present. For example, the effective horizontal FOV in the top left is reduced from 48 to 34 deg. Where the shaded area extends beyond the wire frame (top center and top right), the usable portion of the image source is reduced by that amount. For example, in the top right configuration, filling the horizontal FOV causes approximately 29% of the image source pixels to fall outside of the usable vertical FOV.

In the lower right of Figure 4-1, full strawman performance is shown, assuming an upgrade to 1920 x 1080 image sources. Higher resolution may be possible when 2560 x 2048 (or similar) devices become available, although other system components such as the screen and optics play a role in system resolution as well. The VISTAS configurations are provided for comparison. The temporal multiplexing configuration (lower center) achieves the wide FOV at the expense of vertical pixel density.

Based upon discussions with NASA LaRC, the configuration in the upper left (38 pixels/deg, 34 x 27 deg FOV) was selected as a preferred interim solution. This configuration uses the entire light valve area, and meets or nearly meets both the strawman pixel density and vertical FOV.

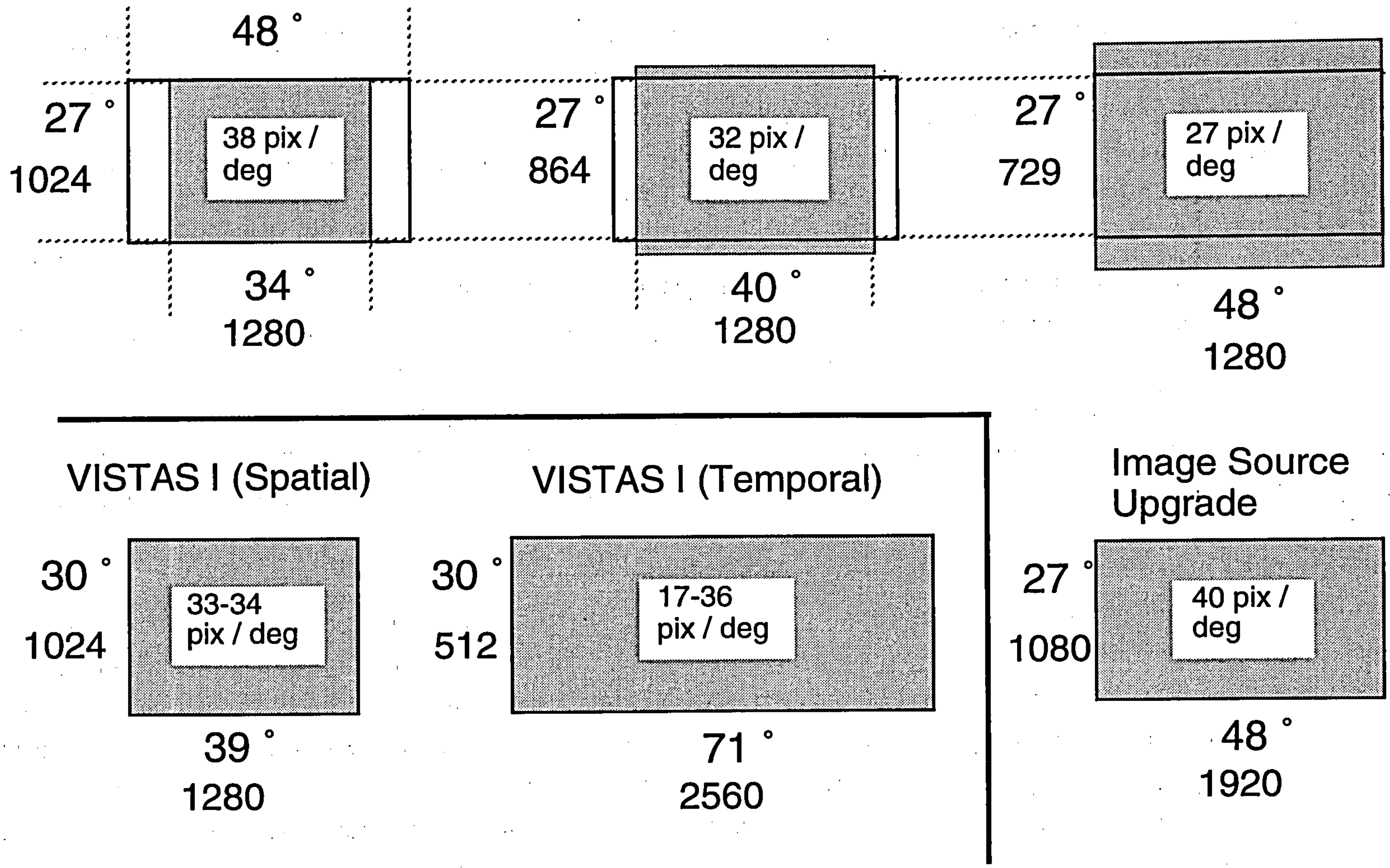


Figure 4-1. Possible Field of View / Resolution Trades

4.1.2 Risk Reduction Areas

One area of potential risk in the selected design is luminance capability. While luminance capability is in many ways enhanced by the decoupling of the image source and the illumination source, the requirements for 3-D and collimation take their toll. This is especially true in light of the downselections made. As stated previously, highly efficient refractive or Fresnel optics were rejected based upon physical and image quality considerations, respectively. A major consideration in the selection of the final collimation method (folded symmetric catadioptric with beamsplitter) over the Pancake Window® was the reduction of risk associated with meeting the strawman luminance requirements. Still, some element of concern persists in this area, due to the inefficiencies associated with both the beamsplitter and time multiplexing approaches. A system-wide estimate of optical power efficiency was performed. With reasonable assumptions for each element or component, it was shown that the strawman requirement of 30 fL to the eye is achievable. The analysis also indicated, however, that if any subsystem performed below the nominal efficiency estimate, performance of one or more other elements would need to be improved to compensate for it. The large number of contributors to the efficiency implies the likelihood that deviations from the assumptions will occur (for example, in the light valve transmittance or the lamp collection efficiency).

Optimizing each and every element for maximum efficiency would add prohibitively to the program cost and jeopardize the service date requirement. As such, an ongoing assessment of the relative efficiencies of the subsystems is recommended, with appropriate action taken as necessary to ensure that achieved luminance performance falls in the neighborhood of the 30 fL strawman level.

Other risk reduction analyses have shown that benefits to the service date requirement can be obtained by loosening or linking certain "soft" requirements in the strawman requirements. Examples of this include the eyewear transmittance, physical size, weight, head relief and head motion box.

While eyewear transmittance is preferably maximized, an initial strawman requirement of 30% was set, in part to allow consideration of polarization based eyewear methods. With the selection of time multiplexing, even 30% becomes a challenging level. Commercial time-multiplexing eyewear are available with a nominal open state transmittance of 32%, but with active shuttering this is expected to fall to 15% or so. At least two methods for boosting the transmittance back to more than 30% were considered, but each involves additional complexity (and hence risk). After discussing the considerations with NASA, consensus was reached that 15% average eyewear transmittance was acceptable.

Size and weight were also considered for risk reduction. A firm size constraint endorsed by NASA LaRC was a maximum width of approximately 30 inches. Evaluation and physical modeling of the resulting scaled system dimensions and head motion box / head relief relationships were perceived favorably in the context of this program. With regard to weight, concepts having clear weight disadvantages were eliminated, but efforts to trim system weight to a minimum, at the risk of reducing stability or increasing program duration, were not deemed critical.

The selected concept provides for significant interdependence between the head motion box and the head relief. Slight reduction in the strawman head motion box dimensions allows favorable adjustments to the head relief as well as reductions in both size and weight of the large elements. Whereas the head motion box represents a volume from which both perspective views are fully visible, the gradual vignetting inherent in the system design in actuality allows the central FOV to be seen from a significantly larger viewing range. The arrangement also provides effective visual cues to lead the observer back to the head motion box. If a larger unvignetted head motion box is desired, this can be achieved to a certain degree by simply moving closer to the display. This flexibility is due to the freedom of head motion supported by the time-multiplexed stereo method, as well as the use of the diffusing projection screen in the optical relay system.

Potential risk factors in other technical performance parameters have been addressed and greatly minimized by incorporating mechanisms and features in the selected design concept which largely eliminate the concerns. One such example is the suppression of ambient light reflections, using the methods described in Section 3.

4.1.3 Detailed Engineering Design Activity

The current design activity concentrated on identifying requirements, concepts, realizable performance parameters, and technology constraints, and resulted in a selected system design concept. Additional design and analysis was performed to further specify the form and performance, and to allow generation of a specification and development plan. It must be recognized, of course, that additional engineering design activity (e.g. optical, mechanical, electrical) is required in order to specify and fabricate subsystems which can be integrated into a working display system. These further design efforts were anticipated and included in the development plan (Section 6).

4.1.4 Upgrade Path

Throughout the concept generation and selection, numerous trades and choices were made based upon the established strawman requirements and technology availability. Many of these choices were made on the basis of providing a display system as soon as possible (with respect to the strawman service date) and with a minimum of risk in doing so.

In one major area, a planned upgrade path has been established to account for a short-term specification trade-off. This consists of upgrading the 1280 x 1024 image source projectors to higher resolution (higher pixel count) when available light valves achieve or exceed the desired capability of 1920 x 1080 which the collimation optics are designed to support. Along with the retrofit of the light valves, modifications to the electronics and projection optics are likely required as well. Consideration will also be needed regarding the image data source (i.e., Silicon Graphics), such as whether the upgraded resolution, frame rate, and interlace factor of the new image source are supported.

It is also clear that, given different requirements, priorities, or service date, some of the previously rejected methods or concepts might merit additional consideration. As an example, the disadvantages of stereo eyewear could be eliminated by adopting one of the smooth pupil motion autostereoscopic concepts considered. Alterations in the required FOV may also call for reassessment of the collimation method selection. Finally, the state of the various image source technologies should be continually monitored as upgrades are considered. The size and weight of the selected beamsplitter-based collimation method could be traded for the smaller and more compact Pancake Window® geometry (given, of course, additional effort in addressing the associated luminance issues).

4.2 Display System Specification Highlights

As the rate and compare analysis began, strawman requirements were identified as a basis for comparison of candidate methods. Following the subsequent down-selection and analysis in Sections 2 through 4, these strawman requirements were updated to reflect the effect of identified technology constraints and the anticipated performance of the selected candidate system. Highlights of the modified strawman requirements (included in the Display Specification, Section 5) are shown in Table 4-2.

Table 4-2. Display Specification highlights.

Parameter	Minimum	Comments
Field of View (FOV)	48 H x 27 V (Initial active image FOV 34 H x 27 V)	Collimation optics to be designed for 48 deg FOV. Upgrade to projection optics, image source, image data source, and electronics required for matching active image FOV.
Pixel Density (Resolution)	40 pixels / deg (Initially 38 pix / deg)	Upgrade to image source, image data source, electronics, and projection optics required for 40 pix/deg.
Pixel Count	1920 x 1080 (Initially 1280 x 1024)	Upgrade to projection optics, image data source, and electronics required for 1920 x 1080.
Gray Shades	32 linear steps	
Head Motion Box	A spherical volume with 6" diameter within which both eyes must be located to see the unvignetted, binocular image. The head motion box is truncated vertically, such that the top 1" and bottom 1" of the sphere are excluded. The center of the spherical area intersects the center line of sight and is located at the on-axis head relief.	Additional viewing volume is expected beyond the prescribed head motion box. Gradual roll-off of display performance (vignetting, reduced luminance and resolution) is acceptable within this additional viewing volume.
Luminance	30 fL @ eye	As seen from head motion box.
Luminance: Contrast Ratio	50:1	
Eyewear Transmittance	15% time-multiplexed 32% open	
Physical Constraints	max of 30" H x 30" W x 30" deep, 400 lbs. total	
Head Relief	15" to nearest system component, 20" on-axis.	
Light Source	≥1000 hours luminance half-life	Replaceable light source.
Image Data Source	2 channels, Silicon Graphics, 1920 x 1080 each channel (initially 1280 x 1024 each channel)	Upgrade to 1920 x 1080 requires upgrade to image source, projection optics, and electronics.
Service Date	2Q, 1997	

The upgradeable image source path is represented in the FOV, pixel density, pixel count, and image data source entries. Several of the parameters have been modified as discussed under the Risk Reduction Areas (Section 4.1.2). New entries have been added to reflect the light source lifetime as well as the electronic interface to the image data source. As a final change to the strawman requirements, the service date has been extended slightly, assuming a program start date of October, 1995.

5.0 DESIGN SPECIFICATION

This design specification describes the required functionality of the Panoramic, 3-D Flight Display System. This specification is intended to be used with the development plan outlined in Section 6. The design specification is derivative of the preliminary display requirements (Section 1.2), with many significant differences. Most significantly, the design specification reflects relaxation of the preliminary display requirements where necessary in order to mitigate system development risk. In addition, the design specification addresses significantly fewer parameters than are cited in the preliminary display requirements. This brevity is accomplished by focusing on those parameters deemed most critical to the system design, most of which encompass or impact a larger set of nonorthogonal requirements found in Section 1.2.

5.1 Scope of Specification

5.1.1 Purpose

The purpose of this specification is to describe the functional requirements of the Panoramic, 3-D Flight Display System, hereafter referred to in this specification as the *display system*. The display system is designed for the motion-base flight simulator environment, with the capability for implementation in an aft-compartment simulation environment of a 757 research aircraft. The display system is not intended for mass production, but rather for limited research applications. General specifications for the display system do not apply to the touch-pad interaction device, which is specified separately at the end of this specification.

5.1.2 Components Covered in Specification

The display system includes the following related components and subassemblies:

- AMLCD light valves, including light sources;
- Collimation and projection optics;
- Power supplies and cooling for the above components;
- Hardware necessary for interfacing any of the above components among each other; and
- Software for test functions or display system component interfaces.

The touch pad interaction device includes the following related components and subassemblies:

- Touch pad cursor-control device (CCD);
- RS-232 interface electronics and cabling; and
- Cursor driver software

5.1.3 Components and Equipment Excluded

The display system specifically excludes the following related components:

- Graphics computers (image data source) and any related power supplies and cabling;
- Either of the two simulators intended to host the display system (ground motion-based or airborne);
- Installation of the display system
- Brackets, fasteners, cabling, or other components required to secure or interface the display system to the host simulator; and
- All software not related to test functions or display system component interfaces.

5.2 Applicable Documents

5.2.1 Precedence

When a requirement in this specification is in conflict with that presented in another document cited within this specification, the requirements specified within this specification shall have precedence.

5.2.2 Related Documents

The following documents were drawn on in the formation of this display specification. The degree to which these documents apply to this specification is limited by the citations occurring within this specification. These documents do not constitute whole parts of this specification.

- Panoramic, Large-Screen, 3-D Flight Display System Design: Final Report (1995).
- Flight Research Program Management (LHB 7910.1). NASA LaRC Handbook (September, 1987).
- RTCA DO-160A-80: Environmental Conditions and Test Procedures for Airborne Equipment.
- MIL-STD-129L: Marking for Shipment and Storage.

5.3 Requirements

This section of the specification presents the functional requirements for the display system and interaction device. The word "shall" conveys a requirement, while the word "should" denotes a recommendation. Unless otherwise stated in the requirements, all requirements shall be met within the full head motion box. The requirements specified here address the following general areas:

- Mechanical/Physical
- Optical
- Electrical
- Environmental
- Interaction Device

5.3.1 Mechanical/Physical

Table 5-1 describes the specification for mechanical/physical components of the display system.

Table 5-1. Specification of mechanical/physical parameters

Parameter	Specification
Cooling	Either passive cooling, forced air cooling, or suction of ambient air for cooling shall be acceptable, provided the following guidelines are followed. Passive cooling shall be acceptable provided heat dissipation does not significantly raise the temperature of the operations environment and the external temperature of the display unit does not present a hazard to operators (see *Temperature: External)*. Active cooling shall be acceptable, provided adequate provision is made for noise isolation, relative to the general noise level of the operations environment. In addition, exhaust air shall not cause discomfort to operators. Forced cool air shall be acceptable provided demand does not exceed the capacity of the available air conditioning system. Suction application of ambient air shall be acceptable provided dust filtering is used and provision is made in the design of the electronics for dust accumulation.
Fasteners	All fasteners used in the display system shall be compliant with section 5.2.1 of NASA LHB 7910.1.
Head Relief	Head relief is defined as the range of physical clearance between the nearest display system component and the head of the display observer. The display system shall provide ≥15 inches of head relief in any direction from the center of the head motion box when positioned for normal installation, and ≥20 inches on-axis. On-axis head-relief shall not exceed 33 inches.
Housing	Fabrication of the display system housing shall conform to the fabrication guidelines found in Section 5.5 of NASA LHB 7910.1.
Maintenance	Where practical and necessary, the display system shall be designed to allow maintenance of components. Specifically, the display system light source(s) shall be user-replaceable. Built-in test equipment should be considered where an advantage exists in doing so.
Markings	The display system shall be marked as per section 5.2.2 of NASA LHB 7910.1.
Temperature: External	External surfaces of the display system intended to be touched during normal operation shall not exceed 35 deg C. External surfaces of the display system which may be inadvertently touched during display system operation shall not exceed 50 deg C.
Volume	The physical dimensions of the display system, including light sources and display cooling but not image data sources, shall be ≤30 inches high, ≤30 inches wide, and ≤30 inches deep.
Weight	The weight of the display system should be minimized, and the total display system shall weigh less than 400 lbs.

5.3.2 Optical

Table 5-2 describes the specification for optical components of the display system. Because many of these specifications are not objectively obvious from the system design, definitions of the specification parameters are included, as well as a recommended procedure for measurement. Inclusion of a measurement procedure in Table 5-2 does not necessarily constitute a requirement for performance testing. Performance test requirements are indicated separately in Section 5.4. Recommended measurement procedures are offered for further clarification of the definition of the specification and constitute a required measurement methodology only where the word "shall" is used.

The following definitions apply to the optical specifications in Table 5-2:

Term	**Definition**
Center Line of Sight	The line of sight that originates in the center of the head motion box and intersects the center of the image.
Color Element	The smallest addressable area of the display. Individual color elements may vary in luminance but are limited to a single dominant wavelength, except in cases where color elements are equivalent to pixels (e.g. subtractive color displays or projection displays using optical combination of multiple image sources).
Corner Line of Sight	The four lines of sight that originate in the center of the head motion box and intersect the four points located 10% from the outer corners of the total FOV along the diagonals formed between these corners.
Pixel	A combination of one or more color elements sufficient to display any color within the color gamut of the display system. Color elements are equivalent to pixels for monochrome displays, subtractive color displays, and projection displays using optical combination of multiple image sources.

Table 5-2. Specification of optical parameters

Parameter	Definition, Specification, and Measurement Approach
Color Element: Failures	**Definition:** Color element failures are defined as the temporary or permanent loss of addressability of individual color elements or clusters of color elements. **Specification:** Each image source of the display system shall have ≤0.5% total failed blue color elements, ≤0.25% total failed red and green color elements. For adjacent failed color elements (clusters of the same color), each image source of the display system shall have ≤10 clusters of 2 failed elements, ≤5 clusters of 3 failed elements, ≤2 clusters of 5 failed elements, and ≤1 cluster of 10 failed elements. This specification applies to total failures, either on or off. **Measurement:** Measurement shall be made by visual inspection, or by image source vendor testing.
Color Gamut: Maximum	**Definition:** The range of hues and saturation capable of being displayed at maximum luminance. **Specification:** The display system shall have a color gamut which is acceptable to NASA. As a guideline, the color gamut should approximate that of a standard color workstation CRT. For reference, the following CIE u'v' color coordinates are offered as an example of a maximum color gamut of a CRT: u' v' red .397 .527 green .125 .559 blue .171 .170 The chromaticity coordinates given above are for reference only and do not constitute a requirement for the display system. **Measurement:** Color gamut should be subjectively evaluated as well as measured from the center line of sight, as well as the four corner lines of sight. Color gamut should be measured as the maximum color gamut (i.e., measured at maximum display luminance). The conversion to 1931 CIE x, y from 1976 CIE u'v' is as follows: x = 27u'/4/[(9u'/2)-12v'+9], y = 3v'/[(9u'/2)-12v'+9]. The conversion from 1931 CIE x, y to 1976 CIE u'v' is as follows: u' = 4x/(-2x+12y+3), v' = 9y/(-2x+12y+3).
Chromatic Uniformity: Large Area	**Definition:** Large-area chromatic uniformity refers to the absence of unintended chromatic differences between the center line of sight and the corner lines of sight. **Specification:** There shall be no subjectively objectionable large area chromatic nonuniformities. This specification for large area chromatic uniformity applies to the center of the head motion box. **Measurement:** Large area chromatic uniformity should be subjectively evaluated and should be empirically determined by measuring u', v' coordinates from the center and corner lines of sight. Uniformity measurements should be made for white images for each stereoscopic image field. Measurements should be taken at 50% of maximum display luminance.

Chromatic Uniformity: Small Area	**Definition:** Small area chromatic uniformity refers to the absence of unintended chromatic differences between two points within a 0.5 deg area across the TFOV. **Specification:** There shall be no subjectively objectionable small area chromatic nonuniformities. This specification for small area chromatic uniformity applies to the center of the head motion box. **Measurement:** Small area chromatic uniformity should be subjectively evaluated and should be measured using the points of largest difference within a 0.5 deg portion of the display TFOV, measured from the center of the head motion box. Uniformity measurements should be made for white images for each stereoscopic image field. Measurements should be taken at 50% of maximum display luminance.
Chromatic Uniformity: Stereoscopic	**Definition:** Stereoscopic chromatic uniformity refers to the absence of unintended variation in color between stereoscopic image fields. **Specification:** There shall be no subjectively visible difference in colors (color breakup) between stereoscopic image fields where a fused image of equal color is intended. **Measurement:** Stereoscopic uniformity should be subjectively evaluated and should be empirically recorded by measuring color gamut for both stereoscopic image fields independently. Uniformity measurements should be made for white images for each stereoscopic image field. Measurements should be taken at 50% of maximum display luminance.
Crosstalk	**Definition:** The amount of light "leakage" from one stereoscopic field to the other, due to imperfect stereoscopic selection or excessive image persistence. Perceptually, the extent to which ghost images are present. **Specification:** The luminance crosstalk between display system stereoscopic image fields shall be ≤5% for white or any primary color. **Measurement:** Crosstalk may be measured by presenting a white image to one stereoscopic channel but not the other. The luminance of the image should be measured as seen from each channel (e.g., through each lens of stereoscopic glasses). The selection leakage is defined as follows: leakage = $(\text{Luminance}_{off} / \text{Luminance}_{on})100$, where Luminance_{off} is the luminance as measured through the nonselected channel and Luminance_{on} is the luminance as measured through the selected channel. This measurement should be performed from the center line of sight, as well as the four corner lines of sight. This procedure should be repeated for red, green, and blue. This procedure should be repeated with the image being sent to the other stereoscopic channel.
Dipvergence	**Definition:** The presence of disparities between stereoscopic eye points in the vertical direction due to vertical misregistration between stereoscopic fields. **Specification:** The dipvergence between display system stereoscopic fields shall be ≤0.08 deg. This specification refers to the maximum dipvergence between stereoscopic fields as measured from two binocular eye points, separated by a nominal IPD such as 2.5", anywhere within the head motion box. **Measurement:** To measure dipvergence, a calibration image constructed of numbered horizontal lines should be presented to each display channel, with the vertical position of selected lines noted with respect to a fixed reference (e.g., a viewing reticle). Samples should be taken at multiple positions on the lines and for multiple lines because image rotation or other image distortions may exist. The physical vertical separation of equivalent test image lines can be converted to degrees of visual subtense as: $2\tan^{-1}(V/2F)$, where V is the vertical separation of equivalent test lines and F is the focal length of the display optics.

Distortion	**Definition:** A form of optical aberration. The net percentage of unintended variation in the position of an image element with respect to an ideal image. Perceptually, the degree to which optical aberrations such as pincushion or barrel distortion are present in the image. **Specification:** The net image distortion of the display system shall be ≤5% distortion over the total, unvignetted, binocular FOV. **Measurement:** Distortion is commonly measured by displaying a uniform grid pattern and measuring the maximum deviation in the displayed grid positions from the expected distance from the center of the grid. Distortion is then calculated as: $2(\lvert h_2-h_1\rvert)/(h_2+h_1)100$ or $2(\lvert v_2-v_1\rvert)/(v_2+v_1)100$, where h_1 and h_2 correspond to the expected and measured horizontal distance from the center of the grid and v_1 and v_2 correspond to the expected and measured vertical distance from the center of the grid. These calculations should be made as a minimum with respect to the four corner lines of sight.
Field Curvature	**Definition:** A form of optical aberration in which the image of a flat object does not lie in a plane, with object points falling off optical axis showing the aberration. Perceptually, the presence of variations in the accommodation distance where none should occur. **Specification:** The field curvature of the display system shall be ≤ +/- 0.25 diopters over the total, unvignetted, binocular FOV. Field curvature, if any, shall be greater in the peripheral FOV than at the center line of sight. **Measurement:** Field curvature should be measured, as a minimum, from the center line of sight, as well as the four corner lines of sight.
Field of View: Total, Binocular	**Definition:** The angular subtense, horizontally and vertically, of the image that is visible with both eyes simultaneously from within the head motion box. Total, binocular FOV is calculated as: Pixels/Resolution, where Pixels is the total number of pixels either horizontally or vertically and Resolution is the number of pixels per deg either horizontally or vertically. Alternatively, FOV may be calculated as: $2\tan^{-1}(I/2F)$, where I is the horizontal or vertical extent of the image source and F is the focal length of the display optics. **Specification:** The display system shall have an unvignetted, total binocular FOV of 34 deg (horizontal) by 27 deg (vertical). However, the display system collimation optics shall be designed to allow a total binocular FOV as large as 48 deg (horizontal) by 27 deg (vertical). This larger FOV assumes an increased pixel count of 1920 x 1080 and a pixel density of 40 pixels/deg. These FOV specifications shall be met for each eye (the display system shall present 100% stereoscopic overlap). **Measurement:** FOV may be measured with a theodolite.
Focus Control	**Definition:** The means by which the focus of the display image on the projection screen may be adjusted. **Specification:** Manual focus control shall be provided. This specification applies to control of image focus on the projection screen and is not intended to require adjustability of collimation distance. **Measurement:** Provision of focus control is evident from the system design (no measurement is necessary).
Frame Rate	**Definition:** The number of times within a one-second interval that all display pixels may be addressed. **Specification:** The display system frame rate shall be ≥60 Hz and must be compatible with the Silicon Graphics image data source. **Measurement:** Frame rate is evident from the system design (no measurement is necessary).

Gray Scale	**Definition:** The number of discretely addressable luminance levels for each color primary in a digitally-addressed display and the algorithm describing the linearity of the distribution of available gray scale steps over the luminance range of the display. **Specification:** The display system shall be capable of displaying ≥32 linearly distributed shades of gray per color channel, where the first luminance step is equal to the background luminance. Linear distribution of digitally-commanded gray scale steps should be obtained by fitting a regression equation to the data describing display luminance as a function of DAC value at the image data source. **Measurement:** To verify the total number of gray shades available per color channel, the luminance of the display should be measured in a dark room while each primary color channel is addressed from zero in the smallest increments possible. To verify the linearity of the gray scale luminance distribution, the values recorded from the above procedure should be plotted against their digitally-commanded values and a regression equation fit to the data.
Head Motion Box	**Definition:** Head motion box is defined as a spherical area of given diameter within which both eyes must be located to see the unvignetted, binocular image. The head motion box is truncated vertically, such that top and bottom of the sphere of given vertical extent are excluded. The center of the spherical area intersects the center line of sight and is located at the on-axis head relief. **Specification:** The display system shall have a head motion box as described above with a spherical diameter ≥ 6 inches and a vertical truncation ≤ 1 inch top and ≤ 1 inch bottom. Additional viewing volume should be provided beyond the prescribed head motion box. If provided, gradual roll-off of display performance such as vignetting, luminance and resolution is acceptable within the additional viewing volume. **Measurement:** Head motion box should be inherent in the display system design, but may be verified by subjectively noting the envelope around the center of the head motion box at which vignetting first occurs.
Image: Artifacts	**Definition:** Any undesirable visual quality of the display system image which is reliably visible to more than one observer. Examples of image artifacts include double images, tiling seams, contrast reversal, image retention, image smearing, and visual discomfort. **Specification:** The display system shall be free of image artifacts within the entire head motion box. **Measurement:** Visual inspection by multiple observers.
Image: Distance	**Definition:** The distance from the center of the head motion box to the plane of visual accommodation. **Specification:** The display system shall have an image distance of infinity. **Measurement:** Measurement of the display system image distance may be conducted through either formal or informal approaches. One informal measurement approach is the use of an SLR lens with split-field focus.
Interlacing (Spatial)	**Definition:** The conservation of display system bandwidth by addressing only a subset of display pixels during each display refresh cycle. **Specification:** The display system shall be spatially noninterlaced **Measurement:** Spatial interlacing is evident from the system design (no measurement is necessary).
Line Failures	**Definition:** Line failures are defined as the temporary or permanent loss of addressability of a complete row or column of color elements or pixels. **Specification:** The display system shall have no line failures, neither on nor off. **Measurement:** Line failures are detected by visually inspecting each image source.

Luminance	**Definition**: The luminous intensity of a surface in a given direction per unit of projected area. **Specification**: The maximum (white) luminance of the display system shall be ≥30 fL when measured after the closest optical element to the eye. **Measurement**: Luminance should be measured from the center line of sight, as well as the four corner lines of sight. A solid white image should be used for measuring foreground luminance. A solid black image should be used for measuring background luminance. A photometer with a one deg acceptance angle is appropriate for these measurements.
Luminance: Asymmetry	**Definition**: The percentage difference in luminance between stereoscopic image fields. **Specification**: The luminance asymmetry of the display system between stereoscopic image fields shall be ≤10%. **Measurement**: The procedure described under *Luminance* is used to measure each stereoscopic image field. Luminance asymmetry is calculated for each of the pairs of measured luminance values as: $(\lvert \text{Luminance}_{low} - \text{Luminance}_{high} \rvert / \text{Luminance}_{high})100$, where Luminance_{low} represents the lowest luminance of the pair and Luminance_{high} represents the highest luminance of the pair.
Luminance: Contrast	**Definition**: The ratio of maximum display luminance to minimum display luminance, as expressed below. **Specification**: The luminance contrast of the display system shall be ≥50:1 from the center of the head motion box. **Measurement**: The luminance and background luminance should be measured from the center line of sight, as well as the four corner lines of sight. Contrast ratio is calculated as: $C_R = L_{max} / L_{min}$, where L_{max} is the higher of the two luminance measurements and L_{min} is the lower of the two luminance measurements.
Luminance: Half-Life	**Definition**: The time required for the maximum luminance of the display to be reduced to below 50% of the initial value over the life of the display. **Specification**: The maximum (white) luminance of the display system shall remain ≥50% of the initial (or required, whichever is greater) luminance value for ≥1000 hours. **Measurement**: Backlight vendor specification or destructive testing of spare.
Luminance: Large Area Nonuniformity	**Definition**: The percentage of unintended variation in luminance between two areas across the display TFOV. Large-area luminance nonuniformity refers to unintended luminance differences between that measured from the center line of sight and the corner lines of sight. **Specification**: The large-area nonuniformity of the display system shall be ≤40%. **Measurement**: Large area luminance nonuniformity is calculated as: $(\lvert \text{Luminance}_A - \text{Luminance}_C \rvert / \text{Luminance}_C)100$, where Luminance_C is the luminance of the image measured from the center line of sight and Luminance_A is the luminance of the image measured from each of the corner lines of sight. A photometer with a one deg acceptance angle is appropriate for measuring large-area luminance nonuniformity.
Luminance: Small Area Nonuniformity	**Definition**: The percentage of unintended variation in luminance between two areas across the display TFOV. Small area nonuniformity refers to unintended luminance differences within a 0.5 deg area of the display TFOV. **Specification**: The small-area nonuniformity of the display system shall be ≤10%. **Measurement**: Small area luminance uniformity is calculated as: $(\lvert \text{Luminance}_{B1} - \text{Luminance}_{B2} \rvert / \text{Luminance}_C)100$, where Luminance_C is the luminance of the image measured from the center line of sight and Luminance_{B1} and Luminance_{B2} represent the image luminance measured anywhere within a 0.5 deg circle within the TFOV. A photometer acceptance angle of no larger than 0.25 deg shall be used for measuring small-area nonuniformity.

Misconvergence: Spatial	**Definition:** The center-to-center misregistration distance between overlapping color elements forming the same pixel, expressed as a percentage of the width of a primary color line. Perceptually, the spatial separation of a color pixel into constituent primary colors. **Specification:** The display system shall have spatial misconvergence of ≤33% of line width. **Measurement:** Spatial misconvergence is measured as the separation of red, green, and blue primaries in a white line, vertically for a horizontal line and horizontally for a vertical line. Misconvergence of white cross-hair targets should be measured in the image from center and corner lines of sight. Misconvergence is defined as: $(line_{white} - line_{primary})/line_{primary})100$, where $line_{white}$ is the half-amplitude width of the luminance profile of the white line and $line_{primary}$ is the half-amplitude width of the luminance profile of the widest of the three primary color component lines.
Misconvergence: Temporal	**Definition:** The degree to which display colors appear to alternate over time, when a single, fused color presentation is intended. **Specification:** No apparent color separation or alternation shall be visible as a result of using time-multiplexed color mixing. **Measurement:** This specification can only be judged subjectively. Evaluation may be made through casual observation, but is best made through a more rigorous procedure which controls viewing conditions and viewing criteria.
MTF (Modulation Transfer Factor)	**Definition:** The minimum modulation transmittance of the display system optics at the maximum display resolution (frequency). Perceptually, the extent to which the display optics faithfully represent image sharpness. **Specification:** The minimum modulation transfer factor of the display system optics at the maximum display resolution (40 pix/deg) shall be ≥0.3 across the maximum FOV of the display system. **Measurement:** The modulation transfer factor, MTF, is calculated for any given spatial frequency as: M_{out} / M_{in}, where M_{out} is the modulation of the image after transmission through the optical system and M_{in} is the modulation of the image prior to transmission through the optical system. Luminance modulation, M, is defined as: $(L_{max} - L_{min}) / (L_{max} + L_{min})$, where L_{max} is the higher luminance of the foreground or background, and L_{min} is the lower luminance of the two.
Pixel Count	**Definition:** Total number of addressable display pixels in both the horizontal and vertical dimensions presented to each eye (i.e., each stereoscopic perspective view). **Specification:** The display shall have 1280 (horizontal) x 1024 (vertical) addressable full-color pixels which are visible without vignetting from the center of the head motion box. The full pixel count shall be available to each eye for each stereoscopic image frame. The display system shall be capable of accepting an image source with 1920 (horizontal) x 1080 (vertical) pixels without replacement of the collimation optics and without loss of either pixel density, FOV, or total pixels (unvignetted). **Measurement:** Pixel count is evident from the system design (no measurement is necessary). However, an upgrade path to the higher pixel count should be demonstrated through analysis of the system design.

Reflectance: Diffuse	**Definition:** The percentage ratio of the display luminance contribution due to ambient light divided by the illuminance on the display due to that ambient light, where the luminance contribution does not include specularly reflected components of the ambient light. **Specification:** The display system shall have a diffuse reflectance of ≤0.4%. **Measurement:** Characterization of the diffuse reflectance is made more complex in the present system due to the large size and complex arrangement of surfaces. Diffuse reflectance is measured by placing a small non-directional light source (simulating a point source) in the center of the head motion box. A small white reference surface having approximately 100% Lambertian reflectance is placed at the first optical element along and normal to the center line of sight. Reflectance is given by ($Luminance_R$ / $Luminance_{WH}$)/100, where $Luminance_{WH}$ is the reflected luminance of the white reference surface and $Luminance_R$ is measured from a second point in the head box and at an angle of 10 degrees from the center line of sight, and aligned such that no specular reflection is included in the luminance measurement. The measurements are made in an otherwise dark room and with the display lamps turned off.
Reflectance: Specular	**Definition:** The sum of the percentages of luminance from equivalent specular light sources reflected by the corresponding display optical elements. **Specification:** The display system shall have a specular reflectance of ≤4%. **Measurement:** Specular reflectance is measured by aiming a photometer along the center line of sight. For each surface contributing significant, noticeable specular reflectance (where a clear image of a light source can be seen), the specular reflectance contribution from that surface is measured by placing a light source with a white diffusing filter in a location such that the corresponding specular image is sampled by the collection angle of the photometer. The reflectance contribution is given by ($Luminance_R$ / $Luminance_S$)/100, where $Luminance_S$ is the luminance of the diffuse source and $Luminance_R$ is the luminance of the reflected image of the diffuse source. Specular reflectance is the sum the contributions from the collimating mirror, the beamsplitter, and all additional significant specular reflections. The measurements are made in an otherwise dark room and with the display lamps turned off.

5.3.3 Electrical

Table 5-3 describes the specification for electrical and electro-mechanical components of the display system.

Table 5-3. Specification of electrical parameters

Parameter	Specification
Control of Luminance	The display system shall provide manual luminance control in the form of a balance control between (or among) stereoscopic image fields or image tiles. Manual controls shall be located on the exterior of the display system or on the interior with an easily opened access panel. Exterior controls shall incorporate appropriate positioning, guarding, and/or lockout to prevent inadvertent actuation or breakage of the control. Controls should incorporate physical displacement and resistance as feedback to actuation.
Control of Stereoscopic Display	The display system shall provide manual control to allow the presentation of a single stereoscopic image field to both eyes (i.e., a monoscopic viewing condition). The control shall allow selection of either the left-eye image or the right-eye image for monoscopic viewing. Manual controls shall be located on the exterior of the display system or on the interior with an easily opened access panel. Exterior controls shall incorporate appropriate positioning, guarding, and/or lockout to prevent inadvertent actuation or breakage of the control. Controls should incorporate physical displacement and resistance as feedback to actuation.
Electrical: Components	Where available, electrical components (e.g., semiconductors, resistors, capacitors, switches, relays, circuit breakers, terminal boards, transformers, connectors) used in the display system should be aircraft approved parts, as per section 5.4.6 of NASA LHB 7910.1.
Electromagnetic Interference (EMI)	Three forms of electromagnetic interference (EMI) are addressed in this specification. EMI can originate from within one display component and affect another display component. Alternately, the EMI can originate within the display system and affect other components in the environment (i.e., aircraft). Finally, EMI may originate from a source outside of the display system and effect display system performance. EMI broadly includes any functional or quality interference associated with electromagnetic emissions, including static electricity and lightning. The display system should incorporate appropriate shielding, bonding, filtering, grounding, and circuit design where appropriate to ensure no EMI effects, neither on nor from the display system. RTCA DO-160 establishes suitable test procedures for EMI in commercial avionics (these procedures, however, are not a requirement of this specification).
Overload Protection	The display system shall incorporate electrical overload protection with fuses or circuit breakers as per section 5.4 of NASA LHB 7910.1. Circuit breakers shall not be used as switches. Overload protection of the primary wiring to the display system and internal wiring cable harnesses shall be provided. Reset controls for circuit breakers shall be readily accessible to operators. Fuses or circuit breakers should have sufficient gap clearance, after breaking or clearing, to prevent arcing at up to 40,000 feet of altitude.
Power	The display system shall be powered with one or more of the following sources of aircraft-available power, as per section 5.4 of NASA LHB 7910.1: 12 V DC, 24 V DC, 115/208 V 60 Hz lab power, or 115/208 V 400 Hz. If 24 V DC is used, filtering and regulation shall be provided. The display system shall not require power converters external to the display system housing.

Table 5-3. Specification of electrical parameters (continued)

Parameter	Specification
Power-On Sequence	The power-on sequence of display system components shall not affect display system functionality or jeopardize the health or safety of the system or users. The preference is for either no required power-on sequence, or a single power-on control. If a fixed power-on sequence is necessary, this sequence should be automated and as transparent to the user of the system as possible. Serial lock-out of power controls may be considered as one form of automation. If automation of a power-on sequence is not possible, the power-on sequence shall be clearly marked at all exterior power switches of the display system.
Video Interface	The display system shall be designed to receive a dual-channel (stereoscopic) computer video signal from one or more Silicon Graphics workstations (RS-343 as applied to a 1280 x 1024 active area display refreshed at 60 Hz).
Wiring	All electrical wiring, both internal and external to the display system, should conform to sections 5.4 and 5.6 of NASA LHB 7910.1.

5.3.4 Environmental

Table 5-4 describes the specification for environmental performance of the display system.

Table 5-4. Specification of environmental parameters

Parameter	Specification
Acceleration	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, during and after exposure to ≤2 g constant (RMS) acceleration on the axis parallel to the center line of sight.
Altitude	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, over a range of at least 0 to 10,000 feet (equivalent pressure altitude)
Humidity: Operating	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, over a range of at least 5 to 80% relative humidity over the full operating temperature range.
Humidity: Storage	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, after storage over a range of at least 5 to 95% relative humidity when stored at a temperature ≤40 deg C. If temperatures exceed 40 deg C, the display system shall operate normally after storage over a range of at least 5 to 80% relative humidity.
Shock	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, during and after exposure to impulse shock of ≤3 g impulse (≤20 ms) on the vertical axis and ≤1.5 g impulse on the horizontal axis. The display shall continue to operate normally both during and after such exposure without measurable loss, either temporary or permanent, in performance or MTBF. This specification is for impulse shock generally applied to the system via the aircraft or simulator airframe and does not address impact shock directly applied to any optical elements or other specific display system components.
Temperature: Operating	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, over a range of at least 10 to 40 deg C.
Temperature: Storage	The display system shall operate normally, either on ground or in a pressurized cabin or cockpit, after storage over a range of at least -25 to 60 deg C.
Vibration	The display system shall withstand the maximum vibration magnitudes and durations reasonably expected to be encountered in aft compartment TSRV flight, including vibration frequencies as high as 2,000 Hz. The display system shall continue to operate normally both during and after such exposure without measurable loss, either temporary or permanent, in performance or MTBF. Temporary losses in image quality during long-term vibration exposure shall be prevented if possible through vibration isolation measures.

5.3.5 Touch Pad Interaction Device

Table 5-5 describes the specification for the display system interaction device.

Table 5-5. Specification of touch pad interaction device

Parameter	Specification
Computer Interface	The interaction device shall use an RS-232 interface. RS-232 interface is defined here to mean any electronics or cabling necessary to plug the output of the device directly into a Silicon Graphics standard mouse input port. The electronics shall support use of cable extensions without incurring signal loss-induced errors.
Degrees of Freedom	The interaction device shall provide two simultaneous DOF. Interaction device buttons may be used to control assignment of DOF (e.g., x-y, y-z, or x-z) or to control a third DOF.
Palm/Wrist Support	The interaction device shall provide physical support for the palm and/or wrist of the user to promote ease of use in turbulence.
Reliability	The interaction device shall have no moving parts other than switches and shall have a mean-time between failure (MTBF) ≥ 80,000 hours. The interaction device shall be sealed against dust and accumulation of finger oil shall not degrade its functionality.
Selection/Cursor Control Modality	The interaction device shall accept selection or cursor control inputs through a capacitive touch pad interface, three finger-actuated switches, and a thumb switch. The switches should be two-position switches and incorporate tactile feedback and displacement.
Software Driver	A software driver shall be provided which translates 2-D touch inputs into relative 2-D cursor movements on the display. Absolute positioning mode is desirable as an optional control mode, but not required. The driver shall allow cursor gain control for use in relative positioning mode. The driver shall also provide hooks for interpreting device button actuation. Driver source code as well as compiled code shall be delivered. Driver software shall be compatible with contemporary Silicon Graphics computers and should be written in a common computer language such as 'C.' Adaptation of the software driver for 3-D cursor control is not a requirement of the display system integrator.

5.4 Performance Tests

The integrator of the display system shall be responsible for providing data to NASA described by the performance tests within section 5.4. The performance tests included here represent the limit of formal testing required to establish compliance with the requirements of Section 5.3. Additional testing may be conducted by the integrator in the course of display system development, but such testing is not a requirement of this specification. Test results may in some circumstances be supplied to the display system integrator by vendors of display system components, in lieu of testing by the display system integrator. Test procedures may be based on those recommended measurement approaches documented in Section 5.3, or alternate procedures mutually acceptable to the display system integrator and NASA.

Not all requirements given in Section 5.3 require performance testing (most mechanical and electrical requirements such as provision of luminance control will be self-evident in the physical design); other requirements (most notably the environmental requirements) can't be empirically tested without destructive testing, which is not warranted by the one-time production of this research display system. In addition, many performance parameters will not be readily tested in the upgradeable portions of the FOV.

For those requirements which are not associated with recommended performance tests in Section 5.3 and which can't be derived from the physical design of the display system, compliance shall be estimated by the integrator where requested by NASA through either: a) documentation of visual inspection; b) examination of historical data regarding component performance (e.g., vendor-provided backlight luminance half-life); or c) generation of analytical estimates of performance.

The display system integrator shall provide performance data to NASA regarding the following parameters:

5.4.1 Required Mechanical/Physical Performance Tests

The display system integrator shall weigh each major display system subassembly as well as the completely assembled display system. The physical dimensions of each major display system subassembly, as well as the volume of the assembled display system shall be measured. The head relief shall also be measured. The display system integrator shall document any steps taken to verify mechanical/physical compliance with NASA LHB 7910.1 and the system maintenance requirement and shall document any NASA-approved deviations from this specification, as well as the reasons for the deviations.

5.4.2 Required Optical Performance Tests

The display system integrator shall provide performance data for the following optical parameters. The display system integrator shall document any NASA-approved deviations from this specification, as well as the reasons for the deviations.

- Chromatic Uniformity
- Color Element Failures
- Color Gamut
- Crosstalk
- Dipvergence
- Distortion
- Field Curvature
- FOV
- Gray Scale
- Head Motion Box
- Image Artifacts
- Image Distance

- Line Failures
- Luminance
- Luminance Asymmetry
- Luminance Contrast
- Luminance Nonuniformity (Large and Small Area)
- Luminance Half-Life
- Misconvergence (Spatial and Temporal)
- MTF
- Pixel Count
- Reflectance (Diffuse and Specular)

5.4.3 Required Electrical Performance Tests

The display system integrator shall document any steps taken to verify electrical compliance with NASA LHB 7910.1 and the EMI requirement and shall document any NASA-approved deviations from this specification, as well as the reasons for the deviations.

5.4.4 Required Environmental Performance Tests

The display system integrator shall provide vendor-supplied data to NASA regarding system component performance within the specified environmental parameters where available, and shall document any NASA-approved deviations from this specification, as well as the reasons for the deviations.

5.4.5 Required Interaction Device Performance Tests

The display system integrator shall verify the operability of the interaction device and software driver in 2-D cursor positioning modes through installation on a Silicon Graphics workstation. The display system integrator shall provide vendor-documented performance data where available to NASA and shall document any NASA-approved deviations from this specification, as well as the reasons for the deviations.

5.4.6 Required General System Performance Tests

In addition to the performance tests described in Sections 5.4.1 - 5.4.5, the display system integrator shall identify any general system performance features not covered in this specification, if any, which may limit the expected usefulness of the display system. Where possible, short- or long-term remediations should be described.

5.5 Preparation for Delivery

5.5.1 Marking

The marking on all display system assemblies and interior and exterior containers shall be legible and permanent. The ESD symbol per MIL-STD-129L shall be placed on the assemblies, and on the packaging materials or on the containers that provide ESD protection.

5.5.2 Packing

Preservation and packaging shall be in accordance with best commercial practice, in a manner that will assure acceptance by common carrier and safe delivery at the destination.

6.0 DEVELOPMENT PLAN

6.1 Program Overview

This development plan is for the design, fabrication and testing of the Panoramic, 3-D Flight Display research prototype described in Section 5, Display Specification. A three-phased program is planned for the development of this system (Figure 6-1). These phases are: a design phase, a fabrication/assembly phase, and an integration/test phase. The period of performance is from October 1, 1995 through April 30, 1997. The total cost of this nineteen month program is $2.125M. The three phases of the program are fully described below.

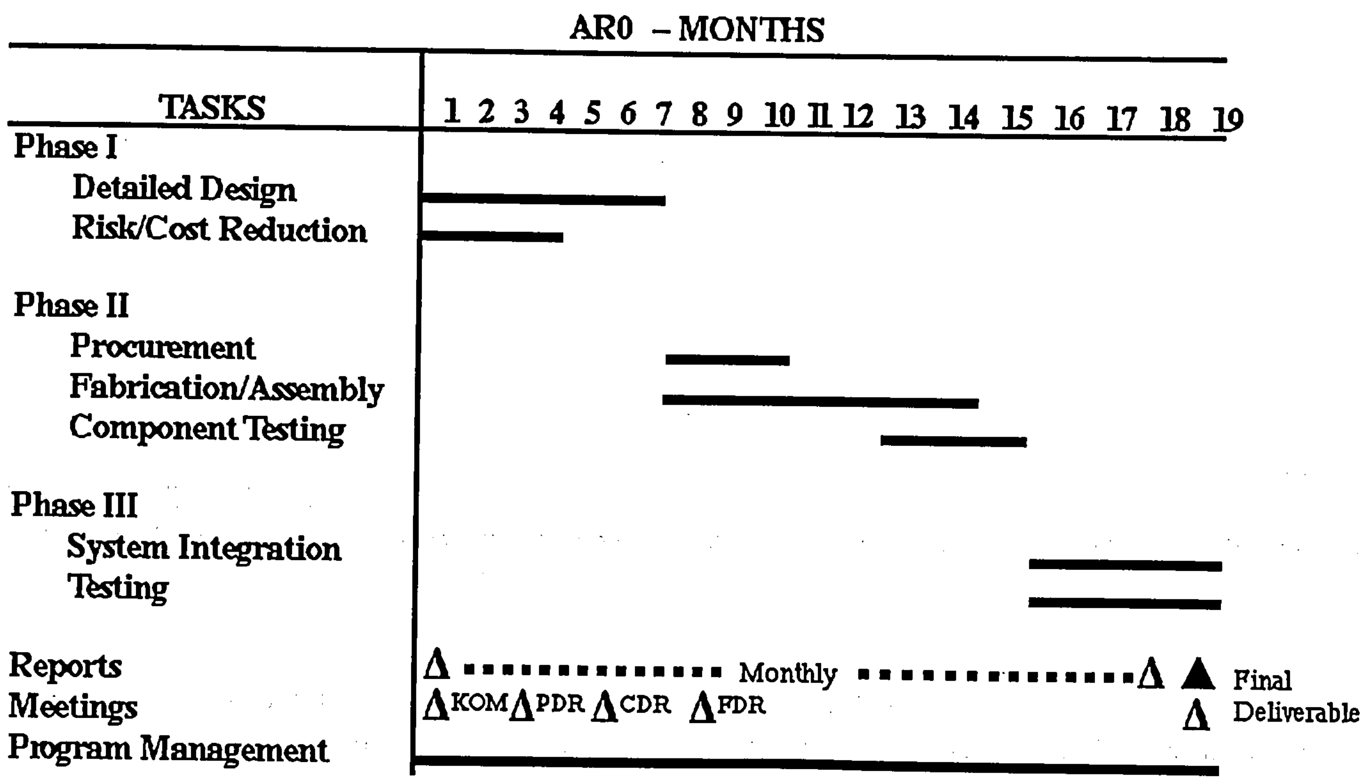


Figure 6-1. Program Milestones for Display System Development.

6.1.1 Phase I- Detailed Design ($625K)

Phase I consists of producing engineering designs of all system components and the overall total system. Where applicable, analyses of the total system (including all sub-systems) will be performed. The deliverable from Phase I will be the engineering designs themselves. This program phase includes the following major program tasks:

- AMLCD Design
- System Optics Design
- Electronics/Software Design
- Interactive Device Design
- Packaging/Hardware Design
- Risk Assessment/Reduction

6.1.2 Phase II- Fabrication and Assembly ($1,125K)

Phase II consists of procurement, fabrication, assembly, and testing of system components and subassemblies. This program phase includes the following major program tasks:

- Image Source Fabrication and Component and Subassembly Testing
- System Optics Fabrication and Component and Subassembly Testing
- Electronics/Software Fabrication and Component and Subassembly Testing
- Interactive Device Fabrication and Component and Subassembly Testing
- Packaging/Hardware Fabrication and Component and Subassembly Testing
- Documentation of Component and Subassembly Testing

6.1.3 Phase III- System Integration ($375K)

Phase III consists of integrating all components and subassemblies into the total system. Also, final testing and evaluation of the total system will be conducted. The deliverable for Phase III will be the completed display system, documentation of test results, and documentation of procedures for maintenance and operation of the system. This program phase includes the following major program tasks:

- Display System Component and Subassembly Integration
- Display System Acceptance Testing
- Documentation of Acceptance Testing, Maintenance Procedures, and Operating Procedures

In addition to the Panoramic, 3-D Flight Display System and associated documentation described in Sections 6.1.1 - 6.1.3, monthly reports and a final report will be delivered to NASA, and program meetings will be supported as indicated in Figure 6-1. The remainder of this development plan includes a detailed description of each of the three program phases (Sections 6.2, 6.3, and 6.4).

6.2 Phase I Development Plan - Detailed Design

This section of the development plan describes the current status of the design of the Panoramic, 3-D Flight Display System. This design represents the baseline against which the detailed design will be developed in Phase I. The following major program elements are addressed:

- System Description
- System Optics
- Image Source and Lamp
- Packaging/Hardware
- Electronics/Display Software
- Interactive Devices
- Risk Assessment/Reductions

6.2.1 System Description

The engineering prototype to be developed for the Panoramic, 3-D, Flight Display System will provide a variety of capabilities for flight display research. This full-color panoramic display system will use state-of-the-art AMLCD light valves to deliver high-resolution, wide FOV imagery in a flight simulator environment. Three-dimensional capability will be achieved by dual-channel stereoscopic presentation of binocular perspective views without corresponding sacrifices in resolution. In addition, the displayed stereoscopic images will be fully collimated to maximize the depth-viewing volume of the display. User comfort will be maximized by careful matching of the two channels and by allowing ample head relief and freedom of head motion. The display prototype is designed to be compatible with motion-base simulator use and to be readily adaptable to flight in a research vehicle for in-flight investigation of crew/vehicle interface and other human factors issues.

The prototype display system (Figure 6-2) will consist of two major subassemblies. The stereoscopic AMLCD light valve projection system will produce alternating high quality perspective views on an intermediate curved projection screen. These views will be subsequently collimated by a symmetric optical system for presentation to the viewer. Image data will be received from two Silicon Graphics-compatible data channels. Either channel may be displayed separately as a high resolution collimated display, or in stereo mode with the use of supplied stereo eyewear. The display will initially provide full binocular image resolution of 1280 x 1024, and will be upgradeable to at least 1920 x 1080 pixels over the 48 deg x 27 deg FOV when suitable light valves become available.

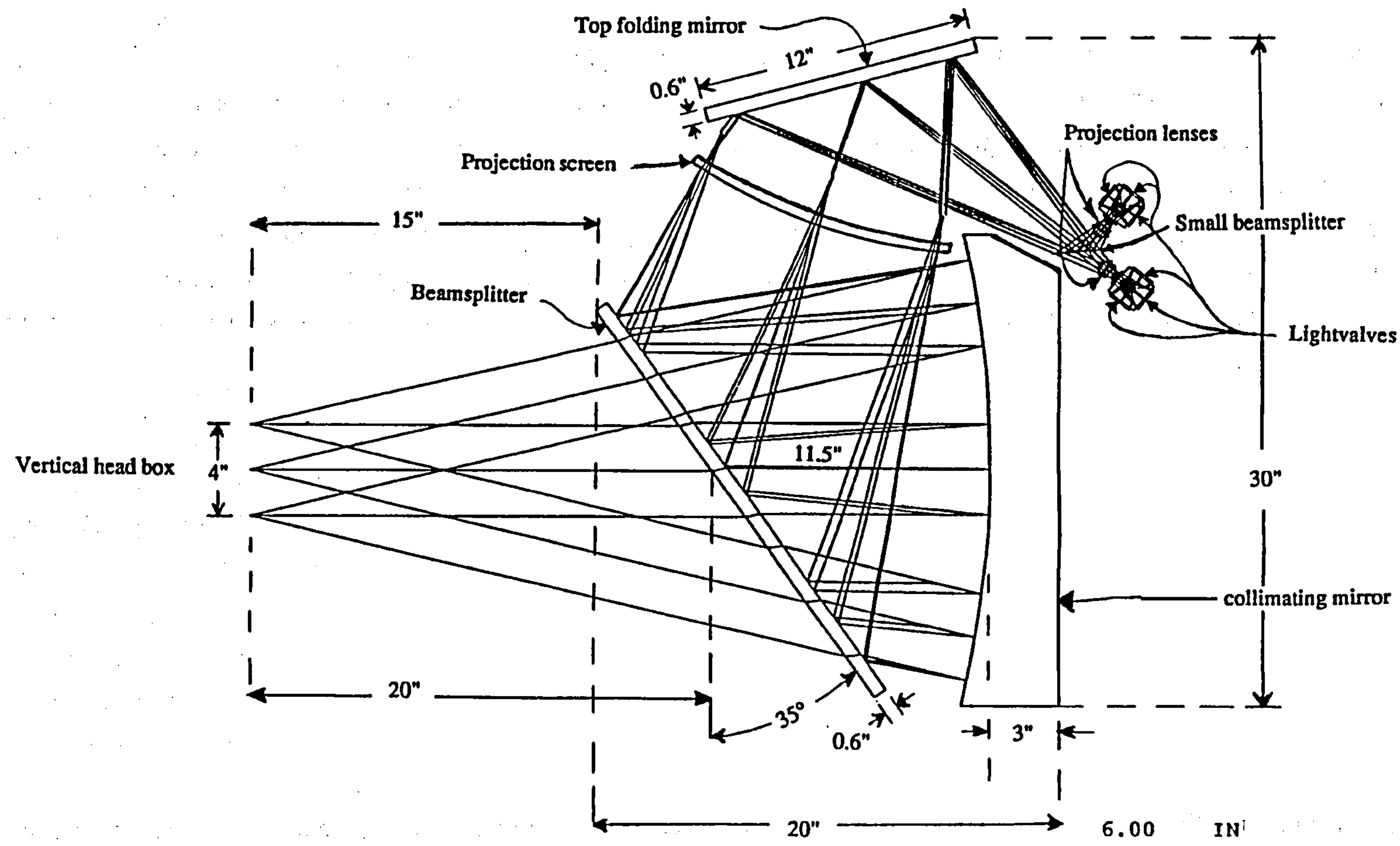


Figure 6-2. Side View of Display System.

6.2.2 Image Source and Lamp

The image source for the display system will consist of six AMLCD light valve panels. The panels will be arranged as two sets of three panels each. Each group of three panels will be illuminated and optically combined to form a full color projector module for a single perspective view. The two projector modules, representing left and right eye views, will be optically merged for projection onto a single screen. The configuration for a single projector module is described further in Section 6.2.3.2 (Projection Optics).

Each Kopin AMLCD panel provides 1280 horizontal color elements by 1024 vertical color elements in a package size of 1.52" (38.72 mm) by 1.36" (34.58 mm). The row scanners, column scanners, and latches are integral to the AMLCD package. A flexible interconnect tape connects the AMLCD to the power source and data inputs. Each pixel is on a 24 micron pitch with an anticipated aperture ratio of approximately 70% and a polysilicon pixel electrode. The AMLCD uses Kopin's high mobility single crystal silicon processed wafers.

Rear illumination for the light valves will be derived from two metal halide arc lamps. These lamps, manufactured by ILC, include an integral elliptical reflector and deliver a tightly focused spot. Nominal lamp power is 400 watts per lamp. The output of the lamps will be collimated and separated into constituent color bands for illumination of the individual light valve panels.

The matching lamp power supply will also be obtained from ILC and will operate from the specified 115/208 V 400 Hz line voltage.

The Panoramic, 3-D Flight Display System can be upgraded to a full 1920 x 1080 pixel resolution when suitable high resolution panels become available. The upgrade will consist of replacing the 1280 x 1024 AMLCD panels with the higher resolution panels. Modification or replacement of the associated interface electronics and projection optics will also be required. Kopin is currently developing a 2560 x 2048 AMLCD in a comparably sized package. They estimate that samples of the AMLCD panel will be available by the mid-1997 time frame. Exceeding the specified 1920 x 1080 pixel count is likely to provide further enhancement of the display system resolution, especially in the central portion of the FOV, although overall performance will be impacted by a number of other factors.

6.2.3 System Optics

6.2.3.1 Collimation. The collimation system (Figure 6-3) will have an aspheric concave mirror with a beamsplitter fold and a spherical projection screen. The beamsplitter will be at an angle of 35 deg with the vertical plane to make the system as compact as possible. The collimation mirror will be aspheric to minimize the resulting dipvergence of a spherical mirror of the same power. The aspheric mirror will reduce the blur size over the full pupil with the result that the left eye image shift from the right eye image is within the dipvergence limit. Additionally, the projection screen will be made spherical to match the curved image of the collimating mirror, permitting the single mirror approach to meet the performance requirement of 40 pixels/deg over the full 48 deg x 27 deg FOV. The first surface of the projection screen, which will have the real image for collimation on it, is designed to be a diffusing surface which disperses the light from the projection optics into the full 10 deg cone of light needed to fill the head motion box with illumination.

Antireflection coatings and polarization control films will be used with the beamsplitter to effectively suppress ambient reflections. Without such contrast enhancement techniques, reflections from both the beamsplitter and collimation mirror would be problematic.

Included in the first phase of the development plan is consideration of methods for providing field lens functionality in the vicinity of the screen to allow increased optical efficiency, as well as a further look at the benefits and disadvantages of the aspheric mirror versus a spherical form.

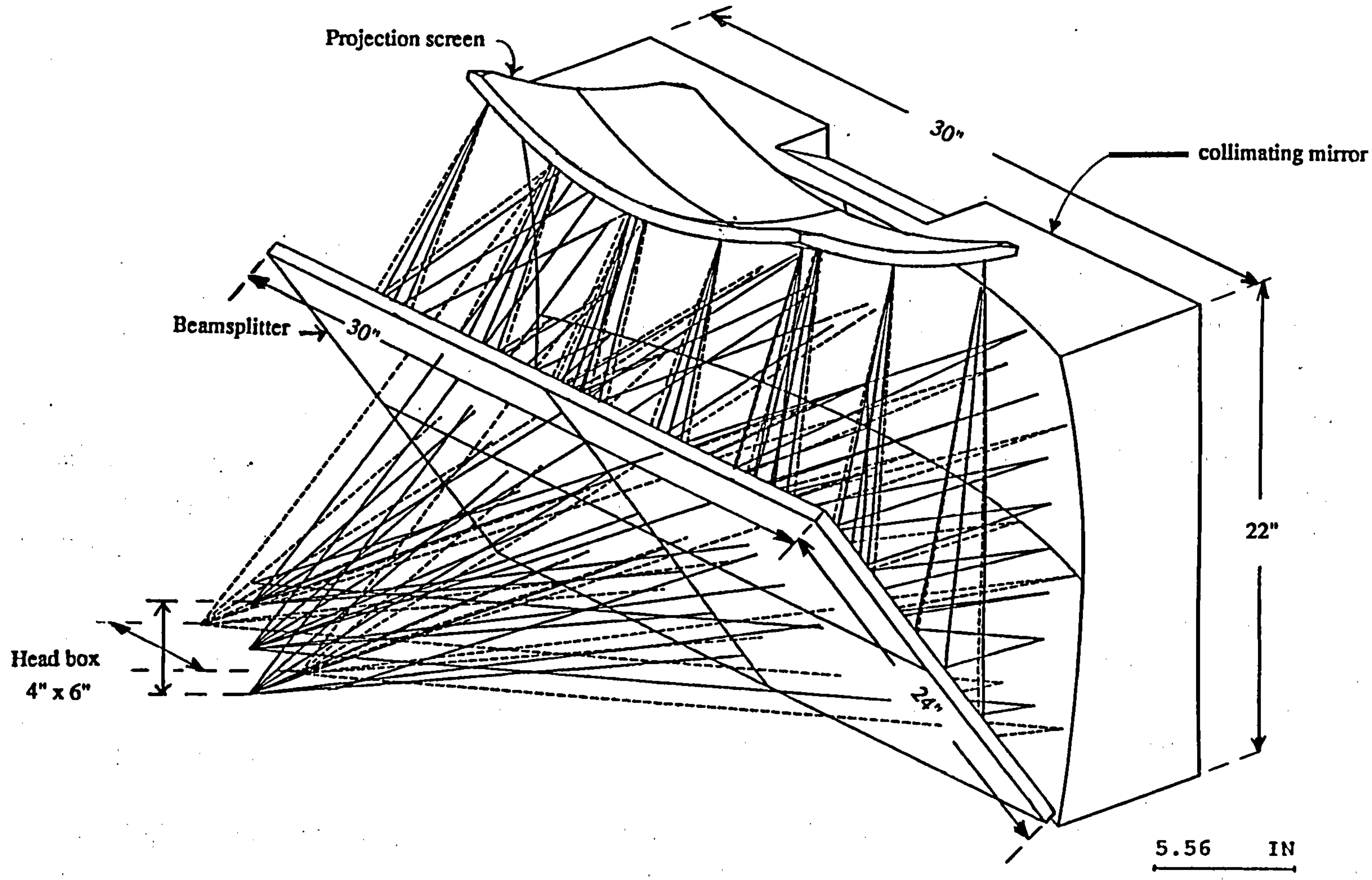


Figure 6-3. Collimation System.

6.2.3.2 **Projection.** The projection optics subassembly (Figure 6-4) will combine the images from six miniature light valves into a curved and magnified real image on the spherical projection screen. To minimize the volume and weight of the display, a fold mirror will be used in the projection optics between the lenses and the projection screen. To provide a collimated stereo image, an additional fold with a polarization beamsplitter will be used between the first fold mirror and the projection lenses. The projection lens will be a four-element system with an internal stop. Alternately (Figure 6-5), the stop could be placed on the first lens surface, allowing a smaller polarization beamsplitter (such as a standard polarizing prism) to be used. The alternate lens would also have a large back focal distance, allowing the three single color light valves to be coincidentally combined with a color cube prism combiner (Figure 6-6).

In the detailed design task of Phase I, we will optimize performance further by making the design more telecentric, increasing the back focal distance, and matching the collection angle to the divergence of the illumination beams. These modifications will improve grayscale and luminance uniformity across the FOV, enhance optical efficiency and permit a more optimum color combining prism arrangement. Consideration will also be given to optical distortion compensation, taking into account the effect of the collimation optics.

The six light valves will be transmission illuminated by the two collimated white arc lamp sources described in Section 6.2.2. The collimation angle will be kept as small as possible while maintaining high illumination efficiency and uniformity. With a color beamsplitter assembly, each collimated white light source will supply red, blue and green light illumination for a set of three light valves. The light transmitted by each of these light valves will then be recombined with another color beamsplitter to provide a coincident color image source for the projection and subsequent collimation display system. Another identical set of color beamsplitters (Figure 6-7), light valves and collimated white light source will supply the other stereo coincident color image source. Polarization elements will be incorporated as described in Section 6.2.3.3 to provide a stereo image pair for the 3-D display and to ensure compatibility with the ambient light rejection method described in Section 6.2.3.1.

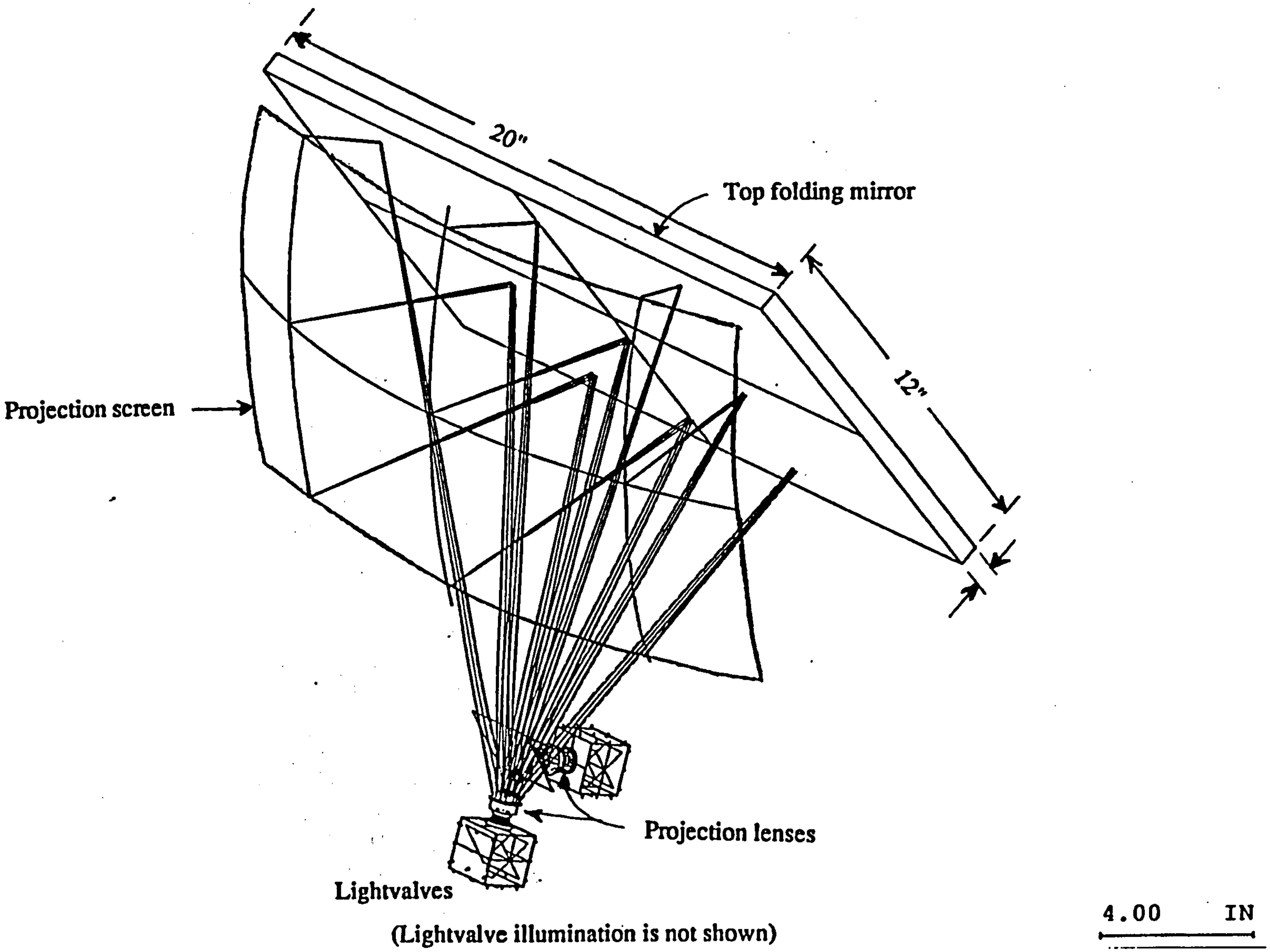


Figure 6-4. Projection Optics Subassembly.

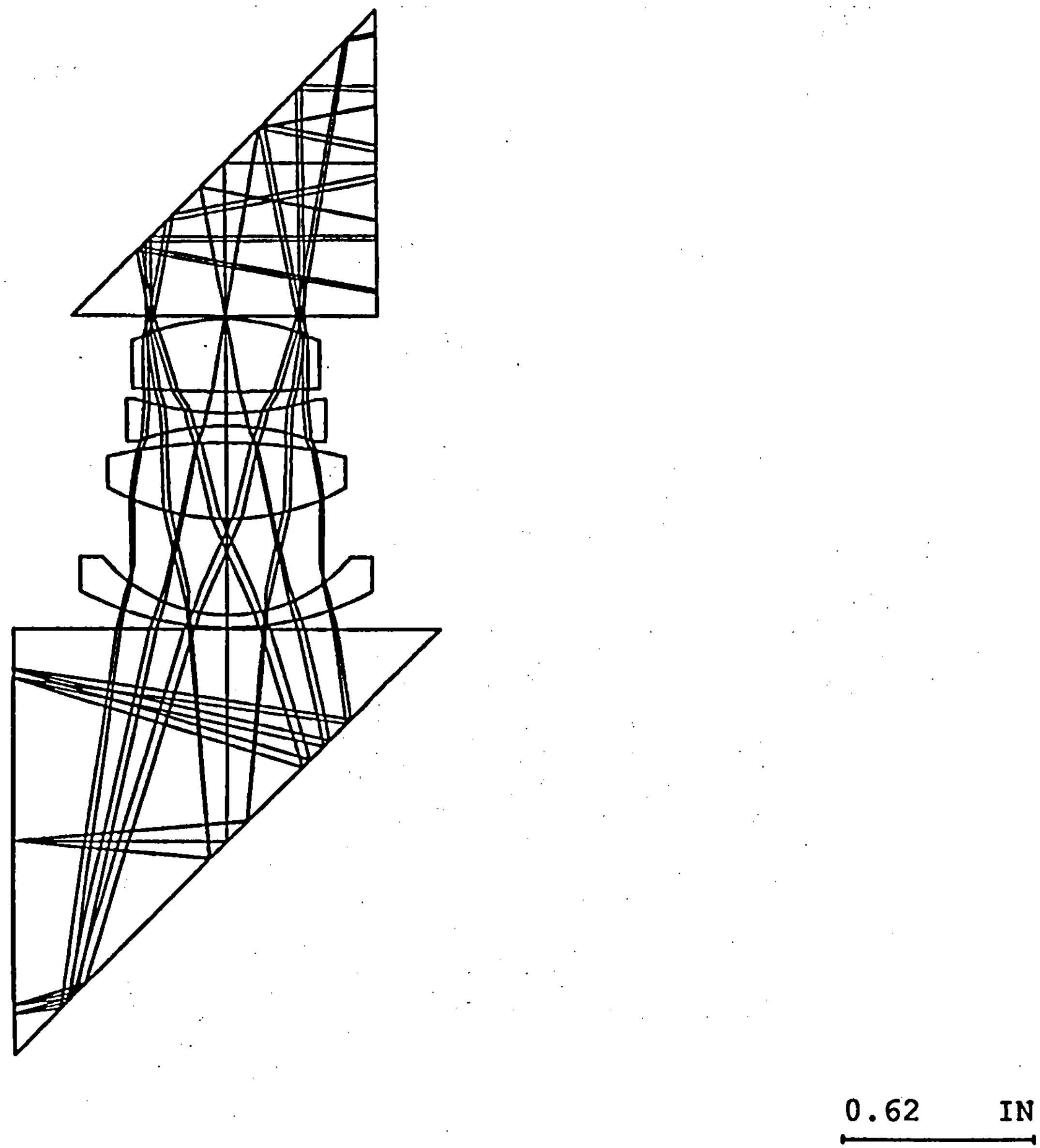


Figure 6-5. New Projection Lens Design.

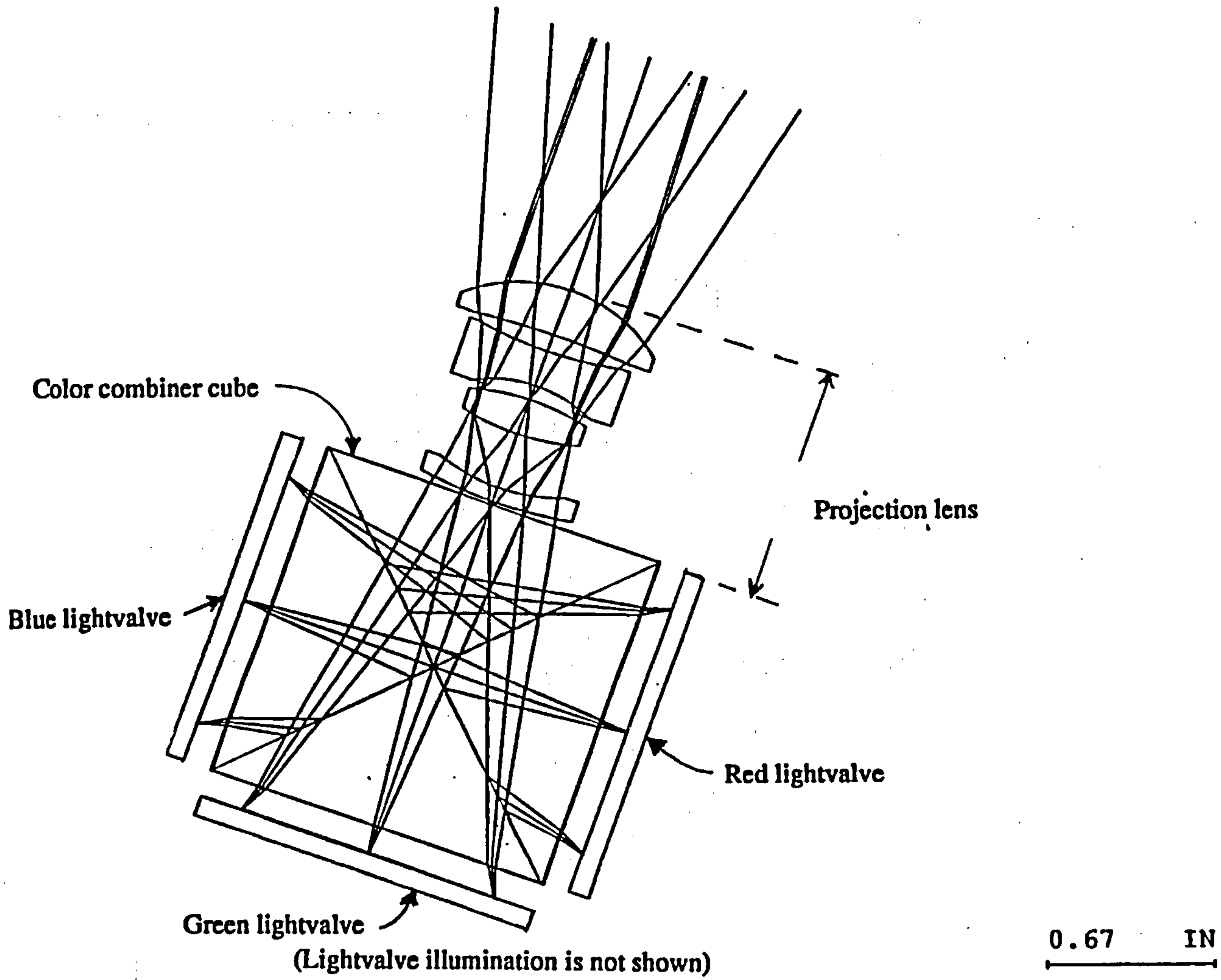


Figure 6-6. Right Stereo Color Projection Lens Assembly.

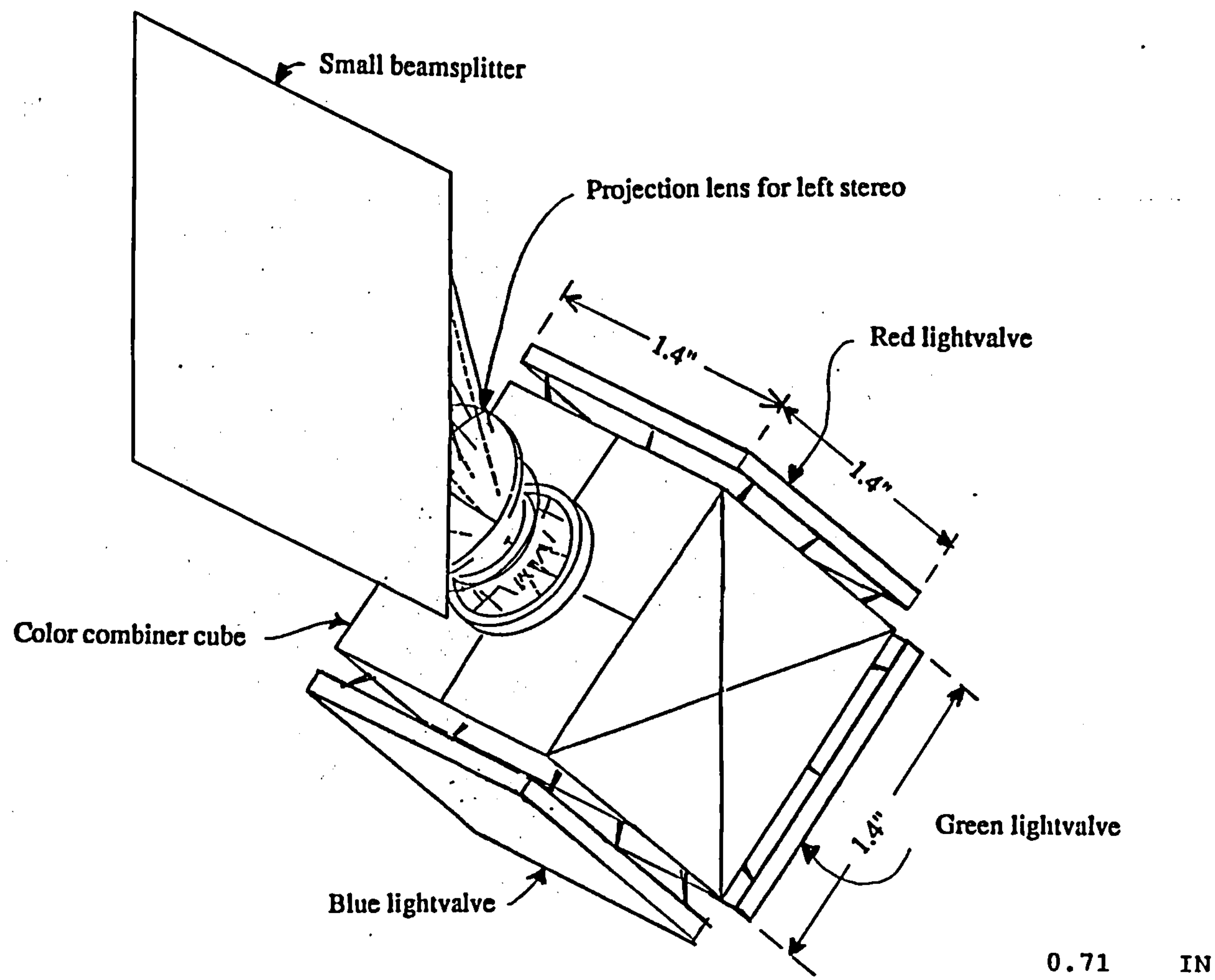


Figure 6-7. Left Stereo Color Projection Lens Assembly.

6.2.3.3 Stereoscopic Selection Method. Stereoscopic capability in the prototype display will be provided by a dual-channel time-multiplexing method. Optical shutters will be located in each of the two projection paths, and will be synchronized such that only one projector is selected (only one projector shutter is open) at any given time. The projector selection will be alternated at a frequency sufficient to eliminate perceived flicker in the displayed image, nominally with a stereo frame rate of 60 Hz and in synchronization with the video frame rate.

The shuttering mechanism will variable retarders (pi-cells) and polarizers to achieve rapid and reliable switching. The elements will be incorporated into the projection optics as depicted in Figure 6-8. Polarizers and retarders, including a variable retarder following the polarizing beamsplitter, will be included and oriented as necessary to maximize throughput efficiency from the polarized light valves and to minimize stereo crosstalk.

Stereo eyewear will be provided and required to ensure delivery of the correct stereo view to each eye. The eyewear (e.g. CrystalEyes®) will include optical shutter mechanisms which will be synchronized with the corresponding shutters in the image projectors.

Luminance balance between the two channels will be adjusted via the relative duty cycles of the corresponding shutters. As a user selectable option, single channel operation (nonstereo, right or left) will be enabled by opening the appropriate projector shutter and closing the other. In this latter case, the eyewear shutters will continue to alternate (to keep luminance constant) but could be removed altogether.

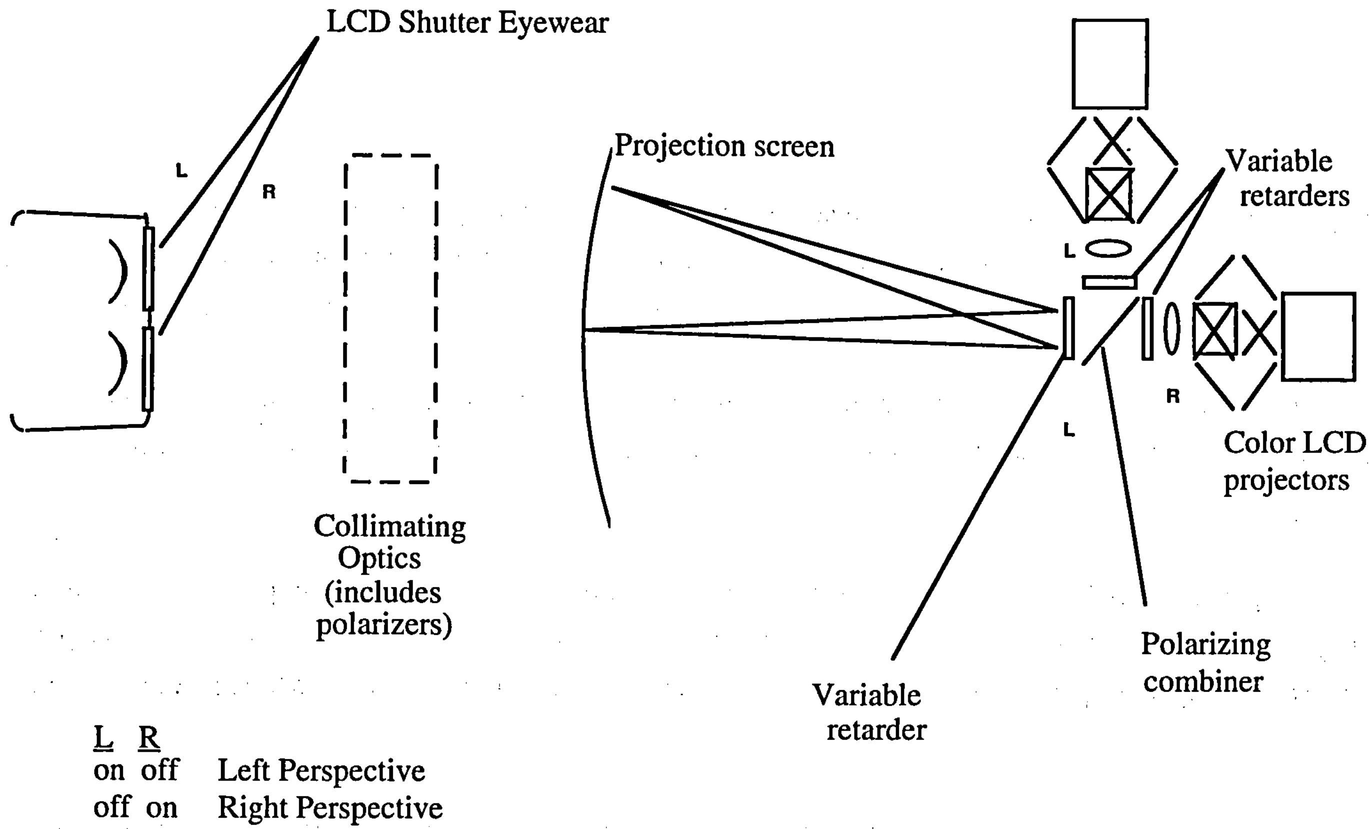
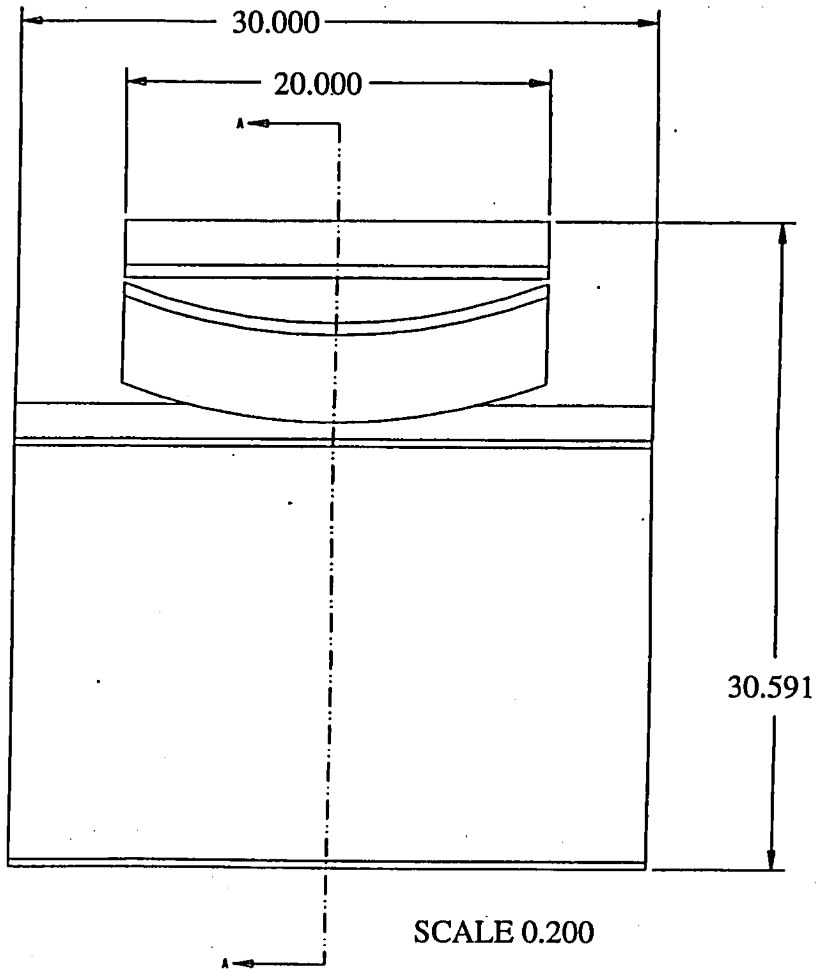


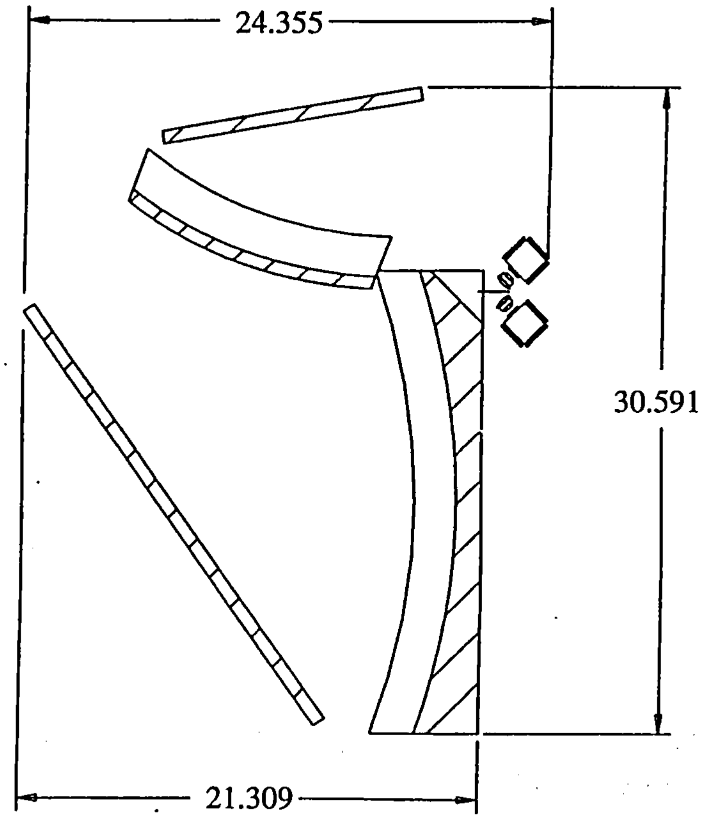
Figure 6-8. Stereoscopic Selection Method (Dual Channel Time-Multiplexed).

6.2.4 Packaging/Hardware

The components for the display will be individually designed, specified, and procured from outside vendors. A support structure will be designed and fabricated at HTC with appropriate adjustments for accurate assembly and alignment. The structure will accurately maintain alignment and acceptable performance over the expected environmental ranges specified. The structure will also be modular to facilitate illumination lamp replacement and will be easily adaptable to the expected higher resolution light valves and corresponding new projection lens system. The overall dimensions of the complete display system are given in Figure 6-9. A three dimensional view of the major components of the full display system is given in Figure 6-10, with a solid model of components in Figure 6-11. A view of the back of the Figure 6-11 solid model is shown in Figure 6-12. A drawing of the complete enclosure is given in Figure 6-13, with a solid model of the enclosure shown in Figure 6-14.



SCALE 0.200



SECTION AA
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Figure 6-9. Display System Dimensions (inches)

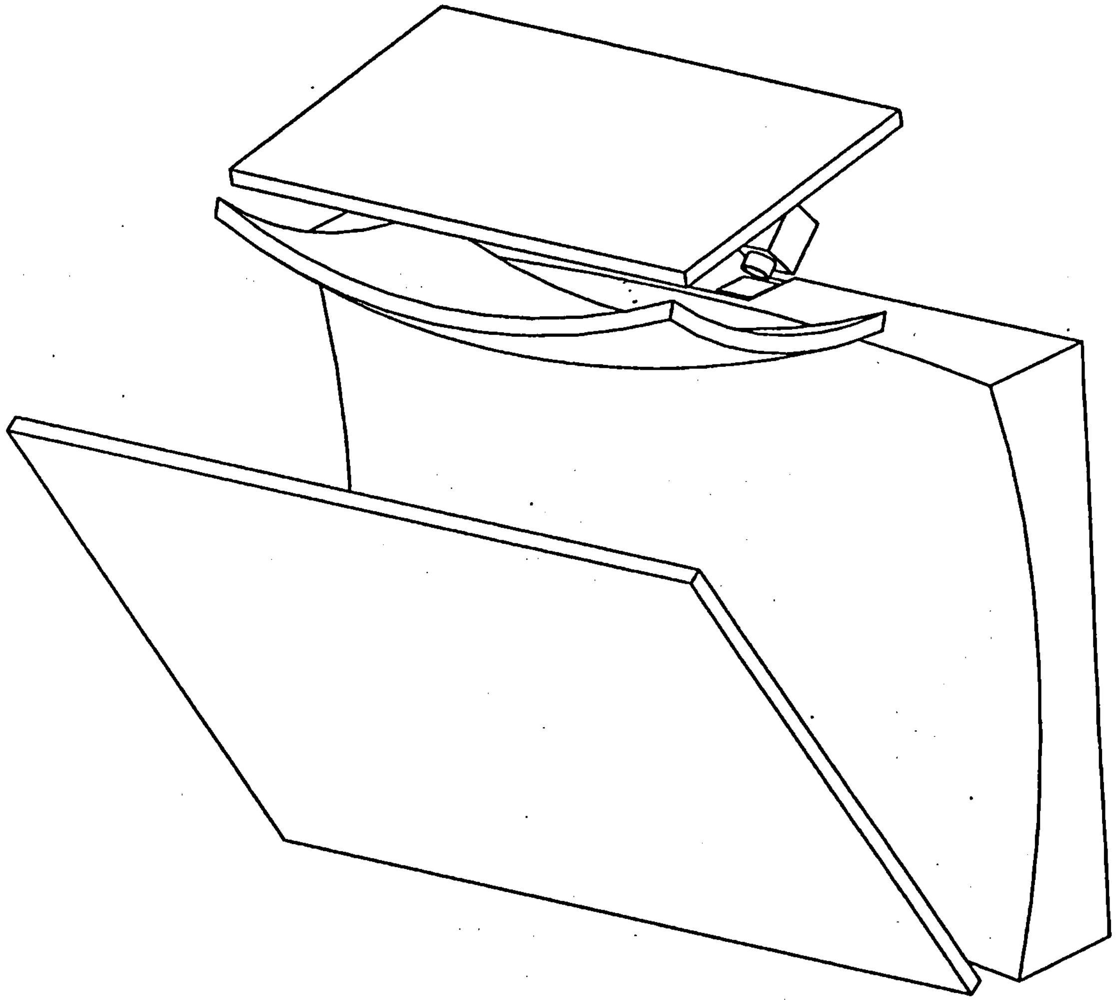


Figure 6-10. 3-D View of Major System Components.

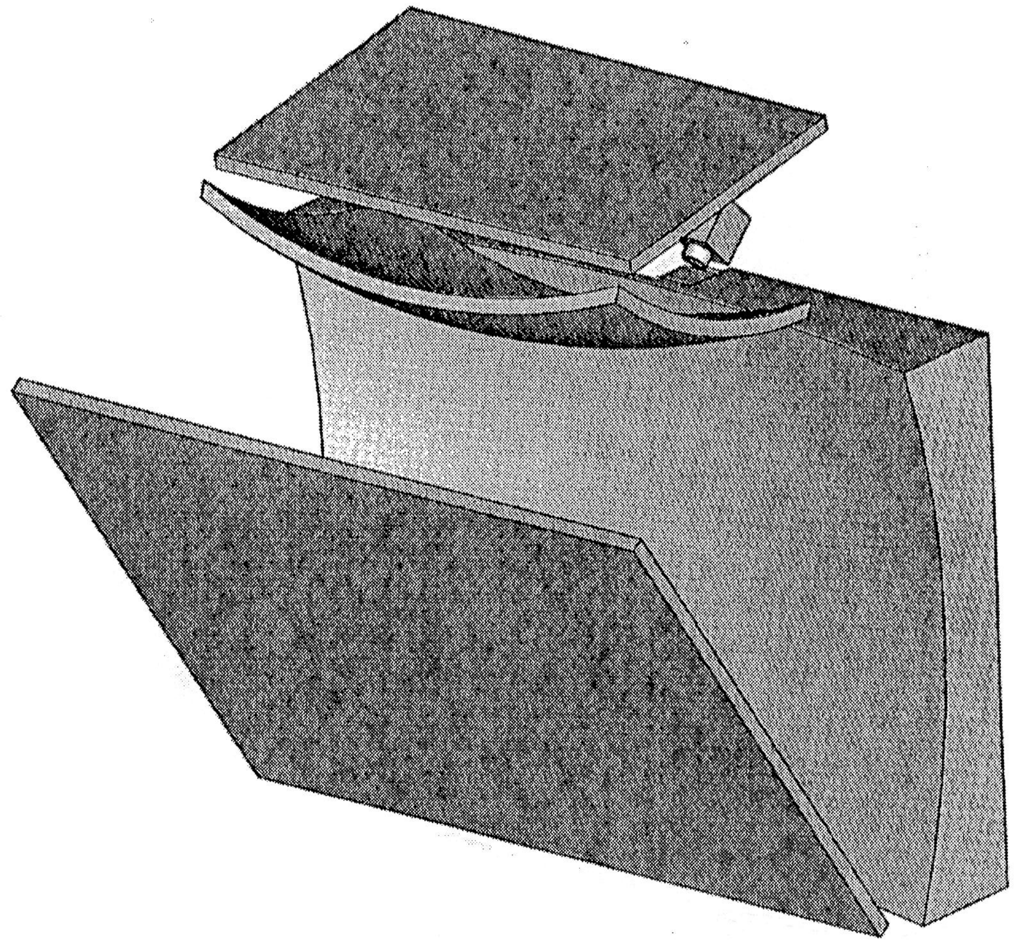


Figure 6-11. Solid Model of Major System Components.

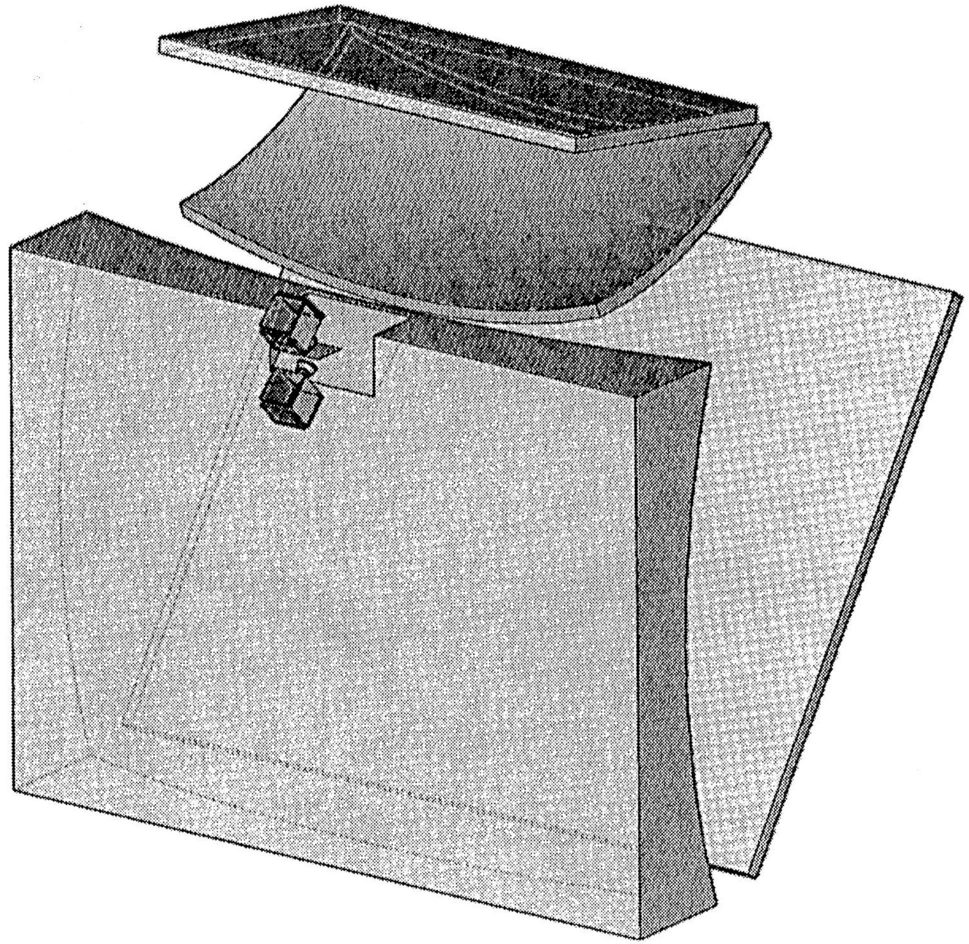


Figure 6-12. Solid Model of Major System Components (Reverse of Figure 6-11).

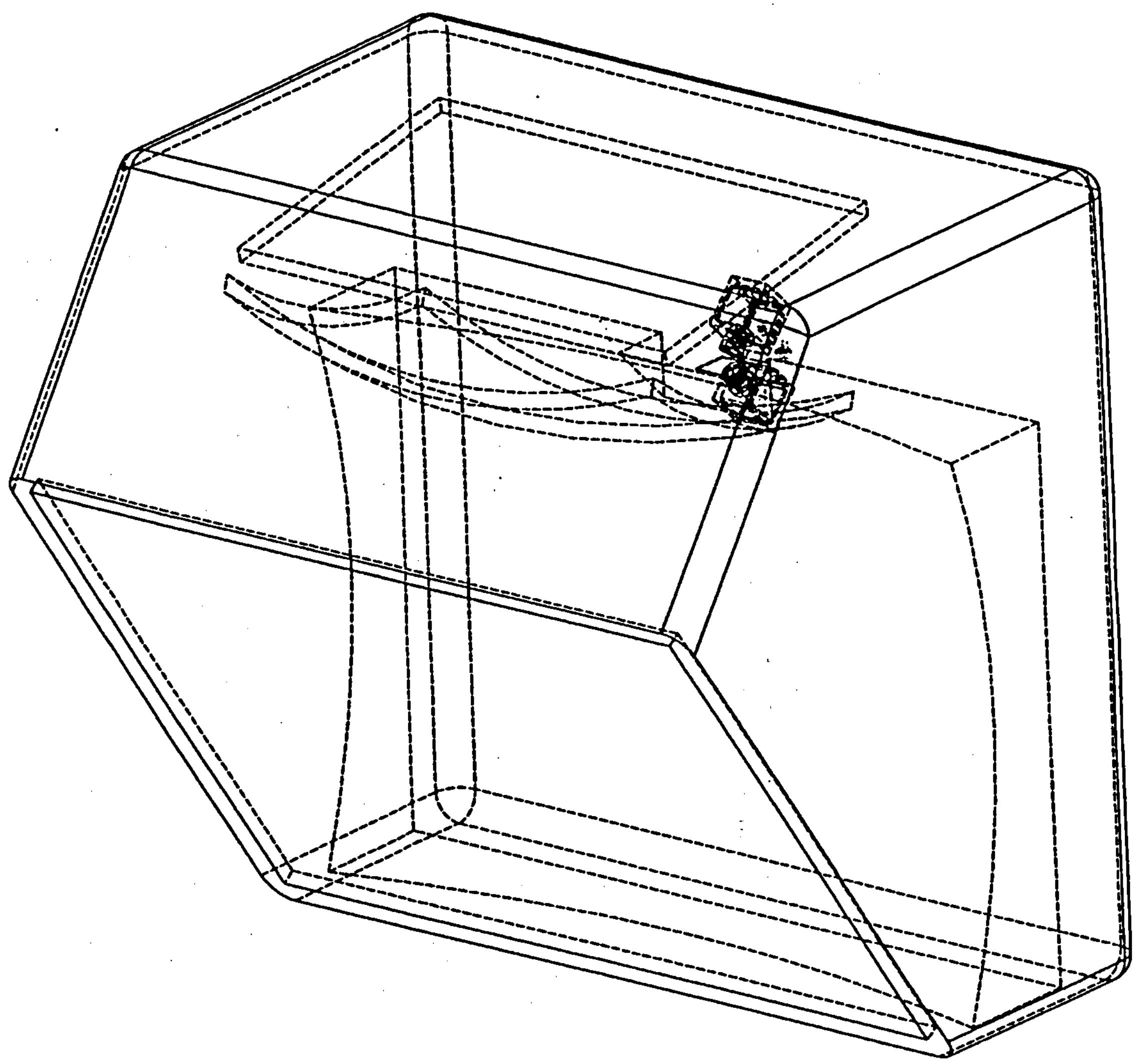


Figure 6-13. 3-D View of Complete System Enclosure.

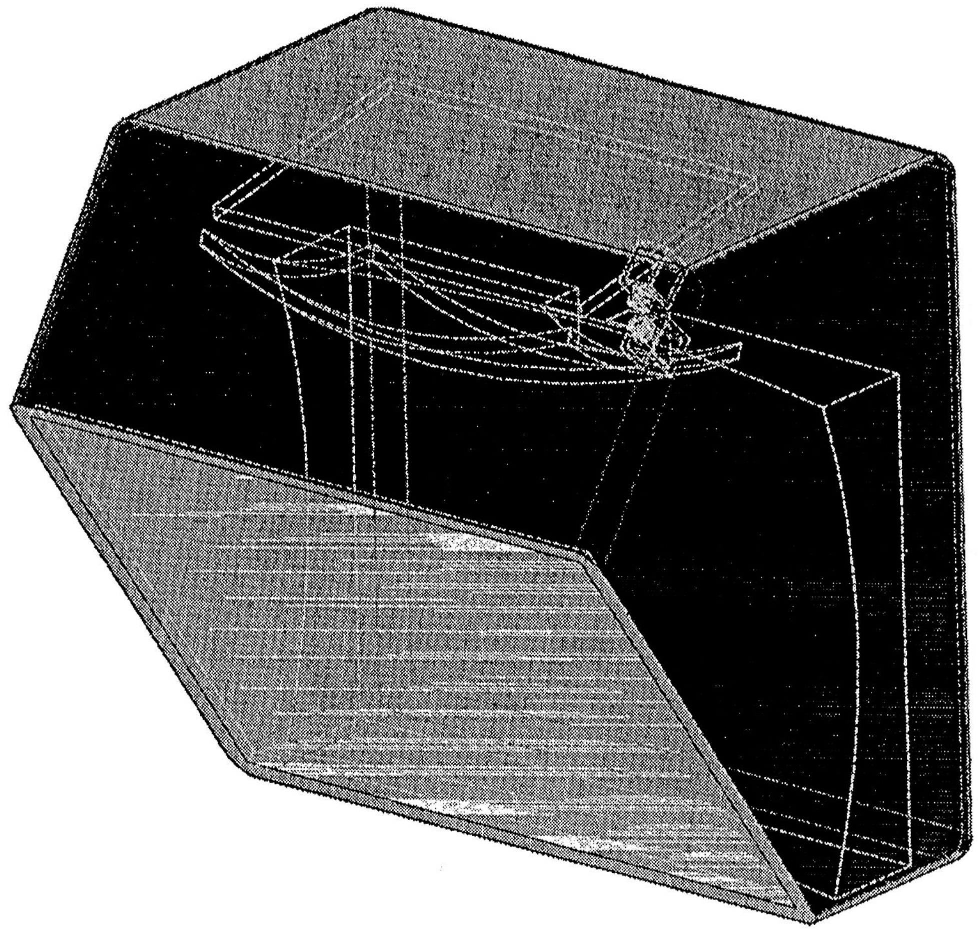


Figure 6-14. Solid Model of Complete System Enclosure.

6.2.5 Electronics/Display Software

The Panoramic, 3-D Flight Display System interface unit will convert the image signals from the image data source into a form compatible with the display system. An additional function of the interface unit will be to supply power to the display system. Figure 6-15 illustrates where the interface will fit into the signal stream from the image data source (Silicon Graphics), while Figure 6-16 is a block diagram of the interface unit itself.

The power of the interface is expected to be under twenty watts. The size of the interface is expected to be in the 3 x 6 x 8 inch range. Only one card comprising analog and digital circuitry is expected to be required, based on prior designs used to drive 640 x 480 flat panel displays; these were one quarter the size of the present application. In addition to this card, a COTS power supply and power signal conditioner will be required. The signal conditioner will be that which Honeywell used to drive the 640 x 480 flat panel displays from the same vendor. The output of the image data source, the Silicon Graphics, is an RS-343 compatible signal that results in an active imaging area of 1280 x 1024 pixels.

Given the modest size and power requirements, and the "plug-it-in-the-video-stream" nature of the recommended interface, the interface unit is expected to be easy to use, unobtrusive and convenient.

Additional details regarding the electronics interface design are presented in Appendix B.

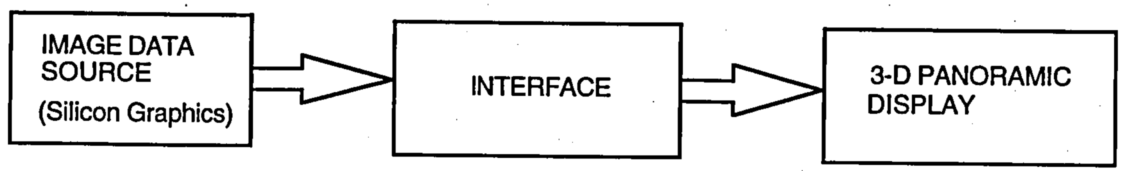


Figure 6-15. Relationship of Interface Unit to Image Data Source and Display.

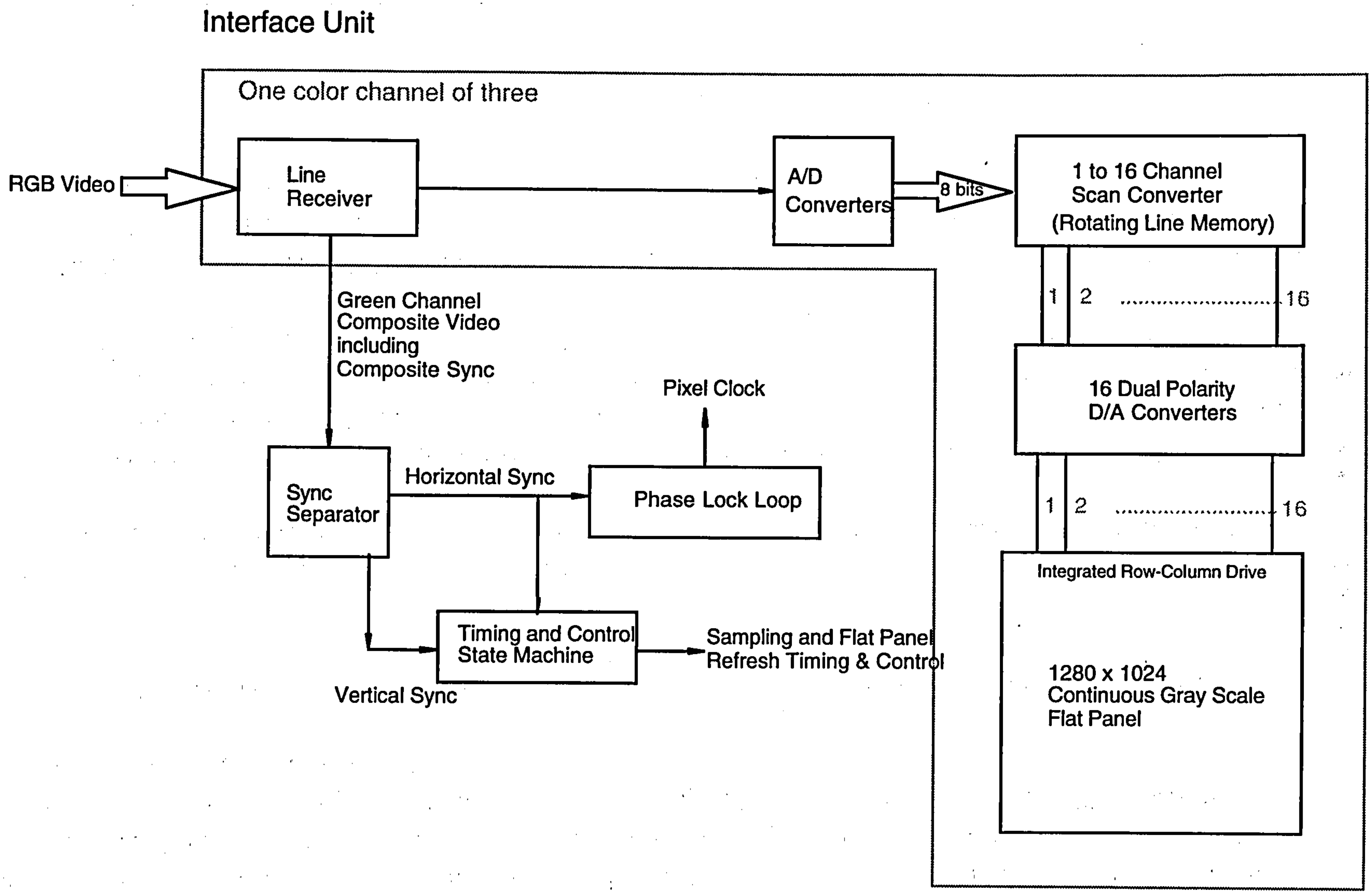


Figure 6-16. Block diagram of the Panoramic, 3-D Flight Display System Interface Unit

6.2.6 Interaction Method

The baseline interaction device will be a modified Boeing 777 CCD (Figure 6-17) and is described in more detail in Section 3.4.1. The touch pad will be mounted in a raised, angled housing to provide wrist support. The touchpad will be capacitive, consisting of a non-reflective conductive coating with an active area of 2.5 x 2.5 inches (excluding the rounded corner areas). The resolution of the touchpad will be 882 x 882 resolvable touch points. The modified CCD will require 28 volt DC power. All buttons will be dual-position switches. The thumb switch is not shown in Figure 6-17.

The Boeing 777 CCD will require some engineering modifications for interface with the Panoramic, 3-D Flight Display System as described below:

- The ARINC 429 interface, standard in the design of the Boeing 777 CCD, is incompatible with the Silicon Graphic RS-232 input device port. Honeywell has included conversion of the CCD to an RS-232 interface in the ROM development cost.

- The Boeing 777 currently expects (requires) interface with software resident in the Boeing 777 AIMS cabinet for some of the advanced CCD functionality. Such functions include absolute positioning mode, "hot corners," variable cursor gain, and actuation of annunciator lights. Honeywell has included development of CCD driver software in the ROM development cost, but the software driver will not include advanced CCD functionality.

- The Boeing 777 CCD is a 2 DOF control device, currently used in a nonstereoscopic application. Honeywell has made no plans for adding a third DOF to the CCD, or integrating a 1 DOF device with the CCD. However, Honeywell will develop a standard 2 DOF software driver with hooks suitable for DOF mode control via buttons.

- The Boeing 777 CCD currently interfaces with a single data stream, while the Panoramic, 3-D Display System requires two (stereo) data streams. Reconciliation of the CCD signal with two data streams for stereoscopic cursor control is not currently within the scope of this development plan.

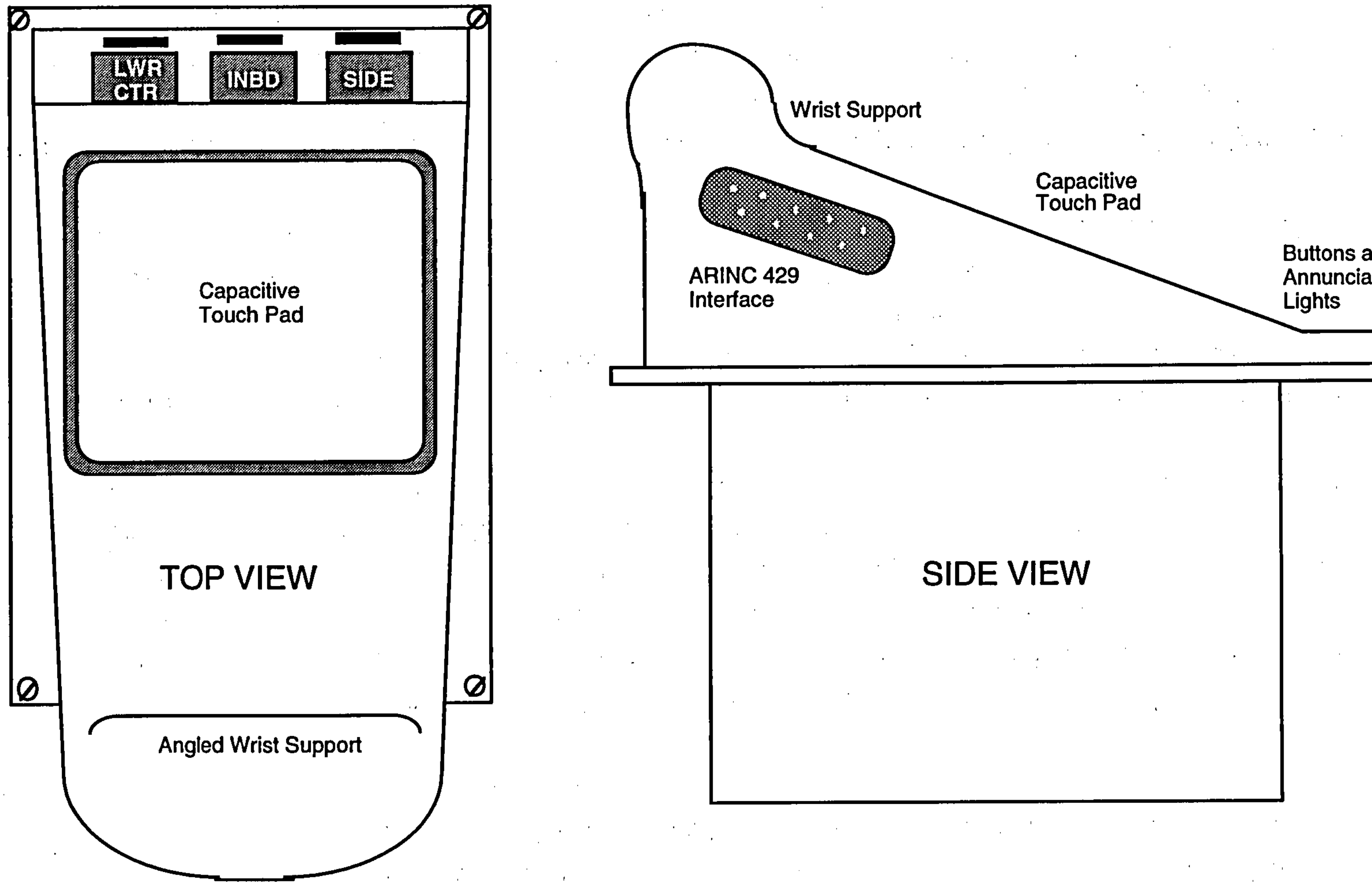


Figure 6-17. Sketch of Capacitive Touch Pad Cursor Control Device (not to scale) (Side thumb switch not shown)

6.2.7 Risk Assessment/Reductions

The display configuration and approach described in this development plan have been carefully selected to minimize the risk in delivering a timely and highly functional panoramic display for upcoming NASA research activities. In the area identified to have the highest uncertainty, namely the availability of light valves having 1920 x 1080 elements or more, an interim solution has been selected, along with recommendation of a straightforward upgrade path.

Despite the trades and selections that have been made, however, a development program of this nature still involves an element of risk. This development plan includes a provision for assessing and anticipating issues which may arise, concurrently with the design and subsequent program phases. Remaining issues associated with meeting the specification will be considered, as will opportunities which arise for improving performance further. In addition to the currently presented program, these opportunities may be quite relevant to the outlook for implementation of display technology such as this in actual cockpit applications. Examples of such opportunities include: reduction of size, weight or cost; performance improvement (e.g. luminance or resolution); and improved user acceptance.

One example of a risk/opportunity area to be assessed is the image source and its potential impact on luminance performance. While the risk in procuring the indicated 1280 by 1024 AMLCD panels is low, the plan to use polysilicon as the pixel electrode material presents a likely constraint on the panel efficiency. A similar constraint results if the desired aperture ratio is not provided. There are potential opportunities to be explored further wherein high aperture ITO pixel electrodes may be used, either as an extension of ARPA-funded activities to develop an enhanced pixel process compatible with the Kopin light valve approach, or from alternate vendor sources.

Another area to be considered relates to the large optical elements. Large optical systems can become prohibitively heavy if normal thickness to diameter ratios for smaller components are simply scaled up. Additionally, although the display system is large, the pupil of the human eye is small, so some compromises in optical component performance can be allowed. This means thinner optical components may have acceptable performance, or alternate materials might be used. To pursue this opportunity for lighter weight and high performance, light-weight/low-cost versions or samples of the largest optical elements will be specified, procured, fabricated and evaluated for system performance impact. Performing these tasks as a concurrent risk reduction activity will allow the core program activities to proceed in the most timely manner while still maximizing the opportunity for delivering high performance in both this and subsequent efforts.

6.3 Phase II- Fabrication and Assembly

This section of the development plan describes the plans for fabrication and testing of system components and subassemblies. The following major program elements are addressed:

- Component Procurement
- Component and Subassembly Fabrication
- Component and Subassembly Testing

6.3.1 Component Procurement

In developing the ROM cost estimate reported in this development plan, Honeywell contacted vendors for estimates of component availability. The estimated delivery times and vendors for major system components are included in Table 6-1. The table entries are given in descending order of estimated delivery time. Note that multiple vendors are listed for some components. Prints to specify optical components were sent to vendors with the requests for quotes. These prints are included in Appendix A.

6.3.2 Component and Subassembly Fabrication

Most system components (see Table 6-1) will be fabricated by vendors and supplied to Honeywell. Two exceptions will be the electronic interface and the CCD interaction device, which will be fabricated at Honeywell. Honeywell will also fabricate the housing and support structure for the display system and will integrate system components into subassemblies (e.g., projection optics subassembly).

Table 6-1. Vendors and estimated delivery times for display system components.

Component	Estimated Delivery Time (weeks)	Vendor
Projection Screen	18-30	Max Levy
Collimating Mirror (aspheric)	25	ERG
Collimating Mirror (aspheric)	25	HEXTEK
50/50 Beamsplitter	16	HEXTEK
Metal Halide Lamp & Supply	12-16	ILC Technology
Fold Mirror	12	Precision Optical
1280 x 1024 AMLCD	10-12	Kopin Corp.
Projection Lenses	8-12	Kreischer Optics
Dichroic Color Combiner Cube	8-12	CVI Laser
50/50 Beamsplitter	8-10	CVI Laser
Variable Retarder (pi-cell)	8-10	Planar Advance
Stereoscopic Eyewear	6-8	Stereographics Corp.
50/50 Beamsplitter	2-4	Denton
1" Polarization B.S. Prism	2-4	Newport
3" x 3" Folding Mirrors	2-4	Melles Griot
AC500 Blue Additive Filters	2-4	CVI Laser
AC600 Red Additive Filters	2-4	CVI Laser

6.3.3 Component and Subassembly Testing

Honeywell will verify component and subassembly performance where necessary. For example, prior to fabrication/assembly of the image source, each monochrome AMLCD panel received from Kopin will be tested optically with an ILC metal halide lamp for luminance efficiency, contrast and contrast uniformity. In addition, each AMLCD panel will be inspected for overall optical quality and flex interconnect integrity.

System components will be procured with copies of test verification data supplied by the vendors where available. Additionally, acceptance testing will be performed at Honeywell for some components. Examples of collimator components/subassemblies performance tests Honeywell will consider are described in Table 6-2.

The projection subassembly has many more components than the collimation subassembly and is likely to require more iterative testing prior to final assembly. The projection lens tests will be performed separate from the rest of the subassembly. Each color cube and light valve subassembly will also be individually tested. The projection lenses will then be tested when assembled with the light valves for alignment of the multicolor images. Assembly with the fold mirror and projection screen will be completed prior to system testing. Examples of projection components/subassemblies performance tests Honeywell will consider are described in Table 6-3.

The illumination subassembly will also be assembled separately to independently verify its performance. Examples of illumination components/subassemblies performance tests to be considered are described in Table 6-4.

The results of Honeywell-conducted testing of components and subassemblies, as well as vendor-supplied performance data, will be supplied to NASA with the monthly program reports.

Table 6-2. Example performance tests for collimation components/subassemblies

Collimation Component/Subassembly	Performance Tests Considered
Beamsplitter	• Transmission @45 deg S vs P polarization • Polarization components effect on transmission and reflection • Flatness in reflection @45 deg • Uniformity in transmission • Deformation with 45 deg support structure and gravity stresses • Vibration effects
Concave Aspheric Mirror	• Reflection, surface figure, roughness
Projection Screen	• Transmission, dispersion angles, field lens effects • Image surface figure • Thickness uniformity • Support structure/gravity stress effects • Polarization changing effects
Collimation Subassembly	• Head motion box • Head relief • Vignetting • Transmission • FOV • Optical distortion • Field curvature and astigmation • Resolution • Binocular tests

Table 6-3. Example performance tests for projection components/subassemblies

Projection Component/Subassembly	Performance Tests Considered
Light Valves	• Resolution • Coalignment ability • Luminance efficiency and uniformity • Contrast and contrast uniformity
Color Cube Prism	• Transmission for each color • Relative illumination between colors
Color Filters	• Spectral transmission
Projection Lens	• Resolution with individual color back focal distances
Top Fold Mirror	• Reflection S vs P polarization • Flatness • Deformation with support/gravity stress • Vibration effects
Polarization Combiner Prism	• Surface figures • Flatness • Thickness uniformity
Projection Subassembly	• Resolution • Transmission • Color image fusion ability • Stability with thermal and vibration stresses • Polarization testing • Optical distortion match to collimator distortion, FOV, field curvature and astigmatism

Table 6-4. Example performance tests for illumination components/subassemblies

Projection Component/Subassembly	Performance Tests Considered
Arc Lamp Collimation Optics	• Collimation • Thermal effects • Light source replacement
Color Beamsplitter Cube	• Transmission for each color • Relative illumination between colors
Color Filters	• Spectral transmission
Fold Mirror	• Reflections

6.4 Phase III- System Integration

6.4.1 Component and Subassembly Integration

Following the fabrication and testing of display system components and subassemblies, Honeywell will integrate all remaining components and subassemblies into the deliverable display system configuration. Subsequent to system-level acceptance testing, partial system disassembly may be required to safely ship the display system to NASA. Should this be necessary, Honeywell will support reassembly of the system at NASA. Honeywell will also provide to NASA documentation of maintenance and operations procedures for the completed display system.

6.4.2 System Testing and Acceptance Criteria

Honeywell will conduct acceptance testing of the assembled display system at a Honeywell location. NASA will be invited to participate in the acceptance testing at Honeywell. Acceptance testing will be directed toward providing evidence that the display system fully meets the requirements given in the display specification (Section 5). However, attention will also be paid to global issues concerning image quality and general system performance which might not otherwise be captured in the display specification. Acceptance of the display system by NASA will be given by NASA acceptance of Honeywell test results, which either fully meet the display system specifications, or meet the display system specifications with NASA-approved deviations. The results of Honeywell-conducted system acceptance testing will be supplied to NASA at the completion of the program. Honeywell will also provide NASA with descriptions of the test procedures used in the acceptance testing.

Appendix A- SUPPLEMENTARY OPTICAL DRAWINGS

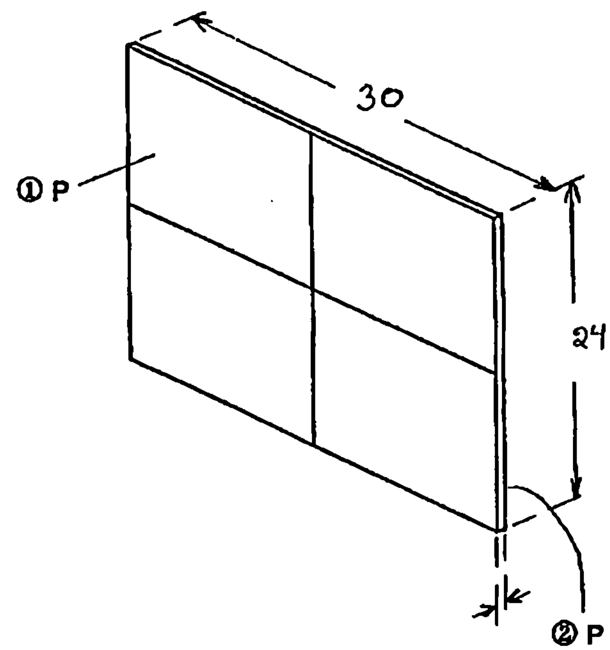
Following are twelve optical drawings supplemental to the development plan presented in Section 6. These drawings were sent to optical component vendors when requesting quotes.

	RADIUS	RAD TOL	POW/IRR	CA
S1	INF	TPF	4 / 2	23 X 26
S2	INF	TPF	4 / 2	23 X 26

EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
24 X 30	± 0.10	0.6000	±0.01	1 ARC MIN

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: BK7 SCHOTT NO. 517642
   N_d 1.5168 ± 0.001 V 64.2 ± 0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED PER 1.0 INCH OVER THE FULL CLEAR APERTURE
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 45° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. SURFACE MARKED ② PARTIAL REFLECTIVE COATING PER MILL-C-4849A FOR REFLECTION ≥ 50% AND TRANSMISSION ≥ 50% (R/T RATIO : ± 5%) AT 45° INCIDENCE AND OVER THE 440 TO 620 MILLIMICRON WAVELENGTHS.



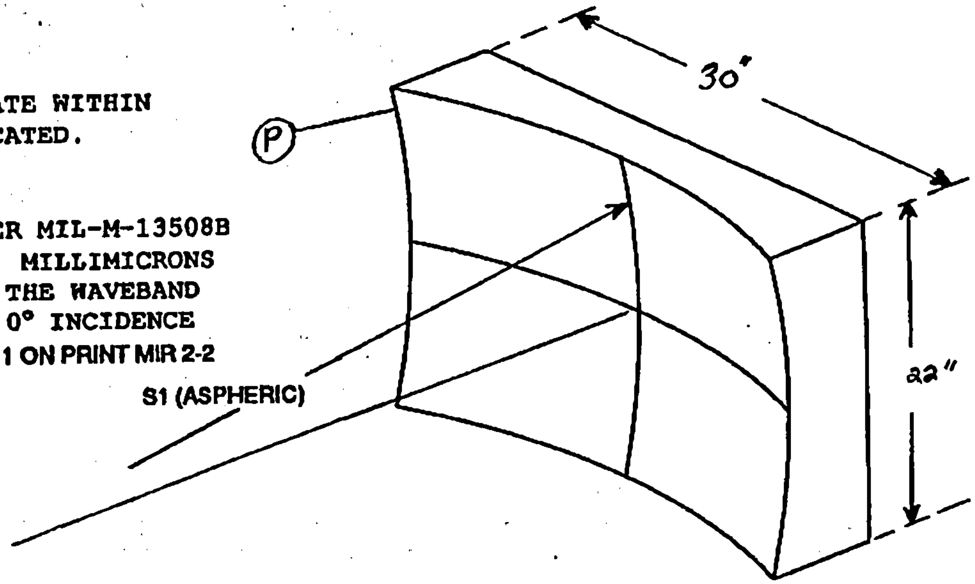
	DR		
	CHK		
	APPD		
PLATE BEAMSPLITTER	SCALE	REL BY	REL DATE
ELEMENT 1	—		

MIR 1 — 2

	RADIUS	RAD TOL	POW/IRR	C.A.	EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
S1	46.0000CC ❽		12 / 3.0	21. X 29	22. X 30	±0.10	3.0000	+0.1000	

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL:ALUMINUM, DUOCEL, ALUMINUM COMPOSITE
   TYPE: NO.
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40
6. 'C' ALUMINUM FILM COATING PER MIL-M-13508B FOR MAX REFLECTION AT 540 MILLIMICRONS WITH REFLECTION > 90 % OVER THE WAVEBAND 440 TO 620 MILLIMICRONS AND 0° INCIDENCE
7. SURFACE SAG TABLE IS GIVEN IN TABLE 1 ON PRINT MIR 2-2
8. SLOPE ACCURACY ± 500 MICRORADIANS



DR	
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APPD	
SCALE	REL BY	REL DATE

ELEMENT 1

—

TABLE 1

MIR 2 – 2

ASPHERIC CONSTANTS

$$Z = \frac{(CURV)Y^{2}}{1 + (1-(1+K)(CURV)^{2}Y^{2})^{1/2}} + (A)Y^{4} + (B)Y^{6} + (C)Y^{8} + (D)Y^{10}$$

ASPHERIC	CURV	K	A	B	C	D
A(1)	-0.02173913	1.634204	0.165714E-05	0.702525E-08	-0.131521E-10	0.158802E-13

CURVATURE OF BASE SPHERE = -0.021739
RADIUS OF BASE SPHERE = -46.000

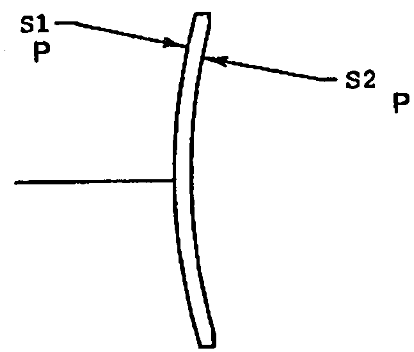
Y	ASPH SAG (Z)	SPHERE SAG	SAG DIFFERENCE
0.000000	0.000000	0.000000	0.000000
0.800000	-0.006957	-0.006957	0.000000
1.600000	-0.027837	-0.027835	0.000003
2.400000	-0.062665	-0.062651	0.000014
3.200000	-0.111480	-0.111439	0.000041
4.000000	-0.174336	-0.174243	0.000093
4.800000	-0.251295	-0.251120	0.000175
5.600000	-0.342429	-0.342142	0.000287
6.400000	-0.447815	-0.447393	0.000422
7.200000	-0.567532	-0.566972	0.000560
8.000000	-0.701664	-0.700993	0.000671
8.800000	-0.850296	-0.849585	0.000711
9.600000	-1.013518	-1.012891	0.000627
10.400000	-1.191429	-1.191072	0.000356
11.200000	-1.384142	-1.384308	-0.000166
12.000000	-1.591791	-1.592793	-0.001002
12.800000	-1.814540	-1.816745	-0.002205
13.600000	-2.052590	-2.056400	-0.003810
14.400000	-2.306190	-2.312015	-0.005825
15.200000	-2.575642	-2.583874	-0.008231
16.000000	-2.861305	-2.872283	-0.010977
16.800000	-3.163595	-3.177576	-0.013981
17.600000	-3.482977	-3.500118	-0.017141
18.400000	-3.819956	-3.840304	-0.020348
19.200000	-4.175059	-4.198565	-0.023506
20.000000	-4.548818	-4.575370	-0.026552

	RADIUS		RAD TOL	POW/IRR	C.A.
S1	24.369	CX	TPF	4 / 2	19 X 11
S2	23.769	CC	TPF	4 / 2	19 X 11

EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
20 X 12	± 0.10	0.6000	± 0.01	1 ARC MIN

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: BK7 SCHOTT NO. 517642
   N_d 1.5168 ± 0.001 V 64.2+ 0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED PER INCH OVER THE FULL APERTURE.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE S2 ANTIREFLECTIVE COATED PER MIL - C- 4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND OVER 440 TO 620 MILLIMICRON WAVELENGTHS.
7. SURFACE S1 A DISPERSION SURFACE CREATED BY ETCHING, COATING, OR GRINDING TO DISPERSE THE LIGHT FROM THE S2 DIRECTION INTO A 10° CONE OF LIGHT. A REAL IMAGE WILL BE PROJECTED ONTO S1 FROM THE S2 DIRECTION.



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SCALE	REL BY	REL DATE

PROJECTION SCREEN

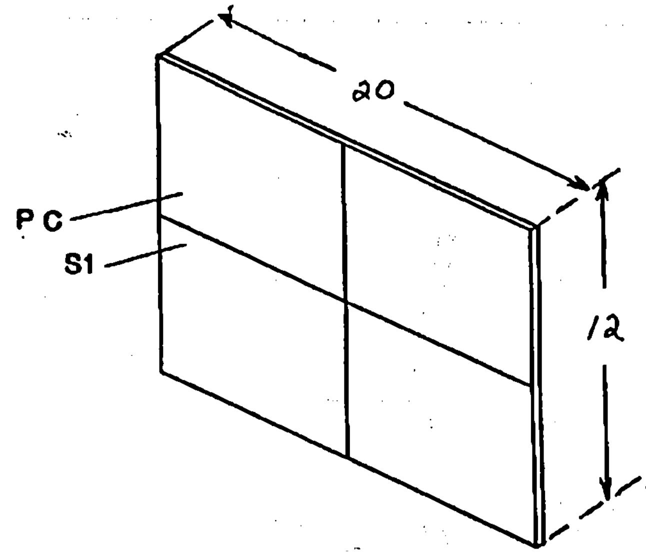
ELEMENT 3

	RADIUS	RAD TOL	POW/IRR	CA
S1	INF	TPF	4 / 2	19 X 11
			/	

EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
20 X 12	±0.10	0.6000	±0.01	

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: BK7 SCHOTT NO. 517642
   N_d 1.5168 ±0.001 V 64.2 ±0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED PER 1.0 INCH OVER THE FULL CLEAR APERTURE.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40
6. 'C' ALUMINUM FILM COATING PER MIL-C-13508B FOR MAX REFLECTION AT 540 MILLIMICRONS WITH REFLECTION > 90% OVER THE WAVEBAND 440 TO 620 MILLIMICRONS AND 35° INCIDENCE



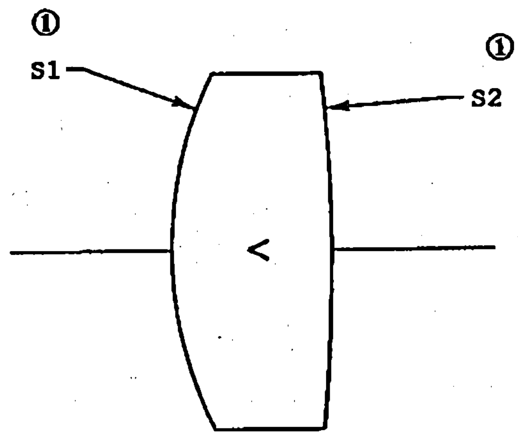
	DR		
	CHK		
	APPD		
	SCALE	REL BY	REL DATE
FRONT SURFACE FOLD MIRROR ELEMENT 1	—		

	RADIUS	RAD TOL	POW/IRR	C.A. DIA
S1	0.7063 CX	TPF	4 / 2	0.5376
S2	3.1777 CX	TPF	4 / 2	0.5523

EDGE DIA	DIA TOL	CENTRAL THICKNESS	THI TOL	WEDGE
0.6153	+0.0 −0.025	0.2734	±0.005	1 ARC MIN

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: LAKN6 SCHOTT NO. 642580
   N_d 1.6425 + 0.001 V 58.0+ 0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. MARK V TO IDENTIFY SURFACE S1
8. BEVEL EDGES AT 45 DEG TO 0.005 MAX FACE WIDTH



DR		
CHK		
APPD		
SCALE 3.63:1	REL BY	REL DATE

ELEMENT 4

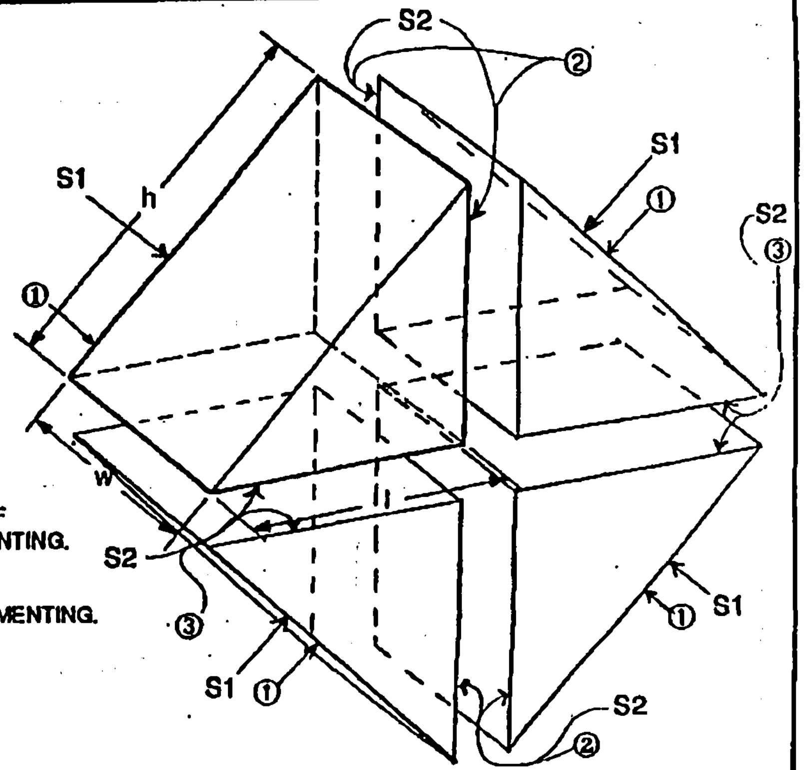
—

				1 — 2

	RADIUS	RAD TOL	POW/IRR	CA	EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
S1	INF	TPF	4 / 2	1.3 X 1.3					± 1 MIN
S2	INF	TPF	4 / 2	0.9 X 0.9					

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: BK7 SCHOTT NO. 517642
   N_d 1.5168 ±0.001 V 64.2 ±0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED..
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. SURFACE MARKED ② RED REFLECTIVE DICHROIC FILTER COATING (COLORBAND COLOR SEPARATION FILTER) FOR 45° ANGLE OF INCIDENCE PERFORMANCE AFTER FINAL PRISM ASSEMBLY AND CEMENTING.
8. SURFACE MARKED ③ BLUE REFLECTIVE DICHROIC FILTER COATING (COLORBAND COLOR SEPARATION FILTER) FOR 45° ANGLE OF INCIDENCE PERFORMANCE AFTER FINAL PRISM ASSEMBLY AND CEMENTING.
9. w = h = 1.40 ; l = 0.99
10. THE FOUR PRISMS WILL BE ASSEMBLED AND CEMENTED AS SHOWN ; THE FINAL PRISM ASSEMBLY WILL BE USED AS A COLOR COMBINING PRISM AS SHOWN IN THE SECOND PRINT (2-2)



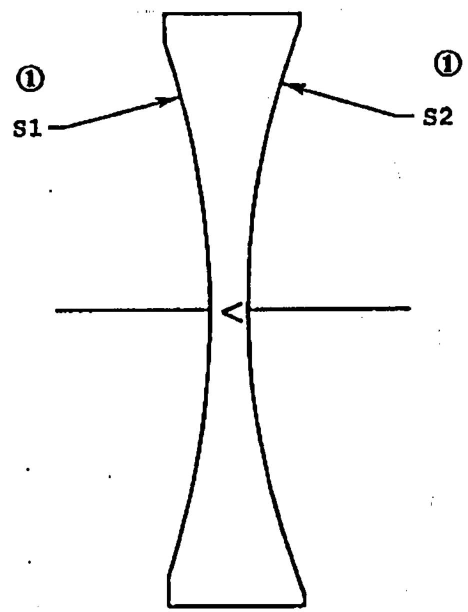
COLOR COMBINER CUBE	DR	
	CHK	
	APPD	
	SCALE / REL BY / REL DATE	
ELEMENT 1		—

	RADIUS	RAD TOL	POW/IRR	C.A. DIA
S1	0.9252 CC	TPF	4 / 2	0.54
S2	0.8709 CC	TPF	4 / 2	0.59

EDGE DIA	DIA TOL	CENTRAL THICKNESS	THI TOL	WEDGE
0.66	+0.0 −0.025	0.0420	±0.005	1 ARC MIN

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: F2 SCHOTT NO. 620364
   N_d 1.6200 + 0.001 V 36.4+0.32
   STRIAE GRADE B , ANNEAL-
   MELT NO.
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. MARK V TO IDENTIFY SURFACE S1
8. BEVEL EDGES AT 45 DEG TO 0.005 MAX FACE WIDTH
9. DIAMETER TO FLAT IS 0.055 (REF)
   WITH SURFACE SAG OF 0.0418 ON SURFACE S1
   DIAMETER TO FLAT IS 0.030 (REF)
   WITH SURFACE SAG OF 0.0533 ON SURFACE S2



DR	
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APPD	
SCALE 5.71:1	REL BY	REL DATE

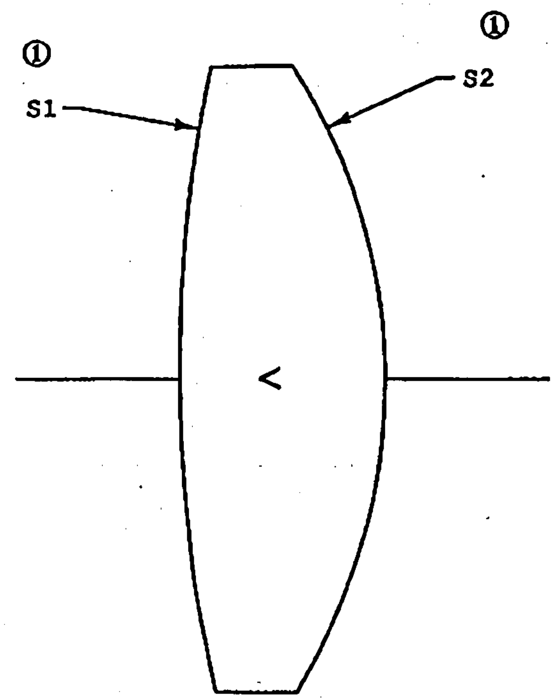
ELEMENT 5

	RADIUS	RAD TOL	POW/IRR	C.A. DIA
S1	1.7891 CX	TPF	4 / 2	0.6330
S2	0.7477 CX	TPF	4 / 2	0.7079

EDGE DIA	DIA TOL	CENTRAL THICKNESS	THI TOL	WEDGE
0.7793	+0.0 −0.025	0.2515	±0.005	1 ARC MIN

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: SK4 SCHOTT NO. 613586
   N_d 1.6127 + 0.001 V 58.6+ 0.32
   STRIAE GRADE B , ANNEAL
   MELT NO.
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. MARK V TO IDENTIFY SURFACE S1
8. BEVEL EDGES AT 45 DEG TO 0.005 MAX FACE WIDTH



DR		
CHK		
APPD		
SCALE 4.99:1	REL BY	REL DATE
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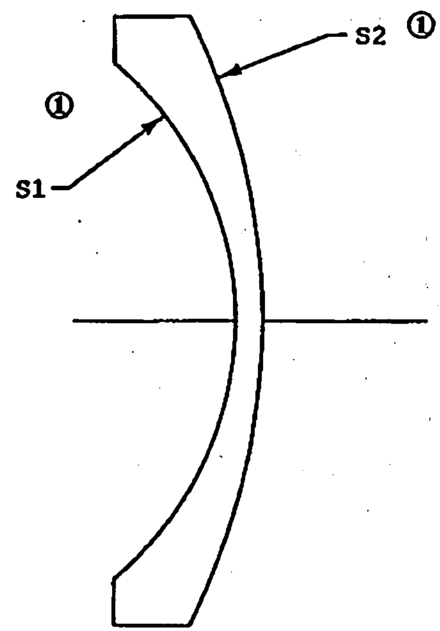
ELEMENT 6

	RADIUS	RAD TOL	POW/IRR	C.A. DIA
S1	0.5351 CC	TPF	4 / 2	0.7743
S2	1.0737 CX	TPF	4 / 2	0.8797

EDGE DIA	DIA TOL	CENTRAL THICKNESS	THI TOL	WEDGE
0.96	+0.0 -0.025	0.0420	±0.005	1 arc min

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: LAKN22 SCHOTT NO. 651559
   N_d 1.6511 ±0.001 V 55.9+0.32
   STRIAE GRADE B , ANNEAL
   MELT NO.
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED.
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40 -
6. 'C' MAGNESIUM FLUORIDE COATING PER MIL-C-675 FOR MAX TRANSMISSION AT MILLIMICRONS.
8. BEVEL EDGES AT 45 DEG TO 0.005 MAX FACE WIDTH
9. DIAMETER TO FLAT IS 0.09 (REF)
   WITH SURFACE SAG OF 0.1687 ON SURFACE S1



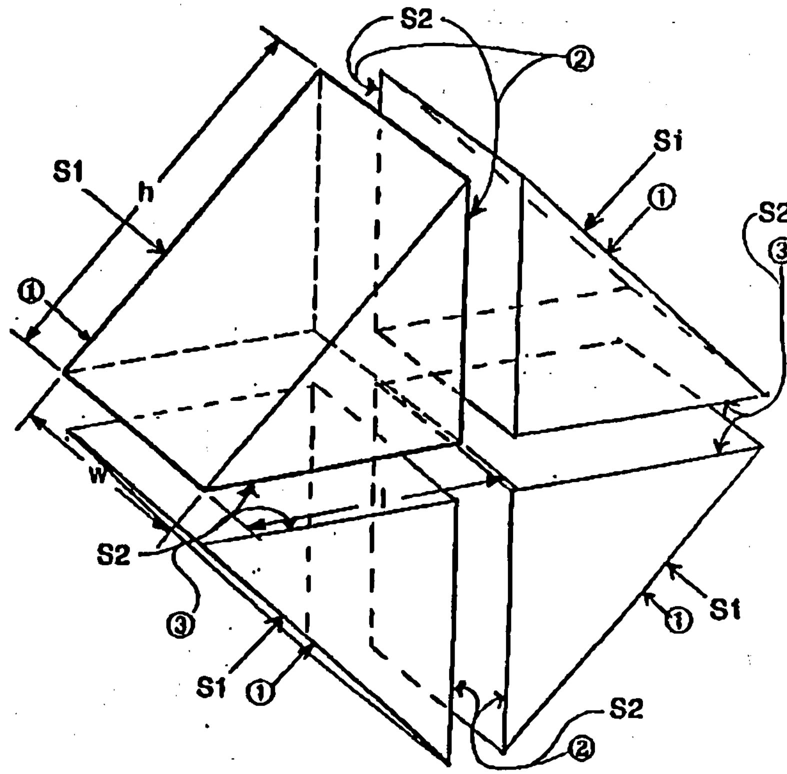
DR		
CHK		
APPD		
SCALE 3.97:1	REL BY	REL DATE

ELEMENT 7

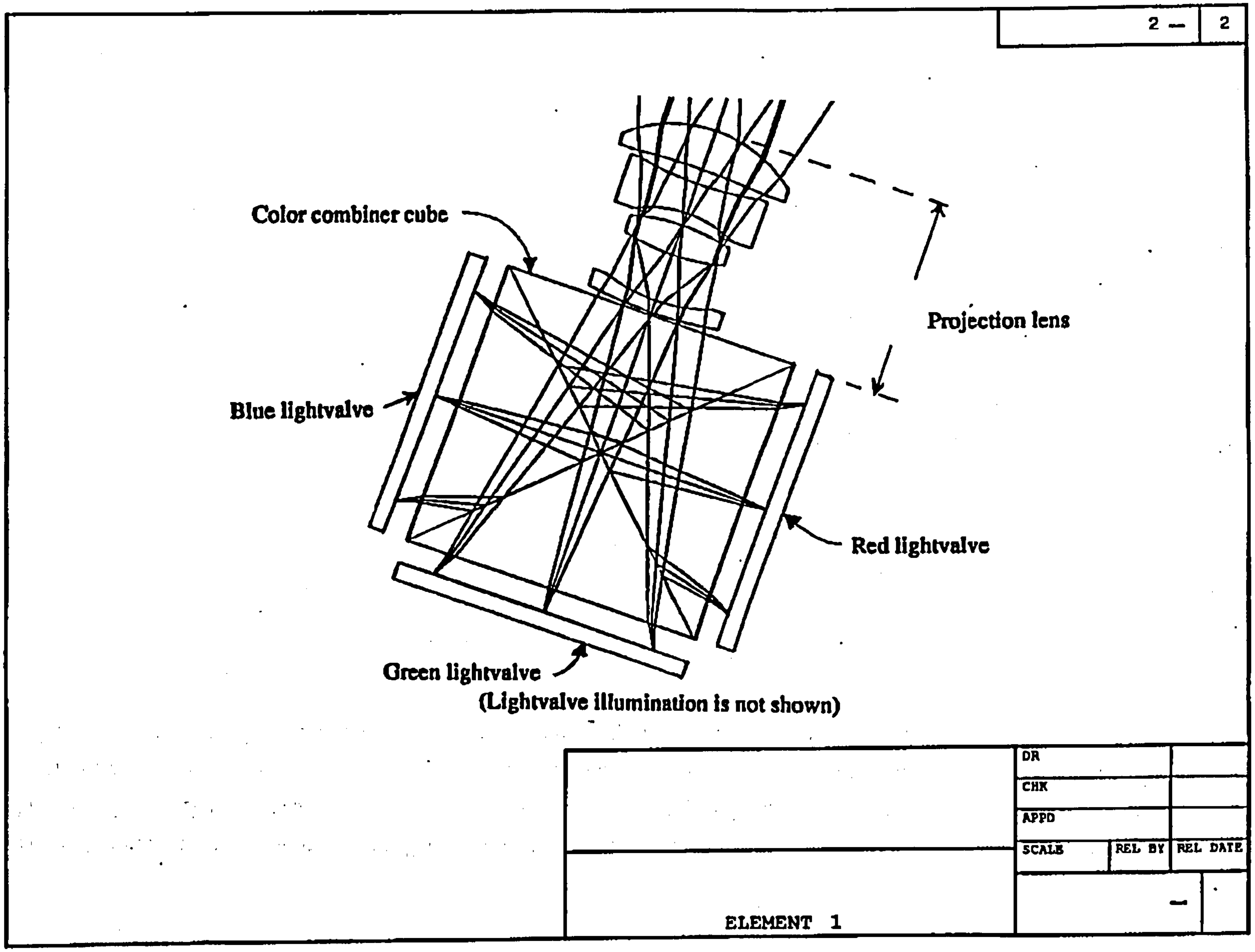
	RADIUS	RAD TOL	POW/IRR	CA	EDGE	TOL	CENTRAL THICKNESS	THI TOL	WEDGE
S1	INF	TPF	4 / 2	1.3 X 1.3					± 1 MIN
S2	INF	TPF	4 / 2	0.9 X 0.9					

NOTES :

1. ALL DIMENSIONS ARE IN INCHES.
2. MATERIAL: OPTICAL GLASS PER MIL-G-174
   TYPE: BK7 SCHOTT NO. 517642
   N_d 1.5168 ±0.001 V 64.2 ±0.32
   STRIAE GRADE B , ANNEAL
3. 'P' PITCH POLISH TO TEST PLATE WITHIN POWER AND IRREGULARITY INDICATED..
4. MANUFACTURE PER MIL-O-13830
5. SURFACE QUALITY 60/40 60/40
6. SURFACE MARKED ① ANTI REFLECTIVE COATED PER MIL-C-4849A FOR ≤ 1.0% MAX REFLECTANCE AT 0° INCIDENCE AND 440 TO 620 MILLIMICRON WAVELENGTHS
7. SURFACE MARKED ② RED REFLECTIVE DICHROIC FILTER COATING (RC-600) FOR 45° ANGLE OF INCIDENCE PERFORMANCE AFTER FINAL PRISM ASSEMBLY AND CEMENTING.
8. SURFACE MARKED ③ BLUE REFLECTIVE DICHROIC FILTER COATING (RC-500) FOR 45° ANGLE OF INCIDENCE PERFORMANCE AFTER FINAL PRISM ASSEMBLY AND CEMENTING.
9. w = h = 1.40 ; l = 0.99
10. THE FOUR PRISMS WILL BE ASSEMBLED AND CEMENTED AS SHOWN ; THE FINAL PRISM ASSEMBLY WILL BE USED AS A COLOR COMBINING PRISM AS SHOWN IN THE SECOND PRINT (2-2)



COLOR COMBINER CUBE	DR	
	CHK	
	APPD	
	SCALE	REL BY / REL DATE
ELEMENT 1		—


2 —
2
Color combiner cube
Projection lens
Blue lightvalve
Red lightvalve
Green lightvalve
(Lightvalve illumination is not shown)
DR
CHK
APPD
SCALE
REL BY
REL DATE
ELEMENT 1

Appendix B- SUPPLEMENTARY ELECTRONICS DESIGN

The output of the image data source, the Silicon Graphics, is an RS-343 compatible signal that results in an active imaging area of 1280 x 1024 pixels. Figure B-1 shows a full frame of video. The frame lasts approximately 16.66 msec as can be seen by examining the spacing between the rising edges of the two vertical synchronization pulses. Note that the sampling frequency used to obtain Figure B-1 introduced some artifacts, including the attenuation of the full depth of the horizontal synchronization pulses.

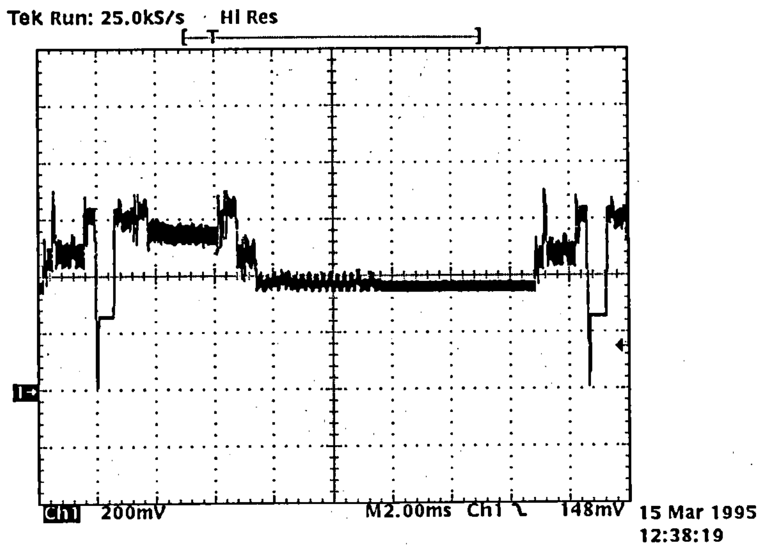


Figure B-1. Full Frame of Silicon Graphics Video

Figure B-2 is magnified about the vertical blank period. It shows that the top of the image shown on a Silicon Graphics screen occurs 35 horizontal synchronization pulses after the rising edge of the vertical synchronization pulse. This implies a strict timing alignment on the interface circuitry. The interface must ensure that the first row of active video sampled from the Silicon Graphics corresponds with the first row to be shown on each of the three AMLCDs.

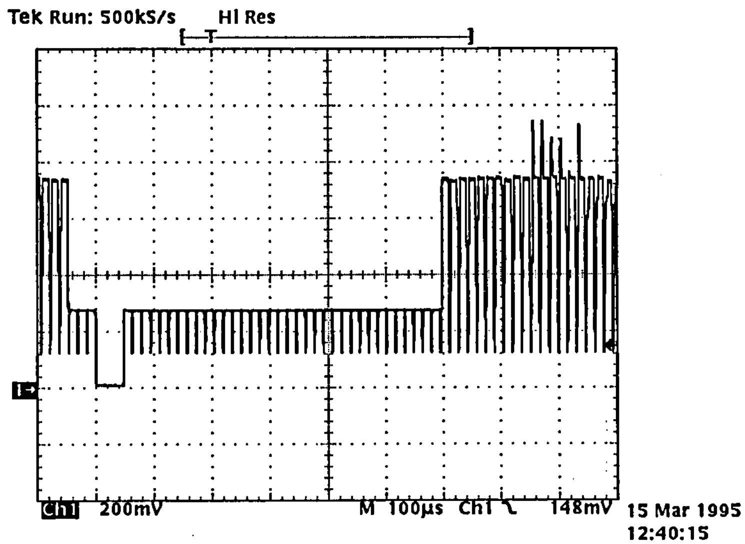


Figure B-2. Magnification About the Vertical Blank Period.

Figure B-3 details the horizontal period in the Silicon Graphics video signal. The active period and the blanking period are shown. In a manner similar to that required to vertically align the picture, the interface must time the sampling and readout of the video to the AMLCDs in such a manner that the video registers with the left and the right edges of each panel.

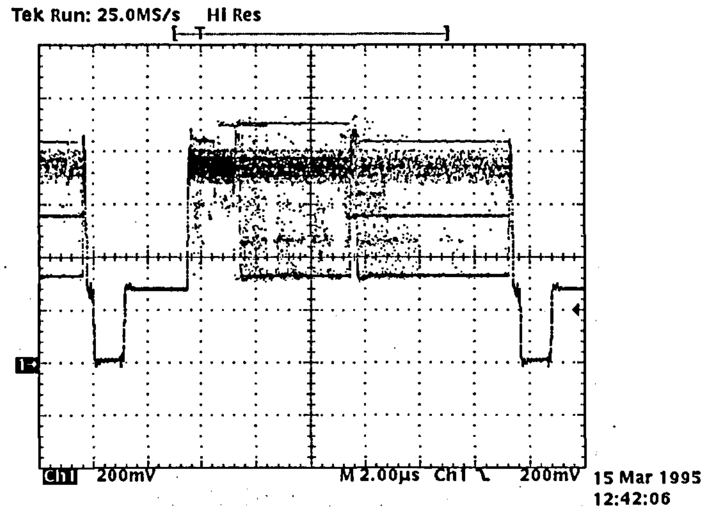


Figure B-3. Horizontal Line from the Silicon Graphics.

Figure B-4 details the start of the left edge and the right edge of the image with respect to the horizontal synchronization pulse. The timing shown was taken from a Silicon Graphics Crimson Elan located in a Honeywell laboratory. It corresponds to the timing obtained from a Silicon Graphics Indigo to within a few nanoseconds. The implication of this is that the timing from various models of the Silicon Graphics is stable and precise and may imply further that a Phase Lock Loop may not be necessary to ensure that the left- right and top-bottom edges of the video match up well with the AMLCDs. The interface system can be timed as a precise and, for the most part, open-loop system, not requiring an extensive amount of feedback. In practice, Honeywell recommends that some small amount of feedback is inserted to ensure that signals are sampled properly. This is typically difficult to do at the high speeds required, but much more easily accomplished given the precision that is evident in the Silicon Graphics output. As will be discussed in greater detail below, the interface can circumvent the need for much higher sampling frequencies because the phasing of the video information is known a priori. The left edge of the video begins 2.32 µsec after the rising edge of the horizontal synchronization pulse. The right edge of the screen begins 160 nsec before the falling edge of the horizontal synchronization pulse which also corresponds with 1.32 µsec before the rising edge of the same synchronization pulse.

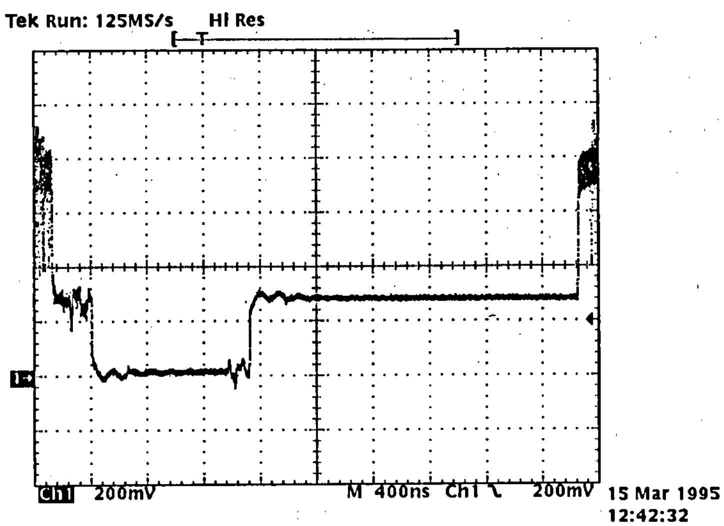


Figure B-4. Expansion about the Horizontal Blank Period of the Input Video.

Taken together, Figures B-1 to B-4 above illustrate the timing required in the state machine - controller of the interface unit to maintain the proper sizing and placement of the Silicon Graphics image within the field of each AMLCD. The four figures show the top-bottom and the right-left temporal alignment. They imply when the A/D conversion process should start and stop and where the alignment signals the AMLCDs need should be placed as well.

Input Requirements for Kopin AMLCD

Figures B-5 and B-6 below indicate the output requirements of the interface circuitry. Given the inputs specified above, the interface unit must provide signals similar to those shown below. A more exact description of the signals was not available from Kopin at the time of the writing of this report. However, the continuous gray scale integrated driver used on the 640 x 480 product is the basis for the higher resolution unit in all major respects except one: 16 channels of analog input are required versus the one channel of the lower resolution unit. This is required to ensure that the video timing signals, the driver and all the support circuitry can operate at significantly more manageable frequencies. Instead of injecting the analog video into the flat panel drive chain at 107 MHz, only 6.7 MHz is required. Thus, the input 1280 pixels must be absorbed by the interface unit and re-partitioned or scan-converted into 16 sub-segments that all get read out simultaneously and written to each flat panel column drive system. Of course, the signals must be converted from digital form to analog form first, and must be inverted with respect to the common voltage level, 8 volts, in order to prevent flicker and preclude damaging electro-plating action on the flat panel pixel electrodes.

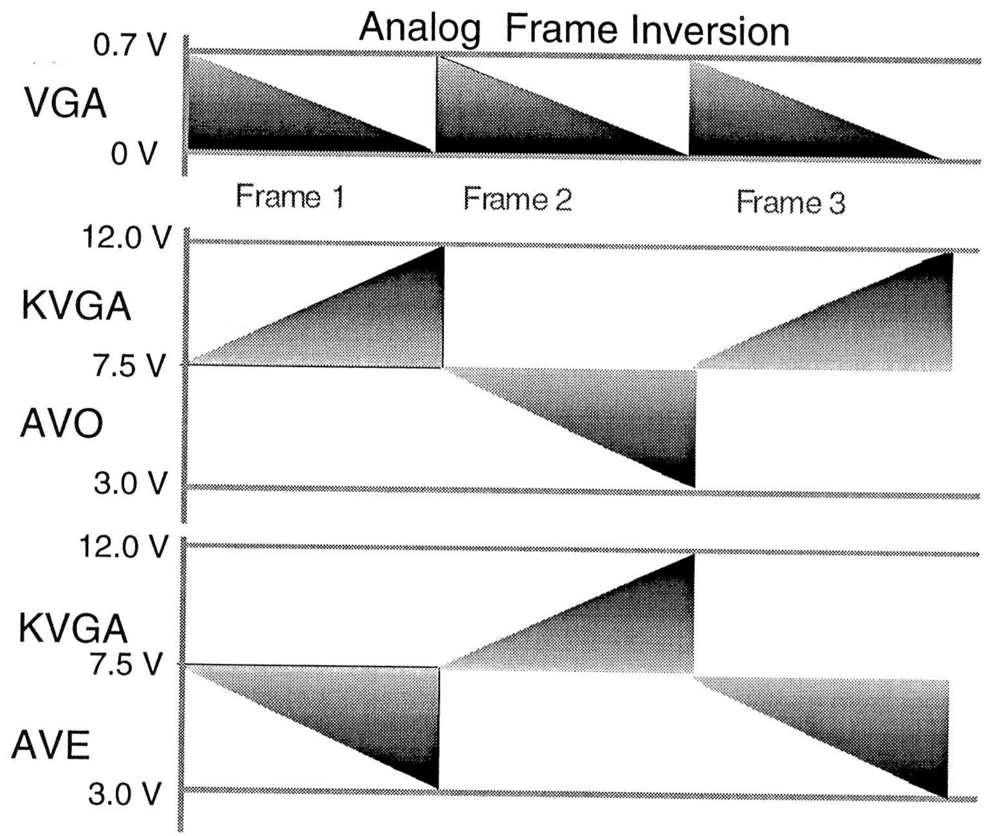
Level shifting circuitry will be included in the driver to bring the RS-343 signal levels through the A/D and the D/A processes to conform with the detailed signal requirements of the panels. Gamma correction will be assumed to take place in the Silicon Graphics, where gamma correction functions are already included. This, of course, assumes that the image seen at the Silicon Graphics is not necessarily of optimal quality when shown simultaneously on the display system.

As an option, Honeywell can insert gamma correction capability directly into the interface unit. But this would entail additional expense. A gray shade look-up-table (LUT) would be required for each color. Additionally, a PC and PC interface (or equivalent) would be needed to load the LUT. Assuming this option is not selected and that the inherent gamma correction capability of the Silicon Graphics is used instead, Honeywell will include gamma correction tables to be loaded onto the target Silicon Graphics platform. This Silicon Graphics-LUT implementation is included in the ROM estimate.

Details of the Interface Circuitry

The 1280 x 1024 output of the Silicon Graphics is conveniently available in analog form in RS-343 RGB (red, green and blue) signal format. All three lines carry the synchronization signals (See Figures B-1 through B-6). The G (green) line is the one typically used in decoders/monitors to derive all the synchronization information. The synchronization signals are composited with the video, that is, the vertical and the horizontal timing signals are encoded together along with the RGB signals. The composited information must be separated and routed through the interface circuitry to the 3-D Panoramic Display to create the final image. The horizontal synchronization will be used not only to time the beginning and ending of each row read-out but also to establish the pixel clock. 1280 clocks are required during the 11.94 μsec active row time meaning that the analog to digital converter on each of the three RGB lines must sustain a clock period of 9.3 nsec, corresponding to a 107 MHz sampling frequency. Note that selecting this as the sampling frequency will require that the driving clock be in precise phase alignment with the Silicon Graphics image generator pixel clock, otherwise the sampling cycle could straddle two pixels resulting in a smeared version of the input image. It is required only that the sampling period fall sufficiently within the timing bin of the source pixel. Other than a one-time adjustment (tapping the correct point via a jumper in the clock generation chain), no other sampling alignment will be required.

The interface will be inserted into the analog video stream of the Silicon Graphics output. This may be effected by a T-type stub, which would appear to the user as a standard loop-through connection. The line receiver (Figure 6-16) will buffer the incoming signal and convert it from a differential signal into a single-ended signal. Immediately following that, the signal will be routed for synchronization separation and A/D conversion. Conversion to digital form as soon as possible will be required to minimize noise injection. The digital form will be required because the signal must be reformatted into 16 channels to drive the 16 integrated column drivers, embedded on each of the three AMLCDs, one for each of the primary colors.



VGA is the standard VGA analog input. Typically 3 analog signals are provided representing Red, Green and Blue. For monochrome RGB the following proportions are added:

MONO = 30% Red + 59% Green + 11% Blue

AVO & AVE show voltages applied to the panel with frame inversion to prevent flicker.

Figure B-5. Inverted Analog Waveforms Needed to Drive the 640 x 480 Continuous Gray Scale LCD (precursor to the 1280 x 1024).

Timing Charts

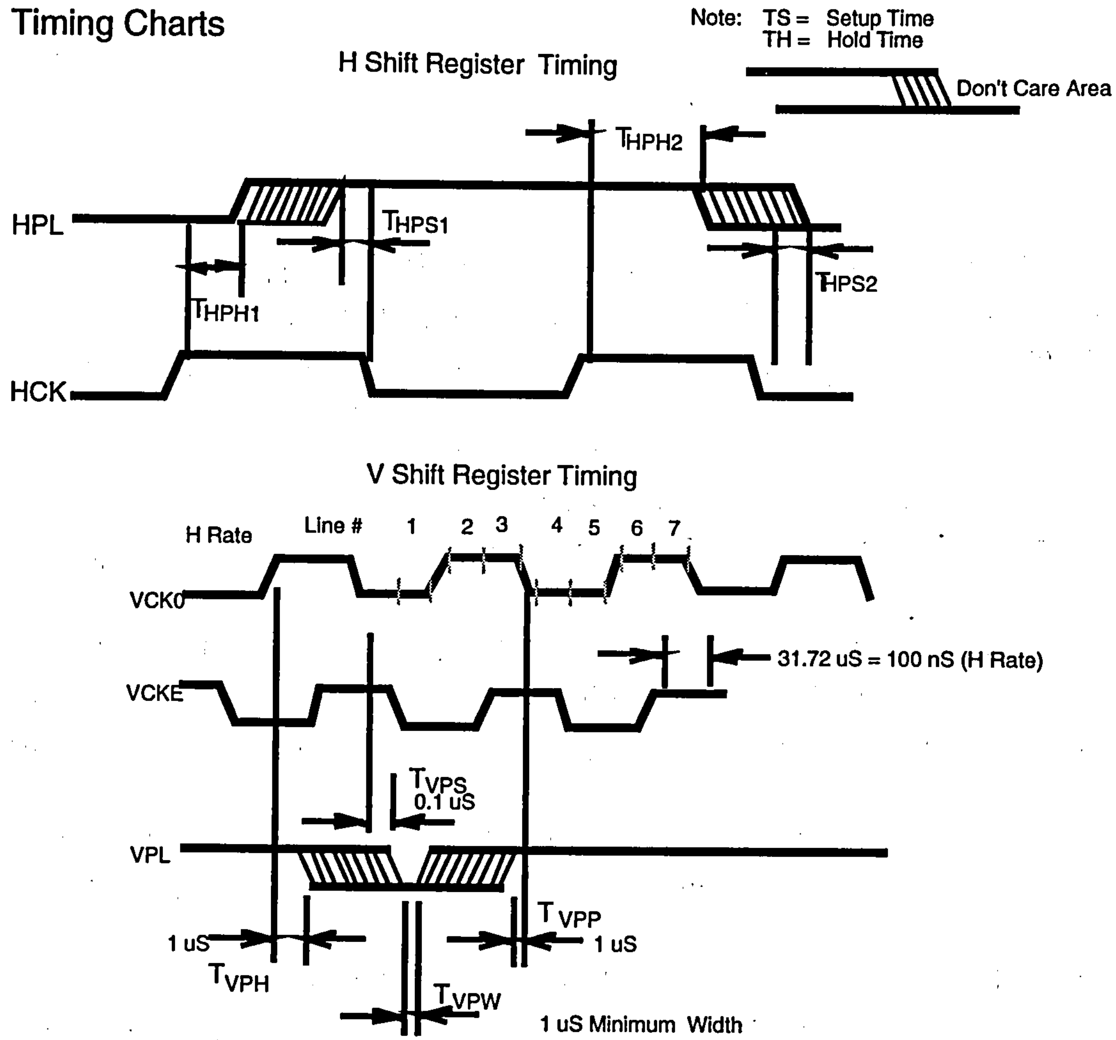


Figure B-6. Timing Required for the 640 x 480 Continuous Gray Scale LCD (precursor to the 1280 x 1024).

The horizontal synchronization will be used to derive the pixel clock (Figure 6-16) using a Phase Lock Loop or equivalent. Because of the precision and repeatability from unit to unit in the Silicon Graphics product line (assumed from a sampling of two units and an understanding of how easy this level of precision is to obtain from standard crystal clock sources and digital circuitry), the Phase Lock Loop will be implemented as a simple multiplexer-delay line and counter; it will pick the delayed crystal driven clock edge closest to the middle of the pixel bin. The middle of the pixel bin will be derived from the rising edge of the horizontal synchronization pulse.

The timing and control state machine (Figure 6-16) will provide the overall coordination between the Silicon Graphics and the AMLCDs. It will ensure that the top-bottom and left-right edges of the input image fall within the corresponding areas of each AMLCD.

The 1 to 16 channel scan converter (Figure 6-16) will be a ping-pong arrangement of memory. The memory will be 1280 pixels long by 8 bits deep. The ping-pong arrangement is needed so that an input line can be stored while a previously read line can be read out in 16 segments, thus providing the AMLCD with the lower rate video needed to refresh the integrated column drivers.

The timing and control state machine will also be tasked with running the row by row refresh of each AMLCD. One significant difference between the standard 640 x 480 panel and the higher resolution 1280 x 1024 panel is the row drive. The high resolution unit allows non-sequential row activation, needed to support the "falling raster" color video option.

The Polarity D/A Converters (Figure 6-16) will be derived from existing circuits developed by Honeywell to drive a 1280 x 1024 AMLCD. Luminance and contrast controls will be included. These latter signals are expected to be one-time settings. Adjustments thereafter will be made using the Silicon Graphics Look Up Tables, most often used for effecting gamma correction.

Appendix C- BIBLIOGRAPHY

The following citations include those referenced in the preceding report, as well as additional related material the reader may find helpful. The bibliography addresses each of the following five topical areas of the report:

- Display Requirements
- Image Source Technology
- 3-D Methods
- 3-D Interaction Methods
- Collimation Methods

Due to the interactive nature of these topics, the organizing categories are not mutually exclusive. Consequently, many of the references found under one heading may contain material equally relevant to another.

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Appendix D- SUBJECT INDEX

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13. ABSTRACT (Maximum 200 words)

The report documents and summarizes the results of the required evaluations specified in the SOW and the design specifications for the selected display system hardware. Also included are the proposed development plan and schedule as well as the estimated ROM cost to design, fabricate, and demonstrate a flyable prototype research flight display system. The thrust of the effort was development of a complete understanding of the user/system requirements for a panoramic, colimated, 3-D flyable avionic display system and the translation of the requirements into an acceptable system design for fabrication and demonstration of a prototype display in the early 1997 time frame. Eleven display system design concepts were presented to NASA LaRC during the program, one of which was down-selected to a preferred display system concept. A set of preliminary display requirements was formulated. The state of the art in image source technology, 3-D methods, collimation methods and interaction methods for a Panoramic, 3-D Flight Display System was reviewed in depth and evaluated. Display technology improvements and risk reductions associated with maturity of the technologies for the preferred display system design concept were identified.

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