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DEVELOPMENT OF DESIGN, TEST AND ACQUISITION CRITERIA FOR AIRCRAFT DOT-MATRIX FLAT PANEL DISPLAY SYSTEMS

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Research was conducted to determine the more important criteria that dot-matrix displays intended for use in aircraft cockpit environments should satisfy in order to be compatible with pilot visual perception and information cognition requirements. Techniques to process and display both rapidly time changing and moving numeric information are presented. The legibility performance of developmental programmable legend switch displays is described including the effect of and methods for masking the appearance of fingerprints. Information processing and display techniques for enhancing the appearance of dot-matrix imagery under both translation and rotation are introduced in association with the description of simulator tests performed on a flat-panel graphics display. Criteria derived as a result of testing developmental video and color dot-matrix displays are also provided. Inconsistencies encountered with existing military grey scale requirements and with the methods currently being developed to objectively describe colors were evaluated and described. No degradation in pliot performance attributable to the

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dot-matrix nature of the display media was revealed by the experiments conducted. The total number of picture elements (pixels) available to present information was assessed as being the criteria issue that is primarily responsible for establishing both the objective performance capabilities of dot-matrix displays and their aesthetic appeal.

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Test and Acquisition Criteria for Aircraft Dot-Matrix Flat Panel Display Systems.

SUMMARY

OBJECTIVE

The objective of the research program conducted was to develop criteria to be used in the design, test and acquisition of dot-matrix flat-panel display systems that would enable these systems to satisfy the information needs of pilots when they are employed in the cockpits of high performance military aircraft.

BACKGROUND/RATIONALE

The technological advancements which have been made in flat-panel display techniques are causing these devices to receive serious consideration for use in both new and established aircraft cockpit information control-display applications. To develop or alternatively to determine the viability of a particular control-display technique for use in a specific cockpit role, the information portrayal capabilities that the control-display system should possess to be able to satisfy the pilot's perceptual and information cognition requirements need to be known. The present investigation was directed at identifying as many as possible of the important dot-matrix criteria and where feasible to apply these criteria to on-going or planned USAF display system developments.

APPROACH

The criteria development approach employed during the present investigation sought: (1) to theoretically adapt criteria already established for electronic and electromechanical displays to the new dot-matrix media and to fill voids using developed human visual capabilities as a guide; and (2) to identify and correct any shortcoming in the criteria developed through the use of ground based flight simulations and bench test experiments.

SPECIFICS

Method

Utilizing the bottom-up methodology, the electro-optical characteristics and image generation performance of developmental dot-matrix displays were measured. These results, when compared with known pilot vision and information cognition capabilities, allowed display system deficiencies to be identified and their sources to be

further investigated. Criteria based on these results were then generated. Display device availability permitting, the developed criteria were also evaluated either conceptually or using experimental flight simulation techniques for compatibility with practical aircraft display operational conditions.

Discussion and Findings

The information portrayal capabilities of various developmental dot-matrix displays intended to depict alphanumeric, graphic, video and color information were evaluated and recommendations for correcting deficiencies were formulated and provided to the display developers. For the depiction of alphanumeric information, where criteria are already relatively well developed, the research was concentrated on the legibility of programmable legend switches, with emphasis on the optical effects of fingerprints, and on techniques for optimizing the interpretability of rapidly time changing numeric information. The latter subject was treated as a subset of the graphics information research area which also included criteria associated with processing data for numeric display and criteria for presenting information using moving scales and the rotation-translation of graphic imagery.

In the case of video information, the criteria for established display techniques were found to be far less developed than had been expected based on the extended period that cathode ray tube (CRT) television type displays have been used in the cockpit. A basis for establishing display luminance spatial characteristics and signal strength to display luminance magnitude transfer characteristics for video systems was found but a conflict between military grey scale requirements and other experimentally verified grey scale criteria remained unresolved at the conclusion of the present investigation. A preliminary assessment of two dot-matrix video displays was conducted.

The color criteria research dwelt principally with determining the source of a muddy mixed orange color which was perceived when spectrally pure red and green primary colors were mixed using preliminary multi-color displays. The implementation by the developer of recommendations to improve the luminance uniformity of the dot-matrix array resulted in displays with pure mixed colors. As a related application issue, the performance of conventional signal indicators and their requirements as set forth in military specifications were also evaluated to serve a potential source of criteria for multi-color displays intended to function in a signal annunciation role.

The investigation of full color criteria centered on the adequacy of the methods which are in current use to designate perceived colors and also on the means used to relate this cognitive attribute of sensed light to measurable variables derived from spectroradiometric data, such as the 1931 CIE chromaticity coordinates. The conclusion reached as a result of this study was that the color a human will attribute to the light eminated by an object or display image (i.e., whether reflected, transmitted, emitted or a combination thereof) is based on the difference between the measured luminance and chromaticity characteristics of the light viewed and those for a reference light to which the observer is color adapted on a spatially selective basis. This concept of color perception is at least ostensively consistent with both the Dominant Wavelength/ Excitation Purity and Munsell methods of characterizing color. This finding raises questions as to the potential validity of the continuing attempts to define a uniform chromaticity diagram upon which equal distances are supposed to represent equal color differences. Since it is possible for a single point on any of the existing chromaticity diagrams to represent different perceived colors, the basic objective of these color characterization efforts would appear to be inconsistent with known human color perception capabilities.

Conclusions and Recommendations

Possibly the most significant finding of the present investigation was that the spatial quantization of a dot-matrix display presentation media does not have to interfere with a pilot's visual performance. An inadequate number of picture elements, be it on a display that is subjectively perceived to be spatially continuous but blurred, or on a dot-matrix display with clearly discernable picture elements (pixels), results in degraded user performance. Virtually all of the visual effects associated with dot-matrix displays result from the high image quality capabilities of this display media and from attempts to portray imagery that is too complex for the number of pixels available on the display. Even when display pixel counts are marginal, however, information processing techniques can be applied which produce good user performance.

Further criteria research is recommended on dot-matrix displays in the following areas: (1) real-time numeric display presentation techniques; (2) the processing of imagery translated along curve paths or which undergoes rotation; (3) the digital processing and depiction of sensed video grey scale signals; (4) pixel count requirements for typical military targets; and (5) color display criteria, in general, starting with a determination of a model describing the human's spatially selective adaptation to colors present within the instantaneous visual field, as a basis for developing a valid system to characterize perceived colors.

FOREWARD

This final report provides an overview of the research conducted by Burnette Engineering pursuant to the development of design, test and acquisition criteria for aircraft dot-matrix flat panel display systems. The investigations described were carried out during the period from 23 August 1982 to 24 November 1983. The research was sponsored by the U.S. Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract Number F33615-82-C-3613.

Mr. George W. Palmer was the Air Force Project Engineer during the period of the contract, which was conducted as a part of a program of advanced display design and development managed by Mr. Walter Melnick.

Dr. Keith T. Burnette served as the principle investigator for Burnette Engineering.

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SECTION 1

INTRODUCTION

The design, test and acquisition criteria applicable to flat panel dot-matrix displays exhibit both similarities to and distinctions from their aircraft electromechanical and cathode ray tube (CRT) display counterparts. The present research effort was conducted with the objective of investigating dot-matrix display optical, electrical and physical properties, for which criteria differences might reasonably be expected to exist, to determine the effect that these properties would have on the human visual system and to establish the criteria which would have to be met in order to assure acceptable pilot performance during the use of such displays.

The detection, analysis and development of corrections for dot-matrix display deficiencies and/or visual effects encountered during the course of the experimental investigation was an implicit part of the research effort conducted. In that the performance of the dot-matrix displays utilized in the investigation was being assessed for the first time, the origins of any unexpected types of display behavior were of interest in and of themselves as potential indicators of design criteria shortcomings, rather than simply as symptoms of possible component failures or host computer software bugs.

The investigation was also unique in other ways. For example, the performance capabilities of the dot-matrix displays used, in some instances, exceeded those of conventional displays. This permitted electronic display variable ranges to be explored for which there was no direct experience to draw on from the display or vision literature. In a like manner, the investigation of image motion induced dot-matrix display visual effects, this having only just become possible with the development of complete display systems, was for the first time assessed as a part of this research program. The criteria issues of interest in this investigation were therefore both varied and in themselves an object of discovery.

In the remainder of this section criteria issues of interest are identified, the research methodology employed is described and the scope of the research conducted is detailed.

CRITERIA ISSUES

Achieving satisfactory pilot performance using any type of display is dependent on a large number of interdependent factors. These factors may be categorized as follows: the method used to encode the information to be displayed, the technique used to implement the display of information, the engineering design of the display system and the choice of display technology. Each of these factors has the capacity to either directly or indirectly influence pilot visual performance. The interrelationship of these factors with the human is illustrated in Figure 1.1. A brief description of each of these factors and of the human visual system follows.

Human Visual System

The functional processes which are believed to be operative in the human visual system are shown in Figure 1.2.[1] As illustrated, the processing by the brain of other types of sensory inputs is believed to be identical to that for vision. The lower four mental processes shown in Fig. 1.2 are basically serial in nature, with each stage requiring higher quality information than the one preceding it in order to permit the next stage of processing to occur. This trend is reversed for the response selection and execution processes.

Sensing involves the detection, electrochemical conversion and transmission of information to the areas of the brain where perception occurs. Perception, in turn, involves the separation of information into entities or categories (i.e. image patterns, colors, sound patterns, etc.) for further processing. In doing this, the mind attempts to apply information acquisition strategies which have proven successful in the past. The strategy actually used can range from trial and error searches, with no a priori concept of what is to be found, to very specific searches for cues (i.e. signatures) which are known to be associated with the entities being sought. The strong influence that a pilot's task dependent expectation of what is to be perceived (i.e. a priori knowledge) has on perceptual success, demonstrates the mental control aspect of perception and also distinguishes it from sensing function which exhibits no apparent parallel mental control capability.

Recognition and identification of information represent two further stages of useable information extraction and classification. Recognition implies that a sufficient collection of perceptual attributes of a perceived entity have been assembled to permit assigning it to a specific category of information. Tanks, trucks, bridges and so forth represent visual object recognition categories just as music, sirens, voices and so forth represent sound recognition categories. Identification implies the assembly of a still larger number of perceptual cues and infers an ability to separate information into even more specific categories. Thus, the ability to classify an aircraft as friend or foe, or to give it a name such as an F-15 or an MIG-25 indicates identification has been achieved.

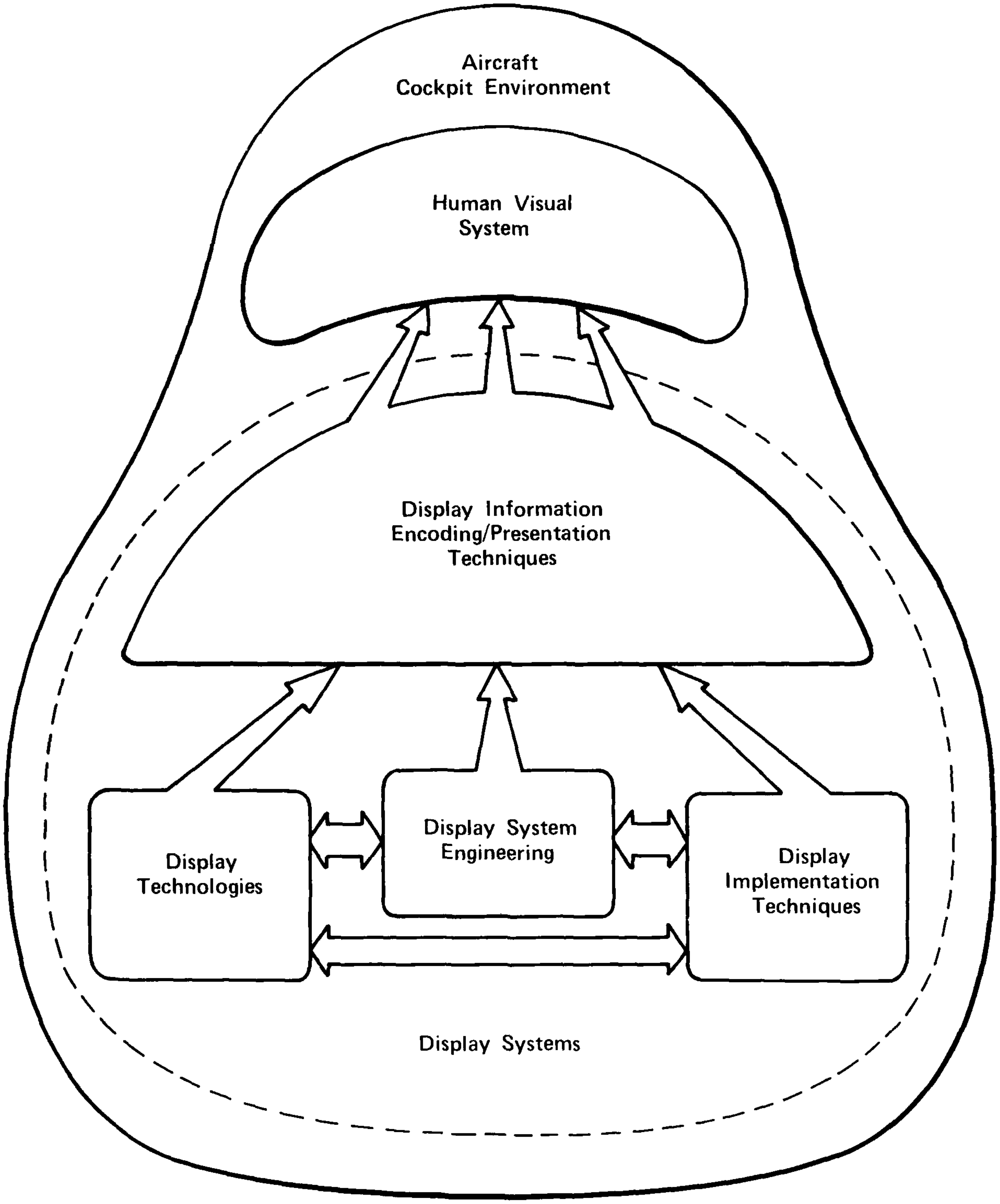


Figure 1.1 Display Criteria Interrelationships

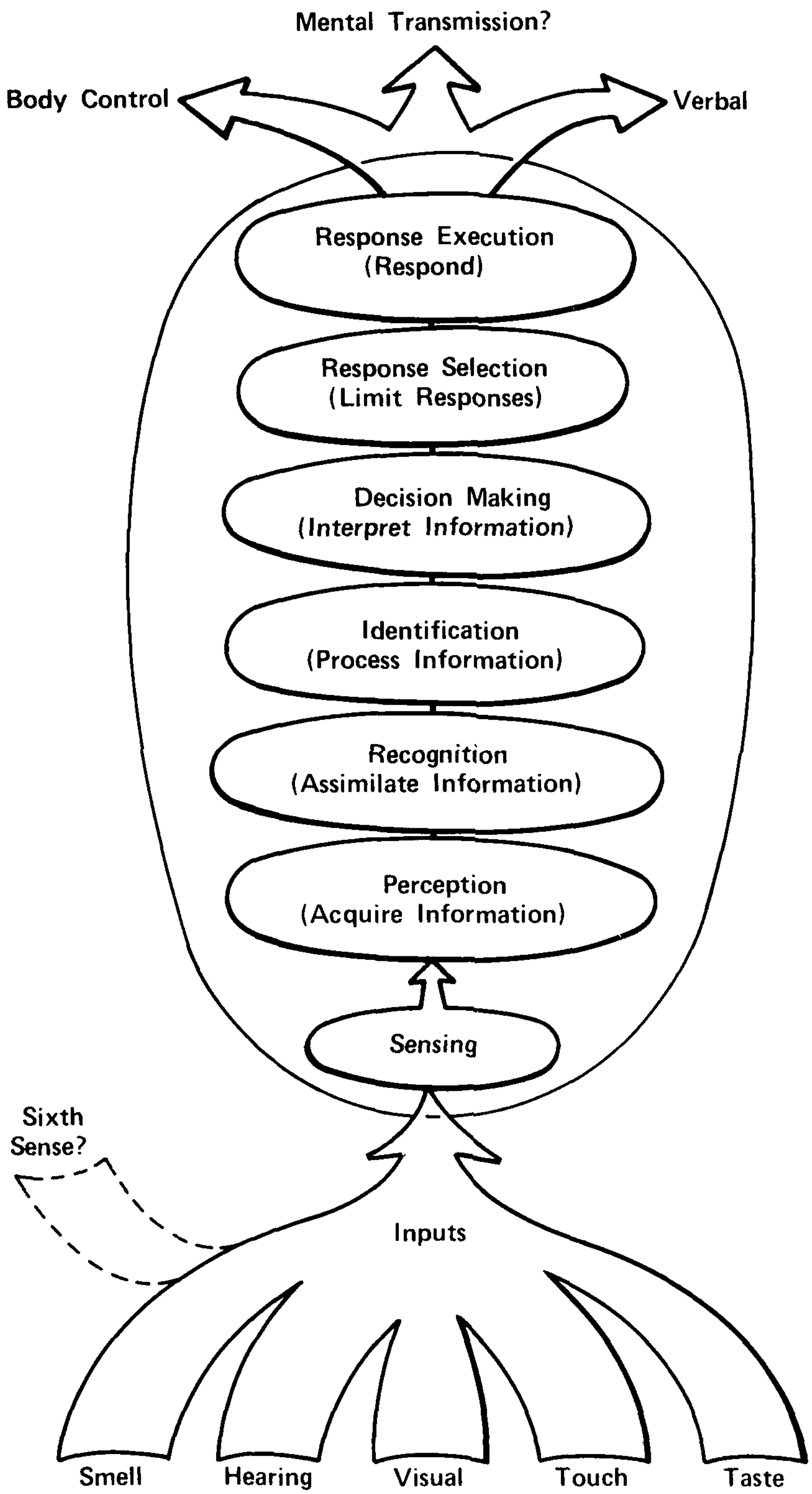


Figure 1.2 Human Mental Response.

Decision making, response selection and response execution can either represent a response to the identified information inputs, or can be the result of mental initiatives on the part of the human. Since these mental functions are only indirectly influenced by dot-matrix display issues, they have not been dealt with explicitly during the course of the present research.

The fundamental question concerning the human visual system explored during the current research effort was whether the use of dot-matrix imagery would adversely affect the human's perception, recognition or identification processes, if used in place of conventional cockpit instruments. As a basis of comparison it is known that aircraft electro-mechanical instruments have been used successfully by pilots for flight control tasks for an extended period of time. These instruments are characterized by high contrast, sharply defined imagery analogous in form to the graphics information presentations of electronic displays, but characterized by smooth continuous image motions.

More recently, cathode ray tube (CRT) displays in the form of both head down displays (HDDs) and head up displays (HUDs) have also been found to be acceptable for the portrayal of flight information by pilots in most of the applications that have been implemented to date. Unlike the electro-mechanical instruments, electronic displays present their imagery as a time sequence of static image frames. When these time quantized samples of a normally continuous event are displayed at 60 frames per second or higher frame rates, they can create the illusion of nearly continuous image motion, provided that the image motion steps, which in reality must occur between the static frames used to depict the moving images, are small.

The strength of this "apparent image motion illusion" is believed to have its origin in the natural temporal sampling of imagery performed by the human visual system during the sensing and perception of visual scenes. As a result of both past and current research on this phenomenon by the author, it is known that the ability to satisfy human expectations, with respect to the way natural objects should move (i.e. satisfying the laws of physics for the time dependent placement of objects undergoing smooth continuous motion), is a necessary criteria for creating and sustaining this illusion.

The imagery produced on dot-matrix displays not only exhibits temporal quantization, but can also exhibit spatial quantization. The display resolution, or equivalently the spacing between picture elements, determines to what extent spatial quantization is visually discernable. Unlike temporal quantization, operational aircraft display examples of the impact of presenting information as clearly discernable spatially quantized image patterns are not available for study.

Stroke written CRTs avoid the issue by virtue of using frames formed as assemblies of continuous vectors. Raster CRTs are spatially quantized along one axis, but due to the degree of raster line overlap produced by the spread of the CRT spot, the effect is not particularly discernable on military aircraft CRT displays. Due to the fact that the aircraft cockpit represents virtually the only place where dynamic CRT display imagery is used to perform time-critical tasks, there is essentially no information to draw on in the literature with respect to this issue.

In much the same way that temporal sampling of information by the human visual system produces a natural precident for the mental processing of time sequenced frames of picture information, the sensing of information by the discrete rod and cone receptors within the retina, with transmission occurring over discrete optical nerves to the visual cortex, produces a natural mental processing precident for handling spatially quantized data. This physical situation is probably responsible for the fact that human visually evoked potential responses for dot-matrix font characters are the same as those obtained for continuous stroke font characters.[2] It is probably also responsible for the good pilot acceptance of a dynamics graphics presentation evaluated during the course of the present research effort.[3]

As a consequence of the preceding theoretical and experimental results, it can be concluded that future criteria research areas of interest for dot-matrix displays should relate more to the development of criteria to avoid the possible introduction of spatial image pattern distortions rather than to the question of the fundamental acceptability of the dot-matrix display as an image presentation technique.

Display Information Encoding/Presentation Techniques

The pilot's ability to assimilate, process and respond to displayed information depends almost solely on the selection of information encoding techniques which are available to implement the transfer of information to the pilot. The choice of display technology, display implementation technique and display system engineering design act primarily as constraints which limit the ultimate effectiveness achievable for the encoded presentation.

Due to the vital role that display information encoding/presentation techniques play in achieving intelligible communications to the pilot and because the dot-matrix characteristic of a display clearly imposes constraints on its information encoding/presentation capability, the present research effort was structured in terms of display information encoding/presentation techniques. Specifically this report is divided into sections based on the general encoding categories of: alphanumerics, graphics, video, and color.

Figure 1.3 lists these four fundamental information encoding categories and some of the display and information presentation attributes which influence their design and implementation.

Display Technologies

Electronic display technologies which are either currently in use or under development for consumer and industrial applications, are listed in Figure 1.4. Of these technologies, only the CRT and incandescent filament technologies have established performance records in military aircraft cockpit applications. Of the remaining technologies, LED segmented displays were the first to be successfully used in an operational aircraft installation as numeric readouts in an F-111 radar altimeter. Production of an LED dot-matrix display, for use in the F-16 aircraft as a data entry display, represents another first. The only other flat panel technology to be successfully applied in a military aircraft cockpit display application to date is a guest host liquid crystal display technique, which has been implemented both in the form of segmented numeric readout displays and as segmented scale displays on the F-20 aircraft.

The Tri-Service Airborne Display Technology Working Group has assessed the development potential of the flat panel technologies shown in Figure 1.4 and concluded that the LED, LCD and TFEL technologies have the best near term development potential for airborne applications. This result is consistent with the advanced state of development of these technologies in comparison to the others shown.

Due to the display criteria emphasis of the present investigation, technology differences and limitations were of interest only to the extent that they might produce display behaviors distinctive from typical dot-matrix display visual characteristics. Such distinctions were encountered (i.e. such as the light dispersion of plasma panel pixels) but were assessed as producing too small a difference in visual perception to merit special treatment.

Display Implementation Techniques

The more obvious distinctions/relationships between display implementation techniques have been illustrated in Figure 1.5. The figure relates the three major display types: head down displays (HDDs), helmet mounted displays (HMDs) and head up displays (HUDs), to the methods typically used (or proposed) to produce the imagery depicted by them (i.e. as shown on the right side of the figure) and to the Tri-Service Airborne Display Technology Working Group categories of aircraft end-product HDD applications (i.e. as shown on the left side of the figure).

Pattern Interrelationships   Image Complexity

Image Quality   Noise   Image Edge Definition (MTF)

Blanking		Image Time Dependence
Sample and Hold		Character Font
Flash Rate	ALPHANUMERICS	Character Size
Update Rate		Character Stroke Width
Refresh Rate		Character Aspect Ratio
Scale Shape		Symbol Shape
Scale Orientation		Symbol Size
Scale Markers	GRAPHICS	Symbol Overlay
Scale Annotations		Image Complexity
Scale Motion		Image Dynamics
Scaling Factors		Image Contrast
Luminance Control		Image Clutter
Luminance Range	VIDEO	Number of Grey Scales
Number of Pixels		Grey Scale Ratios
Density of Pixels		Luminance Quantization
Pixel Active Areas		Color Quantization
Pixel Alignment		Spatial Quantization
Pixel Spacing/Shape	COLOR	Number of Colors
Color Contrast		Color Separation
Color Illusions		Color Saturation
Color Adaptation		Color Control
Display Perspective		Color Superposition
Display Dimensionality		Color Juxtaposition

Luminance Uniformity   Color Uniformity

Viewing Angle   Field of View   Exit Pupil

Figure 1.3 Display Information Encoding/Presentation Technique Criteria

Display Technology	Light Modulation Technique
*CRT	Emissive
Flat CRT	
*Incandescent Filament	
*LED	
Plasma	
VFD	
TFEL	
Phosphor EL	
*LCD	Reflective or Transmissive
Magneto-Optic	
Ferroelectric	
Electrochromic	
Electrodeposition	
Electrophoretic	Reflective
Magnetic Particles	

*Technologies used in bubble canopy aircraft cockpit environment.

Figure 1.4 Display Technologies

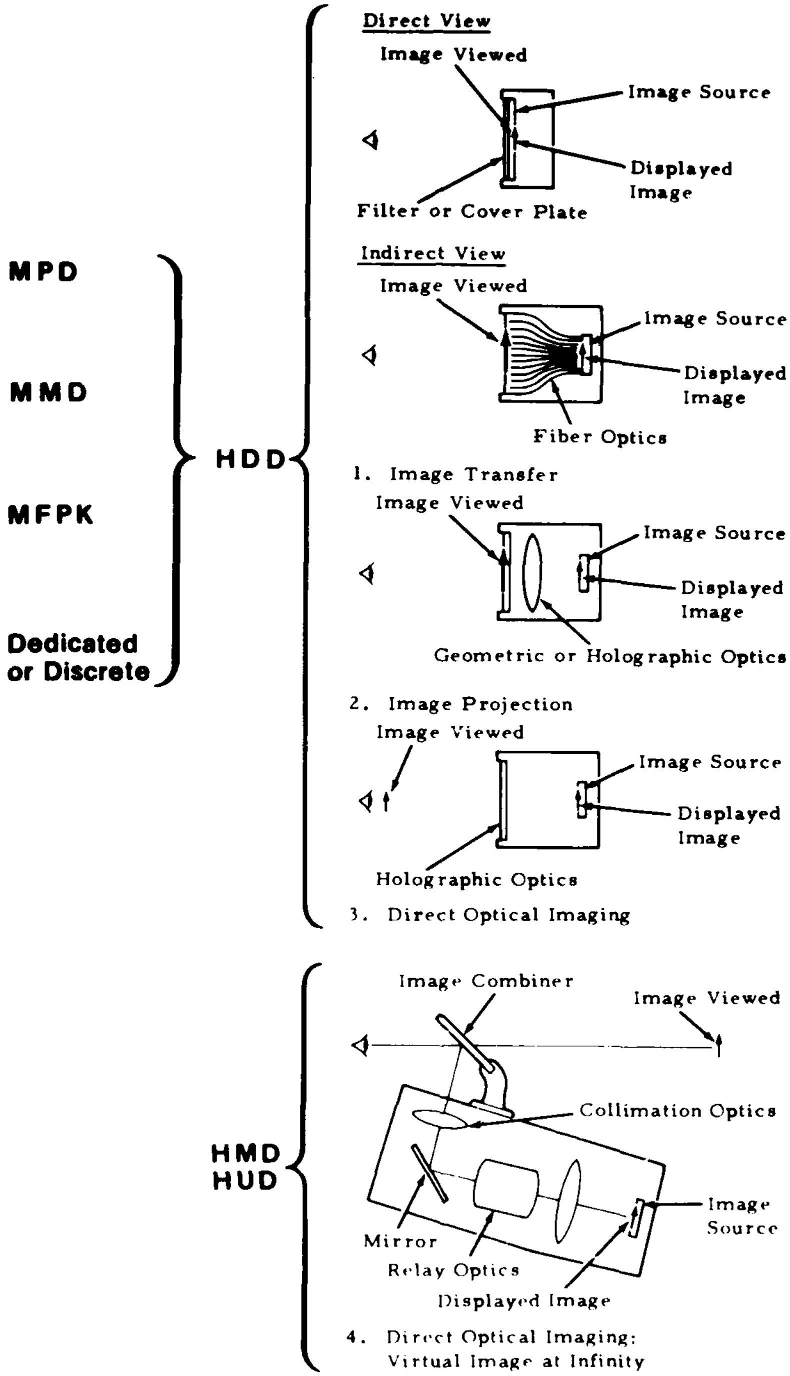


Figure 1.5 Display Implementation Techniques

The MPD (multipurpose display) is a medium frame rate display capable of presenting video, graphics and alphanumerics either individually or in combination and typically has a picture element (pixel) density of 100-125 pixels/inch. The MMD (mission management display) can take two forms: it can be a monitor control display (MCD) or a data management display (DMD). The MCD is a graphics/alphanumeric display having a resolution of 60 pixels/inch or greater with little or no grey shade capability but with a high frame rate capability consistent with producing smooth motion of even the fastest flight control imagery. The DMD is a low frame rate display of 30 pixels/inch resolution or greater which is used primarily to depict time changes in alphanumerics, line graphs, bar graphs and status advisory information. The MFPK (multifunction programmable keyboard) is a low frame/rate display which allows switch legends and functions to be altered under program control and being primarily an alphanumeric display (i.e. possibly with a limited graphics capability) can also utilize resolutions as low as 30 pixels/inch. Depending on the application any of the foregoing displays could be single-color, multi-color (i.e. two primary colors per pixel) or full color (i.e. three primary colors per pixel).

The distinctions between the end-product applications of displays can have an important impact on dot-matrix display criteria. The differences in the resolutions and frame rates (i.e. information update rates) for the different end-product applications are the distinctions of interest. At high resolutions the close spacing of pixels tends to produce the illusion of nearly spatially continuous imagery, thereby making the dot-matrix nature of the actual presentation a mute issue. Likewise, it is known that time changing 7x9 or larger dot-matrix font alphanumeric characters presented at very low update rates (3 Hertz or less) and in a fixed display location will produce visual performance equal to that for continuous stroke characters.[4]

The issue of primary interest in the present research is therefore the intermediate resolution, dynamic image motion, mission management display. On this type of display, the spacing between pixels is still quite discernable and results in both observable steps in rotated lines and in observable jumps when images move between adjacent pixel positions. It can also be shown that attempts to move images in directions other than along the orthogonal XY pixel axes will produce image distortions. These issues were of particular interest in the present investigation.

The primary distinction between the display implementation techniques shown in a simplified form on the right side of Figure 1.5 is based on the different optical approaches used to form the imagery viewed by the pilot. The direct view technique involves those display configurations where the image source is viewed directly by the pilot whereas indirect view refers to those configurations where the image source is remote from the display front surface. The imagery for the first two indirect view display techniques is, respectively, transferred to and projected on a front viewing surface of the display which in turn appears to the observer to be the source of the imagery. In the last two approaches, direct optical imaging is used to produce real or virtual images of the image source. The latter techniques place viewing location constraints on the pilot which are in general tolerated only if no other satisfactory means of achieving the display objective can be found. For this reason the direct optical imaging approach is seldom used in head down displays, but lacking a viable alternative is used exclusively in HUDs and HMDs.

While the optical design employed for indirect view display techniques should theoretically be indifferent to whether the imagery is formed on a dot-matrix or spatially continuous display media, in wide field of view HUD and HMD designs, image distortions introduced by the optics can be compensated by introducing offsetting distortions in the electronically generated display pattern produced by the image source. The resolution dependent spacing between pixels on dot-matrix image sources, by virtue of imposing a minimum image displacement tolerance limit, could potentially complicate this type of compensation. Theoretical analysis indicates, however, that a dot-matrix image source having high enough resolution to satisfy the mission oriented image placement accuracy requirements of specific HUDs and HMDs would also satisfy image distortion compensation requirements.

A display implementation technique issue of importance to dot-matrix display criteria which is only alluded to in Figure 1.5 is the methods used to implement the display image sources. The function of the image source is to modulate light with information by controlling the spatial, the temporal or the spectral amplitude distributions of the light eminating from the source. The three methods used by image sources to modulate light are light emittance, light transmittance and light reflectance control. Fundamental constraints associated with these three light modulation techniques do selectively impact the design criteria applicable to them.

Display System Engineering

Figure 1.6 illustrates engineering issues which influence the eventual performance and utility of a developed display system. The resourcefulness of the engineering which goes into the display system determines whether the information required by a pilot can actually be provided subject to the constraints imposed by the aircraft's installation requirements and its physical environment. Engineering criteria considerations therefore determine the system starting with its feasibility and extending through to the display capability ultimately achieved.

Display System Physical Specifications

Display System Timing, Refresh and Update

Measurement/''est Techniques

Display System Architecture and Interfaces

Aircraft Environmental Considerations

Display Fabrication Processes

Display Assembly Packaging and Components

Display System Software

Display Control and Power Subsystems

Reliability

Figure 1.6 Display System Engineering Criteria Factors

RESEARCH METHODOLOGY

Two distinct but correlatable research methodologies were applied to the investigation of dot-matrix display criteria. The methodologies employed will be referred to as the top down and bottom up approaches.

The top down approach involves incorporating a complete display, fully formatted using proven information/display techniques, into the familiar environment of an aircraft flight simulator cockpit and then, set in this framework, conduct experiments using military pilots under realistic task and workload conditions. The primary advantage of this experimental approach is that the pilot is able to experience the operation of the display with as nearly as possible the same perspective that would be experienced in an actual aircraft. This allows unique features of a display, such as the impact of the dot-matrix character of its imagery, to receive neither over nor under emphasis in the pilot's appraisal of and performance using the display. Simple observations of an operating display allows its aesthetic appeal to be assessed, but fails to provide: the incentive to read or the need to precisely control events based on the information displayed. A flight simulator evaluation forces the pilot to both interpret and control the displayed information and also causes these tasks to be time critical.

Counterbalancing this advantage, the top down methodology also has prominent shortcomings. The first shortcoming is that the display is exercised only within the confines of the flight simulator experiment selected for test and as a result deficiencies or benefits which could appear using different display information formats, flight scenarios or mission objectives need not be detected. Another shortcoming of this approach relates to the difficulties associated with tracing the sources of the display problems which are identified. The information interactions and task complexities which prove so effective in promoting the identification of problems in a flight simulator environment can also serve to impede or totally inhibit the ability to identify the sources of the problems due to the masking effects they introduce.

The bottom-up research methodology utilizes the accumulated knowledge of human responses to visual stimuli and human information processing to anticipate situations which can be expected to result in either degraded or improved pilot performance and/or acceptance of display information portrayals. The confidence level which can be ascribed to predictions made using this technique is based strongly on the availability of experimentally verified information on how the human perceives, assimilates, processes, interprets and responds to various types of display information. The display formatting techniques used to depict information, the task related emphasis placed on the information by the crew member, the crew station layout of the information presented and the potential environmental conditions that can be present while the pilot is viewing the information all influence the mission performance that can be achieved by a pilot using the display. Potential problems/advantages encountered due to the use of a dot-matrix display information presentation media represent additional factors that must be accounted for when using this research methodology.

To effectively use the bottom up research methodology, in addition to understanding the human visual system, a detailed understanding of the display system, and of the technologies used in it is needed to be able to extrapolate the performance to be expected from a particular display system design (i.e., which may or may not be implemented at the time of the assessment). Experimental testing of display components, preliminary displays and final displays is necessary to fill in voids in the technical information data base from which projections are made. The primary shortcoming of the bottom up research methodology is the potential lack of knowledge regarding the operation of the human visual system, the display system, the cockpit system or of potential interactions between these systems.

Three types of experimental tests are needed for use with the bottom up research methodology. Engineering characterization testing provides specific information on the electro-optical properties of a particular dot-matrix display or of the component parts thereof being tested. These results are used in either quantifying criteria or for the theoretical analysis purposes previously described. Single and limited multi-variable bench test investigations provide the primary means for verifying theoretically developed design criteria and for experimentally exploring the root causes of display system problems found using the top down research methodology. This test approach also permits individual display format imagery to be observed in isolation while the full ranges of programmed display input variables are parametrically varied. Doing this assures that any problems associated with the display will be detected. The final type of experimental test also involves bench tests in which variables are changed parametrically, however, the purpose of these tests is to determine human legibility performance or to quantitatively characterize the conditions responsible for observed visual effects associated with the display. These experiments serve the dual purpose of improving the general knowledge available on how the human visual system performs.

By integrating the results of the top down and bottom up research methodologies, the individual limitations of these two approaches cancel one another and only their strengths are retained. The top down approach results in the correct identification of problem symptoms, while the bottom up approach allows rapid identification of the problem causes.

Wherever feasible in the present program, both research approaches have been applied. The need to have full size displays in a nearly fully developed state to achieve meaningful results using the top down methodology, did limit the applications to which this approach could be applied during the present investigation.

SCOPE OF RESEARCH

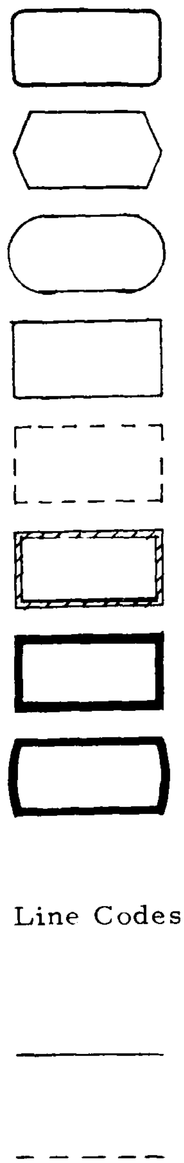
The dot-matrix display criteria research performed under this program was divided into investigation areas based on the display information encoding/presentation technique categories of: (1) alphanumerics, (2) graphics, (3) video and (4) color. Test technique definition and display architecture requirements, which were also important investigative areas, were integrated within the foregoing research categories.

The scope of the research conducted varied dramatically between the identified research categories based primarily on the availability of display units for use in experimental tests and the state of development of existing display criteria. In the case of numeric and alphanumeric display criteria the emphasis was on verifying the adequacy of developed display products and specifications. In the video area, the timely availability of dot-matrix display units constrained the level of research which could be conducted, however, the preliminary assessments of grey scale and resolution requirements accomplished revealed unresolved criteria development issues of importance to both dot-matrix and CRT displays. Graphics and color display criteria development were the major emphasis areas in the current research program with dynamic imagery the primary emphasis of the graphics investigations and the perceived quality of dot-matrix generated imagery on multi-color displays being the primary emphasis of the color investigation.

Alphanumerics, graphics, video and color are discussed in Sections 2, 3, 4, and 5, respectively, with each section intended to be self-contained. The scope of research conducted in each of the four investigation areas is described and also illustrated in a block diagram format in the introductory remarks associated with each of these sections. Figure 1.7 provides a legend for use in interpreting the information provided on the block diagrams in each of these sections.

Solid lines in the diagrams connect blocks which describe: the research tasks performed, unforeseen events encountered and important results obtained. Dashed lines in the diagrams indicate connections to blocks which describe recommended future research. The information provided in the blocks connected by dashed lines have the following meanings: (1) dashed boxes indicate new research areas identified during the course of the present investigation which had not been anticipated when the program was proposed, (2) single line solid blocks indicate proposed research efforts which were deferred in order to pursue higher priority research areas encountered while performing the study and (3) heavy line solid blocks indicate the objectives of conducting the recommended research.

1. Block Codes



Research Topic Areas

Research Scope Constraints

Research Categories or Methodologies

Research Efforts Proposed by BE

Unexpected/Unplanned Efforts or Events

Related USAF or USAF Contractor Efforts

Research Finding/Criteria Results

Major Research Objectives/Results

2. Line Codes

Connection between completed efforts

Connections to incomplete efforts

Figure 1.7 Legend for Research Block Diagrams

SECTION 2

ALPHANUMERICS

RESEARCH OVERVIEW

Past research efforts by Burnette Engineering personnel have provided the USAF with detailed legibility specifications applicable to numeric readout segmented displays and alphanumeric dot-matrix displays. The scope of the present research was therefore restricted to verifying the adequacy of these specifications, determining the performance of dot-matrix interactive switch displays in relationship to them and establishing criteria in areas found to be lacking adequate definition.

The numeric/alphanumeric criteria block diagram shown in Figure 2.1 provides an overview of the research conducted in this area. A description of the tests conducted and of the results obtained relative to the performance of state of the art alphanumeric devices is provided in the subsection which follows entitled Legibility/Image Quality. This is followed by descriptions of the research conducted on the factors influencing the reflectance of displays. Due to its importance, a related reflectance issue, fingerprints, is treated in a separate subsection. The final subsection entitled Further Research sums up the status of current alphanumeric display criteria development and identifies areas where further information is needed.

LEGIBILITY/IMAGE QUALITY

Two functionally similar but optically distinct implementations of programmable legend information switching devices were evaluated. A multifunction programmable keyboard (MFPK) developed by Bowmar Instruments Corporation for use by AFWAL/FIGR in aircraft flight simulator evaluations of MFPK applications is shown in Figure 2.2. Tests of this display showed that it remains legible in environments of up to about 1000fc of incident illuminance. This performance is nearly, but not quite, satisfactory for use in covered canopy aircraft crewstations. Since the display's optical design showed no evidence that contrast enhancement techniques have as yet been applied, an optimized version of it suitable for aircraft applications appears likely. The USAF unit pictured has a two line, 24 character (i.e. 5x7 dot-matrix font) per line, scratch pad display and a touch panel overlayed keypad display consisting of 15 switch displays utilizing 2 rows of 8 characters each to display their computer controlled functions/legends.

The other interactive control-display devices evaluated were configured as individual programmable display pushbutton switch (PDP or

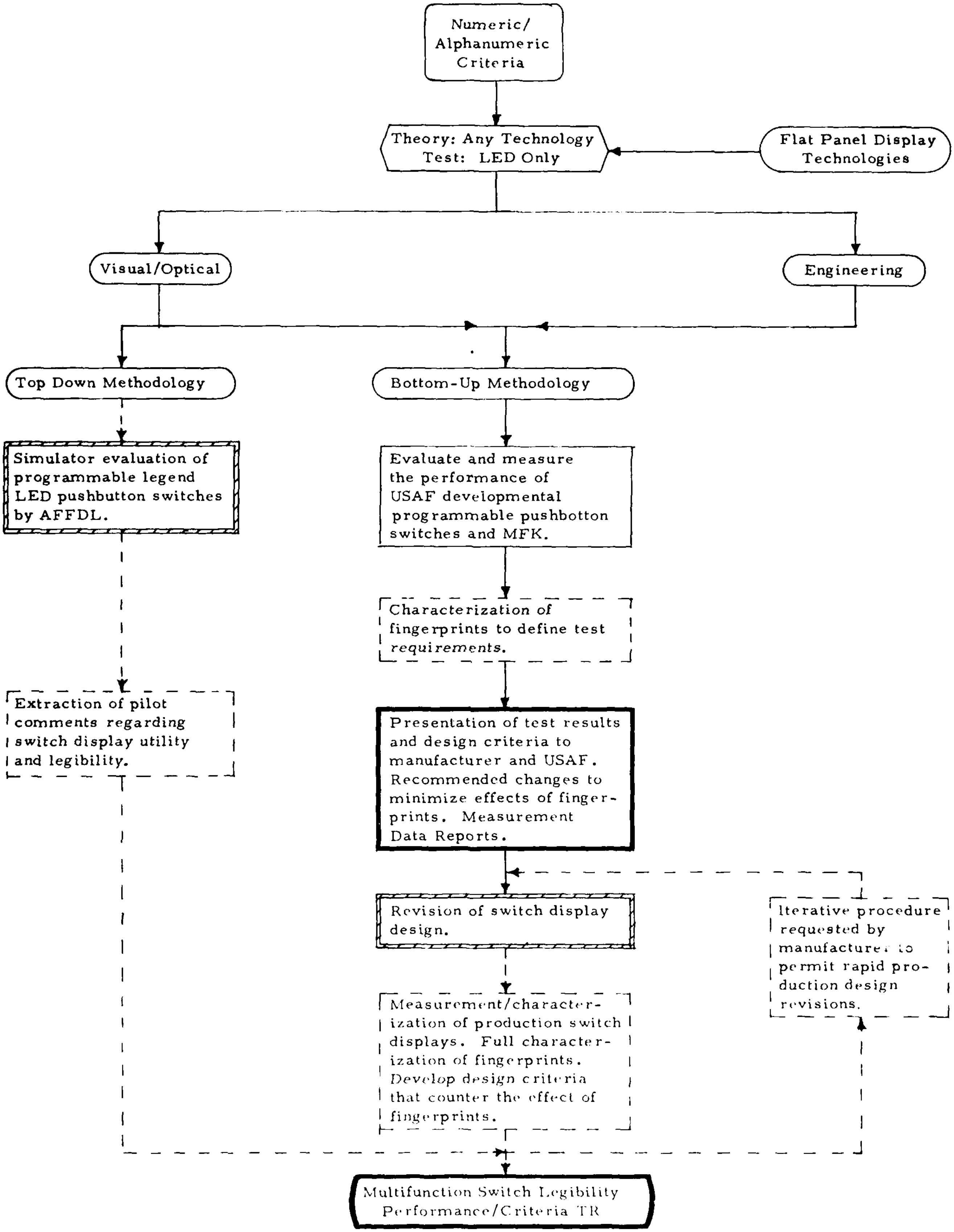


Figure 2.1 Numeric/Alphanumeric Criteria Block Diagram

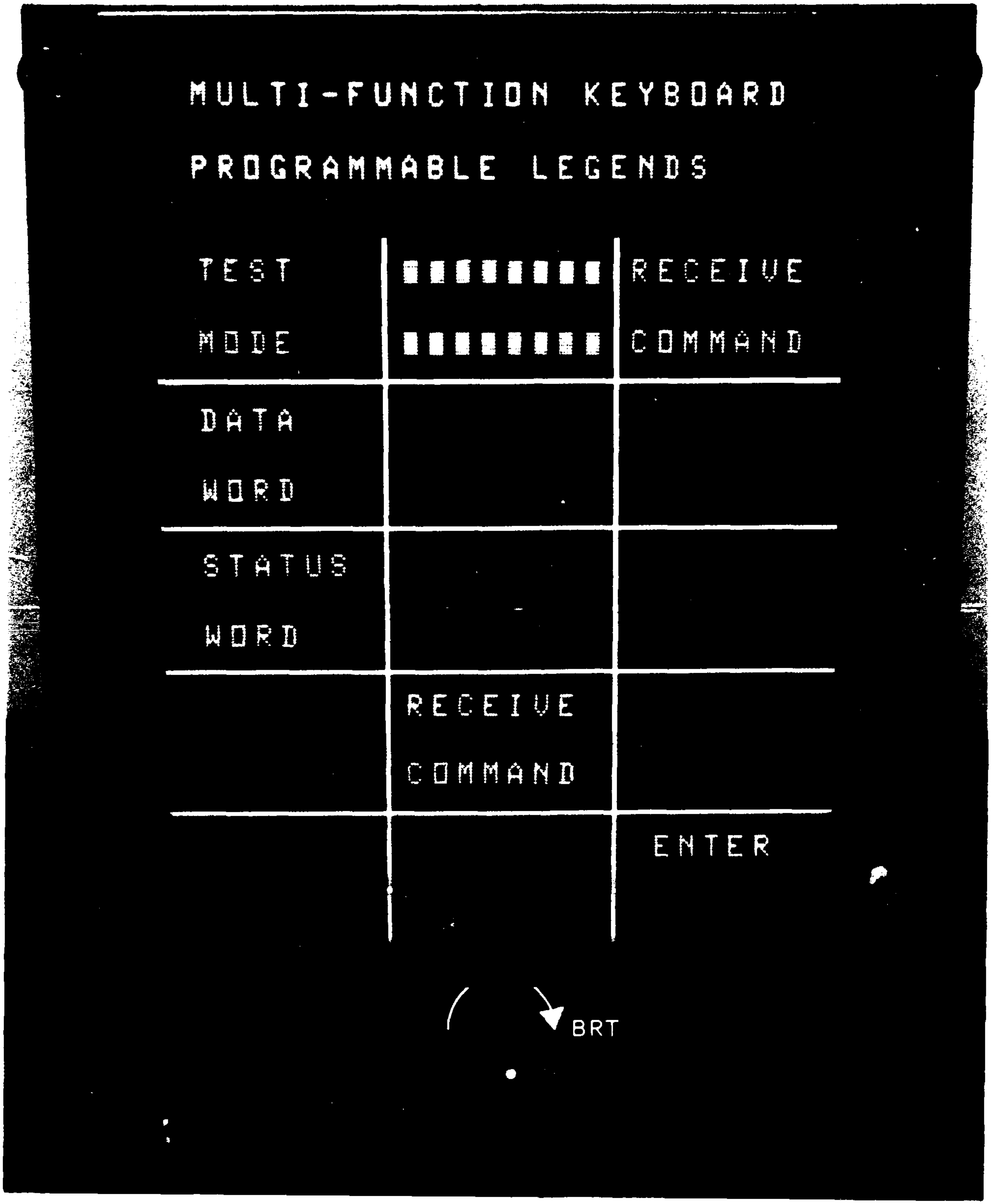


Figure 2.2 Bowmar Prototype Multifunction Programmable Keyboard Display

PPS) units. The operation of these units is the same as it is for conventional pushbutton switches, to the extent that the PPS provides analogous motion and tactile feedback cues, but differs in that the PPS legends and control functions are capable of being altered under computer control. The individual packaging of the PPS units, like their conventional switch counterparts, allows great flexibility in configuring the switches for use singly, in rows, in columns or abbuted in two dimensions to form a keyboard. When the individual PPS units are configured to form a keyboard, the resultant system is functionally very similar to the Bowmar MFPK implementation previously described although other distinctions remain.

A photograph of the display surface of one of the first developmental sunlight readable PPS devices to be built is shown in Figure 2.3. These PPS units were developed by Micro Switch, a division of Honeywell, in a joint venture with the Boeing Aerospace Company, to satisfy the legibility requirements of a bubble/canopy aircraft (i.e. as stipulated by a MFPK/switch design specification originally developed by Burnette Engineering and subsequently adopted the Boeing Aerospace Company for use in their specification to Micro Switch). The specification option selected by Boeing and Micro Switch provides a continuous dot-matrix display surface 16 pixels high by 35 pixels wide with the pixels placed on 25 mil centers. The resultant display is capable of displaying two rows of 5x7 dot matrix font characters approximately 0.175 inch high, a single row of up to 16 pixel (i.e. 0.4 inch) high characters, pictoral symbols or dynamic graphics.

Background/Display Descriptions

A total of eight Micro Switch PPS units were tested. The first five units were developmental devices resulting from a USAF/NASA sponsored MFPK feasibility investigation conducted by Boeing. Although a sunlight readable version of the PPS resulted from this study, its design was not considered to be sufficiently cost effective for use in production switches. The switches delivered to the USAF therefore represented potential production designs which while suitable for their intended use in flight simulator evaluations of the unit's information portrayal capabilities, were not sunlight readable.

Subsequently additional PPS units were procured by the USAF for use in the simulator tests. Although the design of these prototype PPS units was improved, including the use of higher efficiency green LEDs, Micro Switch still did not consider them to be fully sunlight readable.

Both of the preceding generations of PPS units have been constrained by the availability of integrated circuit drivers small enough for mounting within the switch housing. These driver restrictions limit the

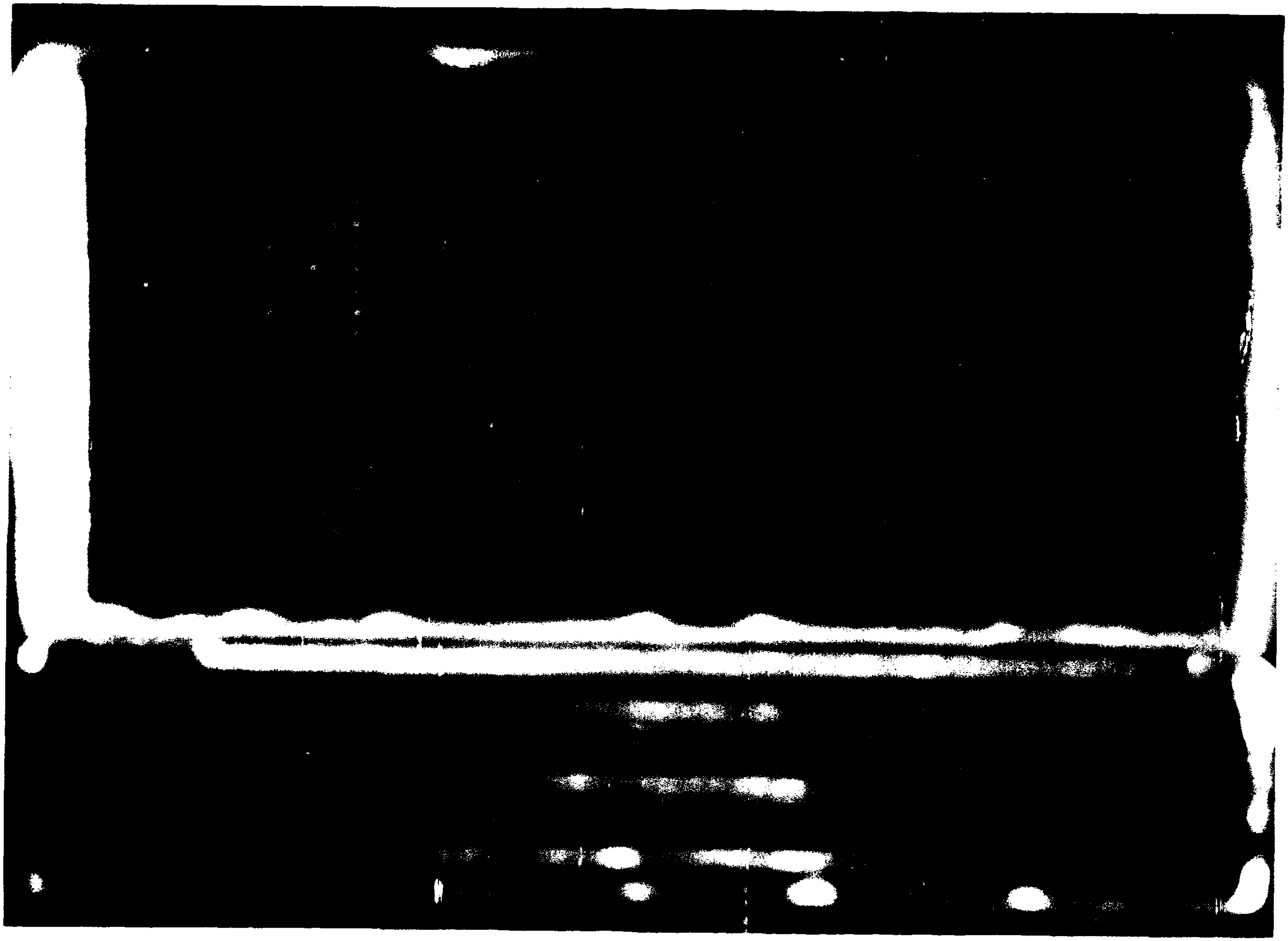


Figure 2.3 Micro Switch Developmental Programmable Pushbutton Switch Display

LEDs to a 1mA time averaged forward current and to a power dissipation per switch of about three quarters of a Watt with 25% of the surface activated.

Production versions of the PPS, which are now referred to by Micro Switch as the Programmable Display Pushbutton (PDP), have not yet been tested. These units are still not considered by Micro Switch to meet the Burnette Engineering sunlight legibility specification but do appear to be visibly brighter than the prototype PPS devices.

The PPS developmental displays used a variety of different LED structures but had in common: 25 mil pixel spacings, a green 565 nm dominant wavelength emission and either a black coating or a mask with 16 mil diameter holes covering the LED surface. The display filter, which ended up being of the plastic absorption bandpass type for the production units, was mounted in the switch bezel so as to permit 45° off angle viewing of the display. The bezel moves with respect to the display during switch actuation. The top surface of the filter has a thin scratch resistant anti-reflection coating applied to it. Other optical surfaces are specular reflecting but also have anti-reflection (AR) coatings. The top surface of all of the switches, with the exception of the one pictured in Figure 2.3, had a medium or light matte finish which noticeably diffused the light emitted by the display.

Switch actuation on the Bowmar prototype MFPK pictured in Figure 2.2 is accomplished using switches centered in each of the front panel designated switch display areas. The switches are activated by pressing on a flexible plastic sheet which covers the entire 5x3 switch matrix surface. The switch implementation technique provides an audible click when activated, limited travel and a degree of tactile feedback. While this approach cannot fully duplicate the switch travel force characteristic designed into individual switches it does allow switch actuation to be felt. Even though the Bowmar touch panel surface is continuous, it is designed so that force applied anywhere near the center of the switch windows will cause activation, whereas pressing in the region of switch boundaries will not. In summary then, except for the differences in feel, the Bowmar approach is equivalent in functional performance to the Micro Switch devices.

Little is known about the optical design employed by Bowmar on their prototype MFPK display except for what could be determined by external observations and measurements. The display produces higher luminance outputs than any of the Micro Switch PPS units tested to date, but also has a much higher component specular reflectance. The top surface of the display and of its earlier concept demonstrator counterpart is matte finished. The plastic appears to be clear with little or no neutral density light absorption properties. Due to the diffusion of light by the matte surface the internal optical design of this display cannot be readily observed.

Luminance

Luminance measurement results for the Micro Switch and Bowmar displays are shown in Table 2.1. All readings were made using a luminance probe with an effective measurement diameter of 26.1 mils and a uniform spatial sensitivity profile. A second emitted luminance column is shown which gives the large probe average luminance values converted to an effective 16 mil diameter (i.e. 2 minutes of visual arc at a 28 inch cockpit viewing distance) using the equation

$$\Delta L_p = 0.75 \left(\frac{d_s}{d_p}\right)^2 \Delta L_s \tag{2.1}$$

where d_s = 26.1 mils and d_p = 16 mils. The emphirical factor of 0.75 accounts for the diffusing effect of the matte finish surface and is applied to all but two of the displays listed. Small area luminance probe measurements taken on the Micro Switch PPS, Serial Number MT, when averaged over the 16 mil diameter luminance averaging area, provided the basis for this factor.

Each of the displays listed in Table 2.1 actually have LEDs smaller than the 16 mil averaging area. This dimension was chosen because it is representative of the apparent size of pixels as seen on alphanumeric dot-matrix displays having center to center pixel spacings greater than two arc minutes apart. For these displays the perceived luminance, ΔL_p, of the individual dots, rather than the area averaged values applicable at higher resolutions, appears to determine the legibility of the display imagery (i.e. at least for the 5x7 dot font displays considered here). This phenomenon was particularly evident for the Micro Switch prototype PPS displays which continue to provide dim but legible dot images (i.e. marginal) under both simulated and natural 10,000fc sunlight viewing conditions.

The Bowmar displays measured represented two legibility extremes. An MFPK concept demonstrator display utilized physically separated yellow 5x7 LED arrays in two rows of four characters to form each switch display with a touch panel overlay to effect switching. The top surface of the display was a medium matte finished plastic with clear windows in a black rear surface coating to permit viewing the underlying displays. The display which is shown in Figure 2.4 was not designed to be viewed in direct sunlight. At the other extreme is a small green emitting dot-matrix LED display. This display was provided by Bowmar to demonstrate a unit which they consider to be satisfactory for use in sunlight readable bubble canopy aircraft MFPK applications.

The Bowmar prototype MFPK described previously and shown in Figure 2.2 falls between these two legibility extremes. Although no detailed

Table 2.1

Luminance/Luminance Uniformity Data

Description of Measured Displays		Number of LEDs Sampled n	Filter Type	Mean Emitted Luminance Measured $\Delta L_s(fL)$ d_s=26.1mil	Mean Perceived Luminance $\Delta L_p(fL)$ d_p=16mil	Coefficient of Luminance Dispersion D in % (1)	Positive Luminance Deviation from Mean $U_L$max in % (1)	Negative Luminance Deviation from Mean $U_L$min in % (1)	Comments
Micro	EL	35	BP(4)	23.7	47.3	26.7	+32.9	-62.0	
Switch	BK	34	BP	23.4	46.7	15.7	+26.3	-35.8	
PPS	EA	37	BP	22.3	44.5	19.7	+47.5	-23.7	
Develop-	EJ	44	BP	19.7	39.3	19.8	+32.3	-46.6	+ Not
mental	BB	34	ND(5) /CP(6)	14.9	39.6+	14.9	+28.0	-32.7	Diffused
	(%V)	(7)		(42.3%)					
Micro	MT	35	BP	85.1	170	16.6	+33.9	-31.9	$G_{MT/MT}$
Switch	MT(3)	35	BP	86.6	173	16.3	+32.7	-30.7	=.9960
PPS	(% Error)	(7)		(1.8%)					(2)
Protype	MN	35	BP	79.0	158	23.7	+44.3	-32.9	
	MW	35	BP	63.9	128	19.6	+53.4	-31.1	
	(%V)	(7)		(27.9%)					
	Luminance Setting		Clear						
Bowmar	1. Max	30	ND	29.4	58.7	12.2	+29.5	-21.2	$G_{max/min}$
MFPK	2. Min	30	ND	1.69	3.4	12.2	+30.2	-29.0	=.942
Demon-strator									
Bowmar	Green	31	Clear	326	866+	16.8	+23.0	-38.6	+ Not
Sample	CHOICE		ND						Diffused
Array									

Notes:
(1) See Appendix A for definitions of D, U_L max and U_L min
(2) G => Correlation coefficient between two sets of data measured on consecutive days
(3) Measured as an error check with a second photometer calibration
(4) BP = > Absorption Bandpass
(5) ND = > Neutral Density
(6) CP = > Circular Polarizer
(7) V = > Maximum variation of device values from the mean (100 x (Max - Min)/Mean).

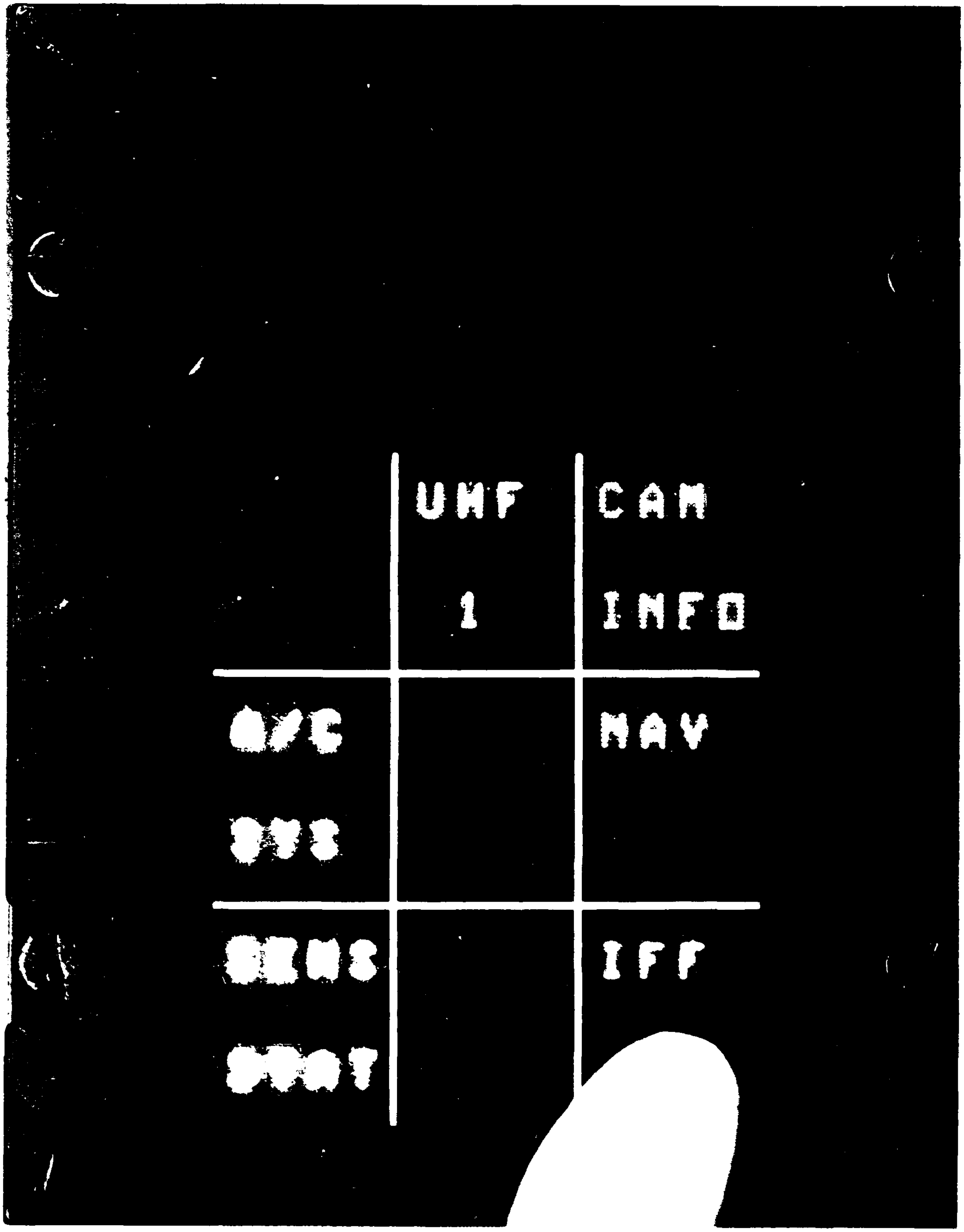


Figure 2.4 Bowmar Concept Demonstrator Multifunction Programmable Keyboard Display

measurements of this display were made during this investigation, its yellow LED arrays are much brighter than those used in the concept demonstrator MFPK display. The high reflectances of the display surfaces and an optical filter design which has not yet been optimized cause it to wash out well before the 10,000fc viewing condition of bubble canopy cockpits is reached.

Luminance Uniformity

The last three columns in Table 2.1 give measures of the luminance uniformity of the displays tested. Previous testing of dot-matrix displays (i.e. 16 mil pixel spacings), which had been assessed as providing satisfactory imagery, has shown that luminance uniformities, U_L, in the range of ± 30% and coefficients of dispersion, D, of 16% or less provide acceptable graphics image portrayals (i.e. see Appendix A for the definition of these terms).[5] It was therefore desired to compare the performance of the present devices with this standard.

In spite of the fact that 7 of the 10 displays tested exceeded the coefficient of dispersion limit and all but one exceeded the maximum uniformity limit, the displays have not been criticized for their non-uniformity when displaying alphanumeric characters and small graphic symbols (if applicable). The displays failing to meet these criteria limits do none the less appear quite non-uniform when all of the pixels in their arrays are energized, with the units having the greatest luminance deviations producing the most severe visual distraction.

The fact that the non-uniformity actually present in displayed messages is not particularly noticeable to the display's user is attributed in large part to the 20 and 25 mil spacings between pixels in the MFPK & PPS type displays, respectively, and to the resulting decreased ability to make direct side by side comparisons. Displaying the full array makes side by side comparisons easier, in that more pixels are available for comparison.

The present displays also have pixel dimensions which are 50% of the pixel spacing or less (i.e. pixel active areas of 25% or less). The dark areas between pixels therefore make visual comparisons more difficult than they would be if displays with pixel active areas approaching 100% (i.e. as is the case with some liquid crystal and TFEL displays) were to be evaluated. It is quite likely that displays of the latter type would require smaller pixel to pixel luminance deviations to achieve the same perceived uniformity results.

Optical Coupling

In addition to measuring the luminance values of activated pixels, changes in the luminance of adjacent unactivated pixels were monitored as display test legends were turned on and off. The luminance changes due to this procedure can theoretically be caused either by electrical or optical coupling between pixels. Electrical coupling was however noted on none of the displays tested and as a result the present discussion will concern itself only with optical coupling effects.

Referring to the Micro Switch PPS test pattern in Figure 2.5 and the Bowmar sample array pattern in Figure 2.6, optical coupling test points may be seen designated with an "X". Tables 2.2 and 2.3 give a summary of the optical coupling test results corresponding respectively to test sites located a minimum of two pixel spaces (i.e. pitch units) from emitting "character" LEDs and for test sites adjacent to emitting LEDs.

In Table 2.2 it should be noted that test sites centered in a "C" test character have couplings of 1.8% or less whereas those within an "O" character have 2.1% or more (i.e. except for the unique monolithic chip structure of the black coated PPS Serial Number BB). Examination of Figures 2.5 and 2.6 shows that the difference is that the character "C" has three fewer LEDs within 2.25 pixel pitch units of the central optically coupled LED location. This indicates that the fall off in optical coupling occurs rapidly as a function of increasing pixel spacings (i.e. 10 LEDs are between 2.83 and 3.16 pitch units of the coupled LED).

Referring to Table 2.3 it may be seen that adjacent and diagonal "on" pixel locations rapidly increase the optical coupling. In this case the one pitch unit proximity of the coupled LED to two activated LEDs on the "C" character but only one on the "I" character appears to cause the "C" coupling values to exceed 7.1% whereas the "I" values are less than 5.8%.

In the character "C" coupling location there are six activated LEDs within 2.24 pitch units of the coupled LED, four within 1.42 units and two within one unit. Even though there are six LEDs within 2.24 pitch units of the coupled LED for the "O" character in Table 2.2, the coupling in Table 2.3 is double that of the same PPS devices in Table 2.2.

The threshold of noticeability for optical coupling, based on previous studies, is approximately 5%. The coupling values of 7.1% and greater in Table 2.3 could therefore be observed, although still with some difficulty at contrast ratios of 10:1 or less. Prior study results have shown that the coupling between a single "on" LED and adjacent "off" LEDs is of the order of 2 to 3%.

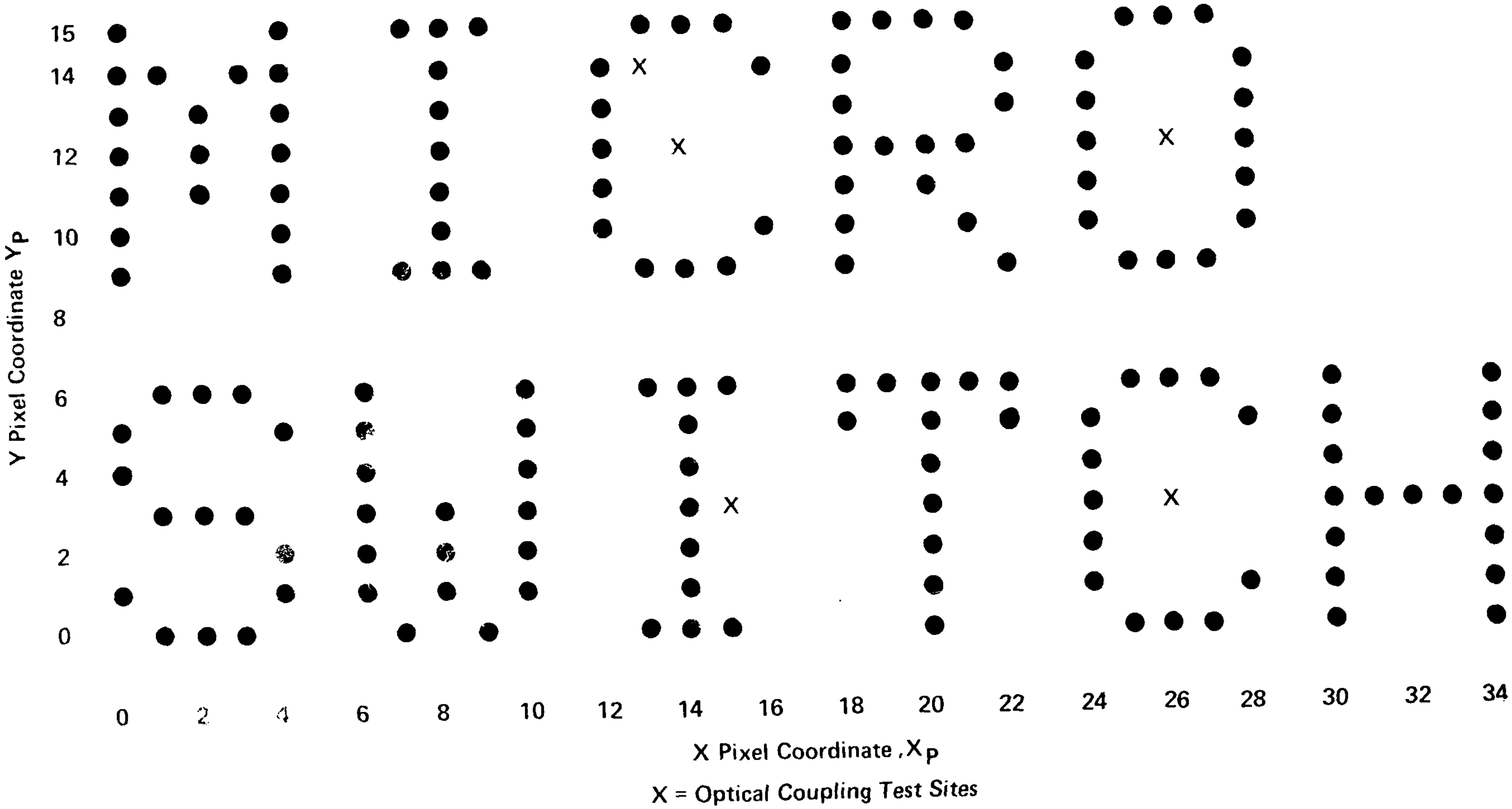


Figure 2.5 Micro Switch PPS Test Pattern

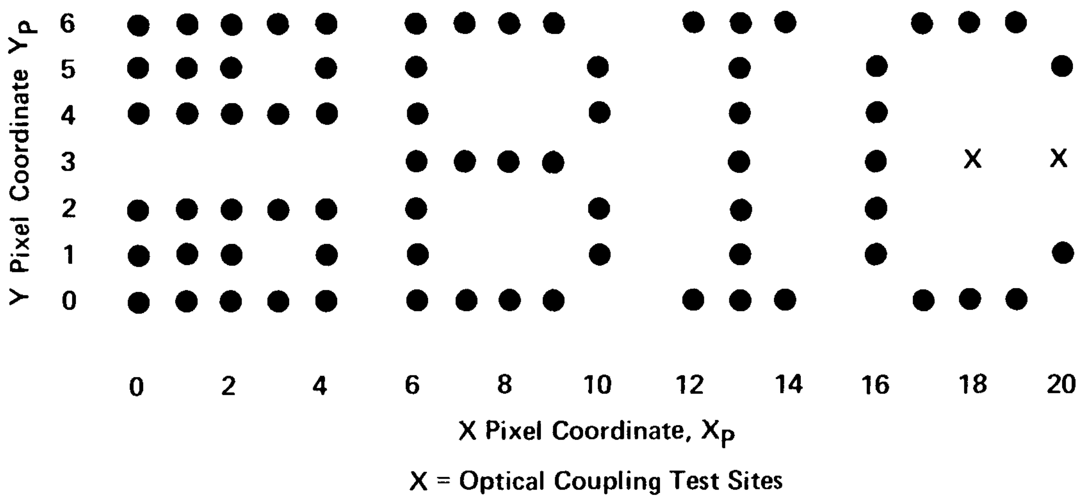


Figure 2.6 Bowmar Green LED Sample Array Test Pattern

Table 2.2

Optical Coupling--Spaced Pixels
(Two Pixel Spacing from Nearest Neighbor)

Type of Display		Character Activated (2)	Pixel Measured (X_p, Y_p)	$\Delta L_{oc}(1)$ in fL	$\overline{\Delta L}_s(1)$ in fL	% Optical Coupling $(\Delta L_{oc}/\Delta L) \times 100$	Comment
	EL	C	Off Area	0.45	23.7	1.9%	Between Pixels (14,11) & (14,12)
Micro Switch Develop-mental PPS	EL	O	(26,12)	0.5	23.7	2.1%	
	EL	C	(26, 3)	0.35	23.7	1.5%	
	EA	O	(26,12)	0.6	22.3	2.7%	
	EJ	O	(26,12)	0.8	19.7	4.1%	
	BB	C	(14,12)	0.22	14.9	1.5%	Black Sur-face Coating - No Mask
	BB	O	(26,12)	0.22	14.9	1.5%	
Micro Switch Prototype PPS	MT	O	(26,12)	2.8	85.1	3.3%	
	MN	O	(26,12)	2.1	79.0	2.7%	
	MW	O	(26,12)	1.7	63.9	2.7%	
Bowmar Sample Array	Green CHOICE	C	(18, 3)	6.0	326	1.8%	
	Green CHOICE	C	(20, 3)	11.0	326	3.4%	

Notes: (1) 26.1 mil diameter luminance probe readings (direct).

(2) Refer to Figures 2.5 and 2.6 to see nearby "on" LED locations.

Table 2.3

Optical Coupling--Adjacent Pixels
(One Pixel Spacing from Nearest Neighbor)

Type of Display	Character Activated (2)	Pixel Measured (X_p, Y_p)	ΔL_{oc}(1) in fL	ΔL_s(1) Adjacent LED(s) in fL	% Optical Coupling ($\Delta L_{oc}/\Delta L$) x 100	Comments
MT	C	(13, 14)	15	172	8.7%	2 LEDs Adjacent
MT	I	(15, 3)	13	226	5.8%	1 LED Adjacent
MN	C	(13, 14)	17	224	7.6%	2 LEDs Adjacent
MN	I	(15, 3)	9	170	5.3%	1 LED Adjacent
MW	C	(13, 14)	12	168	7.1%	2 LEDs Adjacent
MW	I	(15, 3)	5	186	2.7%	1 LED Adjacent

Note: (1) 5.6 mil diameter luminance probe readings (average of 6 or more readings).

(2) Refer to Figure 2.5 to see nearby "on" LED locations.

Optical coupling of the magnitudes indicated above are not considered to be a problem. All of the displays tested appear to be relatively comparable in this respect.

Contrast

Measurements to determine the contrast ratios produced under high ambient illumination conditions were restricted to displays which could be read in a 10,000fc incident illumination environment. All of the displays were viewed under this condition and only the prototype Micro Switch PPS units remained legible. In this context, it should be noted that the Bowmar sample array, while of high luminance, had no form of contrast enhancement. Thus, while this display could potentially be made more legible than any of the other displays tested (i.e. by treating its surfaces and through the use of filters), using only a clear cover caused it to wash out.

Table 2.4 shows the results of contrast ratio measurements made using a photometer oriented with its optic axis perpindicular to the display surface. An illumination source subtending an approximately 25° angle to the display surface was positioned with its center line at 45, 30 and 15 degrees from the display surface normal so as to produce a normally incident illuminance in each case of 10,000fc. Display pixel luminances were then measured with the display test pattern turned "on", L_S, and with it turned "off", L_{DS}. The display emitted luminance, ΔL_S, is the difference between these values

(2.2) $$\Delta L_S = L_S - L_{DS}$$

and the symbol (image) contrast ratio is given by the equation

(2.3) $$CR_S = \frac{\Delta L_S}{L_{DS}}$$

In addition to the "off" pixel luminance values, the luminance of the areas surrounding the pixels, L_{DB}, were also measured and are shown in the table. These values, when used with the "off" pixel reflected luminance value, L_{DS}, allow the contrast of the "off" pixel array in relation to the adjacent background areas of the display to be determined. In the form of an equation this contrast can be written as

(2.4) $$CR_{BS} = \frac{L_{DB} - L_{DS}}{L_{DS}}$$

Table 2.4

Contrast Ratios
(Contrast Ratios in 10,000fc of Illuminance as a Function
of the Light Source Angle of Incidence)

Micro Switch Prototype Serial #	Character Tested	Emitted Luminance ΔL_s(3) in fL	i	Reflected Pixel Luminance and Contrast (3) Source Angle of Incidence					
				$\theta=45^\circ$		$\theta=30^\circ$		$\theta=15^\circ$	
				L_{Di} in fL	CR $= \Delta L_S/L_{DS}$	L_{Di} in fL	CR	L_{Di} in fL	CR
MT	C	172	S	136	1.26	323	0.53	1231	0.14
			B	146	*	282	*	934	
	I	226	S	159	1.42	354	0.64	1121	0.20
			B	148	*	298	*	919	
MN	C	224	S	147	1.52	248	0.90	1021	0.22
			B	120	*	203	*	795	
	I	170	S	179	0.95	279	0.61	1107	0.15
			B	135		230		802	
MW	C	168	S	164	1.02	227	0.74	854	0.20
			B	120		165		835	*
	I	186	S	177	1.05	224	0.83	1059	0.18
			B	128		169		803	

Notes: (1) * => IRR > 4

(2) The illuminance incident on the PPS units was set to 10,000fc with the sensor surface substituted for the display faceplate surface during the measurement. This required beam illuminances of 14,142fc, 11,547fc and 10,353fc, respectively, for the source angles of 45°, 30° and 15° with respect to the display surface normal.

(3) The luminance was measured normal to the display surface using a 5.6 mil diameter luminance probe to sample several locations within the 16 mil diameter emitting aperture and the results averaged.

Unless this contrast can be made small in comparison to the display symbol contrast, the legibility of the dot-matrix array will limit how rapidly the display message can be read. This relationship has been previously defined by the author for segmented numeric readout displays in terms of an Image Rivalry Ratio (IRR) where

$$\text{(2.5)} \qquad IRR \overset{\Delta}{=} \left| \frac{\Delta L_S}{L_{DB} - L_{DS}} \right| = \left| \frac{CR_S}{CR_{BS}} \right|$$

and where image rivalry ratios satisfying

$$IRR > 4$$

assure adequate observer performance levels. Test conditions satisfying this criteria are shown with an asterisk in Table 2.4.

Consistent with observations of the prototype Micro Switch PPS units under both outisde and simulated sun illumination conditions, the contrast ratios shown in Table 2.4 vary from marginal at large source angles to unacceptably low for the 30 and 15^{o} source angles. Contrast ratios of two or higher are generally needed to assure at-a-glance viewing of alphanumeric imagery. Still lower contrast ratios can be tolerated without degrading the pilot's ability to correctly read the displays, but reading is likely to take more time. The criticality of display image contrast ratios is therefore functionally dependent on the task loading levels a crew member is likely to experience.

REFLECTANCE

Diffuse Reflectance

The diffuse reflectance, R_D, of a display surface is related to the ambient illuminance incident on it, E_A, and the luminance reflected from it L_{DD} by the equation

$$\text{(2.6)} \qquad L_{DD} = R_D E_A$$

where in general, the reflectance is given by the equation

$$\text{(2.7)} \qquad R_D = R_D(\Theta_S, \phi_S, \Theta_R, \phi_R, \lambda)$$

In other words, the reflectance is a function of the angles at which the light source and light receptor are oriented with respect to the surface and is also spectrally (color) selective. The reflectance R_D is expressed in units of foot-Lamberts (fL) per foot candle (fc) and in practical applications must be integrated over all angles from which light is incident to provide an accurate value. Since the illuminance E_A is also dependent on the angle of incidence, simple calculations of reflected luminance are not possible.

The term more frequently referred to as diffuse reflectance is a special case of the more general reflectance definition above and applies to surfaces where it is valid to ignore the angular dependence of reflectance. Such surfaces are known as Lambertian reflectors. White diffuse reflecting surfaces used as standards of reflectance usually qualify as Lambertian surfaces out to angles greater than 45° from the surface normal.

Specular Reflectance

The other type of commonly defined reflectance is referred to as specular reflectance. Specular reflectance is typified by the reflections from mirrors or smooth surfaces of any type. Like a mirror these surfaces allow the images of objects reflected from their surfaces to be clearly focused. The imagery produced is a spatially accurate but spectrally (color) attenuated reproduction of the original luminance pattern incident on the specularly reflecting surface. Mathematically the luminance incident on a specular reflecting display surface, L_A, is related to the luminance reflected by it L_{DS} by the equation

$$L_{DS} = R_S(\Theta, \phi, \lambda) L_A \tag{2.8}$$

where R_S has been used to denote the specular reflectance of the surface at the designated angle Θ from the normal, the angle ϕ from a designated reference line in the plane of the surface and at wavelength λ.

In general, optical elements used in display devices can have specular reflectances which are functionally dependent on all of the above variables. If, however, louvered or honeycombed types of filters are excluded, then the ϕ variation may be ignored for typical display filter materials. The angular dependence with respect to the normal to the display surface, Θ, and the spectrally selective properties are applicable to almost all practical display filtering techniques.

Discussion of Diffuse Reflectance

Diffuse reflectance as used here will encompass all non-specular reflections. The scattering and subsequent dispersion of light by rough surfaces and the scattering of light within translucent materials is responsible for producing diffuse reflections of incident light. Dependent on the sizes, shapes, concentrations, absorption characteristics, and spatial distributions of the particle or microstructure interfaces responsible for these reflections, the resultant angular reflectance distributions can vary dramatically from one material to another. Moreover while the physical origins of the reflections are understood, control over the resulting distributions is a matter of manufacturing art more than it is a science. As a result of this and the time consuming nature of precise measurements, diffuse reflectance tends to be described using approximate characterization techniques rather than with formal techniques, at least for display applications.

A simplified approach to diffuse reflectance measurement was used in the present investigation for the purpose of separating diffuse from specular reflection contributions in measurements employing a 10,000fc sun illumination source. The method involved making a measurement of the total reflected luminance at a specular reflection angle. The result of this measurement expressed in equation form is as follows

$$L_D = L_{DD}(\phi=180,\Theta) + L_{DS}(\Theta) = R_D E_A + R_S L_A \tag{2.9}$$

where L_D is the total reflected luminance of the display and L_{DD} and L_{DS} are the diffuse and specular reflection components previously defined.

By rotating the sensor about the surface normal to the display from an angle $\phi=180^\circ$ to $\phi=90^\circ$ or 270°, while maintaining the angle Θ from the normal constant (i.e. source is in $\phi=0^\circ$ plane at the angle Θ from the display surface normal), and again making a measurement, the display reflected luminance is

$$L_D = L_{DD}(\phi=90 \text{ or } 270^\circ,\Theta) \tag{2.10}$$

For a perfect light diffusing material or for a material diffusing equally in all directions at a specified angle Θ, the diffuse reflected luminance at $\phi=180^\circ$ will equal that at $\phi=90^\circ$ or 270°. Since by definition no specularly reflected light can be sensed at the latter angles, the above value of L_{DD} is the display's diffuse reflectance for an angle Θ from the normal.

Whether the above measurement approach is exact or approximate of course rests on the validity of the assumptions made. For most of the surfaces and materials used in displays, these assumptions are at least approximately valid. There are none the less a large number of diffuse reflectors where the method would produce grossly erroneous results.

Diffuse Reflectance Measurement Results

Using the technique described in the previous subsection, the Micro Switch developmental PPS units were measured at angles $\Theta = 15^{\circ}$ and 30°. The four switches, serial numbers EA, EJ, EL and BK, produced mean diffuse reflectance values at $\phi = 90^{\circ}$ of

(2.11) $$R_{DD}(\Theta = 15^{\circ}) = 0.081 \text{ fL/fc}$$

with a variation range of -0.03 to +0.021, switch to switch, and

(2.12) $$R_{DD}(\Theta = 30^{\circ}) = 0.019 \text{ fL/fc}$$

with a variation range of ± 0.01 switch to switch. The developmental unit, designated here as BB for black box, employed an LED surface coating rather than a mask in front of the LED array. The values measured for this unit were

(2.13) $$R_{DD}(\Theta = 15^{\circ}) = 0.052 \text{ fL/fc}$$

and

(2.14) $$R_{DD}(\Theta = 30^{\circ}) = 0.009 \text{ fL/fc}$$

Comparison of the above results show that the surface coated PPS produced significantly lower values of diffuse reflectance. Due to differences in the PPS filters used, the better performance cannot be attributed to the use of the LED surface coating alone and in a switch design optimized to accommodate fingerprints the overall result might also differ.

The values of diffuse reflectance for the four developmental switches, if multiplied by 10,000fc to produce reflected luminance values, are at least comparable to the reflected luminance values measured for the Micro Switch prototype switch series tested. Reflected luminance values for the latter switches are shown in Table 2.4 for contrast ratios.

The Bowmar concept demonstrator MFPK was also measured. Its diffuse reflectance was determined to be

(2.15) $$R_{DD}(\Theta = 26^{\circ}) = 0.026 \text{ fL/fc}$$

With compensation for the difference between the 26° and 30° angles, the diffuse reflectance of this display appears to be about the same as it was for the Micro Switch PPS units.

It is clear from the foregoing measurements that significant reductions in diffuse reflectance are desirable for both types of display.

Discussion of Specular Reflectance

Specular reflections originate at material optical surfaces and interfaces and have been mathematically accounted for using equations developed by Fresnel which are based almost exclusively on the material refractive index changes (spectrally dependent) which occur at these boundaries. In the case of transparent colored or neutral optical media, light entering the material can: be spectrally attenuated, be reflected from an internal specular surface and be reemitted adding to the light reflected by other surfaces. This reflection process is illustrated in Figure 2.7 for a luminance, L_A, incident at 45° on a display front surface. The figure shows a transmissive display media, such as an LED, located behind two plastic sheets of refractive index, n=1.45, which are separated by air ($n \cong 1$). The second plastic layer is representative of the protective covers/filters often placed over replaceable display components with the external optical element being a faceplate/filter.

Primary specular reflections from each of the surfaces in the display structure illustrated are labled by the luminance levels L_1 through L_6. Second and third order reflections are shown only for the faceplate. Dotted lines are used to show these reflections and the emissions are designated by the nomenclature L_{22} and L_{23}. For practical display filters the magnitudes of L_{22} and L_{23} can be neglected.

The minimum specular reflectance for a specular dielectric surface occurs for normal incident light and can be calculated using the Fresnel Equation[6]

$$R_n = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2 \tag{2.16}$$

Substituting refractive index values from the example in Figure 2.7, R_n=3.37% is calculated for all of the plastic/air interfaces. The bare LED surface reflectance is calculated to be 29.8%. This is reduced to 20% when a conformal coating is used and to 2-3% when antireflection coated. Since the Fresnel Equations for non-normal light incidence angles are quite complex due to the polarizing effects of material boundaries,[7] the minimum normal reflectance values will be used for purposes of illustration. The subscription R_n will also be dropped.

Light which is not reflected at a boundary is transmitted, therefore the transmittance, T, at a boundary is

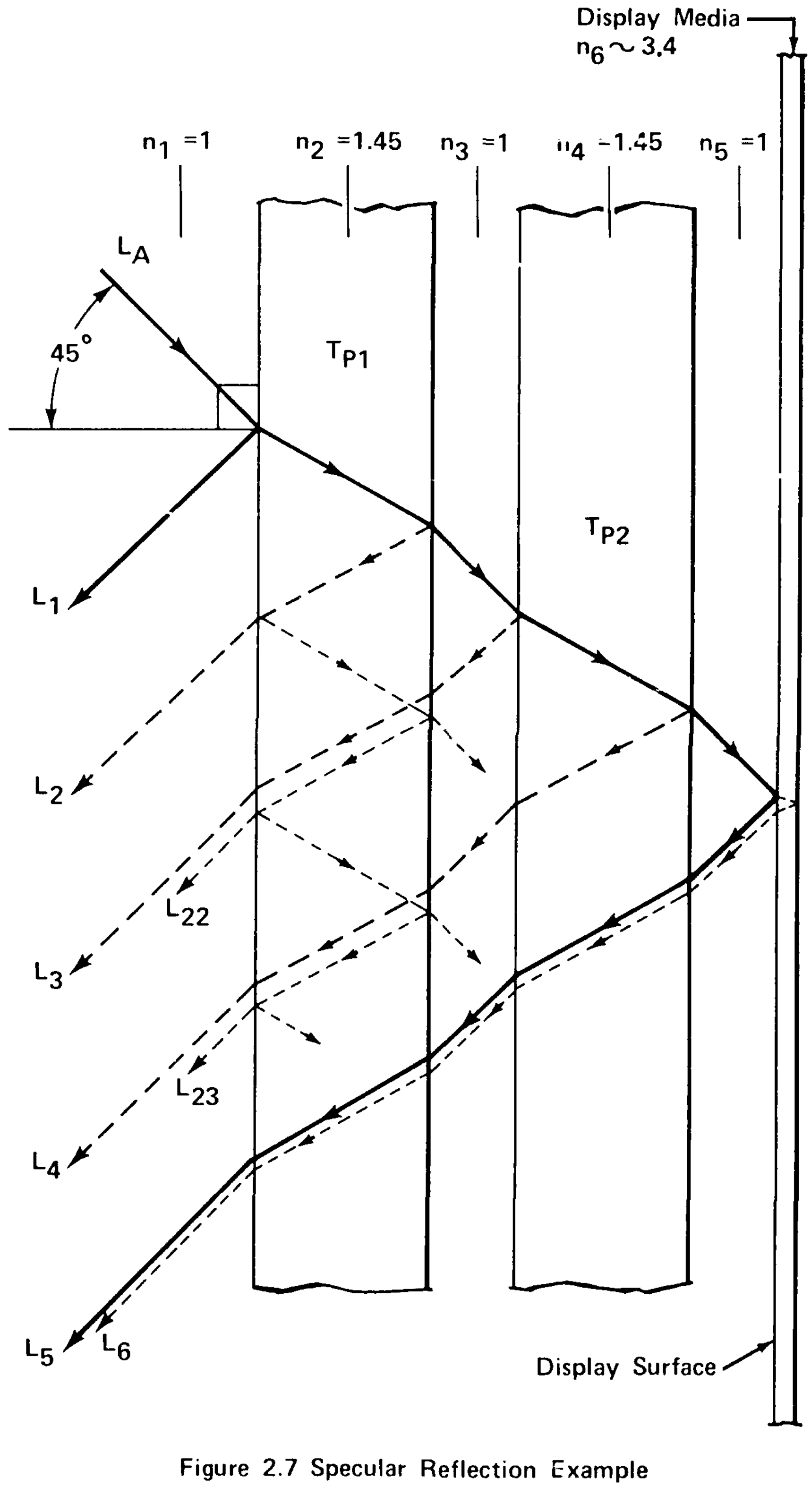


Figure 2.7 Specular Reflection Example

$$T = 1 - R \tag{2.17}$$

The image luminances reflected at each surface actually represent separate images but for thin closely spaced materials the displacement of the images at non-normal angles simple causes the images to be blurred together into a composite image, hence the total display reflected luminance, L_{DS}, is given by

$$L_{DS} = \sum_{i=1}^{6} L_i \tag{2.18}$$

Individually, the reflected luminances for the plastic layers and the display are:

$$L_1 = R\, L_A \tag{2.19}$$

$$L_2 = T\, T_{P1}\, R\, T_{P1}\, T\, L_A = T^2\, T_{P1}^2\, R\, L_A \tag{2.20}$$

$$L_3 = T^4\, T_{P1}^2\, R\, L_A \qquad (T_{Air} = 1 \text{ assumed}) \tag{2.21}$$

$$L_4 = T^6\, T_{P1}^2\, T_{P2}^2\, R\, L_A \tag{2.22}$$

$$L_5 = T^8\, T_{P1}^2\, T_{P2}^2\, R_{FS}\, L_A \tag{2.23}$$

$$L_6 = T^8\, T_{P1}^2\, T_{P2}^2\, T_{FS}^2\, T_I^2\, R_{RS}\, L_A \tag{2.24}$$

where the equation for L_2 shows the order in which filtering occurs. In these equations, T_{P1} and T_{P2} are the internal spectral transmittances of the plastic filters, R_{FS} and R_{RS} are respectively the front and rear surface reflectances of the LED, and T_I is the internal spectral transmittance of the LED.

Table 2.5 gives four examples of the reflectances and associated reflected luminances, L_i, using different filter materials and surface anti-reflection treatments for the display configuration shown in Figure 2.7. The reflectance and reflected luminance values in the first column apply to clear plastic cover plates with specular reflecting surfaces. In the remaining sets of data the front surface is assumed to have a matte finish with the internal filter surfaces antireflection (AR) coated (i.e. a value of AR coated reflectance of R = 0.6% average from 425 to 675 nanometers as claimed by the Tryolit Company, Inc. for plastic AR coatings is used) The distinction between the last three data sets is the front filter internal transmittance employed. Although the notations reference bandpass and high pass color absorption filter characteristics, neutral density filters of the same transmittance would produce essentially the same reflectance results.

Table 2.5

Display Specular Reflectance--Filter Techniques

i	Specular Plastic Surfaces (1) $T_{P1}=T_{P2}=1$		Matte Finish 1st Surface R=0.012 Other Surfaces AR Coated R=.006					
			$T_{P1}=T_{P2}=1$		$T_{P1}=0.30, T_{P1}=1$ (6)		$T_{P1}=0.14, T_{P2}=1$ (5)	
	R_i %	$L_i(7)$ fL	R_i %	$L_i(7)$ fL	R_i %	$L_i(7)$ fL	R_i %	$L_i(7)$ fL
1	.0337	118	.0120	42.0	.0120	42.0	.0120	42.0
2	.0315	110	.00586	20.5	.00053	1.8	.00011	.4
3	.0294	103	.00579	20.3	.00052	1.8	.00011	.4
4	.0274	96	.00572	20.0	.00051	1.8	.00011	.4
Σ 1 - 4	.1220	427	.02937	102.8	.01356	47.4	.01233	43.2
5 (2)	.1520	532	.18831	659.1	.01695	59.3	.00369	12.9
6 (2), (4)	.0156 .1676	54	.01928 .20759	67.5	.00174 .01869	6.1	.00038 .00407	1.3
Σ 1 - 6	.2896	1013	.23695	829.4	.03225	112.8	.01640	57.4
5 (3)	.0228	80	.02825	98.9	.00254	8.9	.00055	1.9
6 (3), (4)	.0229 .0457	80	.02835 .05660	99.2	.00255 .00509	8.9	.00056 .00111	1.9
Σ 1 - 6	.1677	587	.08597	300.9	.01865	65.2	.01344	47.0

Notes: (1) R = .0337 T = 1-R = .9663

(2) Conformal Coated LED: $T_{FS}=T_{RS}=0.20$

(3) AR Coated LED: $T_{FS}=0.03$, $T_{RS}=0.20$

(4) LED Internal Transmittance: LED Light: $T_I=0.95$
White Light: $T_I=0.40$

(5) LED Green Bandpass: LED Light: $T_{P1}=0.70$
White Light: $T_{P1}=0.14$

(6) LED Yellow High Pass: LED Light: $T_{P1}=0.95$
White Light: $T_{P1}=0.30$

(7) $L_A=3500$fL

(8) As a comparison, P-43 Phosphor CRT filters have the following nominal characteristics:

CRT Green Bandpass: CRT Light: $T_{P1}=0.13$
White Light: $T_{P1}=0.05$

The advantage of the spectrally selective filters is that their transmittances for the display color is higher than it is for the assumed ambient white light spectrum.

The last two rows of data in the table correspond to different LED surface treatments. Application of a clear conformal coating to an LED results in a specular reflection reduction due to refractive index matching to about 20%. The use of dyes in this coating allow it to also act as an absorption filter. The last row of data assumes the LED is antireflection coated.

For the purpose of comparison, an ambient luminance source of L_A=3,500fL has been used. This choice was made because display panels in bubble canopy cockpits are intentionally oriented to avoid specular reflections of areas outside the cockpit into the pilot's eyes. In spite of this precaution sun illuminated clothing and other internal cockpit surfaces can result in objects reflecting up to 3,500fL being present at display specular reflection angles.

Referring to the total filter reflectances shown in Table 2.5 it may be seen that two clear sheets of plastic in front of the display produce a reflectance of 12.2% (e.g. one sheet would provide a reflectance of 6.52%). This reflectance level is unacceptably high for use with any type of light emitting display intended for use in a cockpit, irrespective of the additional reflectance the display surface might add. The application of antireflection coating to the plastic and a medium matte front surface in column two reduces the reflectance of the filters to 3% and the addition of absorption filters in columns three and four reduce it to less than 1.5%.

Specular Reflectance Measurement Results

Measurements on the Micro Switch developmental PPS units, which have a matte surface reflectances like that used in Table 2.5, resulted in specular reflectance readings in the range of 2.8 to 3.8%, with switch to switch differences correlated at the 92.9% level using the sun source and reflectometer measurement techniques. Both techniques used for measurement resulted in area averaging over dimensions larger than a single LED and as a consequence the specular reflectance of the diffuse black mask is averaged with that of the LED visible through the holes in the mask. Comparing these results with the predictions in Table 2.5 shows that three fold improvements in the legibility of these displays should be possible through the application of contrast enhancement techniques.

The Bowmar MFPK demonstrator display was also characterized with respect to its specular reflectance properties. This test resulted in specular reflectance readings of about 11%. Although this value is lower than the worst case reflectance situations shown in Table 2.5, it shows that little if any contrast enhancement has been applied to this display.

FINGERPRINTS

The presence of fingerprints on any type of display poses a potential image legibility problem. Existing specifications for displays including low background reflectance CRT and dot-matrix displays assume that precautions will be taken to keep the displays free of fingerprints. Frequent cleaning and the use of gloves (i.e. a frequently ignored flight safety requirement) are generally assumed to be sufficient measures to minimize the occasional inadvertant imprinting of monitor type display faceplates.

The recent development of programmable legend switches and switch keyboards have elevated the importance of fingerprints as a display legibility criteria issue, in that touching the display becomes a necessity. Related attempts to implement transparent touch panel switch overlays (or other techniques) to make it possible to: switch information, designate targets and so forth by physically contacting the display faceplate will further aggravate the fingerprint problem.

Background

Prior to the development of the programmable switches, it had been recommended that a study of the effect of fingerprints be made a part of the PPS development effort. Since simple visual observations of fingerprints reveal a diffuse reflective component, it was subsequently recommended that the display developer apply a very light matte finish to the front surface of the switches as a means of masking the presence of fingerprints, (i.e. in the event no better method could be found for dealing with the fingerprint problem during the remainder of the development effort).

The objective of using a light matte finish was to cause the contrast between the reflecting filter surface and the fingerprint oil to be more closely matched. The introduction of a diffuse reflective component was intended to increase the reflectance of the filter surface at non specular viewing angles just enough to mask the diffuse reflective component of the fingerprint oil but yet not enough to significantly increase the reflected background luminance of this surface in high ambient illumination environments nor to significantly influence its light transmittance properties.

The fingerprint investigation actually conducted by the display developer was restricted to trial and error testing of different filters and matte surface treatment conditions. Developmental programmable switch displays delivered to the USAF utilized a medium matte finish and, although still quite transparent, it appeared subjectively to produce an excessive level of diffuse reflectance. Subsequent prototype switch displays exhibited considerably lower diffuse reflectance levels without noticeably degrading the ability to mask fingerprints. The production version of the switch display, although not measured, appears to provide an even lighter matte finish.

Fingerprint Characterization

In view of the high likelihood of a near term application of the programmable legend switches to aircraft, a preliminary investigation of the optical characteristics of fingerprints was initiated. To restrict the scope of this research, the investigation was confined to making area averaged diffuse reflectance measurements.

A Gamma Scientific Model 191A reflectometer, with the light source set at angles of 30° and 45°, was used to make the measurements. A black specular reflecting surface of known specular reflectance (i.e. nominally 4%) was used to calibrate the photometer system.

The test involved measuring the angular reflectance distribution of the front surface of a clear glass plate both with and without fingerprints. A Photo Research RS-1 white diffuse reflectance standard surface was also measured to provide a response comparison to a nearly perfect light diffuser.

Figures 2.8 and 2.9 show the measured angular reflectance distributions of the three surfaces. Reflectance values recorded as zeros (i.e. noise limited below 0.0001% reflectance) occurred for clear glass at +15° and smaller test angles. Values were measured for angles down to -25° for the -45° source angle and to -10° for the -30° source angle.

Examination of the two figures shows that the effect of fingerprints is: (1) to reduce the specular reflectance of the glass surface (i.e. the result of refractive index matching by the fingerprint oil) and (2) to spread the distribution by increasing the diffuse reflective component. As a comparison with the reflectance distribution of the diffuse standard shows, the overall reflectance characteristic remains highly specular.

A transfer function which characterizes the effect that fingerprints have when applied to a specular glass surface is also shown. The transfer function is calculated by dividing the reflectance of the glass with fingerprints by the reflectance of clear glass. If the transfer function

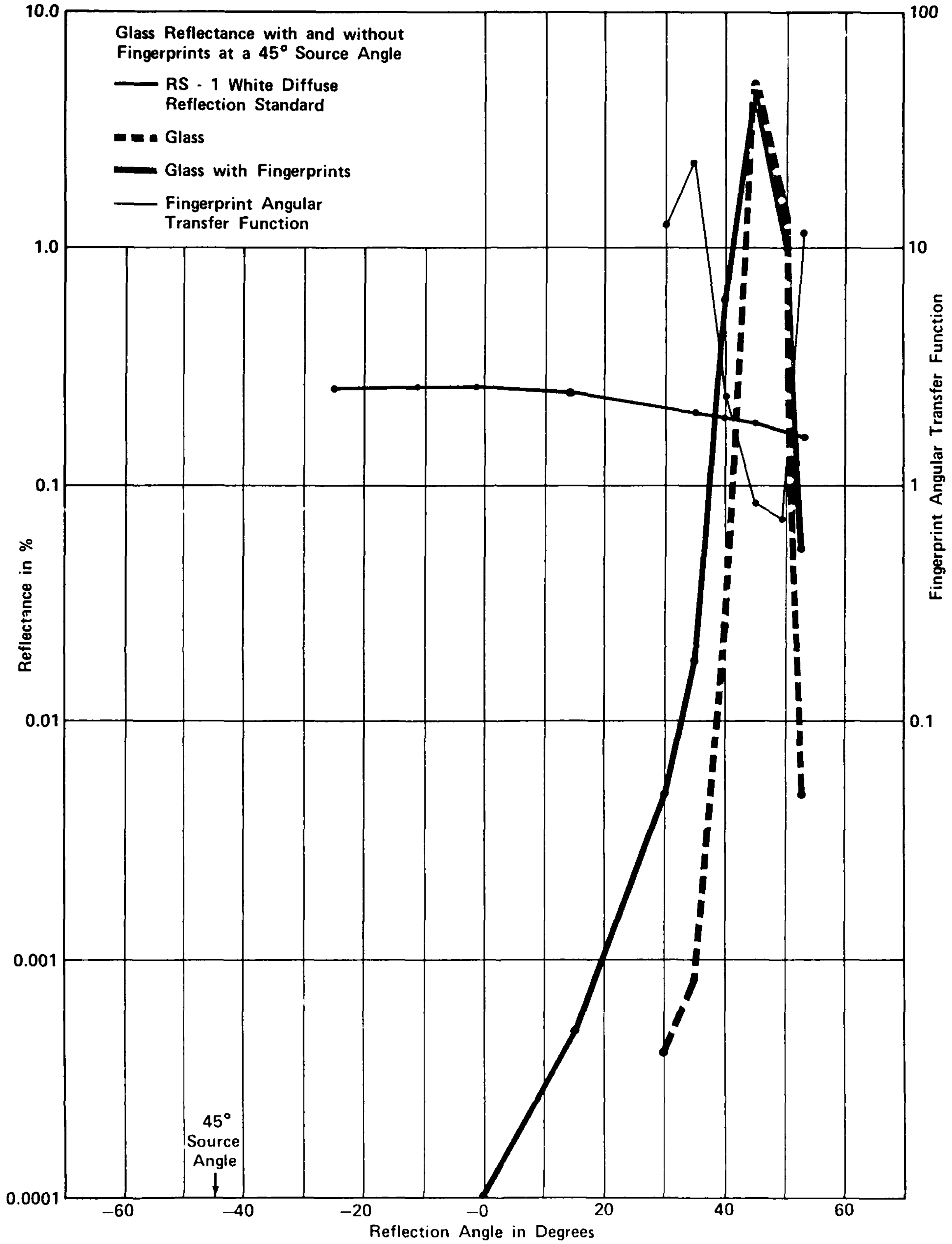


Figure 2.8 Glass Reflectance with and without Fingerprints at a 45° Source Angle

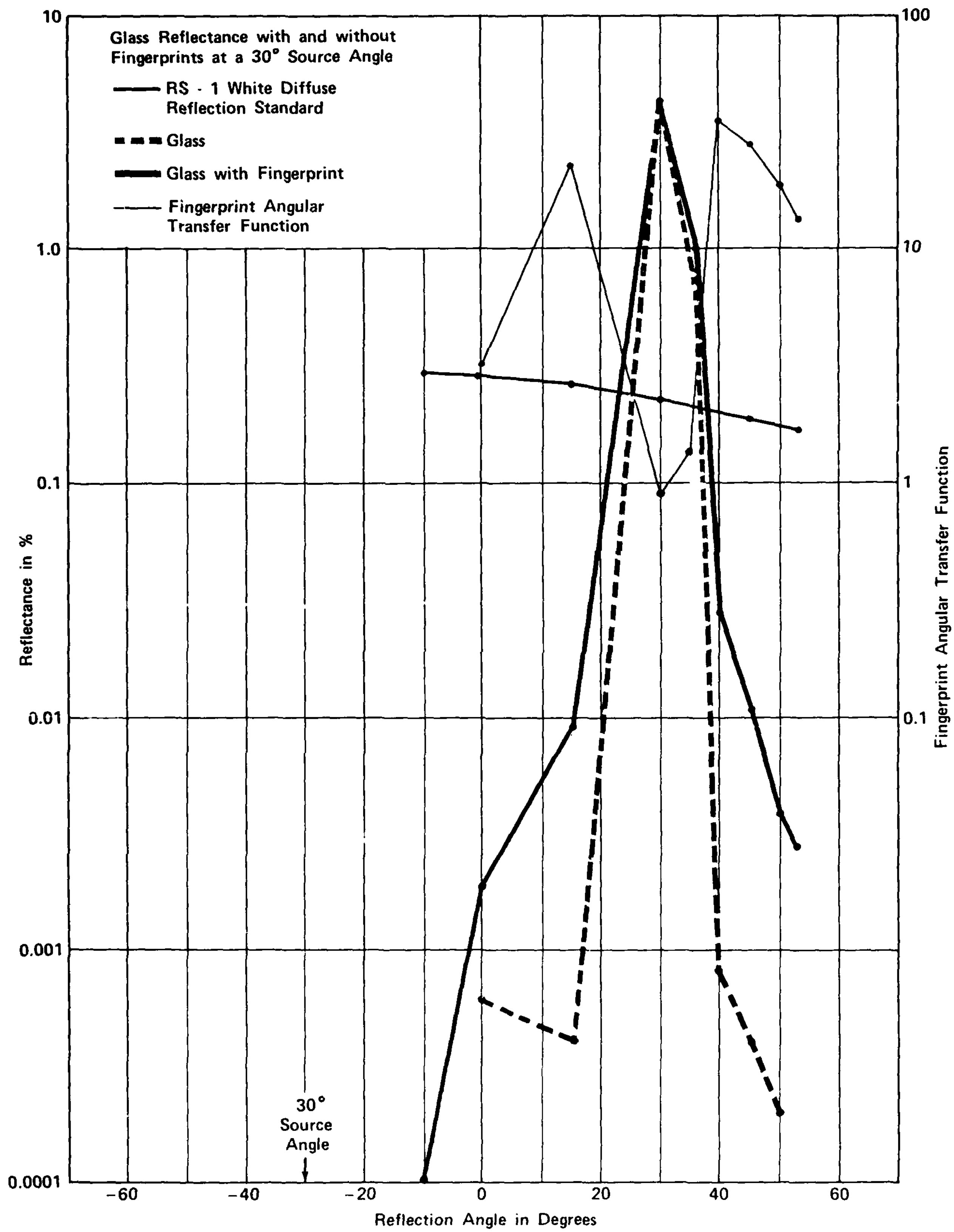


Figure 2.9 Glass Reflectance with and without Fingerprints at a 30° Source Angle

was constant and equal to unity, then it would have no effect on the reflectance of the glass. The transfer function of the fingerprint instead shows that a significant increase in reflectance occurs except in the immediate vicinity of the specular reflection angle.

As a further comparison, Figure 2.10 shows the reflectance distribution of fingerprints on glass to be intermediate between the distribution for a specular glass surface and that for a surface with a medium matte finish. This result verifies the earlier recommendations and would indicate that an optimal matte finish could be achieved using a light matte finish having a reflectance characteristic which nearly matches that of a fingerprinted piece of clear glass.

FURTHER RESEARCH

The visual criteria which must be satisfied to provide legible numeric and alphanumeric displays, are now relatively well established for individual displays. Burnette Engineering specifications prepared for the USAF for both of these types of information have proven to be satisfactory when displays meeting them have been used in operational USAF aircraft. The criteria used in these specifications are however dependent not only on satisfying the pilot's perceptual needs but also on satisfying his information recognition and identification needs.

As an illustration of the problem, investigations of threshold legibility levels for segmented numeric characters about 0.3 inch high have shown that a contrast ratio of 0.1 suffices to provide nearly perfect reading accuracies and comfort level viewing for pilots in a 10,000fc bubble canopy simulator illuminance environment. In spite of this result, which has been amply verified, contrast ratios for the same readouts in an actual bubble canopy aircraft installation require contrast ratios of 1.0 or more to produce comfort level viewing. The difference in these requirements is believed to be due to the severe time critical demands placed on a pilot's attention in the actual aircraft.

The numeric character display has a total possible character set of from zero to nine on each display digit, and with the exception of movements in decimal point positioning can be read with confidence by the pilot that only the magnitude of a number can be displayed. In other words, the possible interpretations of the displayed information are very limited.

Making the numeric characters smaller increases their contrast requirements in order to maintain equal legibility. Likewise changing from numeric to alphanumeric information (i.e. letters which form words or a combination of letters and numbers) also increases the contrast requirement. The larger symbol set, but more importantly the larger number

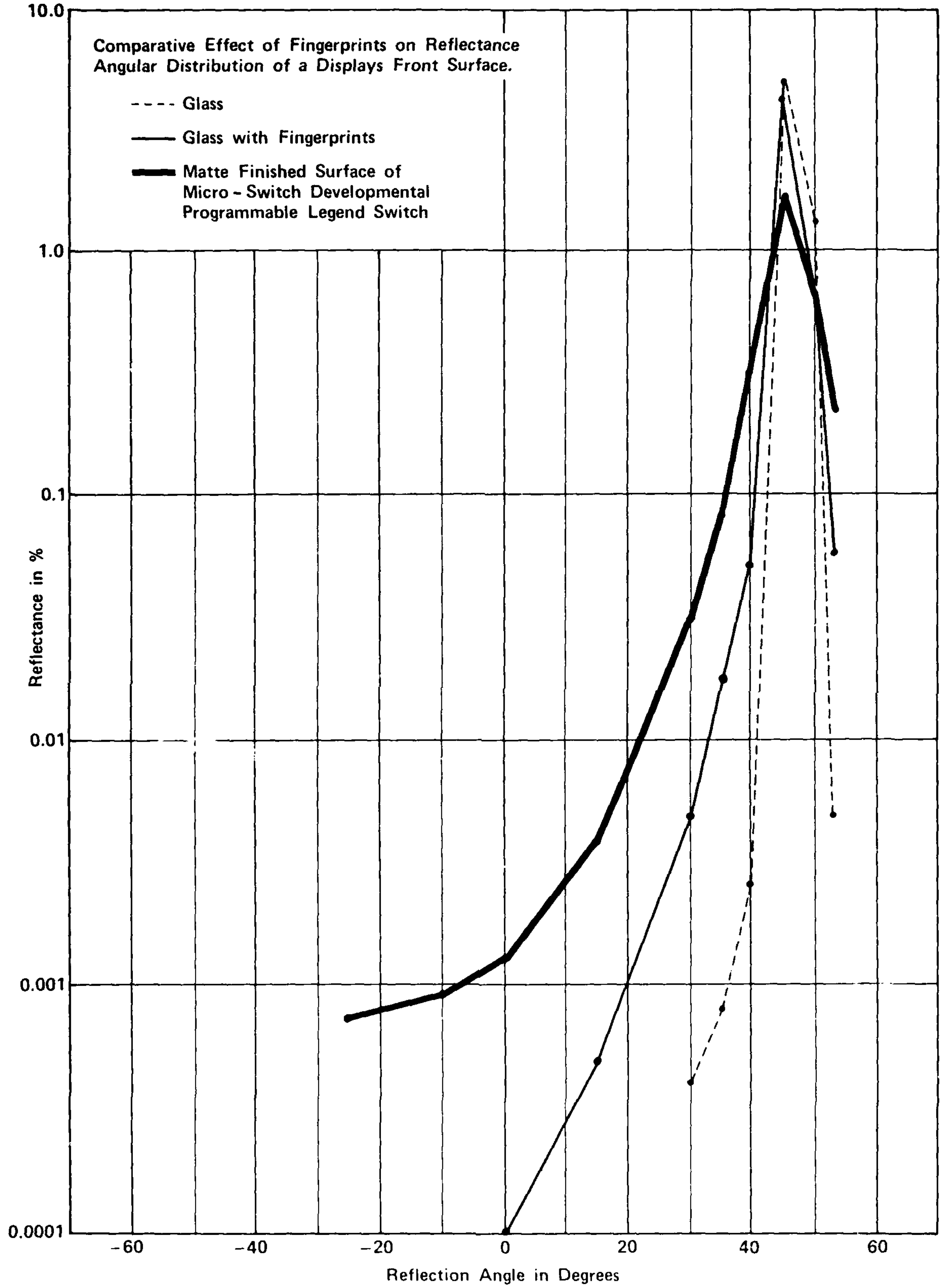


Figure 2.10 Comparative Effect of Fingerprints on Reflectance Angular Distribution of a Display Front Surface

of possible messages which can be displayed influences the contrast requirement. In other words information must be more legible to at least partially compensate for the added time required to process the displayed information.

A contrast ratio of about 1.5 suffices for 0.3 inch alphanumeric characters and the limited message sets employed in practical applications to date, whereas a contrast ratio of 2.0 is needed for the same message set displayed with nominally 0.18 inch high characters.

Information interactions in cockpits containing a number of displays just meeting the foregoing requirements and larger message sets pose the greatest threat to the adequacy of the current specifications in future aircraft. A complete cockpit and the capability to simulate high ambient illumination environment is necessary to evaluate the interactive aspect of information legibility requirements, and short of flight test, no such capability currently exists.

In current aircraft, the applications of message displays have been limited with most of the information which is presented displayed on dedicated, fixed location readouts. At the same time much of the other types of information used by the pilot has been presented on very high contrast electromechanical displays (contrasts of 12 to 18) and integrally illuminated panels. The recent increased use of lower contrast CRT displays has thus far been effective, yet much of the information portrayed still remains in the high contrast domain. The question is whether the legibility of these displays will remain adequate as additional low contrast displays are added to the cockpit and the information portrayed becomes more sophistocated.

Aside from the foregoing considerations, the existing problem area for numeric and alphanumeric display criteria is associated with its technological implementation, and more specifically in the area of optical design. The Micro Switch PPS displays tested are close to meeting the bubble canopy environment legibility requirements, and the production version of these devices may already be satisfactory. Conversely as the discussion of fingerprints indicates, improvements in this area are still necessary. The Bowmar prototype MFPKs delivered to the USAF and NASA exhibit higher luminance outputs than do the Micro Switch prototype PPS units and yet due apparently to inadequate optical design produce contrast ratios more than a factor of 10 below those of the PPS. This indicates that the methods necessary to achieve good display legibility are, as a minimum, not as yet widely known by manufacturers of militarized equipment.

It is concluded that a need exists to document and disseminate design and test technique information in addition to generalized notated versions of the existing specifications for numeric and alphanumeric displays. It is in addition concluded that a more in-depth investigation of fingerprints is warranted. In particular minimum additional testing should include a reasonable pilot population sampling of fingerprints and a more complete angular characterization of the optical distribution extremes encountered in the pilot population samples.

SECTION 3

GRAPHICS

RESEARCH OVERVIEW

The investigation of dot-matrix graphics display system performance criteria described here was made possible as a result of the availability of a 5"W x 4"H green light emitting diode (LED) advanced development model graphics display system developed by Litton Systems Canada Limited (LSL). This display system, which is designated the MMM ADM-I (e.g., Multi-Mode Matrix Advanced Development Model, Version I), was the culmination of an AFWAL/FIGR graphics display development program, started in 1969, to provide a display system capable of legibly depicting the high speed graphic imagery needed by a pilot to perform aircraft flight control tasks. Although technology spin-offs of this and other military/ NASA display development efforts have found earlier consumer, commercial and military applications, this display system is the first to meet stringent military requirements and is also the first to incorporate a complete high speed graphics image processing, generation and display capability.

In the late 1969, early 1970 time period, Burnette Engineering personnel then serving on active duty in the USAF conceived the fundamental LED modular display surface building block construction approach. This technique was utilized in early module development efforts by both General Electric for the USA and Litton, Data Systems Division, for the USAF. During the subsequent display system development by LSL, Burnette Engineering personnel, acting on behalf of AFWAL/FIGR, were responsible for the definition of the display system requirements and in collaboration with LSL participated in the selection and development of the display technology and specifications covering the legibility, information presentation, system architecture and system hardware/software interface. As a result of display technology spin-offs to USAF aircraft, the suitability of some of the design and test criteria developed and applied have already been verified. Others of the criteria were not capable of being tested until a system possessing the necessary unique characteristics of a dot-matrix display was available.

Although early attempts were made to simulate the high image quality punctuate portrayal characteristic of dot-matrix displays using a CRT display (i.e., using a small spot, multiple scan approach to form each pixel), the entire system capability was used up in forming accurate renditions of single symbols and alphanumeric characters.[8] Lacking a means of generating even modest static display formats, much of the specification development had to be accomplished by making theoretical extrapolations of the best available experimental data coupled with projections of anticipated human visual responses. Only in the case of alphanumerics were conventional test techniques applicable and these did not encompass questions of time dependent changes or of moving imagery.[4]

Research Objectives

The objectives of the present research were to assess the visual/optical and engineering performance of the developed display system for compliance with the design requirements established earlier, and to simultaneously assess the validity of those requirements. The methodology described in the introduction was applied to accomplish these objectives. However, unforeseen problems getting the flight simulator computers to provide reliable digital data at a 50 Hertz avionic data rate (i.e., consistent with that used in modern aircraft such as the F-16), resulted in a much more modest application of the bottom-up methodology than had been planned and hence in a less thorough investigation.

Research Summary

Figure 3.1 shows in block diagram form the scope of the research conducted in relation to an overall view of the program which in retrospect needs to be accomplished. The legend for reading this figure is shown in Figure 1.7. As illustrated, the top-down methodology was carried out through to the completion of a successful flight simulator evaluation of the ADM-I display depicting an electronic attitude director indicator (EADI) format. A photograph of this format as presented on the MMM ADM-I display is shown in Figure 3.2. The flight simulator experiment performed, the methods employed and the results obtained have been described previously and will not be repeated here.[3] Criteria developed as a consequence of the effort to get the display and simulator up and running will be described.

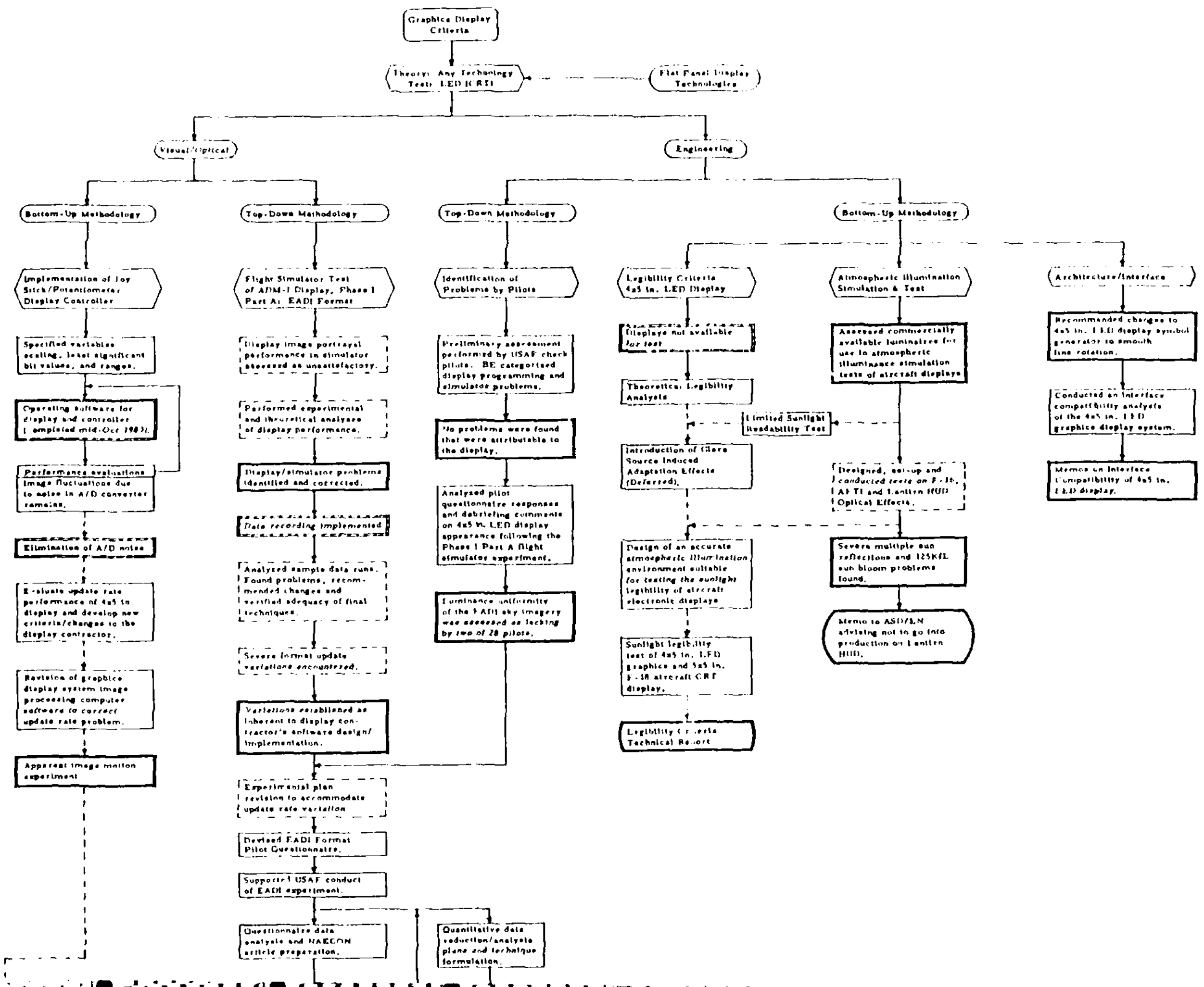
Other investigations shown in Figure 3.1 have been reported in the past and will not be dealt with again in this report.

EXPERIMENTAL EQUIPMENT DESCRIPTION

The experimental equipment employed to conduct the dot-matrix criteria research will be described here only to the extent that it is necessary to understand the results obtained. References are provided to more detailed published descriptions. Subject to the above considerations, the dot-matrix display, the flight simulator and the simulator-display interface will be described.

The primary intent of the descriptions which follow is to provide a background for understanding the display system operating anomalies encountered during the course of setting up and running the flight simulator tests of the MMM ADM-I display system's performance. Due to limitations on the types of testing possible within the limited duration of this research and restricted access to some aspects of the display system's design, the

1of2



Graphics Display Criteria
Theory: Any Technology Test: LED (CRT)
Flat Panel Display Technologies
Visual/Optical
Engineering
Bottom-Up Methodology
Implementation of Joy Stick/Potentiometer Display Controller
Specified variables scaling, least significant bit values, and ranges.
Operating software for display and controller (completed mid-Oct 1983).
Performance evaluations image fluctuations due to noise in A/D converter remains.
Elimination of A/D noise
Evaluate update rate performance of 4x5 in. display and develop new criteria/changes to the display contractor.
Revision of graphics display system image processing computer software to correct update rate problem.
Apparent image motion experiment
Top-Down Methodology
Flight Simulator Test of ADM-1 Display, Phase I Part A: EADI Format
Display image portrayal performance in simulator assessed as unsatisfactory.
Performed experimental and theoretical analyses of display performance.
Display/simulator problems identified and corrected.
Data recording implemented
Analyzed sample data runs. Found problems, recommended changes and verified adequacy of final technique.
Severe format update variations encountered.
Variations established as inherent to display contractor's software design/implementation.
Experimental plan revision to accommodate update rate variation
Devised EADI Format Pilot Questionnaire.
Supported USAF conduct of EADI experiment.
Questionnaire data analysis and HAECON article preparation.
Quantitative data reduction/analysis plans and technique formulation.
Top-Down Methodology
Identification of Problems by Pilots
Preliminary assessment performed by USAF check pilots. BE categorized display programming and simulator problems.
No problems were found that were attributable to the display.
Analyzed pilot questionnaire responses and debriefing comments on 4x5 in. LED display appearance following the Phase I Part A flight simulator experiment.
Luminance uniformity of the EADI sky imagery was assessed as lacking by two of 28 pilots.
Bottom-Up Methodology
Legibility Criteria 4x5 in. LED Display
Displays not available for test
Theoretical Legibility Analysis
Limited Sunlight Readability Test
Introduction of Glare Source Induced Adaptation Effects (Deferred).
Design of an accurate atmospheric illumination environment suitable for testing the sunlight legibility of aircraft electronic displays
Sunlight legibility test of 4x5 in. LED graphics and 5x5 in. F-18 aircraft CRT display.
Legibility Criteria Technical Report
Atmospheric Illumination Simulation & Test
Assessed commercially available luminaires for use in atmospheric illuminance simulation tests of aircraft displays
Designed, set-up and conducted tests on F-16, AFTI and Lantirn HUD Optical Effects.
Severe multiple sun reflections and 125KfL sun bloom problems found.
Memo to ASD/EN advising not to go into production on Lantirn HUD.
Architecture/Interface
Recommended changes to 4x5 in. LED display symbol generator to smooth line rotation.
Conducted an interface compatibility analysis of the 4x5 in. LED graphics display system.
Memo on Interface Compatibility of 4x5 in. LED display.

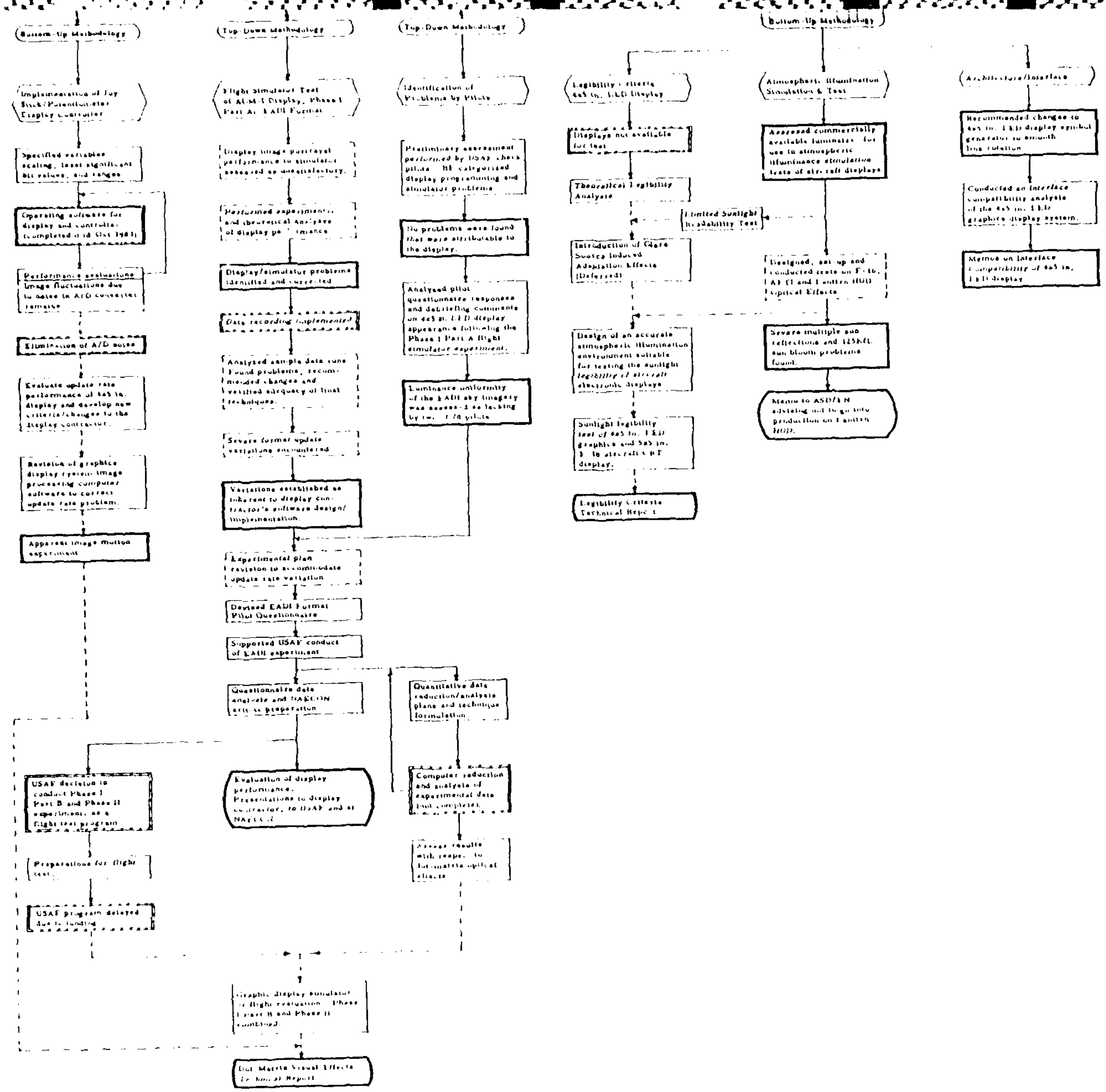


Figure 3.1 Graphics Display Criteria Block Diagram

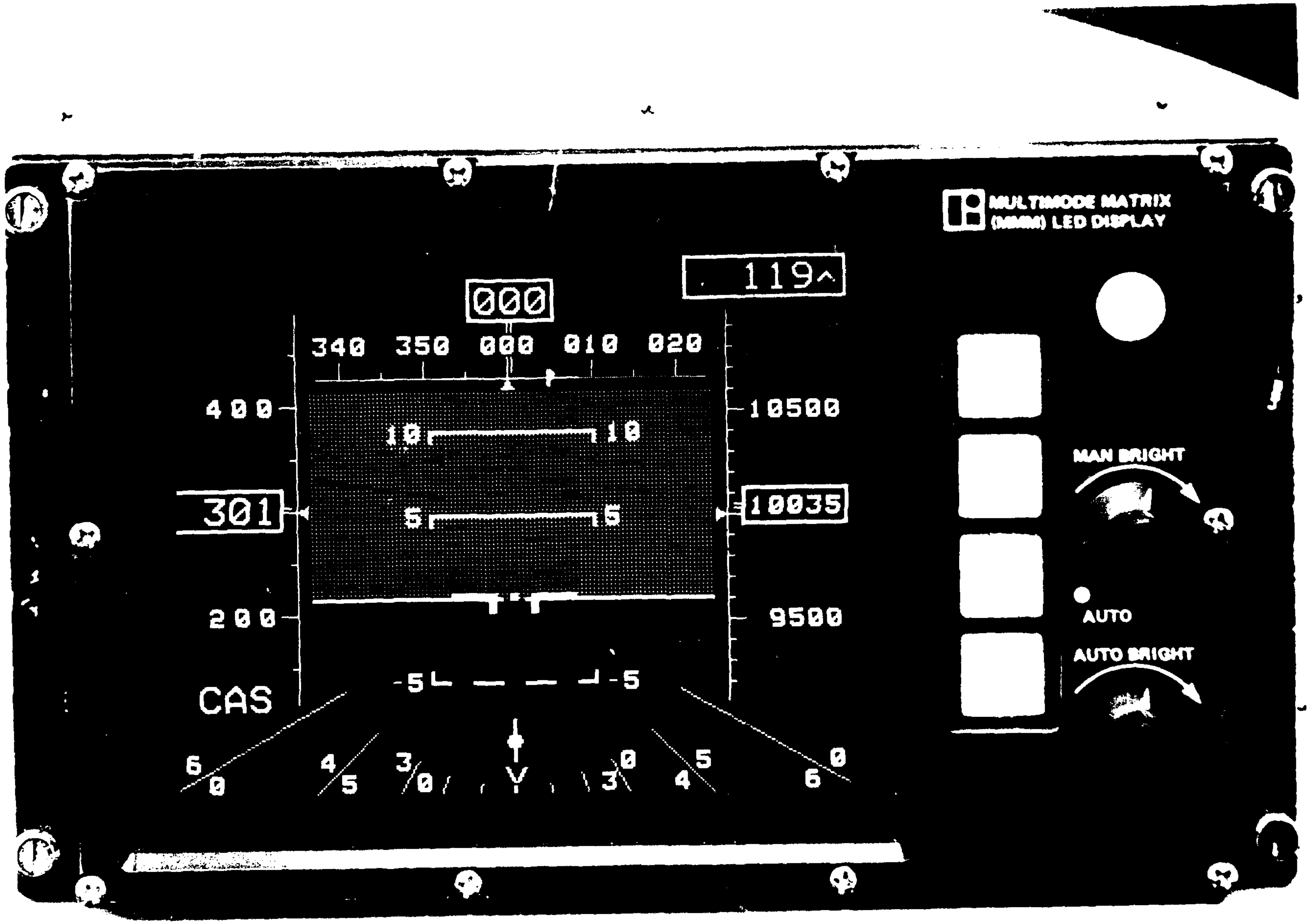


Figure 3.2 EADI Format Pictured on Litton ADM-I Display

sources of all of the problems encountered were not capable of being ascertained. It is known that the 20 millisecond (ms) avionic input data rate requirement stressed the capabilities of both the host computer and the display system, given the tasks these systems had to perform. Since the circuit technologies employed are state-of-the-art by aircraft standards, the limitations encountered are considered to be relevant as indicators of design criteria areas of interest for real-time military aircraft display systems in general and dot-matrix display systems in particular. The emphasis of the present descriptions will be on factors which influence the timing of the information displayed.

Dot-Matrix Display Unit

The display shown in Figure 3.2 is constructed using a 5W x 4H mosaic of nominal 1 inch square 64 x 64 pixel active area modules, which are abutted to one another on all four sides, to form a continuous 62.5 pixel/inch resolution display surface. Each module consists of a ceramic substrate mounted green light emitting diode array affixed to an alignment fixture that also serves as a mounting surface for the module's drive and address electronics, a solid structure for mounting electrical connectors and as a heat sink.

When installed in the display mainframe, the modules are refreshed in parallel at a 500 Hz rate from a dual bit map memory which is located remotely within the image generation and image processor electronics. During each 2 millisecond (ms) refresh period, 64 time sequenced lines of data are displayed, 1 vertical line at a time producing an approximately 31 microsecond (μs) maximum pilot exposure period to each pixel on the display at the 500 Hz rate (i.e. the same line is displayed simultaneously on all 20 modules hence 5 display height rows of pixels are capable of being displayed at any one time). During the display of each line of data on a module, information for displaying the next line of data is entered into the module address electronics from the remote bit-map memory, and at the end of the line display period is latched for display during the next line period, while a new line of data is again being provided to the module from the frame memory.

The timing for the refresh period and the individual line scan times is derived from a nominal 30 MHZ crystal controlled system clock and is therefore very precise. Similarly, the display information update period which acquires its timing from the same source, is also very precisely timed. In this case, while one of the dual memories is being used to refresh the display, the other can be updated with new information. At integer multiples of 2 ms, starting at 4 ms and extending through 40 ms, the functions of the two memories can be interchanged. The result of this is the ability to display picture frames having update rates between 25 Hz and 250 Hz, and yet because of the high 500 Hz picture refresh rate, the perception of flicker is not possible.

The luminance emitted by the display is controlled by pulses used to drive the LEDs. By sending pulse duration control signals simultaneously to the common driver enable line on each module, a uniform reduction in display luminance is achieved. The luminance control signal used for this purpose on the ADM-I display can be derived either manually using a brightness set control knob on the front panel of the display unit or alternatively using a manually trimmed automatic luminance control circuit designed to provide constant display legibility in changing ambient illumination conditions.

Image Generator and Processor Units

The display image generator in the ADM-I display system is illustrated in Figure 3.3. It consists of: (1) a symbol generator utilizing a 128 character alphanumeric/graphic symbol set stored in programmable read only memory (PROM); (2) a vector generator and (3) a sky generator (i.e., half luminance drive utilizing separate but AND gated drivers to display every other pixel on the dot-matrix display surface to form its image). Messages sent from the image processing computer control the operation of the three types of image generator. The symbol generator utilizes a three word (16 bits each) message consisting of a seven bit character code, for use with the symbol PROM, and two nine bit display surface pixel coordinates. Each word also contains a unique symbol generator address. Both the vector and sky generators utilize six word (16 bits each) messages consisting of vector X and Y initial coordinates, relative X and Y vector end point coordinates and an additional two words influencing the method of generating the vector. Additional encoding determines the quadrant in which the end point lies and whether sky fill or a vector is generated.

The image processor computer receives and interprets information sent to it by the host computer in the form of format initialization and avionic data. It also translates the received data into a form compatible with the image generator inputs, performs a built-in test function and transmits display timing measurement results and other performance related status information to the host computer. The image processing algorithms needed to create a display format using the image generator are stored in PROMs resident in the image processor as is the executive routine for operating the display system.

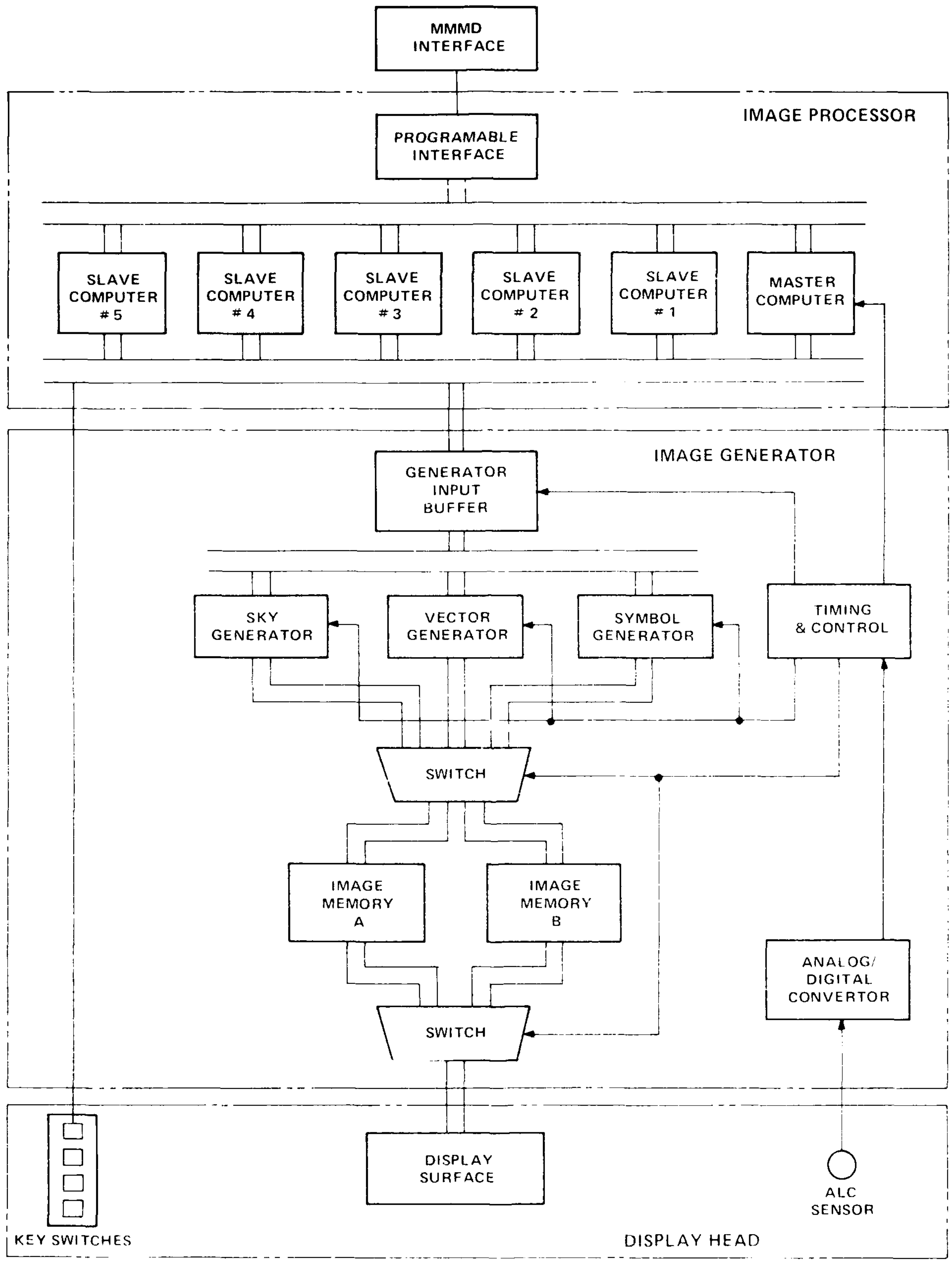


Figure 3.3 ADM-1 Block Diagram

The system architecture, which is also illustrated in Figure 3.3, consists of a master microprocessor and five slave microprocessors (i.e., all are Intel 8086) each having their own memory.[9] The master computer controls the programmable interface input/output (I/O) operations, transfers avionic data to the slaves and controls the transfer of data from the slaves to the image generator.

Display System Interface

The interface selected for use with the MMM ADM-I display system was a Digital Equipment Corporation (DEC) Model DR-11B direct memory access (DMA) interface. This interface was chosen because: it was compatible with several AFWAL/FIGR flight simulator host computers, it possessed the necessary data transfer rate capabilities, and because it had been used on an earlier concept demonstrator version of the ADM-I display system and was therefore familiar to both LSL and the USAF.

To facilitate the eventual transition to a Mil. Std. 1553 interface, Burnette Engineering had in an earlier effort taylored the ADM-I display system requirements for: data message structure, data word encoding techniques, data accuracies, information update rate requirements and to the extent feasible, even the units used, to make them as compatible as possible with the Mil. Std. 1553 techniques employed on the F-16 AFTI aircraft. These requirements were subsequently incorporated into a display system interface protocol which was prepared as the result of a joint effort by the USAF, Litton and Burnette Engineering.[10]

The intent of the present interface discussion is to provide only those details necessary to understand the data flow timing relationships present during the simulator tests. The reader is referred to the interface protocol specification for more detailed information.[10]

The protocol which resulted from this effort, involves four types of messages sent to the display as inputs and two types of messages sent from the display system to the host computer as outputs. The messages sent to the display consist of: (1) an initialization block message, (2) a data block message, (3) a request for short status message and (4) a request for long status message. The messages sent to the host by the display were: (1) a short status block message and (2) a long status block message. All of these messages contain a common message header with word one being a check sum, word two a message type identifier and display format designator and word three being a word count. The remaining words depend on the type of message, with just the 3 words sufficing for the status requests, 4 for the short status message and 20 for the long status message. The initialization and data block messages are of variable length depending on the picture format designated (i.e., EADI, EHSI, and so forth). In the case of the EADI format used in the flight simulator experiments, the initialization block message consisted of 10 words and the data block messages of 29. A more detailed description of the messages will be given in those instances where it is germane to the discussion. The reader is referred to the protocol for further general information.[10]

The PDP-11/50 (host) computer is responsible for initiating the transfer of messages either to the display or from it, using a single cycle DMA technique which results in the transfer of one word (16 bit) at a time between the host and display computers. The process is initiated when the host computer, via the DR-11B interface card, asserts a GO pulse. This action can occur either because the host is ready to transmit a message to the display system or as a consequence of sending an earlier status request message which results in the host monitoring the DR-11B to see if the ADM-I is ready to send a message. Referring to Figures 3.4 and 3.5, a transmission is indicated to the host when the ADM-I asserts an attention (ATTN) pulse and sets the DSTAT A, B and C lines to 0,0,1.

Upon receipt of the GO pulse, the ADM-I programmable interface initiates a cycle request (i.e., CYCL REQ is a direct OR gated pulse response to the GO pulse and hence is of the same 100 ns time duration) to the host DR-11B card and is also responsible for initiating a 20 μs inter-word time out period on the part of the ADM-I master computer when the input buffer is receiving data and a 50 μs inter-word time out when the output buffer is transmitting data. During the allotted time out period, the host computer is supposed to retrieve a new message word from the input buffer, if it is in the receive mode, or it is to load a display status word into the output buffer and reset the DSTAT A, B, C lines to 0,0,0 if it is in the transmit mode. In both cases the successful completion of the data transfer is to be indicated by the PDP to the ADM computer by pulsing the ENDCYCL (i.e., end of cycle) line. A failure by the PDP to transmit this signal is supposed to cause the ADM-I computer to: (1) treat the transmission as if it were complete; (2) revert to the receive mode (i.e., if in the transmit mode) and ignore any further transmissions by the PDP DR-11B interface card; (3) flag a time out error on the DSTAT A, B, C lines, and (4) assert the attention signal (ATTN). The attention signal is also pulsed by the ADM computer in the receive mode when more than 200 words have been received during one DMA cycle.

When the ENDCYCL pulse is generated by the DR-11B it triggers a flip-flop which in turn induces a low to high transition on the INTRO line of the ADM-I master computer. If this occurs during the allotted time out period, then the ADM-I master computer generates an interrupt which

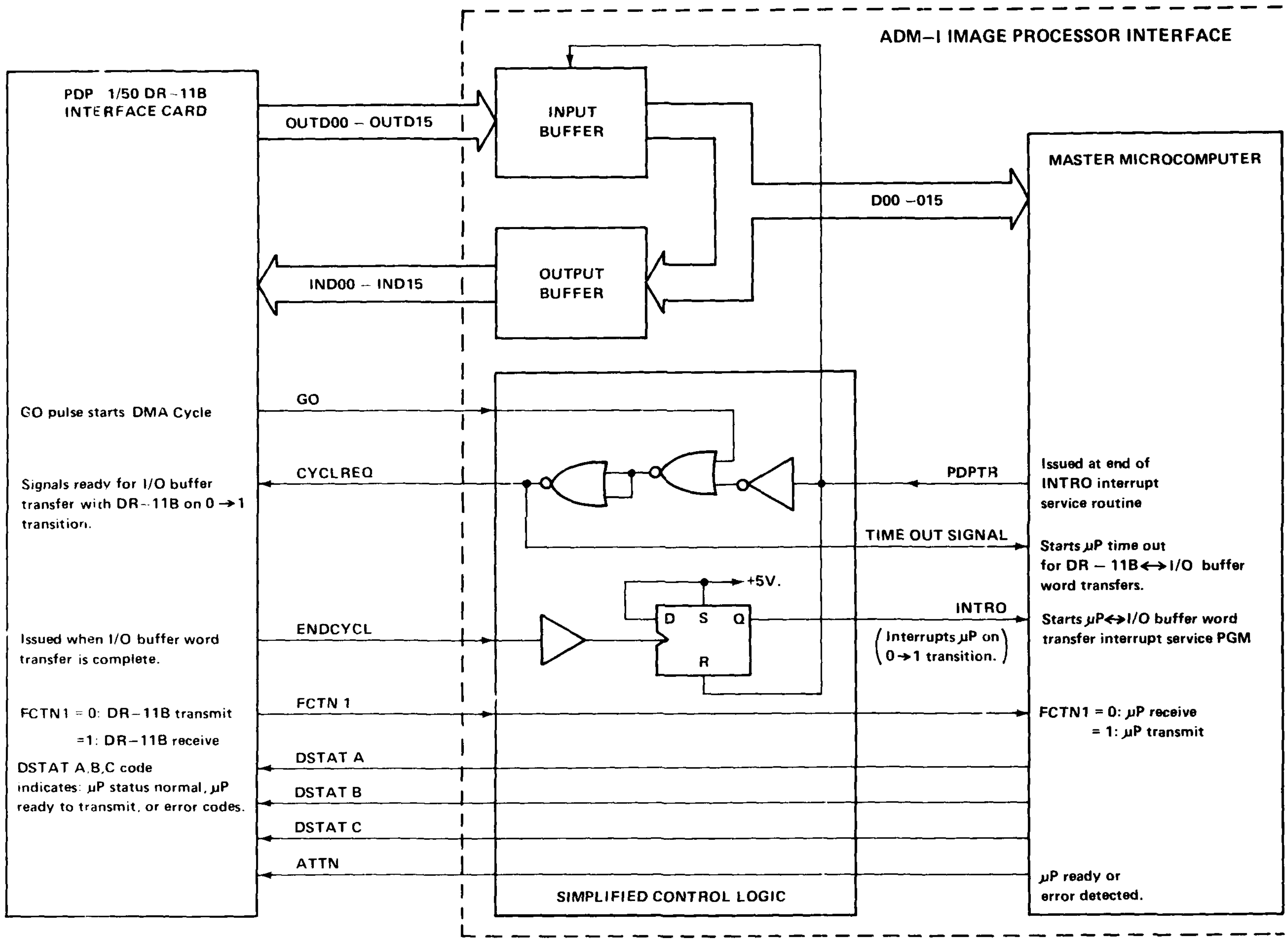
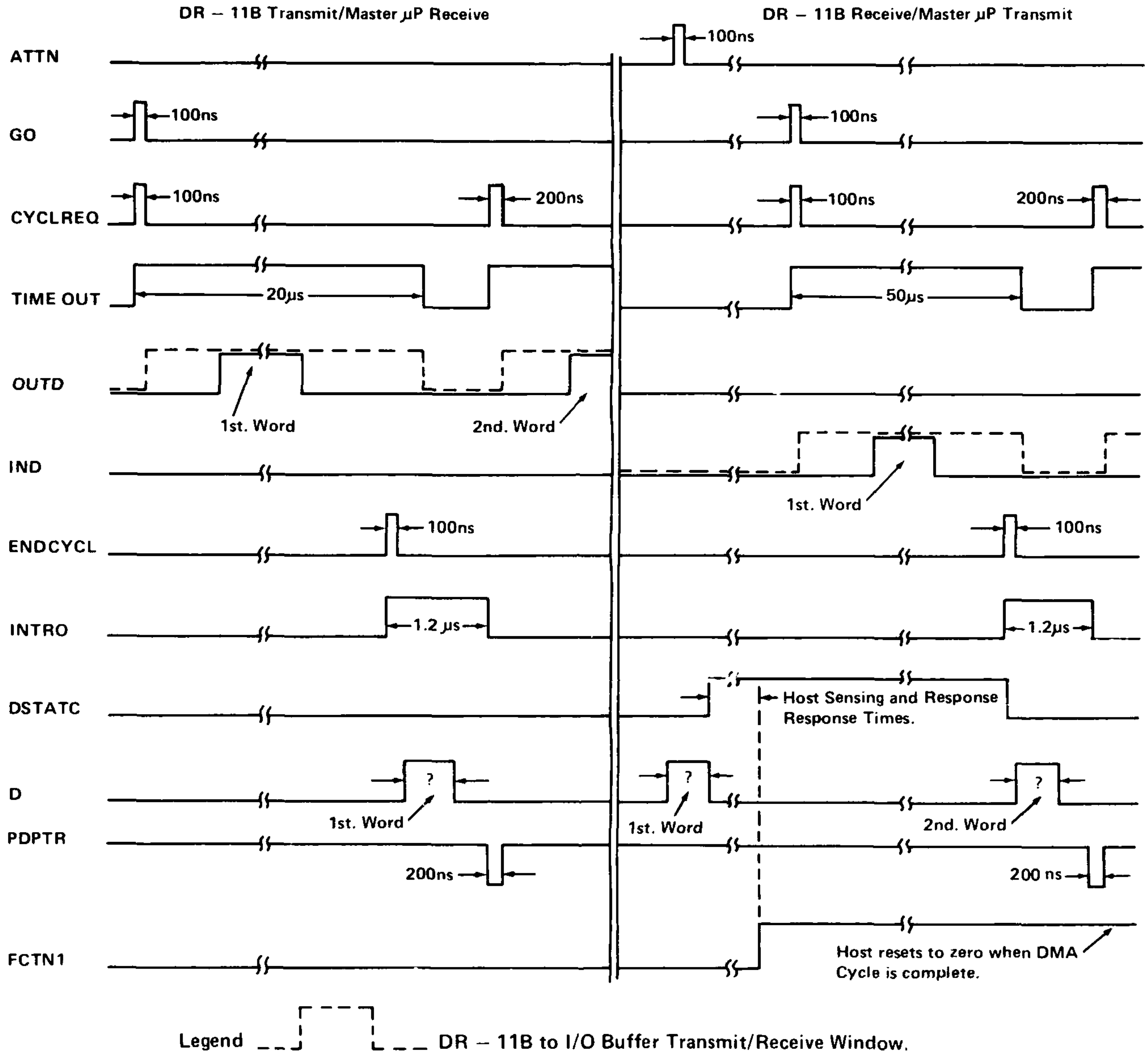


Figure 3.4 Simplified Display Interface Diagram



NOTE: Word count = 0 concludes μP DMA Transmit Cycle and causes ATTN to be pulsed to notify the DR – 11B.

Figure 3.5 Display System Interface Signal Timing transfers control to the applicable data receive or data transmit interrupt service routine. Dependent on whether the FCTN 1 line is set low or high by the host computer at the time of the interrupt, the interrupt service routine is, respectively, to transfer the last word stored in the input buffer by the host computer into the ADM-I master computer; or it is to transfer the next word to be sent from the master computer to the host into the output buffer. In either case, when the interrupt service routine ends, an active low signal is placed on the master computer's PDPTR (PDP transmit) line for a minimum of 200 ns. This low state signal performs three functions. To perform the first function it is inverted and ORed with the GO line to produce a new cycle request pulse. This pulse is responsible for initiating word transfers, (i.e., after the first is initiated by the GO signal) between the host computer's input or output buffer. The low PDPTR signal is also supplied to the programmable interfaces input buffer where it is said to cause data to be read from the DR 11-B (i.e., although its actual function, be it: reset, enable, etc., is not defined). The final function performed by the low PDPTR signal is to reset the flip-flop to permit the ENDCYCL signal to again interrupt the microprocessor during the next word transfer cycle.

Host Computer System

The flight simulator computer system consisted of the previously mentioned DEC PDP-11/50 computer which serviced the cockpit controls and displays, the experimenter's console, and the experimental data recording function. This computer hosted the experimental executive control program and was interfaced to a slave PDP-11/55 via a DEC DA-11B/J interface. The slave computer hosted the simulator's aeronautical model, receiving pilot control inputs from the PDP-11/50 and transmitting back aircraft flight variable values. Variable scaling and the software driver for the ADM-I display also operated on the host computer.

The executive routine ran in the continuous loop illustrated in Figure 3.6 with each block shown performed in time sequence. The loop software architecture was selected in order to provide maximum operating speed. An interrupt driven system would have provided the desired timing control but due to interrupt overhead times was assessed by Systems Control Technology, who programmed the software, as too slow to allow all necessary functions to be executed at 25 and 50 Hertz rates. The open loop control technique actually used restricted the executive to interfacing with: the system common area of the PDP's on-line RAM memory, the ADM-I display, the PDP-11/55 aero model, the conventional instruments/controls I/O buffers, and the data conversions/formating calculations associated with these tasks. Lower

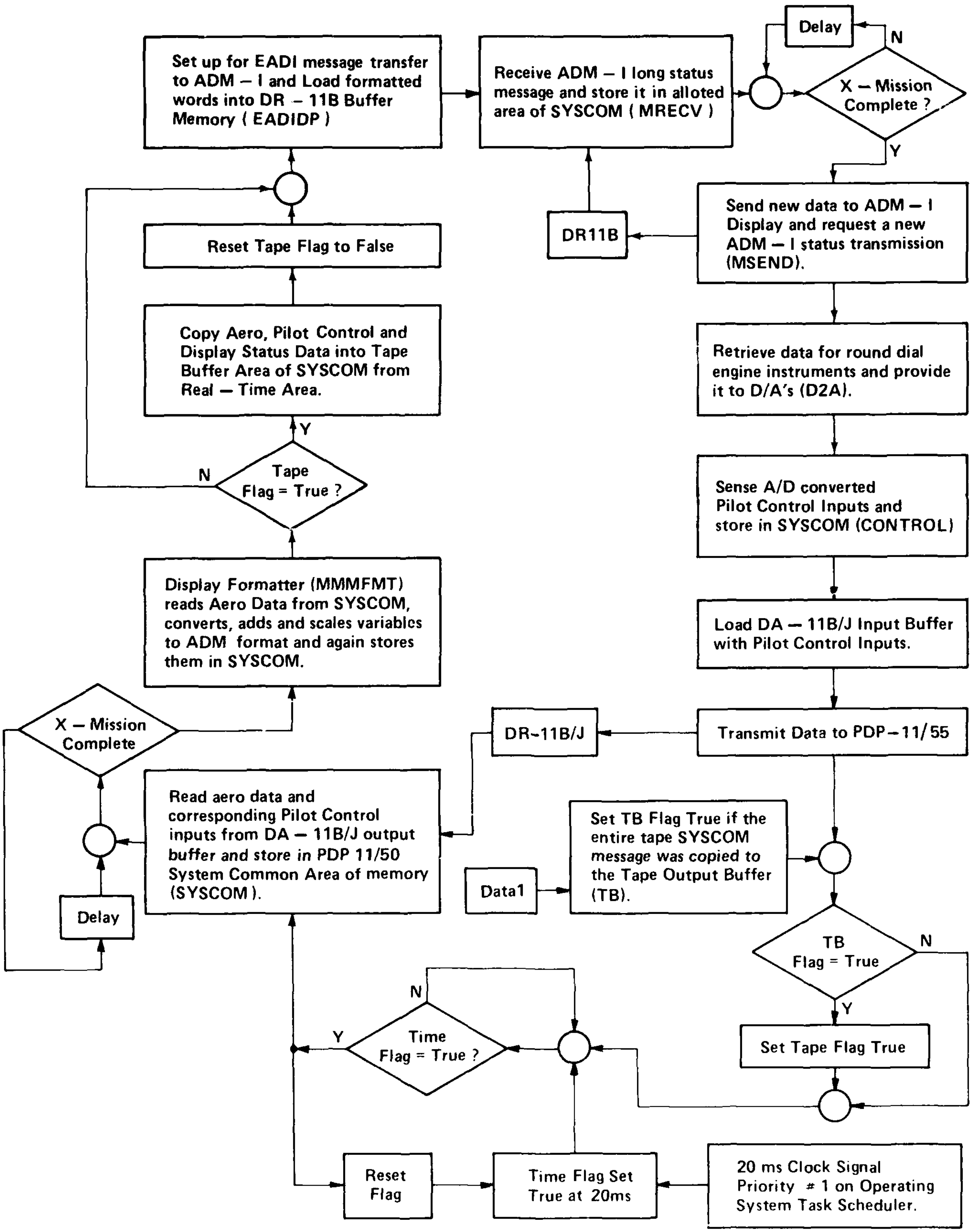


Figure 3.6 Executive Program Task: Priority #2 (DAMAST)

priority software tasks, scheduled at slower rates, provide data to and retrieve it from the buffers the executive program operates on. Thus while this operating procedure can result in repetitive handling the same data in sequential avionic periods (i.e., in that the buffer data has not changed) it should also cause nearly the same execution time for each cycle through the loop.

The data recording task shown in Figure 3.7 also operates as a loop but has a lower PDP operating system priority. As a consequence it is supposed to be able to run only when the executive program is in a delay mode. The PDP-11/50 central processor unit (CPU) time associated with this task is ostensibly restricted to the tape drive output buffer, with the transfer of data from the buffer to the tape drive unit controlled as a DMA transfer which does not use CPU time.

Another lower priority function operating in a separate control loop is the experimenter's console data input/output function. This loop operates with a much longer period, but also has to steal time from the executive program. To provide the experimenters with the status of the ADM-I, a video camera was trained on the display and its output shown on a console CRT. This was done both to give the experimenters a better chance of monitoring visual effects seen by the pilot, but also because the CRT graphics image generators were incapable of displaying the same information shown on the ADM-I at a 50 Hz rate. While the lack of frame synchronization and the spatial line mismatch between the ADM-I and the RS-170 CRT display had been expected to produce beats and moire patterns, neither effect was observed, apparently due to: the 500 Hz refresh rate of the ADM-I display, to the persistence of the CRT and the very poor image reproduction characteristics inherent in the spread spot/bandwidth limited RS-170 image portrayals, respectively.

A single CRT which was operated by the CRT graphics image generator via a DR-11B interface but at a lower operating system priority than the one used to interface the ADM-I (i.e., a hardware priority based on bus attachment proximity to the CPU), was used to portray very limited alphanumeric experimental status information. In spite of the small amount of data portrayed, this function was still time consuming due to the low speed (i.e., "real time" limitations) typically associated with such generators (i.e., 2-5 Hertz).

The A/D and D/A conversion processes attendant to operating the electromechanical G-Force indicator and sensing the throttle, flaps and primary flight controller were also run in a separate software loop together with switch activated functions such as the speed brake. Again, due to its lower priority this function was not supposed to influence the executive program loop timing.

COMMENTS:

1. Data1 is called by PDP operating system when no higher priority task is running.
2. QIO is a DEC operating system call which sends the 512 Word (16 message) full output buffer contents to the tape drive via a DMA like transfer that does not use CPU time.
3. Freq[illegible]ntly interrupted task requiring two to eleven loops through DAMAST to complete DATAREC subroutine.

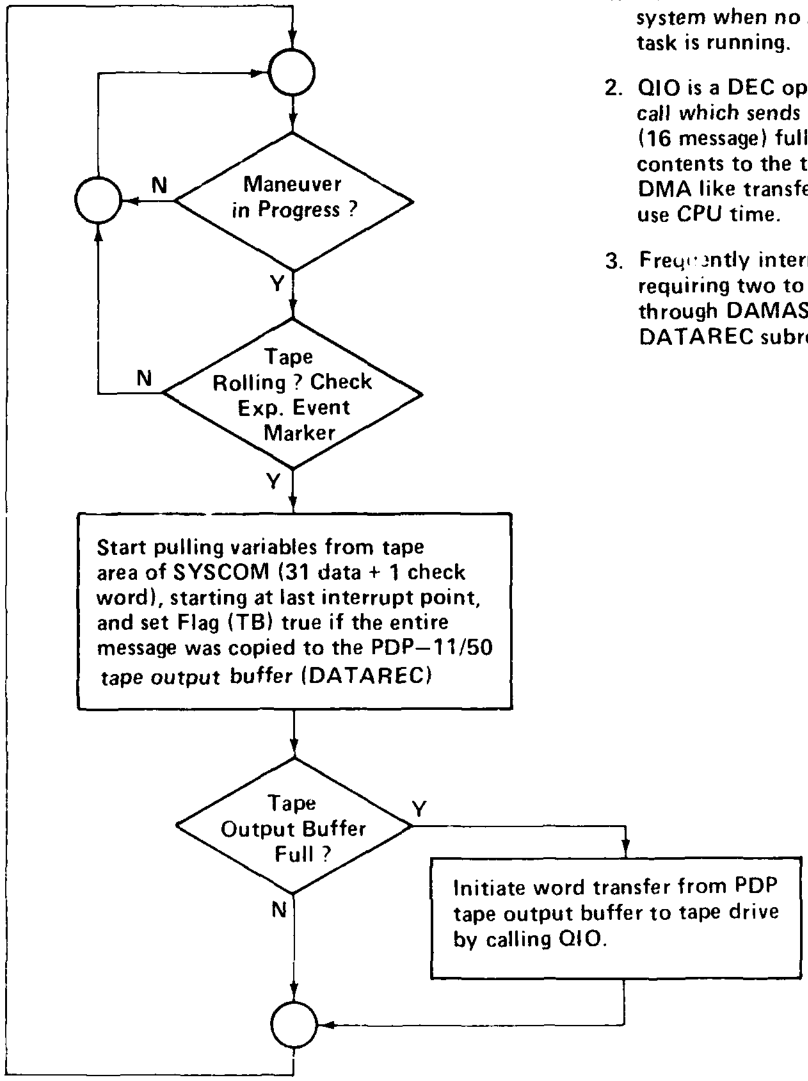


Figure 3.7 Data Recording Task (Operating System Scheduler Priority #3 (Data 1))

The primary unknown in the host computer system was the impact of the computer's operating system functions, which are transparent to the programmer but do involve CPU time to service. Time did not permit determination of the various interrupt durations and periods associated with the operation of this program, but as a minimum it must periodically check each peripheral tied to the CPU bus that is included at the time of system generation. In the scheduler associated with the operating system, the 20 ms clock was given the highest priority with the executive program second.

DISPLAY SYSTEM/HOST COMPUTER OPERATION

As an overall assessment of the display performance experienced while using the electronic attitude director indicator (EADI) format to fly simulated confidence and proficiency maneuvers, all 28 pilots who participated in the formal experiment rated the display as being satisfactory for use in operational high performance aircraft.[3] Although some pilots recommended changes to improve the EADI format design that had been implemented, the dot-matrix nature of the presentation and the unresolved problems with the display's operation that were present during the experiments were either not noticed or were not considered to represent a cause for concern. In spite of the system operating deficiencies present, a basic confirmation of the suitability of portraying even rapidly moving imagery using a medium resolution dot-matrix display having visibly quantized picture elements was obtained.

An analysis conducted on the objective pilot performance results obtained during the investigation showed that the experimental hypothesis that pilot performance would be influenced by changes in the avionic data input rate (i.e., 25 and 50 Hertz rates were tested) and by the format update frame rate (i.e., update periods of 8, 10, 12, 16, 20, and 40 milliseconds were tested) was invalid in that no statistically significant differences in pilot performance could be identified.[11] The issue which the experiment leaves unresolved is whether the aforementioned result is attributable to the fact that the pilot is incapable of benefiting from information presented at the higher rates, or whether the display operating deficiencies were responsible for so degrading the picture timing that the beneficial attributes were masked. This issue could not be resolved with the data available from the simulator experiment. The reasons for this are described in the balance of this section.

Data Recording Time Deviations

Data recording was programmed as a low priority task on the host computer. As a result recording occurred only when time remained at the end of the executive program task execution cycle. Through an analysis performed by Burnette Engineering on data recorded during the simulator check out phase it was found that data corresponding to different display update periods was being assembled and then recorded as a single magnetic tape record using this recording method. As a result of this finding, the method of recording data in the system common area of the host computer's memory was changed by the USAF software contractor so as to prohibit altering the contents of a stored display data record until it had been fully transferred to the tape buffer. Storage of a system clock reading in each data record then allowed assessing the timing of the records finally transferred to magnetic tape storage.

In subsequent analyses performed on the corrected system, it was found that on the average only one out of four or five data transmissions by the display system were actually being recorded. Although this was an expected result it was also found that the times between recordings varied consistently from values as low as 40 ms to as high as 220 ms. The principal source of the data recording interval deviations was traced to higher priority periodic overhead tasks performed at different rates by the host computer's software operating system. A change in the priorities was ruled out by the software contractor, due to the impact it would have on the system performance.

The impact of the inability to record successive display/aeronautical data records was an inability to directly determine cause and effect relationships between host computer and display timing deviations. For instance, a failure by the host computer to transmit information to the display within a 20 ms period between transmissions is reported by the display in the succeeding period when status information is requested by the host computer. Thus if the deviation is recorded the sequence of events leading up to it is lost and visa versa.

In practice the programming of both the host computer and of the display made it possible for either to create deviations from their desired respective timing objectives. The only entirely periodic functions in either the display or the host computer systems were their respective clocks (i.e., which were not synchronized) and the timing of the display's format refresh on the display surface which occurred very precisely once every two milliseconds (ms). All other information transfers occurred in an nonperiodic asynchronous manner and as a result the timing of transfers is dependent on the time changing phase relationships between the program execution cycles operating on the opposite sides of the interface. Thus when one side of an interface is ready for a transfer, the other side need not be ready. The resulting delay or lack of it in receiving or transmitting data can then influence the timing of subsequent transfers when the cycle execution time of either the display or the host computer approaches the time between transmissions.

This interdependence combined with the inability to record all transmission cycles between the display and host computer made it impractical to assign responsibility for the deviations observed in both the display and the host computer cycle timing described in the next section.

<u>Format/Avionic Update Period Deviations</u>

Utilizing the event timing capabilities of the ADM-I display the periods between: (1) input data transmissions received from the host computer by the display, (2) the display's system response times (i.e., the time required to process and interpolate the input data) and (3) its format update periods (i.e., the time between displayed data changes) were sensed and sent to the host computer for recording every 20 or 40 ms depending on the avionic data rate called for by the host computer executive program at the time. As a result of monitoring these timing signals it was known prior to the start of the EADI experiment that variations existed in the timing of both the display format update periods and in the intervals between host computer avionic data transmissions to the display. To minimize these variations the data transmission to and from the display was assigned to be the highest priority task of the host computer subject to programming control. Even with these precautions significant variations which could not be eliminated were present during the course of the ADM-I display performance evaluation experiments.

<u>Experimental Results</u>. Table 3.1 lists update periods in milliseconds (ms) for the input avionic data (I) and the display format update data (F) as a function of the treatment condition (T) and the maneuver (M) flown in terms of a quintile division of the recorded timing data. The 0 and 100% quintite boundaries give the minimum and maximum periods of the recorded data set. Between these bounds the data set is divided into five equal groupings with the data ordered from the lowest period to the highest period recorded and with the periods corresponding to the one fifth boundaries at 20%, 40%, 60% and 80% listed in each table. The data shown corresponds to that taken during the simulation flights flown by Pilot #18 and the sequence in which they were flown is given by the Mission Number listing from 0 to 9 above each table. The treatment conditions refer to the combination of avionic and format update rates sought during each mission. These values are in general achieved only near the center of each table. The maneuver number values apply as follows: 1 = Vertical S, 2 = Steep Turn, 3 = Slow Aileron Roll, 4 = Two Point Aileron Roll, 5 = Immelman and 6 = Unusual Attitude Recovery.

The most significant result indicated by Table 3.1 is that display format update period deviations of up to $\pm$ 8 ms could occur for the 40 ms avionic period treatment condition and of up to $\pm$ 4 ms for the 20 ms period

Table 3.1

Simulation Update Period Performance Data
Pilot #18

Mission 5

T/M		0	20	40	60	80	100%
1/1	I	34	40	40	40	40	46 ms
	F	36	38	40	40	40	44
1/2	I	34	40	40	40	40	45
	F	36	38	40	40	40	44
1/3	I	34	40	40	40	40	45
	F	36	38	40	40	40	44
1/4	I	34	40	40	40	40	46
	F	36	38	40	40	40	42
1/5	I	34	40	40	40	40	45
	F	36	38	40	40	40	44
1/6	I	34	40	40	40	40	46
	F	32	28	40	40	40	48

Mission 3

T/M	0	20	40	60	80	100%
2/1	34	40	40	40	40	45 ms
	14	18	20	20	22	24
2/2	34	40	40	40	40	45
	14	18	20	20	22	26
2/3	34	40	40	40	40	45
	14	18	20	20	22	26
2/4	34	40	40	40	40	45
	16	18	20	20	22	24
2/5	34	40	40	40	40	45
	14	18	20	20	22	24
2/6	34	40	40	40	40	45
	16	18	20	20	22	24

Mission 1

3/1	I	16	20	20	20	20	37 ms
	F	16	20	20	20	20	24
3/2	I	16	20	20	20	20	20
	F	16	20	20	20	20	24
3/3	I	17	20	20	20	20	21
	F	14	18	20	20	20	24
3/4	I	16	20	20	20	20	20
	F	16	18	20	20	20	22
3/5	I	16	20	20	20	20	40
	F	16	18	20	20	20	24
3/6	I	16	20	20	20	20	21
	F	16	18	20	20	20	22

Mission 2

4/1	16	20	20	20	20	41 ms
	12	14	16	16	16	20
4/2	16	20	20	20	20	41
	12	14	16	16	16	20
4/3	17	20	20	20	20	40
	10	14	16	16	18	20
4/4	17	20	20	20	20	40
	12	14	16	16	18	20
4/5	16	20	20	20	20	40
	12	14	16	16	18	20
4/6	16	20	20	20	20	41
	10	14	16	16	16	20

Mission 4

5/1	I	16	20	20	20	20	41 ms
	F	8	10	12	12	14	16
5/2	I	16	20	20	20	20	41
	F	8	10	12	12	14	18
5/3	I	16	20	20	20	20	41
	F	8	10	12	12	14	16
5/4	I	16	20	20	20	20	40
	F	8	10	12	12	14	16
5/5	I	16	20	20	20	20	41
	F	8	10	12	12	14	16
5/6	I	16	20	20	20	20	41
	F	8	10	12	12	14	18

Mission 6

6/1	16	20	20	20	20	40 ms
	8	8	10	10	12	14
6/2	16	20	20	20	20	40
	8	8	10	10	12	14
6/3	16	20	20	20	20	39
	8	8	10	10	12	14
6/4	16	20	20	20	20	40
	8	8	10	10	12	14
6/5	16	20	20	20	20	39
	8	8	10	10	12	16
6/6	16	20	20	20	20	40
	8	8	10	10	12	14

Table 3.1
(Continued)

Simulation Update Period Performance Data
Pilot #18

Mission 7

T/M		0	20	40	60	80	100%
7/1	I	16	20	20	20	20	42 ms
	F	8	8	8	8	10	10
7/2	I	16	20	20	20	20	41
	F	8	8	8	8	10	10
7/3	I	16	20	20	20	20	40
	F	8	8	8	8	10	10
7/4	I	16	20	20	20	20	41
	F	8	8	8	8	10	10
7/5	I	16	20	20	20	20	40
	F	8	8	8	8	10	10
7/6	I	16	20	20	20	20	40
	F	8	8	8	10	10	12

Training #1, Mission 0

T/M	0	20	40	60	80	100%
7/1	16	20	20	20	20	40 ms
	8	8	8	8	10	10
7/2	16	20	20	20	20	40
	8	8	8	8	10	10
7/3	16	20	20	20	20	40
	8	8	8	8	10	10
7/4	16	20	20	20	20	40
	8	8	8	8	10	10
7/5	16	20	20	20	20	40
	8	8	8	8	10	10
7/6	16	20	20	20	20	40
	8	8	8	10	10	12

Training #2, Mission 8

T/M		0	20	40	60	80	100%
7/1	I	16	20	20	20	20	41 ms
	F	8	8	8	8	10	10
7/2	I	16	20	20	20	20	41
	F	8	8	8	8	10	10
7/3	I	16	20	20	20	20	40
	F	8	8	8	8	10	10
7/4	I	16	20	20	20	20	40
	F	8	8	8	8	10	10
7/5	I	16	20	20	20	20	40
	F	8	8	8	8	10	10
7/6	I	16	20	20	20	20	40
	F	8	8	10	10	10	12

Training #3, Mission 9

T/M	0	20	40	60	80	100%
7/1	16	20	20	20	20	42 ms
	8	8	8	8	10	10
7/2	16	20	20	20	20	42
	8	8	8	8	10	10
7/3	16	20	20	20	20	41
	8	8	8	8	10	10
7/4	16	20	20	20	20	40
	8	8	8	8	10	10
7/5	16	20	20	20	20	40
	8	8	8	8	10	10
7/6	16	20	20	20	20	40
	8	8	8	10	10	12

condition. As may be seen the deviations occur both from the designated avionic input and display format update periods which are summarized for each treatment condition in the top half of Table 3.2. In those

Table 3.2

Display Format and Avionic Input Period Test Combinations for EADI Experiment

Period in ns	Treatment Condition Number							
	1	2	3	4	5	6	7	
1. Avionic Input	40	40	20	20	20	20	20	
2. Display Format	40	20	20	16	12	10	8	
Deviation Summary	# of Maneuvers at / Quintile Deviation %							
1. Short Period	6/20%	6/20%	4/20%	6/20%	6/20%	6/20%	6/0%	
2. Long Period	6/100%	6/80%	6/100%	6/80%	6/80%	6/80%	5/80%	1/60%
Minimum Total Deviations in %	20	40	20	40	40	40	20	40

instances where the 20% or 80% update period values differ from the values being called for (as designated in Table 3.2) it may be concluded that deviations were present for at least 20% of the update periods for each value so influenced in Table 3.1.

In no instance in Table 3.1 does the avionic input data rate show that 20% of the avionic data periods were deviant, in that in all cases the 20% and 80% quintile values match the desired values given in Table 3.2. A summary of the format update period deviations is given in the bottom section of Table 3.2. The number of maneuvers in which the quintile deviation level shown in the table occurred is listed before the slash. The bottom row of Table 3.2 shows the minimum number of deviant format update values as a percent of the total number of samples taken. Even this very gross indication of the minimum number of update period deviations shows that in no case were more than four in five of the format update periods at the desired value. In practice, due to the inaccuracies inherent in the quintile data summarization technique, deviation rates much higher than the preceding estimates could have been present (i.e., combined short and long period deviations of just shy of 40% of the total number of samples can be present without influencing the quintile distribution).

It had originally been requested that a summary of the USAF computer data records be prepared that would list the number of occurrences for each update period sensed and reported by the display. This would have permitted histograms of the actual sampled format and avionic update period results to be prepared and analyzed. Due to higher priority data analysis issues, it was not feasible to produce this type of summary. As an indication of the type of result that this form of analysis would provide, a manual tabulation of sampled update period data for a steep turn manuever flown by Pilot #17 for treatment condition number six is shown in Table 3.3.

The format update period percentages shown at the bottom of Table 3.3 indicate that 56.2% of the sampled periods were at other than the 10 ms designated value. If expressed in the quintile form of Table 3.1 the 20% quintile would have been 8 ms and the 80% quintile would have been 12 ms in agreement with the values shown in that table for Pilot #18. The 40% minimum deviation estimate of Table 3.2 for Treatment #6 could therefore be 16.2% low.

The remaining data in Table 3.3 is shown to give some indication of the variability of both the format and avionic update periods. Because the sampling periods were not fixed it was not possible to show the results in equal time increments. For convenience the computer printout sheets, which for the most part had an equal number of samples on each, were tabulated and the results are shown listed in page order (i.e., time) sequence. The total number of 20 ms time periods is given adjacent to the number of samples. The remaining values in the table are the number of occurrences of each of the update periods listed across the top of the table. The lack of consistency indicated between page to page totals is indicative of the fact that there was no apparent trend on a sample to sample basis. The 8, 10 and 12 ms format update samples occurred in what appeared to be random sequences.

<u>Display Timing Performance Assessment</u>. The relative stability of the avionic periods in comparison to those of the display format periods make it appear likely that the display variations arise primarily due to its own internal programming and operational characteristics. The avionic period variations result primarily from computer tasks which start but are not concluded before the 20 ms flag for sending messages to the display is set during each cycle. Having missed a transmission time, an early transmission occurs during the next period. The inability to monitor every data transmission to or from the display prohibits other possible sources of advanced or delayed transmission times to be assessed.

Table 3.3

Distribution of Sampled Update Period Occurrences for Steep Turn Maneuver Flown by Pilot #17*

Sampling Data			Format Update Period T_F in ms				Avionic Update Period T_A in ms										
Page #	Samples/ Printout Page	Total # of Update Periods 20ms ea.	8	10	12	14	16	17	18	19	20	21	34	36	38 +	39	40
1	65	278	25	22	17	1					63				1	1	
2	66	292	21	27	16	2		1	2		63						
3	66	284	22	29	15	0		3	1		61			1			
4	66	290	25	27	14	0	1	5	3		57						
5	66	283	16	31	8	1	3	2	3		58						
6	66	284	33	22	11	0	1				61				2	2	
7	66	283	20	25	20	1	1	1			64						
8	66	282	23	24	19	0		2	2		62						
9	66	290	24	29	13	0	1	1			64						
10	66	279	19	32	15	0		1	1		64						
11	66	279	25	29	12	0	1		4		61						
12	66	281	26	31	9	0			2		63				1		
13	66	284	15	29	20	2	2	2	1		61						
14	66	280	21	34	11	0	1	2	2		61						
15	66	276	18	29	19	0		2	1		60	1			1	1	
16	66	274	19	34	13	0		1	1		62	1			1		
17	66	282	21	36	8	1			3		61					1	1
18	66	174	17	19	6	0	1				39		1				1
Totals	1163	4975	390	509	256	8	12	23	26	0	1085	2	1	1	6	5	2
% of Total			33.5	43.8	22.0	0.7	1	2	2.3		93.2	.2	.1	.1	.5	.4	.2

* Intended update period values were $T_F = 10$ ms, $T_A = 20$ ms. Table shows number of occurrences for each update period listed.

+ Host computer failed to provide data to display in 20.5 ms period allowed, therefore one extra period was needed.

The design of the display permits it to continue interpolating display format data even when no update data transmission from the host computer occurs. Use of the last data transmitted for this purpose causes the display picture to stop moving until the data indicating the new image location arrives. The maximum motion pause is therefore for one period of 20 or 40 ms depending on the desired update rate setting at the time. The visual effect produced by this display presentation defect is perceptible but only as a slight flutter in the motion of moving images. During the steep turn maneuver which had an elapsed time of 99.5 seconds there were 15 missed periods among those sampled. If the missed periods occurred at an equal rate for the periods not sampled a total of 64 image pauses would have occurred for the Slow Turn maneuver of Table 3.6 for an average occurrence frequency of 0.65 Hertz. This may account for the comments of some pilots who noted minor motion perturbations in their verbal comments.

The low millisecond timing perturbations in the display format picture updates could at best only produce only very small image positioning errors. In the few cases where a period to period deviation from -8 ms to +8 ms might occur it would be visually indistinguishable from missing an avionic period. At best the deviations could produce a tremor in the positioning of moving display images but this was not observed on for instance the moving scale imagery, thereby making it likely that the ± 2 and ±4 ms variations (which are more frequent) produce no visually perceptible effect.

Contrary to the performance anticipated based on the design of the ADM-I display image processor, the simulator experiments demonstrated that an interdependence existed between the dynamic activity of the aircraft flight variables and the achieved display format update rates. This dependence, which tends to be averaged out when taken over the duration of an entire maneuver was very evident during high control activity portions of maneuvers. The unusual attitude recovery maneuvers which required the pilot to achieve a wings level attitude as rapidly as possible after being given control of the aircraft by the experimenter produced the highest consistent aircraft control activity, but still only for a brief period of time.

The four Treatment #7 cases in Table 3.4 demonstrate the existence of a relationship between the maneuver flown and the display performance in two ways. First the maximum format update period sensed increases from 10 to 12 ms only for the unusual attitude recovery maneuver (i.e., maneuver #6). Second the frequency with which the display achieved the desired 8 ms format update period decreased from between 60 and 80% of the sampled periods applicable to the other maneuvers to between 40 and 60 percent of the sampled periods for the unusual attitude maneuver and in one instance, Mission #8, to between 20 and 40 percent of the sampled periods. The source of this display format update period dependence on the maneuver flown was traced to the level of aerodynamic activity by examining the individual sampled computer printout values for corresponding display timing and aerodynamic variables for a small number of the missions flown. In those instances when large changes in the pitch and/or roll attitude of the aircraft are made either individually or in combination over a short period the display update period was reduced from the 8 ms minimum period. Pitch rates in excess of 10^{o}/sec and roll rates in excess of 35^{o}/sec appear to be independently capable of extending the format update period. Prorated combinations of these rates such as a 4^{o}/sec pitch rate in combination with a 25^{o}/sec roll rate have a similar effect. The rates of change of other displayed aircraft variables are also believed to have an analogous influence, however, parametric studies would be needed to sort out the relationships.

The important finding here is that an interdependence exists between input variable changes and the display's performance. Based on its design, the display image processor is suppose to interpolate all incoming data before image generation of the corresponding static picture frame occurs. *Theoretically then it should make no* difference how rapidly the input variables change (i.e., how large a difference in the variable magnitudes occurs between updates) since the input register data contents are interpolated and the entire format is generated at the format update rate even when no input data is received from the host computer. The source of the observed interdependence is therefore believed to relate to the data interface between the host computer and the display where the variability of delays up to the limits permitted by the parallel data interface protocol could potentially be responsible for the observed results.

Conclusions. The practical impact of both the deviations in the avionic and the format update periods present in the ADM-I display and the associated simulator system is the superposition of small perturbations in the translation and rotation of moving display imagery. In most practical display applications, including that the EADI format tested, the small magnitude of the format update rate perturbations (i.e., which seldom exceeded 4 ms) would not translate into image motion deviations that would be perceptible by the person using the display. The avionic update rate variations at 20 or 40 ms would be expected to produce perceptible image positioning deviations, but due to their low rate of occurrence in the EADI experiment did not cause a problem. The magnitudes of both types of deviation were too small to cause any degradation in pilot objective or subjective performance for the maneuvers flown using the EADI format. It remains to be determined whether other display formats exist for which the perturbations from smoothness of the ADM-I displays image motion could play a larger role as an influence on the user's performance.

Picture Freeze or Pauses

During simulator checkout and the initial phases of the EADI experiments, an intermittent condition occurred which resulted in the simulator failing to transmit new update information to the display. In some instances the failure was self correcting and after a short pause in the picture motion, the display would resume operation with a jump in the picture position reflecting the change that had occurred in the aeronautical model variables during the intervening delay period when transmissions to the display were halted. In other instances the failure was complete and the display picture would freeze until the system was reinitialized and started over again. Since either condition was considered to be unacceptable, their occurrence made it necessary to rerun the mission being flown at the time the fault occurred.

Although the host computer condition which initiated the pause or freeze was never actually identified due to the long term intermittent nature of the fault, it was determined that the DA-11B/J interface interaction with the host computer operating system was responsible for the interrupt condition. A means was subsequently found for sensing the onset of the interrupt condition and for bypassing it within a maximum of two avionic data periods. After this correction was made, no further problems with picture freeze were encountered during actual experiments.

In spite of this apparent correction, pilots did continue to report events which they described as picture pauses or hangups even though no further picture freezes occurred. These reports are not entirely consistent with the display avionic data transmission sensing results. These results showed no avionic update period greater than twice the desired avionic period occurred during the experiments. Thus, the 20 ms and 40 ms avionic update periods could produce maximum delays of only 40 or 80 ms, respectively. Since it is highly likely that such short pauses would be reported as picture jitter, tremor, jumping or scintillation (i.e., depending on the display image "catch-up" distance actually covered at the end of the pause) rather than as picture pauses or hang-ups, it is believed that the longer information transfer delay periods actually responsible for the pilot reports had to be due to failures by the DA-11B/J interface to update the PDP-11/50 system common area of memory which in turn is accessed to retrieve the aeronautical data that is actually transmitted to the display. Because the performance of this area of the simulation system was not monitored and recorded (i.e., the DA-11B/J interrupts were displayed but not recorded) there is no way of knowing for certain the source of the pilot's observations. It is known that the low occurrence rate of the hang-up/pause observations do not correlate with the much higher frequency of occurrence of the monitored doubled update periods. Thus, since it is known that the display was receiving information transfers, a pause in the display picture can occur only if the information updates sent to the display remain the same. Fixed information transmitted to the display for time intervals in excess of 300 ms (i.e., 15 periods of 20 ms each) would result in a pilot describing the resulting hold in picture motion as a pause or a hang-up.

INFORMATION PROCESSING, PRESENTATION AND TEST

The ability to present information in the form of computer generated graphic formats gives the display system designer virtually complete control over both the visual content and timing of the imagery that is made available to the display's user. While the presentation flexibility that this feature affords is highly desirable, adopting its use also causes the designer to assume nearly complete responsibility for achieving acceptable pilot performance. This is true because the information to be displayed, the techniques for presenting it and the specific display system implementations of the information including to a degree the timing of its presentation are all subject to selection and control by the designer.

One principal objective of the ADM-I display EADI experiment was to investigate the suitability of previously developed criteria for implementing dynamic or time changing graphic information presentations when depicted on a dot-matrix display media as a basis for making further refinements. The EADI format pictured in Figure 3.2 was selected for the experiment to permit the incorporation of time changing numeric readouts and moving scale portrayals of aircraft flight control information and also to permit the dynamic effects of the rotation and translation of the bank angle indicator and pitch ladder area of the format to be assessed. In addition to describing these criteria issues, the present subsection also introduces the effect of digitization noise and the signal conditioning necessary to prohibit noise from having a degrading influence on the performance achievable using a display. Tests developed to establish that the display performance achieved was compliant with the format specifications will also be described.

In a practical sense, the graphics information presentation capability implemented to date on electronic displays has served primarily as a substitute for the earlier electromechanical instrument depictions of flight control, engine and status/advisory information utilized by a pilot. The principal advantage of the electronic display media which has been made use of in these applications has up to this point been limited to the ability to alter format content as a function of the flight segment being flown and to simplify the pilot's instrument cross check through the integration of information which could previously only be displayed effectively in separate indicators. The format components assembled electronically to achieve this result are however typically not new. Rather, to the extent that integration permits, they are faithful replicas of the separate flight/time proven electromechanical display presentations they are intended to replace. This evolutionary method of approaching the integration of aircraft information provides continuity between proven techniques with which the pilot is already familiar and new control-display concepts being introduced. The EADI format pictured in Figure 3.2 was tested as an extension of this approach to the evaluation of the acceptability of a dot-matrix display media for use in the portrayal of aircraft flight control information.

Electromechanical instruments using drum counter numeric readouts, round dials, bar graphs, moving scales and so forth have been used successfully in cockpits for a considerable period of time. Pilot acceptance of these display techniques has been good in those applications where the task to be performed and the display technique have been properly matched to one another and the design of the information format has been executed so as to permit the pilot to acquire information rapidly and with level of accuracy needed to perform the relevant mission tasks. The display format design criteria developed for these displays establish preferred: character sizes; scale major and minor index marker sizes and spacings; and other features which result in good pilot performance. These design characteristics translate directly when an electronic display analog of an electromechanical instrument format is needed.

The visual performance characteristics of a well designed electromechanical instrument are typically as good or better than those achievable using electronic display techniques. The painted display surfaces provide excellent image edge definition and contrast, therefore legibility issues need only be considered in relation to night lighting of the instrument and when sun glare reduces the perceptible contrast of the display imagery. Moving imagery on such displays is under continuous control and as a result the motion is always perceived as being smooth. A final distinction of electromechanical instrument implementations is that three dimensions are typically used for information portrayal purposes. While this feature introduces potential problems with parallax reading errors between for instance a scale and its pointer, the use of the third dimension has the advantage of providing stronger visual cues, especially when symbology overlap occurs.

Aside from the lack of a true third dimension, electronic display techniques also exhibit other fundamental limitations in their visual information portrayal capabilities. The spatial quantization of the pictures produced on raster and dot-matrix generated displays disrupts the spatial continuity normally expected to prevail in realistic visual scenes. Likewise the temporal continuity of a graphics presentation can be disrupted if the rapid succession of discrete static picture frames, which are used to create the impression that portions of the scene are moving, fails to satisfy the criteria needed to make the apparent image motion illusion effective.

Practical experience with both movies and television show that it is possible to produce picture motions that will appear to the viewer to be both smooth and continuous. Viewer experience with shadow mask color televisions allows a similar conclusion to be reached for raster and dot-matrix displays (i.e., at viewing distances small enough to permit the individual color dots to be visually resolved if the viewer so desires). As it turns out, achieving either of these viewing results is not automatic; in fact, specific design criteria must be met to achieve performance equivalence between spatially and/or temporally quantized imagery and its continuous image counterparts. It is the design criteria associated with this aspect electronic display design which were of primary interest in the EADI experiment and in the present section of this report.

The use of numeric readouts to display information typically results in a considerable savings in display surface area needed to depict a flight parameter of interest. Consequently there is a considerable incentive to use numerics in place of more symbolic graphics techniques. In view of the importance of numerics the first two topic areas dealt with in the following discussion relate to: (1) the experimental results obtained for the numerics used during the EADI format experiment and (2) to a description of design criteria refinements which should be considered when applying numeric readouts in the context of a graphics display format. Following this the design criteria issues associated with moving graphic imagery on electronic display surfaces so as to make the resulting motions visually acceptable to the display's user will be presented.

Simulator Evaluation of EADI Format Numerics

Physical Description of Numerics. The presentations of flight control information on the EADI format which made use of fixed location time changing numeric readouts included the airspeed, altitude, heading and vertical velocity variables. In the case of the first three variables the numeric readouts were enclosed in boxes at the left, right, and top center of the display format, respectively, and were accompanied by moving scale depictions to indicate trend information. In the case of vertical velocity the display consisted of a numeric readout without the benefit of a scale to indicate trend data. An arrow to the right of the vertical velocity numeric readout pointed up when altitude was increasing (i.e., positive vertical velocity) or down when it was decreasing. The vertical velocity readout and arrow were contained in a box in the upper right hand corner of the format. With the exception of altitude which used 7x9 dot-matrix character fonts (i.e., ≈ 0.14 inch high), the boxed numeric readouts were all displayed using 10x13 dot-matrix character fonts (i.e., ≈ 0.21 inch high).

EADI Numeric Dwell Times. In order for an observer to correctly read a number depicted using a numeric readout format the number must be displayed f r a sufficient period of time to permit all digits in it to be identified. Single exposures to a number preceded and followed by a blank display can produce correct responses even when the number exposure duration is very short. In fact, by increasing the contrast of a display presentation of any type in inverse proportion to the reduction in exposure duration below 250 milliseconds (ms), the image perceived will appear to be equal in brightness to that of an otherwise identical image viewed for 250 ms or more.

In most practical applications of numeric readouts, a number differing from the one to be read can both precede and follow the viewing time window of interest. In this situation prior simulator studies have shown that digit change rates of 3 Hertz or less (an exposure duration of 333 ms) are acceptable for presenting time changing numerics. Based on this criteria, all but the most significant digit in a numeric readout were zeroed when the avionic feed data for the affected digit exceeded 3 Hertz. Thus, for instance, the units digit on heading, which had a 1^{o} least significant digit was set equal to zero when the heading changed at a rate of greater than 3^{o}/sec., and the tens digit was zeroed when the heading rate exceeded 30^{o}/sec. To prohibit zeroing the entire readout, due to an excessive rate of change in the displayed parameter, the most significant digit was not zeroed even if the rate was too high to allow it to be correctly read.

As implemented, the ADM-I display received both the value of the display parameter and its rate of change at either the 25 or 50 Hertz avionic data rates used during the experiment. The display system signal processing software then used these signals to determine whether the 3 Hertz numeric change rate had been exceeded and hence whether a digit should be displayed or zeroed.

EADI Digit Change Hysteresis. As a part of the specification on the EADI format, a requirement had been included by Burnette Engineering for numeric display readouts to possess a hysteresis characteristic such that a signal change equal to or larger than the magnitude of the least significant digit displayed would be needed to alter the displayed numeric value. The intent of this requirement was to avoid the digit fluctuations induced when noise modulated onto the input avionic signal produces erratic digit transitions onto what would otherwise be an essentially constant sensed signal (i.e., as is frequently the case for digital multimeters, for instance).

The LSL implementation of this requirement in the display system's EADI format software consisted of truncating the input signal if they are increasing or there is no change (i.e., Rate $\geqq 0$) or to add a one to the number and then truncate it if the number is decreasing (i.e., Rate < 0). Since a positive to negative rate change forces a one display unit transition to occur, this algorithm not only did not provide the desired hysteresis transition characteristic but was actually capable of accentuating the digit fluctuation problem.

Simulator Experimental Findings. In the actual computer simulation, the overall effect of the aeronautical model operating on the pilot control inputs resulted in the four numeric readout signals being electronically filtered to the point that signal fluctuations were effectively eliminated and as a consequence a signal hysteresis characteristic was unnecessary. Several pilots did comment on the lack of correspondence between the scale and numeric readouts for the heading numeric for decreasing heading angles. Since the moving scale associated with the heading display changed in 1/4 degree increments the numeric would for instance read 5° for a transition from 5 up to 6 degrees but would shift to a 6 degree display if between 5° and 6° a maximum heading angle was reached and a decrease started to occur. In other words, a control input made by the pilot with the intent of decreasing the heading angle could instead cause the heading numeric readout value to increase temporarily (i.e., on the numeric readout but not on the heading scale). Still further reductions in the heading angle resulted in the numeric transition occurring as the signal reached the integer value of each angle. It should be noted that a properly designed hysteresis characteristic based on signal amplitude values, rather than signal rate of change, would permit achieving an exact correspondence between the heading numeric and scale readings to be displayed (i.e., subject to the accuracy to which the presentations are capable) and yet still eliminate the fluctuations produced by signal digitization noise.

During the simulator checkout phase of the experiment, pilot comments revealed that the 3 Hertz numeric digit change rate limitation was considered to be acceptable for all but the vertical velocity readout. The vertical velocity readout was not considered to be sufficiently responsive by the pilots (i.e., in hindsight, the lack of a scale to give trend information is believed to have caused the pilots to ask for the display of the vertical velocity digits at higher rates of change). The potential need to make a change of this type had been anticipated. The technique used involved scaling the vertical velocity rate data downward to reset the zeroing threshold rate to any arbitrary value above 3 Hertz. The EADI experiment was conducted with the vertical velocity rate data scaled to half the actual value, thereby producing a 6 Hz threshold for zeroing the vertical velocity digits.

The results of the experiments revealed several problems with the aforementioned techniques for controlling numeric exposure durations. First, and as already mentioned in the case of vertical velocity, the digit change rate of 3 Hertz, while slow enough to permit correct readings, was not always considered to change rapidly enough by the pilots to permit accurate tracking of the flight parameter values.

Having made the change to 6 Hertz in the rate at which vertical velocity digits were zeroed, many pilots then felt the vertical velocity changed too rapidly. Although the latter result probably does indicate that a rate between 3 and 6 Hertz is needed, the conclusion is not unequivocal. The uncertainty results from the fact that the most significant digit in the numeric readouts depicted values at the full avionic input data rate (i.e., at up to the 50 Hertz change rate) since this digit never zeroed. Thus for displayed numeric readout values near zero, the most significant digit occurred in the units or the tens place of the number being displayed and parameter changes at rates of up to 50 Hertz were displayed to the pilot. Vertical velocity was a primary flight control parameter only during the "Vertical S" maneuver, however, a transition through zero vertical velocity occurs every time the aircraft transitions from a climb to a decent attitude. This design shortcoming was further emphasized by virtue of the very high sensitivity of the 1 foot per minute units chosen to display vertical velocity. Heading which also goes through zero value magnitude transitions had a much smaller rate of change for the typical flight maneuvers flown and it is apparently for this reason that the problem was not noted for this variable as well.

The final problem with the EADI depiction of numeric values that was noted by pilots during the experiment was that too many significant digits of information were being displayed at any given instant. A large number of the pilots expressed the view that making all five of the vertical velocity and altitude readout digits responsive to changes in these variables was excessive in that some digits were always changing. The additional accuracy of display was also cited as increasing workload, in that the display of 1 foot accuracies at for example 20,000 feet of altitude tends to cause one to try to unnecessarily control to that level of accuracy.

Conclusions. The issue of whether numeric readouts provide a satisfactory technique for the display of a particular variable depends in large part on how rapidly the variable changes and the accuracy to which the variable must be capable of being read to be useful. A familiar scale display can typically be read much more rapidly than a numeric readout particularly when the information is changing rapidly as a function of time. Applications that are well suited for display using numeric readouts occur when nearly static numbers with multiple digit accuracies must be conveyed as is the case for example for radio frequencies, navigational coordinates and when calibrating range or altitude monitoring equipment.

The EADI format design employed in the ADM-I display evaluation experiment had been adapted from a format previously used with success on CRT displays during earlier flight simulator experiments. In these experiments, the display of vertical velocity using a numeric readout alone had caused no problems. However, the pilots had been involved in benign flight scenarios made up of a sequence of high level navigation legs. The reading problem that pilots had with essentially the same numeric presentation in the current experiments is attributed to the aerobatic nature of the Vertical S; Steep Turn; Immelman; Slow and Two-Point Aileron Roll; and Unusual Attitude Recovery maneuvers flown. The general dissatisfaction of the pilot's with the numeric readout presentation of vertical velocity for these maneuvers (i.e., in spite of the overall good performance achieved) indicates either: (1) that the numeric presentation techniques employed need further refinement or (2) that a numeric presentation alone, in any form, may not suffice for such an application.

Numeric Display Presentation Technique Refinements

To be able to make the numeric readout presentation of rapidly time changing information perceptible to a pilot, it is necessary for a fixed portrayal of the number to occur for a period of time which is long enough to permit it to be correctly read. Since rate controlled zeroing of the digits in a number cannot be extended to the most significant digit without introducing the possibility of causing a low magnitude time changing readout to be incorrectly displayed as zero, and the failure to control the change rate of the most significant digit, makes it possible for it to change so rapidly that it cannot be read, display situations can arise for which numeric presentation techniques are simply unsuited to perform.

Three strategies for enhancing numeric information format presentations during periods of time when the information is changing rapidly include: (1) the display of a periodically updated signal, the precise value of which is sampled and held for a fixed time interval that is long enough for it to be read; (2) the display of a signal which is updated only at the precise points in time when a predetermined change in the signal magnitude being displayed has occurred; and (3) scrolling the numeric digits to create a visual impression analogous to that of the rolling drum counter type of display presentation used in automobile odometers. Each of these numeric presentation techniques requires some degree of special processing to make it work effectively, but while improving on the direct display of sensed signals, these techniques still cannot make the numeric technique suitable for use in any display situation that might arise.

A generic problem with the numeric display of time changing information is that the time at which a displayed number is valid has already past by the time the display observer is able to read and comprehend the display readout. To make time changing numeric information meaningful to the observer the author postulates that it is necessary to provide the information to the observer in a manner that will foster the ability to correctly anticipate the values and/or the timing of the succession of numbers that will be displayed.

Periodic Update Using Precise Magnitudes. When displayed information is changed periodically, that is with a fixed time interval between successive numeric readout presentations, the change in the signal magnitude between updates allows the trend of the signal to be assessed by the observer. In order for a variable that is being monitored on a numeric readout display to be correctly recognized as increasing or decreasing at a constant rate, a minimum of three update periods must be observed to be able to determine that the two consecutive changes in the variable are equal to one another. In a similar sense, the comparison of the magnitude increments between as few as two successive time periods allows an increasing or decreasing signal magnitude trend to be determined by the display observer.

The primary problem with this numeric presentation technique is that the signal magnitude changes between successive update periods can be appreciated by the pilot only if the time is taken to mentally compute the differences in magnitudes that occur between successive readout values. This procedure requires that at least two mental calculations be made by the pilot in order to establish a trend. Although a small number of variable magnitude/rate-of-change conditions exist which can make tracking variable changes using the numeric readout technique feasible, (i.e., (1) small magnitude integer value changes in numbers, (2) constant magnitude change increments of 1, 2, 4, 5, 10 units or multiples thereof, and (3) under high rate of signal change conditions where only the most significant digits have to be tracked to give meaningful results) in general the trend in number changes is difficult for an observer to appreciate, particularly under the time critical operationing environment of an aircraft cockpit. Table 3.4 illustrates this fact by depicting number sequences for which the trend present can be discerned with varying degrees of difficulty. The top half of the table shows number sequences for which rate changes are relatively easy to mentally discriminate with increasing difficulty ordered from the left to the right in the table. At the asterisk in each sequence a change in the increment magnitude is made in either a single step or more gradually as would be more typical of a periodically updated display number sequence change. Up to the point where the first change in the number sequence occurs, a constant rate is fairly discernable; thereafter, the new rate is not typically that easy to recognize.

In the bottom half of Table 3.4 number magnitude increments are illustrated which would be difficult to comprehend using a numeric display presentation alone. In these cases it would for instance be difficult to recognize whether the rate of change of a number is increasing or is decreasing, even though it would continue to be easy to determine whether the magnitudes of the numbers are increasing or are decreasing.

Timed Display of Recognizable Magnitude Increments. To take advantage of the fact that some magnitude changes are more recognizable than others, the changes in numbers can be processed for display using only easily recognized number magnitude increments. In this way, the appreciation of trend information is caused to depend on the

Table 3.4

Illustration of the Difficulty Appreciating Trends in Sequentially Displayed Progressions of Numbers

$\Delta=5\rightarrow4$	$\Delta=10\rightarrow12$	$\Delta=2\rightarrow1$	$\Delta=4\rightarrow5$	$\Delta=4\rightarrow5$	$\Delta=4\rightarrow6\rightarrow4$
205	210	224	230	231	233
210	220	226	234	235	237
215	240	228	238	239	241
220	260	230	242	243	247*
225	270	231*	246	247	253
230	280	233	251*	251	259
234*	292*	235	256	256*	265
239	304	236	261	261	271
243	316	237	266	266	275*
247	328	239	271	271	279
251	340	240	276	276	283

$\Delta=13\rightarrow14$	$\Delta=17\rightarrow19\rightarrow21$	$\Delta=\Delta+1$	$\Delta=\Delta+10$	$\Delta=3\rightarrow\Delta=2\Delta\rightarrow\Delta=192$
217	212	203	203	203
230	229	204	213	206
243	246	206	233	209
256	263	209	263	215*
269	282*	213	303	227
282	301	218	353	251
295	320	224	313	299
309*	339	231	383	395
323	360*	239	463	587
337	381	248	553	779*
351	402	258	653	971

* Asterisk indicates first occurrence of increment change

observer's ability to perceive and respond to the mental comparison of the time intervals between the display of successive numbers as being equal, increasing (slower) or decreasing (faster), rather than on the much more demanding and time consuming cognitive processes needed to mentally calculate and compare the differences between a progression of numbers where the display of their magnitudes is unrestricted. This is the essence of the function that a moving scale display performs when conveying trend information to an observer. In the latter case the speed or equivalently the timing of familiar scale index markers moving with respect to a fixed reference marker establishes a trend. The display of numbers changed by known easily anticipated magnitude increments at the times at which the corresponding signal value is reached is about as close as it is possible to come to providing trend data using a numeric readout display.

No display utilizing the technique just described has been implemented to date to the knowledge of the author. Many displays zero less significant digits based on truncation or rounding algorithms (i.e., the accuracy of the zeroed digits being lost in the process), but the signals are either periodically or asynchronously sampled based on considerations other than the timing of display digit changes. Timing the display of an integer or fractional number change to coincide with the time at which the next fixed integer or fractional signal magnitude increment is reached provides a precise readout at the time the change occurs and therefore provides an accurate basis for trend information that is perceived based on the timing of the changes.

To work properly the magnitudes of the number changes depicted on the display must be capable of being anticipated over the period of several display updates in order to permit the perception of a trend in the timing of the numbers displayed. At the same time, to achieve reasonable display accuracy the magnitude increments of the values displayed should be chosen so that the maximum perceptible digit change rate threshold is approached but not exceeded. Number increments of 1's, 10's, 5's, 2's, 4's and decimal multiples thereof satisfy this need in varying degrees from best to worst, in the order indicated, as do fractional increments based on the same numbers as divisors. In general, because increments of 1's, 10's, 100's and so forth are most easily recognized, numbers incremented by these amounts are most effective based purely on a visual recognition and human response time selection criteria. In practice, however, digit increment selection must also account for the accuracy of the information that is needed to perform the assigned aircraft mission and for the signal rate of change which determines how fast the single most rapidly changing individual digit of a numeric readout display can change and still be correctly read. Although all of the non-zeroed digits in a numeric readout can change as a function of time only the least significant non-zeroed digit, which will be referred to here as the active digit, A, requires special processing.

Table 3.5 illustrates the signal rate of change dependent selection criteria for choosing between four different techniques that can be used to implement the numeric readout display of time changing numbers. The table is intended to be relevant only to the information processing of the active display digit, A, which is representable in a number string as follows:

(3.1) . . . U U U A . O O O . . . . ; X

where fixed zeros appear to the right of the active number, A, and the digits to the left, U, are changed in single unit increments. The quantity, X, is a decimal multiplier which correctly places the decimal point with respect to position indicated. The technique for incrementing the active number A is selected in Table 3.5 based on the rate of change of the signal being displayed. This allows the accuracy of the numeric readout to maximized without exceeding the digit change frequency reading threshold.

The first row in Table 3.5 shows the active digit changing at up to a 4 Hz rate. When this rate is exceeded then the next digit to the left becomes the active digit and the digit in question is zeroed. The problem with this technique is that having just exceeded the rate threshold, 4X, nearly 2.5 seconds can elapse before the new active digit is again incremented. During this period the user has no trend information since intermediate values are not displayed.

The second row in Table 3.5 causes units incrementing to be followed by fives incrementing when the signal rate causes the units to increment faster than 4 Hz. Switching at this point to incrementing by fives reduces the digit change rate to only 4/5 Hz. While this improves the trend indication, nearly 1.25 seconds can still elapse between the times incrementing by fives occurs.

The third row in Table 3.5 adds incrementing by two's as an intermediate number sequencing possibility between ones and fives. This technique produces a maximum digit timing interval of 0.625 second when incrementing by fives for signal rates between 8X and 20X. Although Row 4 shows still another scheme which adds incrementing by fours, it is not clear that this incrementing magnitude would improve the perception of trend information, particularly since the fours increments are not as easily tracked.

Table 3.5

Least Significant Time Changing "Active"
Digit Signal Rate Selection Criteria

Complement of Digits Displayed		Change in Digit Place A in Increments of:				
		Ones	Twos	Fours	Fives	Tens*
1. 1's & 10's	R(1) T(2)	0.4X-4X 2.50 -0.25				4X -40X 2.50-0.25
2. 1's, 5's and 10's	R T	2X -4X 0.5 -0.25			4X -20X 1.25 -0.25	20X -40X 0.50-0.25
3. 1's, 2's, 5's and 10's	R T	2X -4X 0.5 -0.25	4X -8X 0.50-0.25		8X -20X 0.625 -0.25	20X -40X 0.50-0.25
4. 1's, 2's, 4's 5's, and 10's	R T	2X -4X 0.5 -0.25	4X -8X 0.50-0.25	8X -16X 0.50-0.25	16X -20X 0.3125-0.25	20X -40X 0.50-0.25
Example of Active Digit Number Sequences		0 1 2 3 4 5 6	0 2 4 6 8 10 12	0 4 8 12 16 20 24	0 5 10 15 20 25 30	0 10 20 30 40 50 60

* Shown for illustration purposes only, since 10's and 1's are redundant (i.e., X (10) = 10X (units))

1. R is the signal rate of change where X represents the decimal digit magnitude place (i.e., for instance 1/100's, 1/10's, 1's, 10's, 100's, etc.).

2. T is the display time interval before the digit is again incremented at the designated signal rate of change R.

The lower half of Table 3.6 when compared with the upper half illustrates the expanded numeric display capability made possible when using the signals processing technique of Row 3 of Table 3.5 rather than the one shown in Row 1. By adding incrementing by twos and by fives as is illustrated in Columns 1 and 2 and in Columns 3 and 4 of the lower half of Table 3.6, higher accuracy information can be displayed without exceeding the active digits change rate reading threshold. Whether this accuracy is needed or not, depends on the parameter being monitored, its range and its magnitude.

The addition of the fractional changes at the magnitudes indicated in the lower left hand side of Table 3.6 would in most instances represent excessive accuracy for parameters like airspeed, altitude and mach number. In this case, the zeroing of the fractional and possibly even the units place to eliminate excessive display accuracy could be justified to prevent the pilot from attempting to unnecessarily control to the displayed accuracies. Conversely, for parameters such as heading the fractional accuracy of the display could be necessary in mission segments such as approach and landing. When the active digit occurs in one of the more significant digit positions in a number, as is illustrated in the lower right hand side of Table 3.6, the additional accuracy offered by rate controlled digit sequencing becomes desirable independent of the purpose of the parameter being displayed. On the basis of the foregoing considerations it can be concluded that numeric readout signal processing should independently account for both the number of significant figures needed and the rate of change of the active digit.

To accommodate rapidly changing numbers, only those digits positions satisfying the visual dwell times needed to permit correctly reading a digit can be displayed as other than zeros. The inherent shortcoming of the numeric display technique then, is that situations can arise for which the display's user will not be adequately informed, due to the limitation imposed on the number of significant figures that can be displayed by the rate of change of the signal. This situation is illustrated in the top half of Table 3.6 where increasing rates reduce the displayed number accuracies. If for example, as is shown in Column 4, the vertical velocity of an aircraft exceeded 40 feet per second causing altitudes to be displayed in increments of 100 (i.e., a 4 Hz rate threshold or a 0.25 second digit dwell time limit for the active digit), a pilot could be quite satisfied with the readout at an altitude of 20,000 feet and yet receive insufficient information below 1,000 feet. This example illustrates a situation for which the numeric presentation can become inadequate irrespective of its mechanization. Under this condition the numeric readout display must either be supported or supplanted by some alternative display presentation technique.

Table 3.6

Effect of Signal Rate Control
of the Numeric Digits Displayed

Signal Rate in Units/Sec	.04-.4	2-4	4-40	200-400
Decimal Multiplier X	0.1	1	10	100
Signal Magnitude Example Values	258.70 258.[illegible]0 258.90 259.00 259.10	258.00 259.00 260.00 261.00 262.00	250.00 260.00 270.00 280.00 290.00	200.00 300.00 400.00 500.00 600.00
Number Format	UUU.A0	UUA.00	UA0.00	A00.00
Insertion of Two and Five Increment Steps				
Signal Rate In Units/Sec	.4-.8	.8-2	40-80	80-200
Decimal Multiplier X	0.1	0.1	10	10
Signal Magnitude Example Values	258.60 258.80 259.00 259.20 259.40	258.00 258.50 259.00 259.50 260.00	240.00 260.00 280.00 300.00 320.00	200.00 250.00 300.00 350.00 400.00
Number Format	UUU.A0	UUU.A0	UA0.00	UA0.00

Through the use of a digit sequence selection algorithm cued both by the rate of change of the signal to be displayed and by the number of significant figures of accuracy desired, the most appropriate time sequence of displayed numbers could be selected automatically so as to provide optimum digit display dwell times and readout accuracies.

In closing, it should be noted that Tables 3.5 and 3.6 were formulated for illustration purposes using the arbitrary assumption that a 0.25 second *minimum digit dwell time* (i.e., a 4 Hz change rate) would be the digit rate discrimination limit for a pilot in an aircraft cockpit operating environment. This is considered to be a fair assumption for illustration purposes if only because of the ease with which pilots were able to read display digits changing at rates of up to 3 Hertz during the simulator tests. Experiments to establish the maximum digit rate thresholds suitable for use in actual aircraft and the dependence of those rates on the number magnitude increments being used (i.e., changes by ones rather than fours, for instance), have not as yet been conducted, nor has related non-aircraft cockpit environment data been found in the literature. Care should therefore be exercised in selecting digit rate thresholds for use in actual aircraft applications.

Scrolled Digit Presentations. Scrolling a digit in a numeric presentation involves physical translation of the digit on a display surface. The historic analog of this display technique utilized drum counter electro-mechanical displays wherein numbers from zero to nine were inscribed at equal spacings on the surface of small continuous drums which could then be independently or sequentially rotated up or down as the signal being displayed increases or decreases. The automobile odometer is probably the most familiar practical application for this type of display, but it is also in common use in aircraft flight instruments and controls used to set number values (i.e., communication frequencies and navigation coordinates).

Trend cues provided by driven versions of these displays result from the speed and direction of motion of the digits as seen through a viewing window. The observer's ability to perceive trend for these displays is probably intermediate between that for a time changed numeric (where several digits update periods must be viewed before a trend can be established) and a moving scale display presentation. The electronic display implementation of this technique involves emulating the visual appearance produced when the numeric moves into, through and then out of a viewing window. To establish the most efficient eye tracking of the digit motion it is desirable for the number to enter the viewing window gradually and to fade from view in the same manner. It is therefore preferable for the boundary of the window to gradually appear to occlude those parts of a digit that fall outside of it, rather than generating or blanking it abruptly at the edge of the window.

Although the moving digits do improve trend perception, they introduce their own unique set of viewing problems for an observer. Some of these problems have historically been related to the constraints on implementing electromechanical drum counters. The circumference of the drum determines the maximum size of the digits inscribed on it. Thus 0.2 inch high numerics spaced at least one half of the height of a character apart require a drum that is a minimum of 3 inches in circumference or 0.95 inch in diameter to depict digits numbered zero though nine. Practical space limitations in aircraft instruments have typically limited drums to about half this diameter and as a result have resulted in the characters depicted on them being too small to be read at a glance. Uniformly illuminating the recessed curved surfaces of the small drums for night use has also been a problem.

When implemented as an electronic display analog, the drum circumference and lighting problems with the conventional scrolled digit indicator are eliminated. The issues which remain include some which are unique to the electronic display presentation techniques and others that are common to both techniques. The latter issues include: (1) the area occupied by the viewing window and its relationship to the viewing time the observer has to track and read the active digit, (2) the method used to change digits which are more significant than the active digit (i.e., which change more slowly) and (3) the handling of digits which represent digit places which are less significant than the active digit (i.e., digits which change more rapidly).

Figure 3.8 a, b and c show the progression of the active digit translation as time passes in a standard window configuration. The height of the window, h_w, less the height of the numeric character, h_c, gives the distance the digit is able to translate, h_t, before being abruptly or gradually occluded by the window boundary, that is

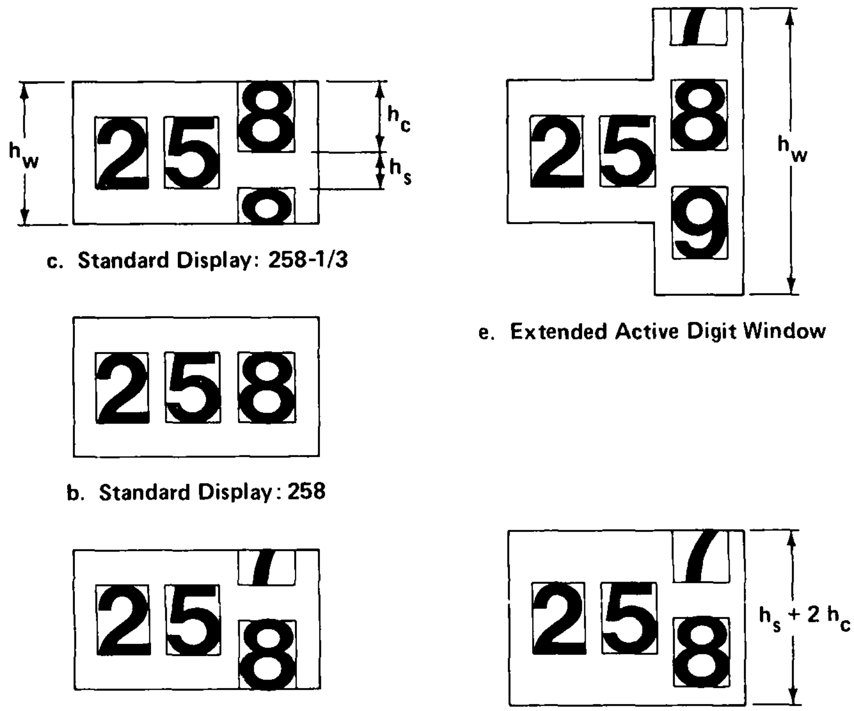
(3.2) $$h_t = h_w - h_c$$

The time the active digit remains displayed with no occlusion, $\mathcal{T}$, is therefore given by the equation

(3.3) $$\mathcal{T} = h_t/s_c$$

where s_c is the speed of the digit with respect to the display surface.

To match this display time to the time a digit would appear on a time changing numeric readout the new digit being scrolled into the display window would have to be fully formed at the time the old digit starts to be occluded upon exiting the window. In other words, if the two



c. Standard Display: 258-1/3

e. Extended Active Digit Window

b. Standard Display: 258

a. Standard Display: 257-2/3

d. Viewing Exposure Time Matched to Time Changing Digit Readout.

h_w = Window Height

h_c = Character Height

h_s = Digit Height Spacing

Figure 3.8 Digit Scrolling Relationships techniques are to be considered to be visually equivalent, the viewer should not have to wait to shift attention from the exiting to the entering digit. To achieve this special case, the following display window format geometry requirement

(3.4) $$h_w = h_s + 2\,h_c$$

would have to be met (i.e., as is illustrated in Figure 3.8d), where h_s is the spacing between digits. If this criteria is met, then the time, τ, available to view the scrolled digit would satisfy the relationship

(3.5) $$\tau = \tau_c = 1/f_c$$

where f_c is the frequency at which a time changing numeric display digit is incremented and τ_c is the corresponding time period that the digit is displayed before being incremented. To match the time changing numeric display's viewing time τ_c the following relationship between the digit scrolling speed and the display format dimensions must therefore be satisfied

(3.6) $$\tau_c = 1/f_c = h_t/s_c = (h_s + h_c)/s_c$$

or

(3.7) $$s_c = f_c\,(h_s + h_c)$$

This relationship shows that the maximum scrolling speed permissible while still producing a digit viewing time, τ_c, is directly proportional to the distance between successive characters on the display (i.e., $h_s + h_c$). In other words, larger readouts can be scrolled at higher speeds without dropping below the viewing time limit. Assuming that $f_c = 4$ Hz, and a 0.2" high character with a 0.1" space between characters, Equation 3.7 would predict that a scroll speed of 1.2 inches/second would produce the same 0.25 second viewing time as a 4 Hz time changing digit. Since the eyes are capable of tracking 10 inches/seconds image speeds at a viewing distance of 28 inches (i.e., 20°/second) with no degradation in visual acuity the limitation on reading scrolled digits would be a viewing time constraint imposed as a result of the motion being confined to a small window, rather than an image speed constraint.

The foregoing example shows that the scrolling of numerics is feasible for the practical numeric readout sizes used in aircraft. The rendition of a 1 inch/second image speed on an 120 line/inch resolution electronic display would however result in moving the image in four line steps of 0.033 inch each at the 30 Hz update (frame) rate typical of aircraft CRT displays. Since the 0.033 inch steps would be quite visible at a 28 inches standard cockpit viewing distance, it would be necessary to observe the criteria associated with achieving apparent image motion (i.e., described elsewhere in this report) in order to achieve a scrolling motion that appears to be smooth. Step sizes would of course be reduced for lower information change rates, eventually reaching the point where apparent image motion considerations are no longer important and the minimum motion increment associated with the display's resolution governs the step perceptibility. Conversely if a digit is changing at the equivalent of a 1 inch/second change rate, then the next most significant digit would have to move at ten times this speed. For the example just given the 30 Hz frame rate limitation would produce a 0.33 inch interval between the locations at which a digit can be displayed. The impression that the digit is being scrolled would be lost in this event. Rather than perceiving the digit as moving, but at a speed too high to be read, as would be the case for a conventional drum counter display, a 30 Hz frame rate electronic display would be perceived as flashing successive numbers.

It can be concluded for the preceding example that electronic scrolling of digits, using the standard display configuration of Figure 3.6d would result in essentially the same data change rate limitations that apply to display formats using static time changing readouts. The advantage of digit scrolling is therefore limited to the trend cue (i.e., the ability to anticipate the next digit to be displayed) that this technique provides to the pilot. By increasing the display update rate beyond the 30 Hz rate assumed in the example image motion which is perceived to be smooth can be achieved at higher image speeds. The viewing window size and the reading exposure time of the moving digit still produce an ultimate practical limit on the effectiveness of this display technique, however.

Figure 3.8e shows a commonly used method of extending the viewing time available to read a digit. Opening up the entire window in this manner would make it more difficult to read the whole number, as several numbers could then be seen simultaneously and potentially be confused in a conventional readout implementation. For an electronic display the active digit place can be determined by algorithm and only the desired location then need be expanded. Likewise the methods of changing low rate of change digit locations and the ability to zero and freeze high rate digits become options that the designer can choose.

As an overall assessment, scrolled digits appear to provide a clear advantage over time changing digits only when the viewing window size is large enough to extend the pilot's exposure time to the scrolled digits. The disadvantages of the technique are that it takes up more display real-estate, and requires display update rates that are much higher than those needed for time changing numeric displays. The technique also places a resolution (pixel density) requirement on the scrolled display which influences the potential perception of stepped image motion. As a final consideration the additional software costs and image processor size and run-time/speed requirements associated with the implementation of scrolling, make the technique most appealing as an extension of already sophisticated graphic and video display systems.

Moving Scale Design Criteria

Pilot Acceptance of EADI Format Scales. As is illustrated in Figure 3.2, the EADI format design included two vertical moving scales, with airspeed depicted on the left and altitude on the right; one horizontal moving scale, which depicts heading; and a round dial bank angle indicator consisting of a stationary scale and a moveable bank angle pointer that was located near the bottom of the format. Among the 28 pilots who participated in the evaluation, none reported any problems in reading or viewing these scales at either of the test avionic data periods (i.e., 20 or 40 ms) or at any of the display format update periods (i.e., 8, 10, 12, 16, 20 or 40 ms) employed.

Although these results invalidated the experimental hypothesis, that changes in these rates would influence pilot acceptance and performance, they none the less validate the design criteria developed by Burnette Engineering for use in their information processing and presentation design. These criteria will be discussed in the remainder of this section. To obtain more complete information on the subjective and objective test results of the EADI format experiment, the reader is referred to articles published in the 1983 and 1984 NAECON Conference Proceedings.[3,11]

Apparent Image Motion Phenomenon. During the nineteenth century, it was found that two spots of light, separated by a distance and turned on in time sequence could be reported by an observer to be perceived sequentially, simultaneously or in a state of apparent continuous motion between the first and second spot activated.[12] A more detailed investigation of the phenomenon conducted by M. Wertheimer revealed that, in addition to the spot spatial separation, the: activation times of the two sources, the time interval between activation times, and the luminances of the spots also influenced the perceived motion.[13] The effect, which has been designated "optimal movement" in the literature, was found to have been most thoroughly investigated by W. Neuhaus.[14] An example of one test condition from the Neuhaus investigation illustrates the strength of this illusion. When two light spots subtending a diameter of 0.09° each and having exposure time durations of 10 ms each were spatially separated by an angle of 1.72^{o}, (i.e., about 0.84 inch at a 28 inches viewing distance) optimal movement was produced for temporal exposure separations of between 80 ms and 300 ms (i.e., apparent image speeds between 5.7 and 21.5^{o}/sec). When smaller spatial separations were used, the speed threshold for apparent image motion was reduced.

Contrary to expectation when the various studies (as well as the more recent descriptions) of this topic were originally reviewed in the mid seventies, no attempt to form a link between this phenomenon and the apparent image motion illusion created by motion pictures or more recently by television could be found. Likewise, no experiments which pursued the natural extension of the experiment to three or more spaced time sequenced lights could be located.

The author considers the optimal movement phenomenon to be a limiting case of a more general apparent image motion phenomenon which must operate in order to accommodate the physiology associated with the sensing and perception of motion in general visual scenes. In contrast to our impressions of the world, the signals sent to the visual cortex for interpretation via the optic nerves have already been spatially quantized. The result of visual sensing is therefore a mosaic of spatially sampled discrete signals where the individual signals reaching the visual cortex can represent the output of single foveal cone receptors up through large groups of peripheral rod receptors. In a similar fashion the signals transmitted via the optic nerves to the brain are not continuous amplitude modulated signals, but rather are pulse frequency encoded quantized signals. As a consequence of these physiological facts, the visual cortex of the brain has already had to adapt to accept and process spatially sampled time sequential picture frames. It is this feature of the visual system which makes it possible to create the impression that properly designed electronic display pictures are continuous in both time and space.

The illusion that image motion is continuous even though its presentation actually occurs in spatially displaced steps is therefore considered to be a natural consequence of visual cortex processing of the temporally and spatially sampled information it normally receives from the eyes. Since the mental processing necessary to create the impression of apparent image motion would have to have evolved conditioned by object motions which satisfy natural physical laws it is postulated that the same laws have to govern the motion of imagery presented utilizing motion pictures, CRTs and dot-matrix displays. This fundamental proposition serves as the basis for developing the criteria applicable to the design of dynamic format display presentations.

Summary of Current Display Presentation Techniques. In the case of motion pictures, the camera records static pictures of the scene just as it existed during each of the fixed frame film exposure time intervals. By precisely timing the interval between the camera film frames of the scene, and by reproducing this picture frame time interval accurately during projection, an exact scaled replica of the time sequence of object locations in the original scene can be recreated in the projected scene and the conditions needed to produce apparent image motion are automatically satisfied. The only potential shortcomings of this display process is the image smear which results from object motion relative to the camera field of view while a frame is being exposed and the failure to achieve synchronization between the original camera and the final projection frame rates.

The resolution of high quality projected film pictures typically exceeds the resolution limits of the human's visual system. However, even when this is not the case, the grain structure of film is not apparent. The grey scale encoding of the information presented in movies tends to mask the spatial quantization of this display media by introducing grey scale transitions between areas of differing contrast. In addition, the optical transfer function limitations of the movie camera and film projector systems tend to disperse sharp object contrast transitions over spatial recording and projection areas which are much larger than the microscopic film grains and thereby produce the visual impression that the picture is blurred, rather than being quantized.

The stroke written CRT display's picture frame presentation capabilities are very similar to those of the motion picture projector in that there are no spatial restrictions on the viewing screen placements of the displayed picture frame images. The principal difference between the two display techniques is that the stroke written CRT is typically not operated from a camera sensor, which simply records the natural object motions in a scene as they occur, but rather, its imagery is under software control. The nearly unlimited control over picture spatial positioning, in combination with the use of continuous signal image position control algorithms which are periodically sampled and displayed makes it possible to maintain an almost exact correspondence between the locations of ideal and actual display imagery on a stroke written CRT display. The limitations of the motion portrayal capabilities of such displays consist of image motion deviations induced by variations: from an equal signal processing delay time interval, from a failure to maintain a constant frame rate and from the use of digital signals where the errors associated with signal quantization increments can influence image placement on the display screen.

Raster written CRTs which restrict image spatial placement in the direction normal to its scan lines and dot-matrix displays which restrict image placement in both X and Y directions provide the most severe constraints on achieving the apparent image motion illusion. This is true because at the time that it is desired to display a picture frame, the ideal location for displaying the image need not be in spatial registration with the discrete raster line or XY matrix structure that the display must use to portray it. The visual effect produced when an image occupies slightly misplaced locations in each of a sequence of picture frames is best described as image jitter.

The consideration of apparent image motion in this report will concentrate on the criteria issues associated with dot-matrix displays. It should be noted however that similar considerations are also applicable to the special cases of movies and CRT displays when digital signal processing or computer generated animation techniques are employed to produce the displayed pictures.

<u>Design Impact of Apparent Image Motion</u>. To produce the impression that image motion is smooth and continuous, it is necessary for the image positions actually realized on the display surface to agree with the observer's expectation of where they should occur based on an extrapolation of the past motion trend. Since the spatially discrete nature of a dot-matrix display surface does not permit the positioning of images between discrete pixels, as a next best motion depiction, the movement of the image between the allowed discrete pixel positions should be timed to coincide with the motion of an ideal continuously moving image. In other words, the time at which a continuously moving image would reach the next pixel location should correspond as accurately as possible to the time at which that pixel is energized to depict the image motion.

Since the human visual system temporally samples dynamic visual scenes and from consecutive samples produces the mental impression of smooth image motion; by providing the correct visual samples on the display the motion can be made to appear continuous, even though it is in reality made up of discrete spatial steps. Conversely, if the motion depicted on the display fails to correspond to the observer's expectation, the observer's visual samples indicate a descrepancy with the expectation and the motion then appears as it is, discrete, and depending on the type and magnitude of the deviation possibly also erratic.

Figure 3.9a illustrates the time dependent position of a point on a horizontal line which is being translated vertically at a fixed speed. Figures 3.9b, c and d show methods which have been demonstrated to produce apparent image motion when time framed spatially separated samples of the object motion are displayed. Provided that the spatial motion of the displayed line falls within the required range of spatial increments Δy and frame timing intervals T, no visually perceptible difference between the continous and sampled image motions would be discernable for the display techniques illustrated in Figure 3.9. Moreover the perceived luminance of the line, ΔL_p, would appear the same for each viewing condition if the following relationship

$$(3.8) \qquad \Delta L_p = \Delta L_a = \frac{\tau_b}{T_b} \Delta L_b = \frac{\tau_c}{T_c} \Delta L_c = \frac{\tau_d}{T_d} \Delta L_d$$

is satisfied.

Notice that perceptual equivalence to a continously moving object is achieved for the motion picture example of Figure 3.9b even though the eyes are exposed to a picture frame image which is held stationary for a time interval τ_b nearly as large as the elapsed time period T_b between successive picture frames. The results of Neuhaus for two light spots show in fact that apparent image motion can be achieved even when the second displaced spot of light is turned on before the first is turned off. For the motion picture example this would be equivalent to a frame temporal overlap condition where $\tau_b > T_b$. Although the temporal overlap of frames is not feasible for a motion picture camera, where the film must move between each frame, electronic display media which exhibit persistence could satisfy this image exposure condition. The perceptual result of a display persistence condition which causes the image exposure times, τ, to exceed the frame period, T, is image smear.

A display situation which is closely analogous to the motion picture example of Figure 3.9b occurs when an electronic display is refreshed several times during each motion picture frame update period, T_b. This was the case for the ADM-I display when operated for instance at a 20 ms update period. In this case the display pattern would be repeated 10 times at 2 ms intervals before a new update pattern, with the imagery moved to a new location, would be displayed. Alternatively for a 8 ms update period only four 2 ms interval refresh pulses were displayed before new interpolated avionics data was presented. The pulse conditions required to produce equal perceived luminance for the ADM-I display and the motion picture technique is as follows

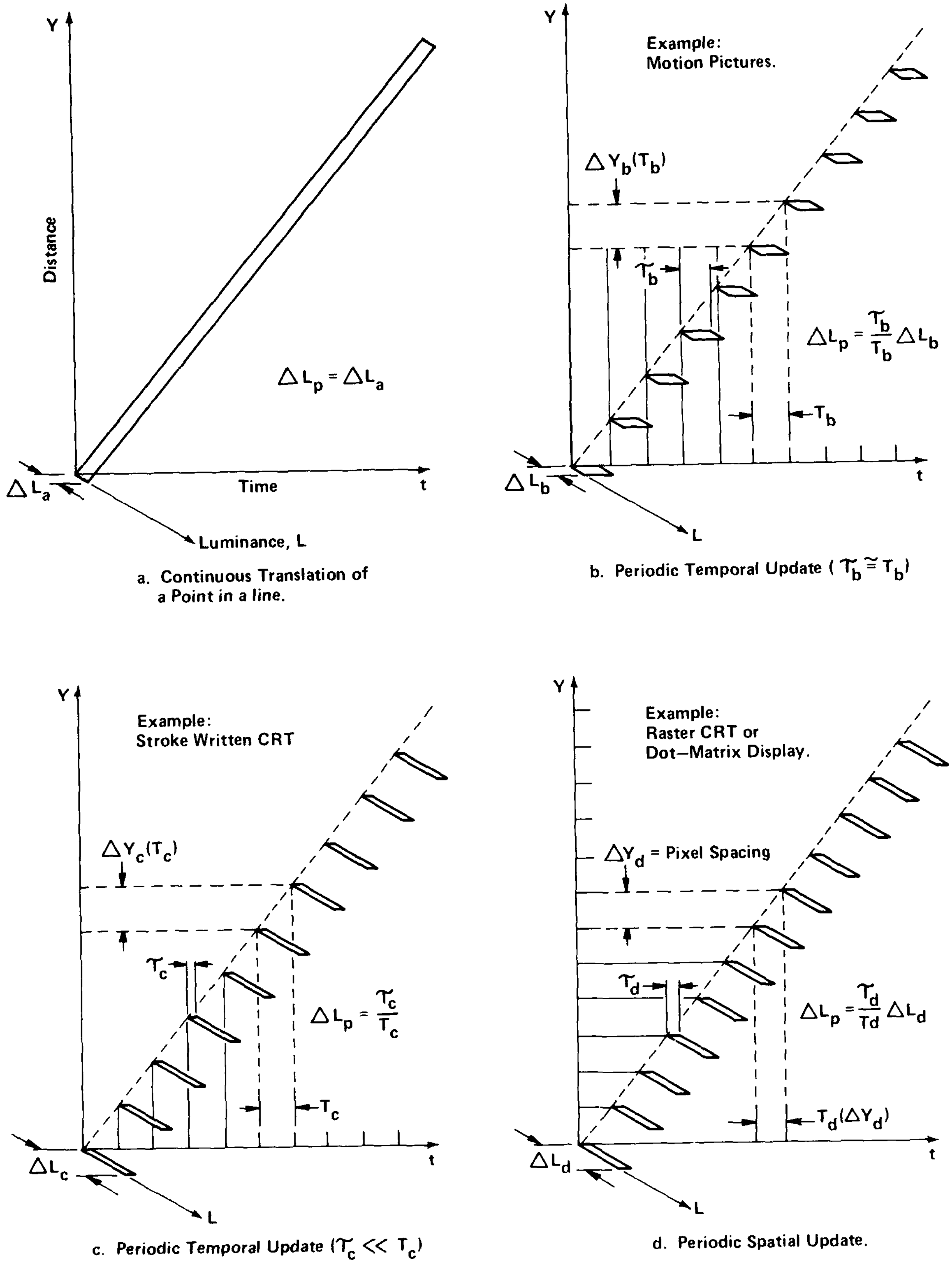


Figure 3.9 Methods of Achieving Display Image Motion Perceived as Continuous

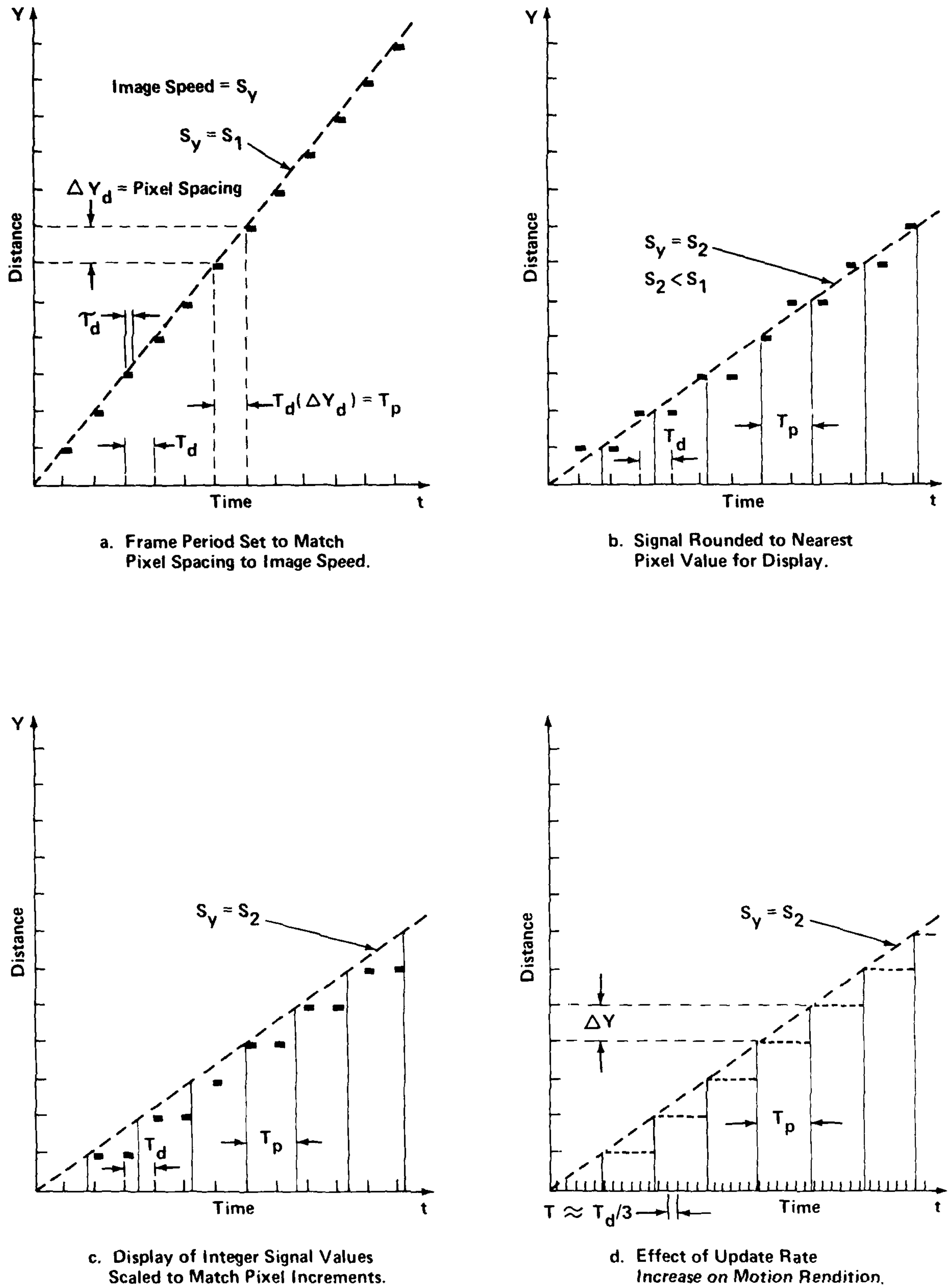
$$(3.9) \qquad \Delta L_p = \frac{\tau_b}{T_b} \Delta L_b = \frac{n_r \tau_r}{T_d} \Delta L_d = \frac{\tau_d}{T_d} \Delta L_d$$

where n_r is the number of refresh pulses during each update period T_d of the electronic display and τ_r is the display's refresh pulse duration. In summary then, electronic display techniques including CRT and dot-matrix displays will produce imagery which is visually equivalent to that of motion pictures when a sequence of short duration high luminance refresh pulsed frame exposures are substituted for the single longer duration lower luminance exposures associated with each frame of a motion picture presentation technique. Alternatively the motion picture presentation result can also be achieved with single very short duration but high luminance pulsed depiction of each picture frame (i.e., as illustrated in Figure 3.9c and 3.9d).

The important distinction between the dot-matrix display apparent motion drive criteria of Figure 3.9d and those shown for motion pictures and stroke written CRTs in Figures 3.9b and 3.9c is that spatial registration of the ideal and display image positions is assured in the latter case if proper signals are used and signal-display timing is maintained whereas for a dot-matrix display achieving *spatial registration* between the image and the display matrix represents an added design constraint. Figure 3.9b shows that the speed of the image and the pixel spacing determines the required timing of the display picture frames. In the likely event that periodic update of the display picture presentation is employed, then it is necessary for the update rate to be high enough so that the image spatial positioning error will be small.

The update period T_d shown in Figure 3.9d is satisfactory for the speed and pixel spacing shown but if the image speed were for instance to be changed as illustrated in Figure 3.10a, then the available pixel positions restrict the accuracy of the dynamic image motion depicted. Figure 3.10a is a repeat of Figure 3.9d with the luminance axis eliminated. Figures 3.10b and 3.10c employ the same update period $T=T_d$ as Figure 3.10a, but the image speed to be displayed has been reduced from $Sy=S_1$ to $Sy=S_2$, an arbitrarily selected lower value. In Figure 3.10d the image speed of $Sy=S_2$ is maintained but the update period T has been reduced (i.e., the frame rate has been increased).

In all four of the drawings shown in Figure 3.10: (1) the short horizontal lines represent the duration of the display drive pulses, τ_d (i.e., τ_d is actually a much shorter pulse than the lengths shown for illustration purposes in Figure 3.10 would indicate), (2) the dashed diagonal line represents the path that an ideal image in continuous



a. Frame Period Set to Match Pixel Spacing to Image Speed.

b. Signal Rounded to Nearest Pixel Value for Display.

c. Display of Integer Signal Values Scaled to Match Pixel Increments.

d. Effect of Update Rate *Increase on Motion Rendition.*

Figure 3.10 Effect of Image Speed and Update (Frame) Period on Dot-Matrix Display Image Motion

motion would follow and (3) the vertical lines represent the ideal time to start driving each successive pixel. Figures 3.10b, c and d should be compared with those in Figure 3.9 where apparent image motion (i.e., smooth continuous motion) has already been demonstrated. In making this comparison, Figure 3.10d may be seen to give a good match to the movie illustration of Figure 3.9b except for a small variable frame time delay/advance, τ_f, as measured from the ideal time to display the next frame of information. Notice that the variable time delay/advance τ_f must be less than one update period in duration, that is

(3.10) $$|\tau_f| < T$$

By analogy to the motion picture example it can be concluded that update period-image speed combinations like those shown in Figure 3.9d will cause the apparent image motion illusion to be operative, provided that: (1) the display refresh rate $f_r \geqq 1/T$ is high enough to prevent flicker, that is

(3.11) $$f_r > \text{CFF (critical fusion flicker frequency)}$$

(2) the pixel pitch time interval T_p (i.e., see Figure 3.10) has a value less than the apparent to sequential image motion threshold T_{p1} below which apparent image motion is induced, that is

(3.12) $$T_p < T_{p1}$$

and (3) that the frame time delay/advance interval τ_f should be small in comparison to T_{p1}, that is

(3.13) $$|\tau_f| \ll T_{p1}$$

Equation 3.11 is the standard requirement to avoid the perception of flicker in static pictures portrayed on electronic displays. The dependence of flicker on picture area, contrast ratios, refresh rates and light adaptation levels are relatively well known and apply equally well to each of display techniques that have been considered here. For this reason, this criteria will not be discussed further in this report. Unless stated to the contrary it should be assumed that when update rates low enough to cause flicker are considered in this report then the updated information is being refreshed at a rate, f_r, satisfying Equation 3.11.

Image translation time intervals, T_p, (i.e., the time interval between the times update pulses are applied to successive pixels), that are chosen to satisfy Equation 3.12 can be produced apparent image motion provided that the other motion criteria are also satisfied. Precise values for the T_{p1} limit could not be explored using the methodology applied during the ADM-I display EADI format flight simulator experiments, and as a result numerical values for this parameter can only be estimated at this time from the work of Neuhaus. Using this approach, T_{p1} values are expected to be in the range of

$$(3.14) \qquad 250 \text{ ms} < T_{p1} < 420 \text{ ms}$$

where, for a given test condition, subject to subject variations could be as much as 100 ms, even though the results for each subject were repeatable and where longer pulse exposure durations cause the shorter intervals between updates. For time intervals greater than T_{p1} the images are seen as successive, that is the motion appears to be stepped rather than continuous between updated pixels. It is probably no accident that the corresponding frequency threshold for apparent motion

$$(3.15) \qquad f_{p1} = \frac{1}{T_{p1}} = 2.4 \rightarrow 4 \text{ Hz}$$

is in good agreement with the maximum update rate at which alphanumeric characters can be changed before they can no longer be read with accuracy. In other words, giving an observer sufficient time, T, to correctly interpret an alphanumeric readout before changing the information depicted

$$(3.16) \qquad T > T_{p1}$$

is equivalent to holding an image in one location for a long enough period, T, to firmly establish its spatial location. As a consequence of these relationships, stepped image motion on a dot-matrix display occurring at time intervals satisfying Equation 3.16 cannot be avoided except by increasing the pixel density to the point that single pixel motions cannot be resolved. Assuming a display of high image quality pixel pitch spacings of

$$(3.17) \qquad \Delta x = \Delta y < 0.4 \text{ minutes of arc}$$

or

$$(3.18) \qquad \Delta x = \Delta y < 3.26 \text{ mils (28 inches viewing distance)}$$

would be required to eliminate stepping entirely. This would mean that under ideal viewing conditions a display resolution of about 300 pixels/inch would be needed to totally eliminate the perception of image stepping although resolutions in the range of 100 to 125 pixels/inch would probably suffice to minimize the effect for most viewing conditions.

The opposite extreme of the apparent image motion range is restricted by the time interval between updates, T, becoming so short that successive image update appear simultaneously when

$$(3.19) \qquad T < T_{p2}$$

on the display screen. In the case of the Neuhaus experiments this condition was characterized by the two light spots being reported as turning on and off at the same time. Under the darkened room and image size test conditions employed by Neuhaus, a time interval, T_{p2}, between updates of 50 ms (an update rate of 20 Hz) was always sufficient to produce simultaneity. This result indicates the simultaneity response is closely related to the phenomenon responsible for the perception of flicker and as such can be expected to depend on the image size, its luminance contrast and on the observer's light adaptation level.

The time interval characterization of the apparent image motion/simultaneous display image transition is not in itself sufficient to describe this limit, even for the special case studied by Neuhaus. Increasing the light pulse durations or the spacing between the two light sources increased the update period, T_{p2}, needed to perceive the lights as being simultaneous (i.e., reduced the apparent image motion range). Conversely when successive stepped positions of the image actually monotonically translate rather than sequencing back and forth between two fixed locations, new motion cues are added to the perception process which enhance the perception of apparent motion. In this case, physical tracking of the motion by the eyes and head strengthen the illusion that the image is in continuous motion rather than being spatially incremented and simultaneity causes several different positions of the image to be visible at the same time. This is the equivalent of image smear (i.e., the comet tail decay) of continuously moving objects. When the head and/or eyes track the image motion, the same location on the retina is refreshed each time the display image is energized. The repetition produces a high perceived luminance for the tracked image and causes the fixed part of the picture which is moving on the retina to be deemphasized due to the lack of repetition.

The failure to time the display of an image so that Equation 3.13 is satisfied results in the image being displayed either too soon or too late. Perceptually the image appears spatially displaced from where it should be by up to one half a pixel spacing from the ideal location. As a function of time, these position deviations (i.e., illustrated in Figures 3.10b and c) cause the image to appear to translate in an erratic manner rather than smoothly. On the ADM-I display where variations of up to $\pm$ 8 mils were possible due to the 16 mil pitch of the pixels on the display surface, an initial failure to design the display format to minimize the position deviation problem resulted in very noticeable format motion fluctuations. These variations not only made objective readings of some of the display's linear scales difficult but in some cases also produced an objectional level of jitter in the different moving parts of the EADI display format. This problem had been anticipated and when the alternative linear moving scale designs accounting for this problem were implemented smooth image motion was thereafter achieved.

Image Motion Continuity Design Factors. Three image processing considerations influence the ability to achieve the ideal display drive conditions shown in Figure 3.9, that are needed to produce the appearance of continuous (smooth) image motion. In all three cases the fundamental issue is the accuracy of the timing or positioning of the display imagery in relation to the track that a continuously moving ideal image would follow. The image processing considerations which influence motion continuity are: (1) the timing of the discrete image position changes (i.e., which has already been described), (2) the magnitude of the least significant bit (LSB) for digitized display input signals in relation to display image pattern scaling and (3) the reduction or elimination of signal noise induced image position fluctuations. The primary image interpretability issue relates to achieving a match between the discrete raster or dot-matrix spatial steps and the parameter magnitude values which are meaningful in terms of the task to be performed.

Just as the periodic temporal sampling and display of a signal can result in signal amplitude (i.e., image position) quantization errors, the digitization of sensed or derived aircraft signals can also produce signal amplitude quantization errors during display. To minimize the potential errors that digitizing a signal can produce, the signal should be processed to produce a LSB magnitude for the signal transmitted to the display which is an integer multiple smaller than or equal to the signal amplitude selected to produce a one pixel increment in the location of the display symbology representing the variable magnitude on the display surface.

The result of a failure to satisfy this criteria is illustrated for the horizontally oriented heading scale format shown at the top center in Figure 3.11. When this format was depicted on the ADM-I display, the binary number representation of the heading information that was used to animate the scale index markers and numeric annotations had an LSB value which the display was programmed to interpret as 1/2

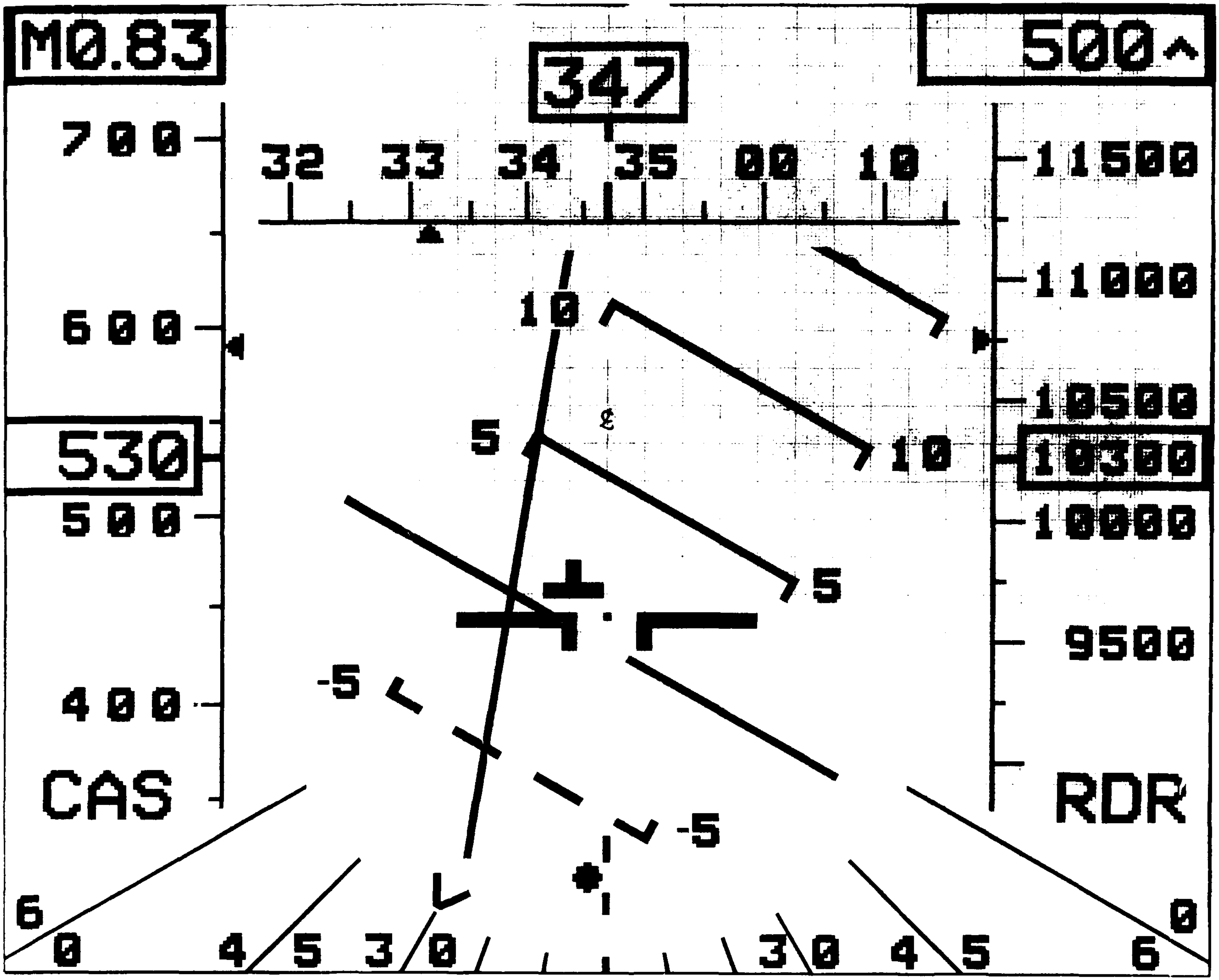


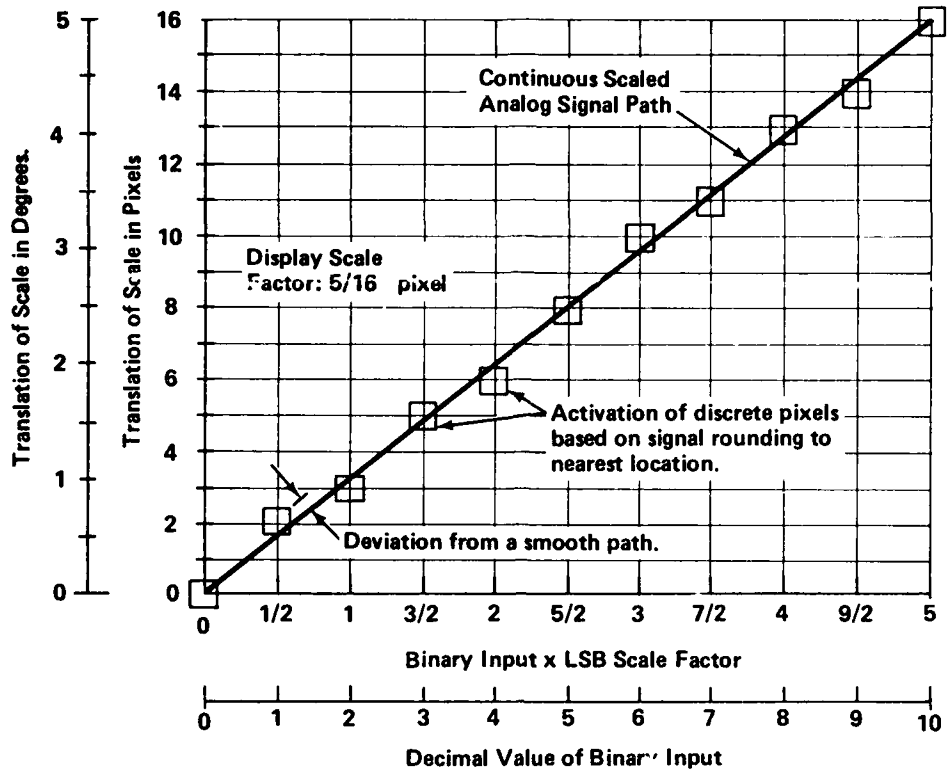
Figure 3.11 Preliminary Dot-Matrix EADI Format Design

of a degree. The display format presentation had, however, been selected to provide a 50° wide heading angle presentation that was scaled to spread the 50° over 160 pixels of an available format window which was 188 pixels wide (i.e., the 188 pixel width of the heading window was chosen to permit the display of numeric scale annotations above the corresponding moving scale index markers with minimum obscuration at the end of the scale). While this design choice very nearly matched the display format layout which had been recommended by pilots for portraying heading data, it resulted in a display scaling factor of $5/16^{\circ}$ per pixel which is not an integer multiple of the $1/2^{\circ}$ binary signal LSB sent to the display. The mismatch results in a variable digitization error (i.e., image display position error) as is illustrated in Figure 3.12a.

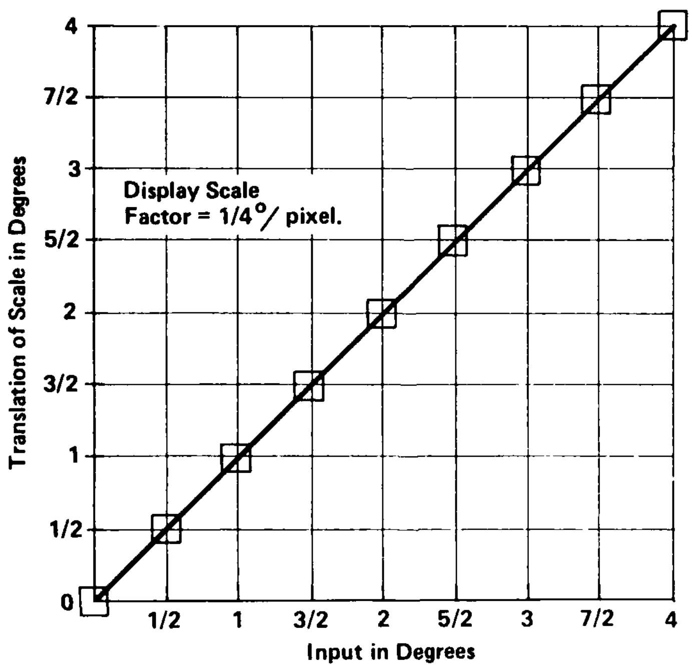
The deviations shown in Figure 3.12a result from the inability to produce matched digital image motion steps for the allowed input signal amplitude increments. This form of deviation cannot occur on a display that has continuous image positioning capabilities such as a stroke written CRT display as long as analog beam deflection signals are used. It could be present: (1) on dot-matrix displays, (2) on raster written CRT displays (i.e., for image positioning transverse to the raster scan direction) or (3) on any display depicting digitally processed video signals.

Figure 3.12b shows the effect of scaling the display image displacement magnitudes so that they match the input signal LSB values. In this case there is a pixel corresponding to each input signal value and as a result there is no deviation built into the system as a result of the format programming employed. When a design achieves this match, it prohibits the scale motion fluctuation illustrated in Figure 4.12a which is perceived as image jitter due to the erratic motion of the image.

Referring again to Figure 3.12b it may be seen that the scaling chosen to correct the LSB/pixel scaling mismatch results in every other pixel on the display being skipped, that is the $1/2^{\circ}$ LSB produces a two pixel translation minimum each time the input data changes. For image speeds too slow to produce apparent image motion, the two pixel image motion increment is made more perceptible than necessarily by the $1/2^{\circ}$ LSB. For this reason the LSB value for the input data should in general be chosen to produce a one pixel motion increment. Thus in the case of the example just given an LSB of $1/4^{\circ}$ or any binary multiple less should be employed.



a. Pertubations in Heading Scale Translation



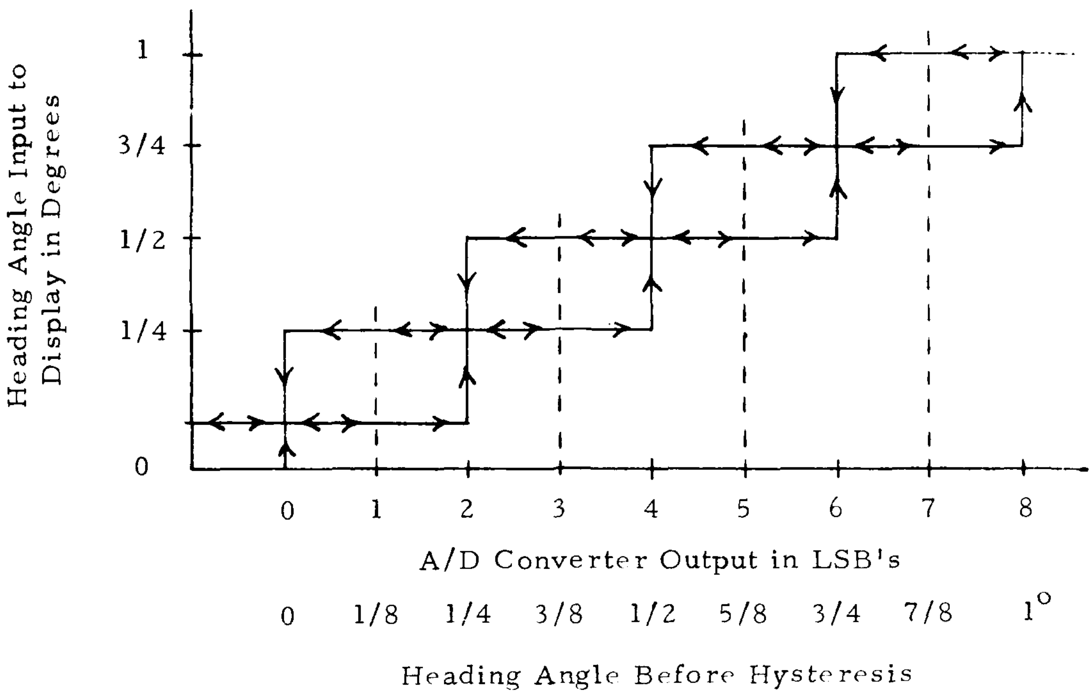
b. Scaled to Promote Smooth Motion.

Figure 3.12 Effects of Display Scaling Factors and LSB Values on Scale Translation

Noise is another important issue which has to be considered in the processing of digital signals for display. Even the presence of a nearly infinitestimal noise fluctuation on an input signal that is analog to digital (i.e., A/D) converted can result in fluctuations in the digital signal by one LSB value, if the fluctuation happens to occur at a digital signal transition point of the A/D converter. A technique for eliminating this problem without degrading the time response of the system involves the use of hysteresis processing of the digital signal as is illustrated in Figure 3.13. By selecting an LSB value one half the magnitude of a one pixel increment or smaller, fluctuations equal to one LSB that are induced by noise can be filtered out and yet not degrade the accuracy of the information being displayed. For example, a noise perturbation causing the sensed heading angle to fluctuate between $1/4^{\circ}$ and $3/8^{\circ}$ would result in a steady $1/4^{\circ}$ heading angle input signal to the display. A similar $1/8^{\circ}$ signal change between $3/8^{\circ}$ and $1/2^{\circ}$ would transition the signal to the display to a steady $1/2^{\circ}$. In either case a noise perturbation of greater than one LSB would be required to cause the hysteresis processed digital signal sent to the display to fluctuate.

The need to incorporate a hysteresis algorithm to prevent fluctuations in displayed image positions (e.g., and numeric readout values) was found to be unnecessary for the computer simulated EADI format experiments, except for directly displayed A/D converted signals. The aircraft aeronautical model, by virtue of inertia effects incorporated in its aircraft dynamics calculations, functions as an effective filter of input signal variations. This is therefore one aspect of an electronic display system's operating performance which cannot be effectively evaluated in an aircraft simulator with its aeronautical model hosted on a digital computer.

Image Interpretability Design Factors. The interpretability of imagery is dependent primarily on the design of the format used to present it and on its legibility. These two factors determine the speed with which the display information can be assimilated by a pilot. In the case of moving scale information, rapid interpretation is known to depend on the values assigned to major and minor scale index markers which in turn determines how readily intermediate scale values can be mentally interpolated or motion trend information can be assessed. These design issues have been thoroughly studied in relation to static or near static information presentations and the results, which may be found in the literature,[15] also apply to dynamic information portrayal designs. The present discussion will therefore concentrate on dot-matrix and dynamic image presentation issues.



Legend:

⟷ Transition is bidirectional for a 1 LSB change in A/D converter output

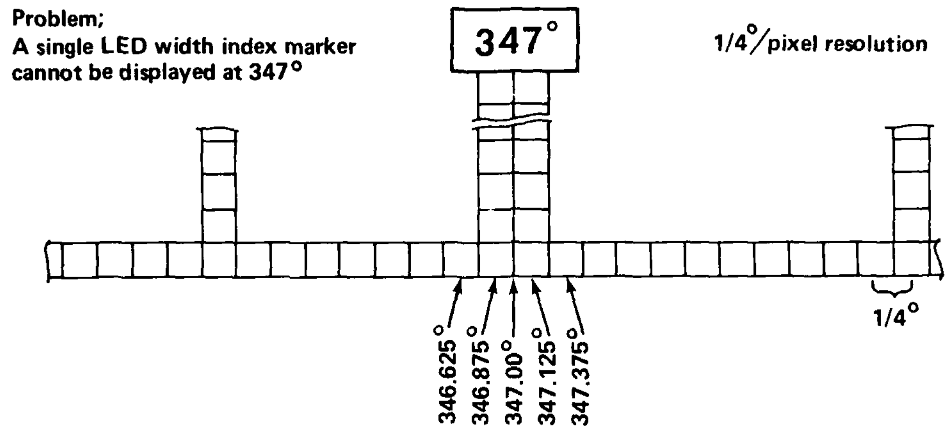
⟵ ⟶ Transition is unidirectional for a 1 LSB change in A/D converter output

Figure 3.13 Elimination of Quantization Noise Using Hysteresis

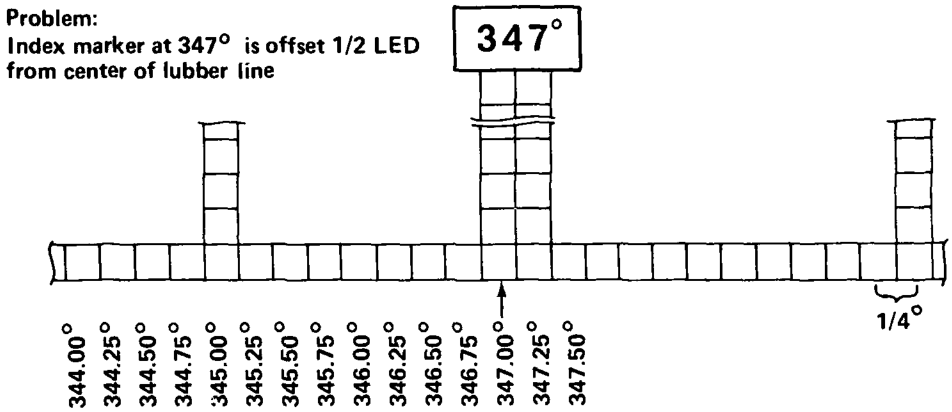
Dot-matrix displays by virtue of their discrete image positioning constraints introduce the possibility of a new level of scale reading accuracy. Each time the scale moves, it does so by a fixed discrete increment and if this step is assigned a value which is meaningful in terms of the task to be performed, it can at least potentially serve as an additional reading/control cue. Just as major and minor scale divisions must be assigned readily interpretable value increments: 1's, 2's, 5's, 10's and so forth, for pixel increments to have meaning, they also must have readily interpretable values. In practice this means that the display of a 500 foot altitude scale should be formatted on the dot-matrix display (i.e., or digital bit-map for other digitally processed electronic display media) so that the one pixel spacing equals 1, 2, 5, 10, 20, 50 or 100 feet, depending on the space available, rather than by arbitrarily assigning a scale length on the display which could even result in non-integer value increments. In this way each step of the scale can with experience have meaning to the pilot.

Another problem in format design which occurs for dot-matrix and other digitally encoded electronic displays is illustrated in Figures 3.14 a and b. These figures are expanded views of the heading scale shown in the EADI format of Figure 3.11. The interpretability problem arises due to the desire to emphasize the position at which the scale is to be read by using a two rather than a one pixel wide index marker. The result is that the single pixel wide moving degree markers on the scale cannot be centered under the two pixel wide read point as is illustrated in Figure 3.14a. Accuracy can be achieved by assigning the reading point to one or the other half of the major marker as is illustrated in Figure 3.14b but this places an added reading burden on the person using the scale. A means of resolving the problem is shown in Figure 3.14c where the reading line has been split and also spaced from the scale. This design prohibits obscuration of the single pixel wide moving scale markers and yet still permits accurate unambiguous heading indications to be displayed. Although the design in Figure 3.14c proved quite satisfactory during the EADI experimental evaluation, the point of this illustration is not the superiority of the Figure 3.14c design but rather is the need to be aware of the restrictions imposed by a XY matrix image presentation grid. A dot by dot mapping of an intended format design as is illustrated in Figure 3.11 allows virtually all potential flaws to be encountered and resolved as a step prepatory to programming the display format, which, in any event, requires that such a map be prepared.

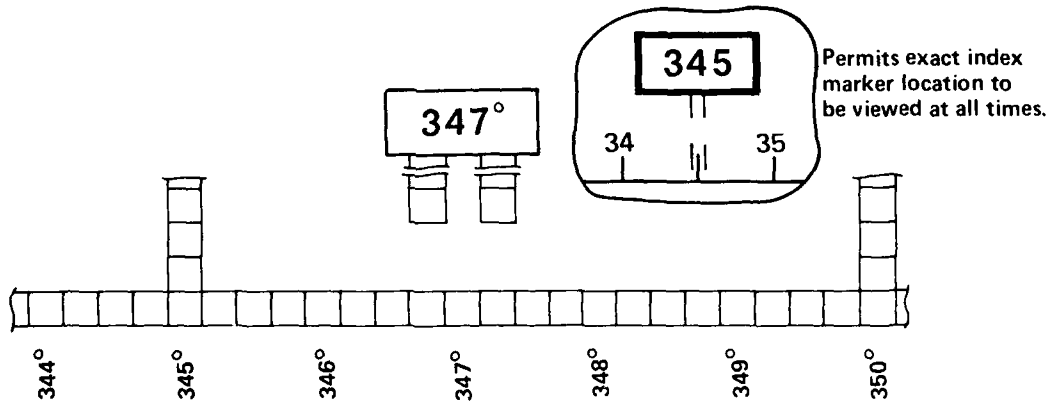
In the tight area confines imposed by typical aircraft display installations, the ability to provide an unobscured view of the scale numeric annotations, as has been done in Figure 3.14, is not always possible. For this reason, the design of the airspeed and altitude scale



a. Approximate Presentation with Present Format



b. Alternative Approximation with Present Format



c. Exact Presentation with Altered Format

Figure 3.14 EADI Heading Scale Value Assignments formats shown on the left and right side of Figure 3.11, respectively, make it necessary to blank the moving scale numeric annotations at the top and bottom ends of the scale and during periods of time when they would otherwise interfere with the information displayed in the airspeed and altitude numeric readout boxes. The EADI format programming resulted in the blanking of entire letters when the permissible display window boundaries were overlapped by any part of an image. This type of image masking proved to be quite satisfactory when a scale was in a state of continuous translation. The abrupt appearance and disappearance of entire readouts were much less noticeable than had originally been anticipated and typically did not interfere with the desired illusion that the scale annotations pass under and are occluded by the numeric readout boxes.

The primary shortcoming of the abrupt blanking and appearance of the numerics occurred during periods of time when the pilot was attempting to hold an aircraft variable at a fixed value on the scale. In some instances this control process resulted in the scale numbers moving in and out of the area where blanking of the annotations occurs. The result was that the number could appear to fluctuate on and off, and since the entire number is affected simultaneously, the visual effect is quite pronounced. Although none of the 28 pilots noted this design issue in their questionnaire responses, some did report noticing it verbally. A later version of the display which was flight tested in a helicopter by National Research Center of Canada personnel incorporated a line at a time (i.e., gradual) occlusion of its numeric scale annotations. This design approach virtually eliminated the image fluctuation effect due to the smaller area of image being turned on and off at any one time. The gradual occlusion and appearance of the moving numeric annotations at the top and bottom edges of the altitude and airspeed boxes greatly accentuates the illusion that the scale annotations pass under and are obscured by the box containing the fixed location time changing numeric readouts. The primary advantage of this image formatting technique is that it assures that the pilot's attention cannot be distracted from other display viewing tasks as a result of a scale numeric annotation appearing to flash as it is generated or blanked.

Format Rotation and Translation

One of the most noticeable visual effects associated with dot-matrix, raster written CRTs and other electronic displays that are operated using digitally processed signals, occur during periods of time when the format: (1) translates in a direction other than along its pixel axes, (2) rotates or (3) translates and rotates as a combined format motion. The most easily identified visual effect associated with these motions is the appearance of stair steps along lines and image boundaries when the format rotates. Consequently the generally negative aesthetic response to witnessing the rotation of a digitally generated format centers on the stair steps generated as the format moves.

Pilot questionnaire responses regarding the performance of the pitch and roll portion of the electronic attitude director indicator (EADI) format were mixed. Slightly over a quarter of the pilots rated the presence of the stair steps on the display as not affecting the reading of other display information. Slightly under one half of the pilots considered the presence of the stair steps to be an annoyance to reading other information. An additional one fifth of the pilots rated it as "slightly degrades performance" and one rated it "greatly degrades performance". None thought the fifth category "unacceptable may compromise flight safety" applied.[3] In a related question the pilots were asked to rate the effect of the stair steps on the ease of maintaining a wings level attitude in comparison to a standard attitude director indicator. The result was that 4 pilots rated it "much easier", 5 rated it "slightly easier", 6 rated it "about equal" and the remaining 13 rated it "slightly more difficult". None chose the final response: "much more difficult". Fighter pilots did not like the additional roll angle control cues afforded by the stair steps whereas pilots of large aircraft tended to like the added cues.

In comparison to questions on other issues the responses regarding stair steps produced by far the most negative results from the pilots regarding the display's operation, and the only negative comments regarding an issue related primarily to the dot-matrix nature of the display presentation. In a question in which the pilots were asked to rate the suitability of the display for use in actual aircraft to perform high performance maneuvers, seven of nine pilots with head-up display experience (i.e., a similar integrated display format) rated it as being suitable with the other choices being "suitable with modification" and "unsuitable". In all 11 pilots rated it suitable and 17 rated it as suitable with modifications (i.e., with all but one of the changes recommended being to the format design, instead of the display itself). None of the pilots considered the display to be unsuitable and only two of the pilots recommending modifications cited minimizing the noticeability of the stair steps as an issue.

Based on the foregoing results, taken together with the subsequent analysis of the objective performance analysis results [11], it can be concluded that the impact on the pilots of the dot-matrix rendition of the EADI format rotating and translating imagery is primarily aesthetic in nature. This result should not be construed as a general validation of dot-matrix image presentations, however, in that the pitch and bank information presented was not actually degraded by virtue of the dot-matrix visual effects associated with its portrayal. In other words the stair step distortions of rotated lines do not actually reduce or otherwise influence the accuracy with which bank or pitch angles can be read by the pilot on the EADI format that was employed but could potentially influence other format designs. A simple illustration of this occurs for the pitch ladder numeric annotations. In the experiment performed, these characters were always depicted in a vertical orientation, rather than being rotated as the roll angle changes (i.e., they were inverted for roll angles greater than $\pm 90^{\circ}$). As a result of this design choice, the characters always remained equally perceptible. Had the characters actually been rotated, the dot-matrix presentation media would have resulted in their shapes being distorted. The likely consequence of implementing pitch ladder numeric scale annotations that rotate as the pitch ladder does (i.e., as is conventional for electromechanical ADIs and stroke written CRT EADIs) would therefore have been reduced character recognition performance.

In this section the factors which have been found to influence the visual appearance of dot-matrix (i.e., or digitally generated) displays are identified. The primary effects associated with the rotation and translation of imagery using a XY matrix grid display media are: (1) distortions of image shapes including stair stepped lines and serrated image edges and (2) the introduction of an erratic component to the motion of imagery which the pilot would normally expect to be smooth and continuous.

<u>Visual Effects Due to Image Translation Along Non-Orthogonal Axes</u>. The previous techniques described to produce and enhance the illusion of apparent image motion on moving scale display formats become largely ineffective when a format can rotate as well as translate due to the nonuniform spacings of pixels along such image paths. As will be recalled, the techniques depended on scaling the input signals and setting their least significant bit (LSB) values to match the digital input signal magnitudes to the digital grid pattern forming the display surface. More specifically the matching actually occurred only along the X and Y pixel display surface axes along which the horizontal and vertical moving scales were oriented to take advantage of the uniform pixel spacing found in those directions.

In the event that the direction a scale or image is to be translated in is not oriented parallel to one of the two orthogonal pixel axes, then two problems will result. The first problem is that the row and column spacing in the direction of motion is larger than it is in the

X or Y pixel axes directions and moreover is a function of the angle between the motion direction and the pixel matrix orthogonal axes. The second problem is that adjacent rows and columns of pixels in the motion direction, no longer have a pixel precisely centered where the direction of motion intersects the pixel row and column axes.

The first problem is actually only a problem if the axis along which the scale is to move changes direction as a function of time. If an image translation orientation angle with respect to the matrix remains fixed, then scaling can be accomplished just as it was for the dot-matrix orthogonal axis moving scale format designs already described. If instead, the scale can operate in different orientations then the motion perturbations previously described cannot be fully compensated. In that case, only the use of the highest update rates possible will serve to minimize the perturbations to smooth image translation.

The second problem results from the fact that an image designed to be recognizable using an $X_F x Y_F$ matrix font size can have a positioning error tolerance of as much as $(\pm \Delta X_p/2, + \Delta Y_p/2)$ with respect to the desired motion track across the display surface, where ΔX_p and ΔY_p are the pixel spacings along the X and Y axes, respectively. The visual effect of this problem is that an image translated in a direction other than 0^o, 90^o and 45^o with respect to the display grid XY axes will also exhibit perturbation motions to the left and right or above and below the desired track of up to $\pm \Delta X_p/2$ or $\Delta Y_p/2$, respectively.

The combined result of the two motion problems, say for an image following a general curved image track on the display surface, is a small erratic perturbation from the desired track. The resulting motion is perceived as image jitter on lower resolution displays and as a tremor in the image on higher resolution displays. This characteristic of motion is common to all displays using a matrix grid to depict their imagery. The ability to perceive the effect is very much dependent on the size and shape of the images being viewed and whether they are presented alone or in the context of a complete display format structure. Single moving line and point images produce the largest visual effects.

Visual Effects Due to Image Rotation. Image rotation on a XY matrix grid surface can take two forms. In one form the image itself is rotated about its center of gravity. In this case the recognizable features of an ideal rotating image are expected to appear at a continuim of angles between 0^o and 360^o as time progresses. In the second form of rotation the image is displaced from the origin it rotates about and the image itself may either rotate or remain in a fixed orientation as the image circles the origin.

Recognition tests run on continuous imagery such as alphabetic characters at other than upright orientations or while in a state of rotation show that image recognition accuracy and response times degrade for all but small rotations from the typical upright viewing orientations. Dot-matrix or grid font construction characters are known to produce equal viewer performance to their continuous counterparts for upright or rotated images provided that the matrix is rotated rather than trying to depict the rotated character or a fixed orientation matrix grid. To achieve equal performance for dot-matrix rendered alphanumeric characters which are rotating or at fixed rotation angles with respect to a fixed orientation grid as is achieved for continuous characters, the dot-matrix font size, $X_F x Y_F$, required to depict the characters increases appreciably with respect to its upright dot-matrix character counterpart. Thus while a 7x9 matrix will match the recognition performance of upright continuous alphanumeric characters, a 15x21 matrix is necessary to achieve the same objective for rotated characters.[8]

Two conclusions are capable of being drawn from the foregoing result. First, unfamiliar imagery requires a larger pixel matrix to render it recognizable. Second, imagery that is capable of being rendered using predominantly vertical and horizontal lines requires fewer pixels to make it recognizable when using an XY matrix grid display media that is oriented parallel to the character line dimensions. Combining these results it can be concluded that imagery which is unfamiliar or has no constraints on its line/edge orientations can be rendered using a dot-matrix format, however, the matrix font size must be large enough to permit a rendition which makes the imagery recognizable. The dot-matrix or matrix grid requirements for rotated characters are therefore equivalent to those applicable to the recognition of any electronically generated sensor-video display imagery which due to their bandwidth limitations may also be represented by a finite picture element depiction capability.

The dynamic image portrayal shortcomings associated with image rotation using a matrix grid stems from the inability to portray the image at its ideal location (i.e., as was also true for image translation at non-orthogonal angles) but also because the lack of registration between the desired image pattern and the matrix grid available to depict it at angles of other than 0° and 90°. In the latter instance, the approximate representation of the image at different orientations keeps changing as the image rotates. Thus, even for an image shape which is made up of enough pixels to make it recognizable, it will still appear to have boundaries that move with respect to the image as it rotates.

It can be concluded then that moving a fixed orientation image in a circular or curved path around a point of rotation produces essentially the same type of visual effects that image translation in a straight line does at angles other than 0^{o}, 45^{o} and 90^{o}. The additional visual effect described above is then introduced when the image is also rotated about its own center of gravity.

Format and Display Design Criteria. There are few effective measures that can be taken to improve the visual appearance of imagery that rotates or follows time changing straight line or curved paths on dot-matrix or digital grid matrix generated pictures aside from increasing the pixel density. Degrading the image quality of the pictures by adding blur can diffuse the pixel image edges and mask the visual effect problems thereby making the display picture aesthetically more pleasing. This method of improving the subjective appearance of rotating/translating imagery is often achieved automatically on CRT displays due to the inherent blur associated with that display media. The apparent improvement in the pictures achieved in this manner is deceiving in that it can create the impression that no problem exists while in reality it may be masking the fact that an inadequate number of pixels are being used to depict an image. Care must therefore be exercised when introducing blur to improve the aesthetic appearance of a display.

An alternative method of improving the appearance of rotating/translating imagery when using a dot-matrix presentation technique is to employ grey scale encoding of the imagery displayed. This type of image processing is achieved automatically when a video camera is used to encode graphic picture imagery. The benefit occurs as a result of the fact that serrated image edges and rotated line stair step discontinuities tend to be encoded at reduced grey scale levels whereas the continuous body of the image appears at full luminance. The advantage of this technique is that the image edges themselves are not appreciably blurred yet the projections of the serrations from the image or the indentations into it are displayed with reduced contrast and therefore are made less noticeable. The disadvantage of the technique is that it is difficult to achieve efficient real-time algorithms that allow the technique to be applied directly to computer generated graphic imagery without the intermediate action of the video camera.

A third general technique for improving the appearance of rotating/translating display imagery generated on an XY matrix grid pattern has been conceived by the author, but as yet has not been demonstrated. The objective of the approach is to minimize the large discontinuous motions of the serrated edges of lines and images as the latter rotate. These abrupt changes in the position of the steps forming a line boundary or image edge are perceptible to the viewer as a momen ry flashing motion and are believed to be one of the primary factors which make the stair step images subjectively objectionable. Algorithms used to implement line rotation typically operate using angle least significant bit values that are restricted to the accuracy that the viewer needs to monitor and control the displayed angle. By introducing much smaller LSB values for the input variable and by making the vector enerator capable of responding to the small LSB by moving the line steps or image edge serrations in single pixel steps, the large discontinuous steps between allowed step locations can be reduced to the point that apparent image motion is possible even for very slow angular change rates. Eliminating or greatly reducing the flicker like phenomenon associated with line stair step and image edge serration motions should greatly reduce or eliminate the objectionable aspect of rotating/translating dot-matrix display imagery.

Display Performance Test Techniques

A unique feature of dot-matrix displays is the ease with which image positioning can be ascertained using photographs of pictures portrayed on the fixed XY matrix pixel pattern forming the display surface. In earlier efforts this feature of the dot-matrix display was used to assess the image generation hardware and image processing firmware programming of the display system by providing test input variable values and then determining whether the correct image shapes were displayed at the correct imagery position reference points on the display surface. Moreover because a dynamic picture is just a sequence of static display frames, the correct sequence of data messages allows the dynamic programming performance of the display to be assessed as well.

Burnette Engineering used the above technique in the definition of requirements for the original ADM-I display acceptance tests. The procedure allowed for the identification of design and program errors for display issues such as: (1) the blanking of numeric characters when excessive rate limits for a digit were exceeded (i.e., rate variables were separate inputs); (2) the rounding or truncation of input variable values; (3) the inversion of pitch ladder scale annotations when either the pitch or roll angle exceeded 90° and (4) the performance of moving scales, symbols and format areas for both in and out of range input values. During the present effort this technique was used to verify that the display continued to perform as designed and to check out issues such as the input signal hysteresis characteristic performance of scales and numeric readouts.

Although originally intended as a tool for evaluating the display performance, this test technique also ended up being used extensively during the simulator checkout phase of the present investigation. To verify the correct scaling of signal magnitudes and the settings of least significant bit values, variables send to the display by the host computer could be directly assessed by the errors that were produced in the display picture presentations. Trouble shooting time was greatly reduced using this technique since the source of a particular deviation magnitude could typically be predicted directly based on the effect it had on the display picture generated.

Another important test feature which was implemented during the early design stages of the ADM-I display development was a test pattern generated from a ROM program contained within the display symbol generator. The purpose of this display image generation feature was to permit assessing the performance of the display head and symbol generator independent of the image processor function. This allowed a clear separation to be achieved between image processor (i.e., programming interface and host computer) problems and any potential display or symbol generation problems. Since this separation can otherwise be quite time consuming, particularly when the responsibility is split for different parts of the system, the existence of the test pattern resulted in a considerable time savings during the programming and checkout phase of the program.

In retrospect a further savings in time could have been achieved by building test pattern generation messages into the system to test the image processor and another to test the interface protocol between the display system and the host computer. In this case there is a need to be able to insert a short sequence of messages to achieve a complete test of the display system and interface real-time data handling performance. As a consequence, the built-in test capability required would be in essence a firmware implementation of the type of test originally discussed at the beginning of this section.

CONCLUSION

In spite of the strong emphasis that the subject matter of the present section has of necessity placed on the visual effects associated with dot-matrix display presentations, there has in reality been no evidence encountered either in the present investigation or elsewhere in the author's experience which would suggest that pilot performance would be degraded in any way through the use of dot-matrix displays. Just as a CRT display generating a 300 line raster could not be used in an application where 480 lines are required to make the pictured imagery recognizable, the same is true for dot-matrix displays. All evidence to date would indicate that equally legible CRT and dot-matrix displays of the same resolution would produce equal pilot performance.

In practice most dot-matrix display technologies demonstrated to date exhibit image quality much better than that achieved on comparably specified CRT displays due to the lack of the Gaussian spot spread function which is characteristic of the CRT's spatial luminance emission distribution. Degrading the dot-matrix displays' image quality by either diffusing its display surface through filtering, by mixing the signals fed to adjacent pixels, or through a combination of both, a picture of essentially the same image quality as the CRT could be achieved including the virtual elimination of all of the visual effects herein described. The question which remains unanswered is whether the resulting loss of image quality is actually justified in order to eliminate dot-matrix visual effects. The answer to this question is clearly no for dot-matrix displays with sufficiently large XY pixel dimensions. For lower resolutions the issue does not yet have a certain answer.

SECTION 4

VIDEO

RESEARCH OVERVIEW

The research conducted on video dot-matrix display criteria is summarized in the block diagram shown in Figure 4.1. As the diagram indicates, the research planned for this topic area (i.e., shown using solid blocks) was quite limited from the outset. This was the case due to the lack of a developed dot-matrix display, in any technology, capable of depicting even the minimum information content 525 line video imagery used in aircraft cockpit applications. The inability to create a full dot-matrix picture foreclosed the possibility of conducting a meaningful experimental investigation employing the top-down methodology. To a lesser extent, the lack of a full size display also limits the ability to perform comparative measurements of dot-matrix with CRT displays.

As an alternative to measurement data comparisons of full size CRT and dot-matrix video displays, a theoretical comparison was conducted instead. To complement this investigation, the performance of two dot-matrix video demonstrator displays were evaluated. This provided a means of verifying the theoretical analysis conclusions reached and served to supplement the information available on dot-matrix video display capabilities. The development of both of the dot-matrix video displays assessed was completed by their manufacturers during the period of the present research program. One of these displays was a 2x2 inch, 64 pixel/inch green LED display developed by Litton Systems Canada Limited (LSL) with partial support provided by the Canadian Department of Industry Trade and Commerce. The second display was a 128x128 pixel, 125 pixel/inch green LED display developed by Optotek Limited under an applied research program jointly sponsored by the U.S. Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory and the Canadian Department of Industry, Trade and Commerce.

The time available to work with the video demonstrator displays was limited and consequently only preliminary assessment could be conducted. In the case of the LSL display, exposure to the display consisted of examinations of its performance during visits to LSL's plant. The OTL display delivery to the USAF came very late in the program and as a result its analysis was also restricted.

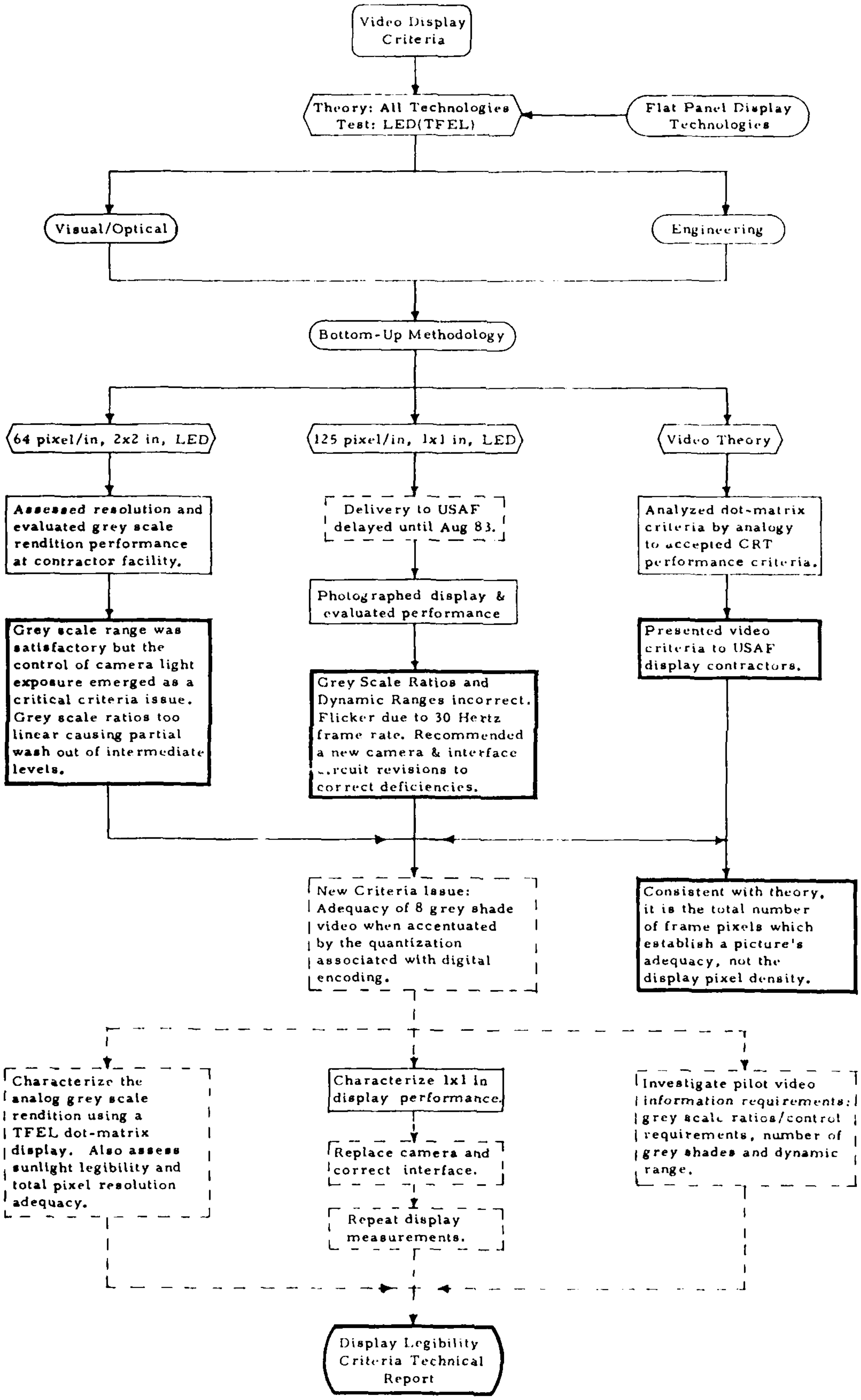


Figure 4.1 Video Display Criteria Block Diagram

The evaluation of the video dot-matrix displays raised issues for which answers were sought by analogy to comparable CRT displays. In some instances this approach proved to be quite satisfactory. In other cases, the approach raised more questions than it answered. This was particularly true for display image grey scale requirements, where great difficulty was encountered in identifying the origin of and experimental substantiation for the grey scale relationships and luminance dynamic ranges in current use in military CRT display specifications. This deficiency in grey scale criteria was emphasized in the two dot-matrix video displays assessed because both employ discrete grey scale levels in the portrayal of analog video camera signals. An approach for carrying the video investigation that is described in this section forward is illustrated by the dashed connection lines in Figure 4.1.

In the remainder of this section, video theory is discussed relative to a spatially quantized portrayal with emphasis on issues raised by the observed performance of the dot-matrix video demonstrator displays. The section is concluded with a description of further research suggested by the results of the present investigation.

VIDEO INFORMATION PRESENTATION FACTORS

The feature that distinguishes video from other types of display information is the use of luminance amplitude modulation to encode the information that is to be conveyed to the viewer of the display. While video imagery has historically been associated primarily with the replication of sensed scene information using sources such as television cameras, radar antennas, sonar sensors, infrared sensors and so forth; computer generated imagery which incorporates luminance level encoding also qualifies as video imagery. The luminance amplitude relationships between the signals presented on a display (i.e., irrespective of the source of these signals) and the spatial relationships between these luminance modulated signals establish the information transfer capacity potential of a video image presentation.

As is indicated in the foregoing discussion, the design criteria issues important to video displays are related to the display's ability to faithfully generate a range of luminance levels in response to input signal levels and concurrently on its ability to depict these changes in luminance through independent control of its individual spatially distributed picture elements. The degree of precision with which a video display has to perform its image rendition function is determined by the criticality of the user task it supports and the need this imposes to be able to achieve correct and complete user assimilation of the information displayed. In other words, the objective of portraying the video information has a large influence on establishing the design criteria the video information system must be able to meet. This subject will be discussed first in this section followed by a discussion of the spatial (resolution) criteria and luminance (grey scale) criteria that electronic displays including those employing a dot-matrix presentation media should satisfy.

Task Related Criteria Issues

The conventional objective when presenting video imagery on an electronic display (as typified by the cathode ray tube (CRT) display), whether it is employed for the portrayal of home television programming or to depict information to the pilot of an aircraft, is to present a perceptually faithful replica of the scene which is sensed. The display picture is typically scaled both with respect to its luminance and with respect to its size to make it compatible, respectively, with the illumination environment that the display observer is adapted to and to make it fit the geometric constraints imposed by that viewing environment. In both of these cases, however, the scaling is intended to be proportional, retaining the same relative luminance (or radiance as is appropriate for radar, FLIR or laser sensors) that is present in the sensed scene while also retaining the same relative spatial, temporal and color (i.e., if applicable) relationships that are present in the sensed scene.

Technology limitations have historically prohibited achieving the foregoing objectives in either home or aircraft electronic display applications. The significance of this failure depends rather strongly on the function the display is intended to perform and in that context on the consequences of its inability to perform in a completely satisfactory manner. To illustrate this point, two extreme situations will be considered.

In the case of home television displays, deviations from the performance ideal need not pose a serious problem. The information portrayed on a home TV is not capable of being directly compared with its source by the viewer and as a consequence deviations between the displayed and sensed scenes can become quite severe before a problem becomes evident to the viewer in absolute terms. In addition, there are no consequences associated with the failure of a television to accurately display program information to the viewer aside from degrading the aesthetic appeal of the picture displayed, or the inconvience a total failure might cause by way of arranging for repair or replacement of the unit. In short, the home television application, against which the general public and many military display users unconsciously assess display performance, is probably the least critical and at the same time the most forgiving to the presence of performance abnormalities. Spatial image distortions, grey scale deviations, picture smear, scintillation, and color shifts must become quite extreme before becoming noticeable while displaying typical commercial television program materials. It is, in fact, during the display of superimposed graphics imagery that these problems are most likely to be noticed.

At the opposite extreme from the home television application lies the military requirement to display superimposed graphics on sensor video imagery, such that the two portrayals are in spatial registration with one another and are dependent on and/or responsive to pilot control inputs to the system. In this case the success of a mission and ultimately the safety of the pilot and aircraft depend on the fidelity of the sensor video portrayal and the accuracy with which graphic imagery can be positioned with respect to it. Only when a faithful reproduction of the sensed scene is achieved can a pilot with confidence fully apply his past acquired knowledge of such scenes for image interpretation purposes.

Spatial Discrimination Criteria Issues

Severe space limitations in a cockpit make it desirable to limit the areas devoted to the display of information. As the result of a need to be able to scan for targets over large scene areas, the display area constraint results in a need to display video information at high resolutions and consequently to take maximum possible advantage of the pilot's spatial perception capabilities. Coincidentally it is also desirable once a potential target is detected to be able to then zoom in on specific smaller areas of interest. This need places severe demands on the sensor systems which have to provide the necessary picture field of view and scaling capabilities while also being capable of adapting to changes in irradiance and/or signal levels. In terms of video display criteria, the small display viewing area constraint translates to a requirement for the maximum number of picture elements feasible, constrained only by the limits imposed by the pilot's ability to make use of the information displayed.

The displays actually used in aircraft represent a trade off between cost and achieving the foregoing pilot performance goal. The display technologies available, including the new dot-matrix technologies, experience rapidly increasing technological problems and costs when the number of picture elements on a set size display surface is increased. This has historically produced a strong incentive to limit the density and total number of picture elements to a point where the pilot performance returns from further increases starts to diminish, and not at the point where further increases would have no beneficial effect on the pilot's visual performance.

In the past, technology limitations have made the argument for higher resolution untenable, and hence not worthy to pursue. Although recent technology advances have altered this situation somewhat, the cost of developing practical high resolution displays suitable for aircraft cockpit use still places them beyond the current state-of-the-art. The criteria for video displays in the cockpit therefore remain at this time a matter of a cost/capability trade off that is only indirectly influenced by pilot visual capabilities. Current direct view cockpit CRT displays are specified to provide 120 lines/inch resolution at 5% relative modulation. A dot-matrix display of 100 lines/inch resolution can produce an at least equal and potentially a better sensor signal image rendition capability depending on the percent modulation it is capable of achieving. Due to the discrete pixel structure of their display surfaces, dot-matrix displays typically have percent modulations which approach 100%.

Grey Scale and Luminance Criteria Issues

A grey scale is literally a scale made up of progressively darker grey (neutral color) areas between white and black that have known discrete luminous reflectance increments between each adjacent area. Evolved for use in television studios, a uniformly illuminated grey scale chart can be used to assess the fidelity with which the luminance signal is sensed, transmitted and displayed. The relative magnitude of the grey scale chart luminance steps should be exactly reproduced on a receiving television studio monitor for a properly designed and adjusted television system. Standard Electronic Industries Association television grey scale charts go from 3% (black) to 60% (white) reflectance in nine linearly or logarithmically related steps.

As the preceding description indicates the relationship between the light sensed by the camera and the resulting luminance levels in the TV monitor picture of the grey scale chart is supposed to be one of direct proportionality thereby allowing an area and magnitude scaled replica of the object scene to be reproduced on the video display screen. When a human views a television screen with these conditions satisfied, a scaled reproduction of the light eminated toward the camera by the real scene is emitted by the display toward the eyes. The fidelity of the reproduction determines the quality of the complete television system.

Military aircraft cathode ray tube (CRT) video display designs are closely patterned after the designs of commercial television monitors in all but their cockpit environmental design features. This is particularly true of their signal line scan standards and of their grey scale rendition characteristics. Major differences in these displays do exist in the larger luminance (i.e., brightness) control range and video amplifier bandwidth capabilities of the military CRT display as compared to television displays.

The 3 to 60% reflectance range employed in grey scale charts is representative of the range of reflectances possible in typical uniformily illuminated natural scenes. Thus while brighter whites and darker blacks are both feasible and visually perceptible, the vast majority of natural and man-made objects can be rendered (i.e., though not optimally) with a display having a 60:3=20:1 dynamic luminance range.

The grey scale chart rendering of black, white and the intermediate greys have the property of appearing approximately the same to an observer over a wide range of ambient illumination conditions and hence over an equally large range of reflected luminance values. The basis for this relatively invariant appearance of the grey scale chart in changing light ambients appears to originate in the adaptation of the human visual system to the changing light levels. The conclusion to be drawn from the apparent constancy of grey scales is that the luminance within a scene is perceived in relative rather than in absolute terms.

When digital grey shades are to be used to form a video display picture it is necessary to know how many grey scales have to be depicted and the relationship between the grey scale levels in order to provide an adequate rendition of the scene being sensed. To minimize the number of grey shades which have to be generated on the display, it becomes desirable to employ equally perceptible grey scale increments. A generally accepted rule for achieving this objective on military aircraft CRT displays is for successive grey shades to be a multiple of the $\sqrt{2}$ apart in luminance. This requirement is intended to make each level easily discernible and yet not be so widely spaced that meaningful scene information is lost.

The conventional mathematical formulation of this military grey scale requirement is expressed as follows:

$$L(n) = (GR)^{n-1} L_D \quad , \quad n = 1,2,... \tag{4.1}$$

where L_D is the display reflected luminance, $GR = \sqrt{2}$ is the grey scale ratio and L(n) is the measurable luminance of the "n"th grey shade. The condition where the display is "off" is considered to be the first grey shade (n=1), and military specifications call for eight grey shades (n=8) to be legible, in all but the highest cockpit ambient illumination conditions (i.e., six grey shade legibility is required in a 10,000 fc illumination environment). Evaluating the military equation for equally perceptible grey shades we obtain:

n	1	2	3	4	5	6	7	8
$L(n)/L_D$	1	1.41	2	2.83	4	5.66	8	11.3

This table shows that only an 11.3:1 luminance dynamic range is needed to satisfy the current military requirements for video image portrayals. Assuming such a display is set to depict a 60% reflectance "white", its lowest shade (n=1) could portray a 5.3% reflectance "black".

While there is no question that an analog video CRT display satisfying the foregoing criteria would create, the appearance of a satisfactory scene depiction, in the sense of conventional TV program depictions, it is not clear that these criteria are sufficient to make full use of the pilot's visual capability to acquire information from the displayed scenes. What the criteria do appear to be capable of doing is to create the illusion that the displayed scene information is complete. Provided that a direct visual comparison of the original scene and the scene as depicted on the display is not carried out, then an observer would not on an absolute judgement basis realize what is missing.

Visual evidence would indicate that the eyes are capable of making effective use of a reflected light range of 100% to 0.9%, that is, a luminance dynamic range in excess of 100:1. By comparison, a TV or LLTV sensor is likely to encounter a minimum 20:1 dynamic range and those of radar and FLIR sensors are typically much larger. In view of this, the limited 11.3:1 dynamic range objective of military CRT displays appears to be too small.

Grey scale criteria applicable to digital shades of grey employed in a video picture also appear to require further investigation. Although eight ($\sqrt{2}$ grey scale ratio) shades of grey are called out nearly universally in military video display procurement specifications, no experimental basis for this requirement has been located. Just discriminable luminance differences ΔL satisfying the relationship

(4.2) $\quad \Delta L/L_D = 0.015$

(i.e., this relationship is known as the Weber-Fechner fraction) are applicable when the observer is adapted to daylight luminance levels. This relationship establishes a discrete grey scale ratio, GR = 1.015, below which continuous and quantized luminance changes are not perceptually distinguishable from one another. This discrimination ratio increases as the size of the constant luminance image areas compared decreases. Therefore, for video display luminance (i.e., terrain mapped imagery) pattern sizes of practical importance, quantized grey scales at ratios of 1.03-1.05 would in most cases be perceived as being continuous. The clearly discriminable military grey scale ratio convention of $GR=\sqrt{2} \approx 1.41$ assures that successive grey shades can be distinguished from one another, but produces a picture in which the terraced (quantized) nature of the image luminance is capable of being perceived. The question of practical importance is, however, whether the pilot can make use of more than eight equally spaced grey shades when interpreting a video picture in an aircraft cockpit environment.

Investigations encountered to date which attempt to answer this question fail to provide complete information regarding the grey scale encoding and display of the video picture. Studies stating video requirements cite the $\sqrt{2}$ requirement, without references or proof. Eight to 11 grey shade maximum requirements (for equally perceptible grey shades) are also cited without references or proof. Observations of displays and photographs which satisfy these criteria tend to substantiate the claim, however, quantitative data to substantiate these subjective observations and to develop the constraints on their application are desirable. For example would a displayed scene divided into areas of direct sunlight illumination and shadows, which can result in a dynamic range much greater than 11.3:1, benefit from a larger display dynamic range and an additional grey shade rendition capability?

LUMINANCE TRANSFER CHARACTERISTICS

CRT Displays

As previously described, an accurate luminance and size scaled reproduction of a sensed scene is the ultimate goal of any TV camera-display system. In other words, the displayed scene luminance, L, should be linearly related to the luminance in the scene sensed by the camera, L_X, by a constant multiplier, K, such that

(4.3) $$L = K L_X$$

The luminance transfer characteristics of CRT displays can typically be approximated by a non-linear equation of the form

(4.4) $$L = K_1 y^{\gamma 1}$$

where: K_1 is a constant, y is the CRT input signal (i.e., proportional to beam current) and the constant exponent gamma, γ, is typically between 2 and 3.5. To linearize the overall camera/CRT display luminance transfer characteristic, either the camera or the CRT must therefore be electronically compensated for this non-linear characteristic.

By providing the camera with a transfer characteristic of the form

(4.5) $$y = K_2 L_X^{\gamma_2}$$

where L_X is the scene luminance and y is the camera output signal, the overall luminance transfer characteristic obtained would satisfy the expression:

(4.6) $$L = K_1(K_2 L_X^{\gamma_2})^{\gamma_1} = K_1 K_2^{\gamma_1} L_X^{\gamma_1 \gamma_2} = K L_X^{\gamma}$$

If the camera gamma, γ_2, can then be set so that the total system gamma satisfies the expression:

(4.7) $$\gamma = \gamma_1 \gamma_2 = 1$$

the desired linear relationship, Equation 4.3, between the scene and display luminances can be successfully approximated.

While a linear system transfer characteristic can also be obtained by compensating the signal transfer characteristic of the CRT display, to make it linear, a noise reduction advantage occurs when a TV camera signal emphasized by a $\gamma_2 < 1$ transfer characteristic is broadcast. The preferential increase in the signal amplitude of the dark grey shades makes the emphasized signal less susceptible to interference by noise picked up during transmission. This signal to noise advantage, that gamma emphasis of the camera signal produces, has caused commercial television to adopt this technique as a signal treatment procedure.

The foregoing approach to linearizing CRT luminance transfer characteristics has proved to be quite satisfactory in its application to commercial television. For military applications, in which display system performance should achieve good objective as well as subjective performance, the CRT's non-linear transfer characteristic poses a more difficult problem. In practice, each individual CRT has a different luminance transfer characteristic. Still larger deviations occur between different manufacturers, phosphor materials, or CRT electron optic designs. Thus, while Equation 4.4 provides a satisfactory approximation for commercial television applications, the gamma of each CRT has to be compensated individually to provide a reasonably good overall linear system transfer characteristic approximation. In practice, the power law of Equation 4.4 can not accurately describe the entire luminance transfer characteristic of a CRT display for even one brightness setting. Accurate luminance renditions would require that gamma constants corresponding to new fits of the nonlinear CRT characteristic be made as the brightness of a cockpit CRT is changed. Since the adjustment of brightness is necessary for cockpit CRTs in order to maintain satisfactory contrast over the full range of atmospheric illumination conditions encountered by a pilot, cockpit CRT displays typically exhibit severe grey scale distortion due to this built-in source of luminance transfer characteristic nonlinearity.

As a consequence of the CRT display's actual luminance transfer characteristics, the CRT display/sensor systems used in aircraft seldom produce linear luminance transfer function relationships (i.e., undistorted grey scale responses). Because changes in either the brightness or contrast controls influence the luminance image rendering properties of the display (i.e., rather than just changing its respective luminance outputs and grey scale ratios); adjustments in these controls can alter the relative emphasis between the grey scale levels present in a displayed picture. It is therefore left to the pilot to monitor and adjust the picture until a "best possible" portrayal is obtained. Since this extra source of workload cannot typically be accommodated by the pilot, little reliance tends to be placed on video CRT imagery unless it is mission critical to do so, in which case a two man crew is usually needed, one of them to adjust the video pictures which are repeated at the pilot's work station.

In order for current cockpit CRT displays to do more than appear to provide subjective satisfactory pictures, automatic compensations of their nonlinearities as brightness and contrast controls are adjusted by the pilot need to be introduced. The availability of computers in the cockpit would allow storing a library of control characteristics as a function of the display contrast and brightness control settings made by the pilot, which would permit compensating the CRT for nearly linear operation at all times. The author is aware of no attempts to implement this needed control capability at the present time.

Flat Panel Displays

The almost exclusive use of CRT displays to portray video information has resulted in the existing requirements for such displays and the sensor signals that are inputted to them being tailored to be compatible with the operating characteristics of the CRT display, and in particular to the limitations its use imposes. The single most important example of this, which is relevant to dot-matrix displays, is that the parallel line-at-a-time low bandwidth digital input signal capability of a dot-matrix display must be converted to a serial high bandwidth analog input signal capability of a CRT in order to display available video signals. While this conversion and the attendant loss of signal fidelity is necessary for tube type video cameras which like the CRT are based on the scanning of a single electron beam, this would not have to be the case for solid state infra-red detectors and charge coupled device (CCD) based TV cameras. In practice it is of course nearly impossible to find even the latter devices in other than a serial output configuration.

The practical result of the CRT's dominance of video signal requirements is that as higher resolution displays are sought, higher and higher speed circuitry is needed to support the transmission and handling of the serial data. This also makes conversion of the serial data to parallel for high speed computer image processing and reconversion to serial after processing more difficult. In contrast, digital sensor data could be sent in parallel to the computer, processed and then displayed on a dot-matrix display without ever having to convert the data to the high speed serial format.

Another area where the CRT restricts achieving optimal display performance relates to its nonlinear signal to luminance transfer characteristic and to the variability of that characteristic. In dealing with analog amplitude modulated signals for television broadcast it is frequently pointed out that even if the CRT did not have a nonlinear input signal transfer characteristic, it would probably have been given one anyway due to the enhancement in the noise immunity that applying signal emphasis in the transmitter circuits provides. While this may be true, in an aircraft where the video cable runs are relatively short and alternative methods of dealing with noise are possible (i.e., digitization of the video signal for instance), it is not as clear that sensor signals would be gamma compensated if the design of these systems had not been based so strongly on the TV example.

The variability of CRT gamma values and the need to make different displays compatible with a variety of different sensors leads to the conclusion that a standardized signal transfer characteristic is necessary at the aircraft sensor/display interface irrespective of the display or sensor technology used. The present system in essence assumes that any one display can be matched to any one sensor through the use of internal adjustments built into each. This was never entirely true even when a single sensor was hardwired to a single display, but the approach is still used even though the sensor and the display it feeds can now be subject to mode control by the pilot.

INFORMATION PORTRAYAL CAPABILITY CRITERIA

Under conditions of unlimited atmospheric visibility, pilots want the maximum possible unobstructed view of the external scene to be visible through the aircraft canopy and windscreen. This situation provides the pilot with the capability to make full use of his eyes for surveying his situation relative to the assigned aircraft mission, the objective being to locate targets and threats at the maximum range possible. The use of radar, FLIR and EO sensors enhances this capability by further extending the pilot's visual range of detection and by providing windows through atmospheric or illumination conditions which degrade or eliminate the possibility of direct visual observations.

Information Density

To fully satisfy the capability of the eyes to perceive visual information on a video display is a significant challenge even in benign illumination environments. A picture having the image quality to satisfy all aspects of vision including motion detection and vernier acuity threshold capabilities would have to possess a picture element (pixel) linear density in the X and Y directions in excess of 300 pixels/inch (120 pixels/cm) in order to fully satisfy the pilot's visual capabilities. Such a picture would be perceived to be identical to viewing real-world scenes directly with the eyes, a feat presently achieved only on high resolution photographs and potentially on the recent high resolution monochrome graphics TV monitors which are reputed to display 4000 discernible lines on a 19 inch diagonal, 4:3 aspect ratio screen (350 lines/inch on a 11.4 inch screen height).

Investigations of the spatial response characteristics of the human visual system using 100 fL luminance test patterns predict limiting resolutions for the eyes of about 60 cycles per degree of subtended visual arc which translates to a minimum separable acuity of 0.5 minute of arc. Classical minimum separable acuity studies conducted on still higher image luminance patterns predict a limit of 0.4 minute of arc in relatively good agreement with the spatial frequency test result.

An advantage of the spatial frequency characterization technique over conventional methods is that the sensitivity of the eyes as a function of the spatial frequency can be determined. This type of investigation shows a peak sensitivity for the eyes for spatial frequencies between about 2 and 10 cycles per degree of visual arc, the higher frequency being associated with higher image luminances. These results have been used in combination with the spatial frequency response characteristics of existing aircraft cockpit CRT displays to argue that even the 120 line/inch resolution technology limit of current military CRTs is unnecessarily high since peak human spatial frequency sensitivity translates to a 41 line/inch resolution at the standard 28 inches cockpit display viewing distance.

This type of analysis fails to account for the fact that target detection, recognition and identification are attempted by the pilot at the maximum range feasible and hence with the focus of the pilot's attention being concentrated on the minimum perceptible critical detail dimension needed to detect, recognize or identify a target, respectively (i.e., on a two octave range of the maximum perceptible spatial frequencies components of the image spectral distribution). The fact that these frequencies are less perceptible does not alter the fact that the task commands the pilot's visual attention to only these frequencies, and they certainly could not be seen if they were not to be displayed. The problem with the analysis resulting in the lower resolution recommendation is that it undoubtedly compared the higher frequency spatial frequency components of the image spatial frequency spectral distribution to its entire spectral content rather than recognizing the human's capability to selectively examine any two octave region of the spectrum which is of interest while ignoring the remainder of the spectrum.

The almost universal desire of pilots to acquire targets head up when that is feasible, is in no small part due to the lack of resolution capability exhibited by CRT displays limited to the current 120 lines per inch image portrayal restrictions of current cockpit video displays. The shortcomings are self evident when the CRT display's picture a scene which can be directly viewed and compared with the display portrayal result. There is clearly no comparison between the two sets of imagery.

Information Content

A video picture portrayed on a raster written CRT display is in its vertical direction divided into the number of lines that make up its active raster. On new military video displays this vertical quantization or sampling of the sensed scene is, according to the most recent NATO monochrome video standard, STANAG 3350 AVS, supposed to provide both a 525 line Class C and an 875 line Class A, 60 Hertz frame rate picture display capability (i.e., or alternatively a 625 line Class C, 50 Hertz frame rate picture in combination with the 875 line picture). On current US military aircraft the basic specifications employed are the Electronics Industries Association (EIA) RS-170 (525 line) and RS-343 (875 line) documents. The old and new standards are in substantial agreement with one another with the newer version being more detailed. The 525 line picture is made up of nominally 483 active lines per screen height whereas the 875 line picture uses nominally 809 active lines.

In practice, the number of active lines making up a display's vertical height is not a hard and fast rule unless commercial television imagery is to be displayed. Closed circuit television systems can use more or fewer active lines, where the upper limit is constrained only by the total number of lines and the time lost to beam retrace the screen width in preparation for the start of each line and to retrace the screen height before the start of each picture field.

In the vertical direction, the CRT and dot-matrix displays are seen to be alike in their spatial quantization characteristics. In the horizontal scan line direction on a CRT display, the amplitude modulated signal can be either digitized or in a continuously variable analog form. The analog signal technique is typically employed in military sensor video displays, but, irrespective of its form when displayed, the horizontal direction on a CRT also consists of quantized information domains.

The existence of the horizontal information portrayal quantization on raster written CRTs results from the bandwidth limitations of the video amplifiers used to control beam intensity in combination with the approximately Gaussian luminance spatial distribution of the light spot that the electron beam produces. The bandwidth of the amplifier determines how rapidly the display can respond to input signal amplitude changes and therefore acts as a constraint on the number of horizontal pixels (i.e., discernably different signal levels) that can be reproduced across the screen width. Using a 10 MHZ video bandwidth, as is required by the Class C STANAG 3350 AVS standard (i.e., RS-170 requires only 3 MHZ), the 0 - 63.2% amplitude transition, 3db response time of the amplifier, $\mathcal{T}$, would be:

$$(4.8) \qquad \mathcal{T} = \frac{1}{w_{3db}} = \frac{1}{2\pi f} = 53.1 \text{ ns}$$

This response would appear to make a 0-100% rise time of 90-100 ns possible with little or no overshoot designed into the video amplifier. The video standard only requires a 10 - 90% rise time to occur in less than 100 ns.

The total line duration called for in the video standard for Class C operation is 63.5 μs/line (i.e., 1/(525 lines) x 30 Hz). Using the specified line retrace blanking interval of 9.4 μs gives the time duration available to scan the active length of the line as 54.1 μs. The maximum number of horizontal pixels capable of being displayed in response to a square wave input (i.e., neglecting spot size effects and assuming no amplitude dwell time occurs at either the maximum or minimum signal levels) would be:

$$(4.9) \qquad N_{H\ Max} = 54.1\ \mu s/100\ \text{ns} = 541 \text{ pixels}$$

Introducing the effect of a finite CRT half intensity spot size (which for military CRTs is typically equal to the vertical line spacing) would require the convolution of the Gaussian spot with the square wave CRT response function just described. The result of this would be a reduction in the number of near full amplitude luminance transitions possible per screen width and hence in the number of pixels.

While it could be argued that the criteria used to define the width dimension of CRT display pixels in the preceding discussion are either too lenient or too stringent, the point is that the CRT bandwidth and spot size do limit the display's capability to faithfully reproduce sensed scene luminance changes which occur over distances that exceed a minimum dimension in the horizontal scan direction. Thus while these CRT areas lack the distinct physical boundaries that are characteristic of dot-matrix displays,they do define the dimensions of display picture information elements (i.e., pixels). In the context of the maximum information content that a display can portray, the function performed by a CRT and by a dot-matrix display may therefore be concluded to be the same. In this same limit, the dot-matrix display may therefore be thought of as being a CRT display which lacks image blur. A useful benefit of this analogy is that dot-matrix displays can be used to provide a definitive means of investigating task related video picture information requirements which,due to the difficulty of defining the horizontal dimension of CRT pixels, has met with only limited success in the past.

To avoid any misunderstanding of the CRT/dot-matrix display pixel analogy just introduced, it should be noted that the analogy is not entirely correct except at the stated CRT bandwidth/spot-size image rendition limit. Although neither technique allows image detail finer than their respective pixel dimension spacing limits to be depicted, the CRT limit is reached as the result of a progressive degradation in image quality as the spot size gradually restricts the spatial frequency luminance amplitude rendition capability of the display. In comparison, the fixed separations between the discrete pixels on a dot-matrix display restricts the spatial frequency periods that can be displayed to integer multiples of the fundamental spatial period and converts signals at all other frequencies for display on those which are available. This distinction has been interpreted as being an advantage for the CRT. The author considers this conclusion to be premature in that it fails to account the high image quality of dot-matrix display pixels which is often as good as that of the scene being rendered. Thus while some portions of the original scene imagery will be converted to higher or lower spatial frequencies than in reality should be the case (i.e., by virtue of the restriction imposed by the spacing of the pixels) the discrete pixels still provide an enhanced ability to see the resulting converted signal modulation of the luminance on the individual pixels.

In summary image distortion mechanisms exist for both CRT and dot-matrix displays. The CRT display information portrayal limit occurs when the information on adjacent pixels is so intermixed by the spread of the CRT spot that there is effectively no perceptible difference in the information portrayed on the adjacent pixels. The result is a picture with its defects masked by image blur. The dot-matrix display information portrayal limit occurs because the pixel spacing eliminates the possibility of showing higher spatial frequencies and converts lower frequency signals to the frequencies the display is capable of generating. While this clearly distorts the original scene information, the resulting imagery remains highly legible due to the excellent image quality of the dot-matrix display pixels. Experimental evidence to permit expressing a preference for one or the other of these display techniques for video information depiction purposes does not yet exist. In the limit of display pixel densities which are limited by the human's visual capability limits, it can be concluded that the dot-matrix approach is to be preferred due to its ability to maintain high percent modulation levels.

FURTHER RESEARCH

The recommendations to be described here for further research on video displays and the information presentation techniques they employ will be introduced within the context of providing an overview of the current status of the knowledge developed to date on this subject. The discussion will attempt to highlight the major problem areas and if appropriate their sources.

Independent of the display implementation techniques used, the minimum number of total pixels required in a picture is governed by two factors. One factor is that scene objects must be depicted by a sufficient number of pixels to make them, in turn: detectable, recognizable and finally identifiable. Concurrently with striving to make the smallest possible critical detail dimension of an image legible, the number of pixels present in a picture must also be sufficient to depict a large enough area of a sensed scene to enable the pilot to assess the target's relationship to other scene information. Research on video image pixel requirements has been conducted on CRT displays, however, the results have not been conclusive. The failure to achieve conclusive results is attributed to a continuing attempt to correlate image recognition and identification performance to the number of pixels forming the image height (i.e., actually CRT lines/image height) rather than trying to relate the pixels to the image critical detail dimension of an image which it is known to be the key variable by virtue of simplier alphanumeric character studies. Owing to the fact that image critical detail dimensions are known to vary significantly in relation to the heights of different military targets, it is not surprising that target size has not been successfully correlated to a critical number of pixels needed to make it recognizable. Further research aimed at determining the critical detail dimension (i.e., or equivalently the critical spatial frequency) characteristic of various military targets and in addition the number of pixels required to define that dimension is needed. Once the number of pixels required to define the critical detail dimensions of typical military targets are known, scaling of the sensor scene and the physical separation between imagery which must appear concurrently on the display determine the maximum display pixel dimensions. The latter quantity is clearly quite sensitive both to the mission being performed and on the capabilities of the sensors (i.e., zoom magnification, etc.) which provide the sensor-video imagery to be displayed.

The density of pixels used to portray video imagery, contrary to the commonly held beliefs, appears to influence neither objective performance nor subjective appearance of a display, provided that the pixel dimensions (i.e., total number of pixels) used to portray a sensor scene is adequate in the sense described in the preceding paragraphs. Even for low density dot-matrix displays having discrete pixels that are visually well defined, the pixel structure used to generate a picture will fade into obscurity when reading the display if the viewer's attention is not specifically directed to it. This cognitive phenomenon is so complete that many people given a brief exposure to such a presentation (i.e., several minutes) would not even be aware of its dot-matrix character.

The factor which is critical in making the cognitive phenomenon described above effective is that the minimum image critical detail dimension of the information needed by the viewer to recognize an object or scene, consisting of a number familiar objects, be spread across a number of pixels (i.e., the minimum number is not yet known but it is five or less). The most likely source of the belief that legible pixels are a problem is the 525 line standard raster written CRT display used in homes and in the cockpit. Although the combination of grey scale encoding and image blur typically result is subjectively pleasing pictures, the superposition of high contrast graphic lines or alphanumeric characters at an angle with respect to the raster direction can make the raster legible. This visual result is actually an indication of the inadequacy of the pixel dimensions used to depict pictures on these displays for other than aesthetic purposes, a fact which is typically obscured due to the combined effects of the grey scale encoding and image blur.

Based on the preceding facts, the only real source for the need to have high density pixels on a cockpit display is the need imposed by the limited panel space available for display installation. In this context, an area of further research is the determination of how densely pixels can be placed without any undue loss of information as a result of the spatial frequency limits of the human visual system. Increasing the pixel density and simultaneously increasing the number of lines scanned and the video bandwidth so that the same area is scanned with more lines definitely increases viewer performance. The position currently held is that this process reaches the point of diminishing returns at a resolution of 120 lines/inch (i.e., about a one arc minute line separation at a 28 inches viewing distance), however, in practice this limit appears to be the result of the resolution limits of the CRT displays used rather than being due to limitations of the eyes as claimed. The fact that stair steps are considered a problem for rotated graphic lines on raster written 120 line/inch, 5% relative modulation specified CRTs, raises a question as to the validity of the 120 line/inch limit even for a CRT display. In any event, further research to determine more realistic pixel density limits for use with the higher image quality dot-matrix displays should be conducted.

The discrepancies noted in the preceding discussion for commonly held views of video display criteria are believed to be the result of the present video display technology having evolved in parallel with CRT developments, rather than having been the result of developments directed at meeting predetermined pilot visual capabilities. In practice, the evolution of cockpit video displays and the recognition that a need still exists for continued improvements in image rendition capability both disappeared when the subjective performance of cockpit CRT displays became acceptable to pilots during the mid 1970's. For the reasons described in this report, pilot acceptance is not a valid criteria for assessing the performance of a cockpit CRT because the pilot cannot appreciate what is missing in a display presentation unless a side by side comparison with a totally accurate presentation is possible. If current display capabilities actually made full use of the pilot's vision, pilots would be going head down to recognize and identify detected targets, rather than visa versa, as is presently the case.

The grey scale encoding of video imagery serves to provide visual cues which assist in the discrimination of sensor-video imagery. Before these cues can become effective, however, minimum image picture element content requirements must first be exceeded in order to provide the fundamental image structure upon which the grey scale encoding of its pixels can be applied. The addition of chromaticity encoding to a grey scale encoded picture produces the capability to reproduce sensed scene color imagery and in so doing provides yet another increase in the information content of a video picture. Provided that the display image presentation capabilities of a video display are added in the sequence just described, that is: spatial control, luminance control followed by color control; the image rendering capabilities of a display are progressively improved. In other words, the spatial luminance rendition capabilities of a video display cannot be made fully effective unless the spatial characteristics are first established. Likewise faithful color rendition of real world scenes can only be achieved based on first achieving control over luminance (i.e., including adequate pixel contrasts to make the color encoded imagery depicted legible) since luminance establishes the value scale coordinate axis in color space, and true color scene renditions cannot be achieved without it.

Based on the order established above, it is recommended that pixel density, pixel content and grey scale requirements be investigated prior to investigating chromaticity requirements. Chromaticity is placed last because luminance controls both the brightness of a color and its value (i.e., grey scale or tint level), and value in combination with chromaticity establishes the color perceived. Thus unless the human's perception of grey scales is understood, a full understanding of color cannot be achieved. The integration of chromaticity is left to last because achromatic displays are in current use in aircraft and research results that would improve grey scale rendition capabilities could be applied immediately.

SECTION 5

COLOR

RESEARCH OVERVIEW

The research conducted on color dot-matrix display criteria is summarized in the block diagram shown in Figure 5.1. Lacking a developed full size multi- or full-color dot-matrix display, no mechanism existed for employing the top-down methodology in this research area. The planned program was to involve investigations of multi-color display design criteria and to a lesser extent full-color display design criteria. The color research was intended to identify and investigate electronic display issues which: (1) are emphasized by the dot-matrix display media, (2) have no counterpart in the established CRT display technology or (3) provide potential display information benefits or limitations with respect to alternative techniques.

The planned research was divided into theoretical and experimental phases for both the multi-color and full-color investigations as is indicated in the Color Display Criteria block diagram of Figure 5.1. Each of these four areas will be described only briefly here as the output of this effort has already been provided to the USAF in the form of briefings, presentations to affected contractors and working reports.

MULTI-COLOR DISPLAY

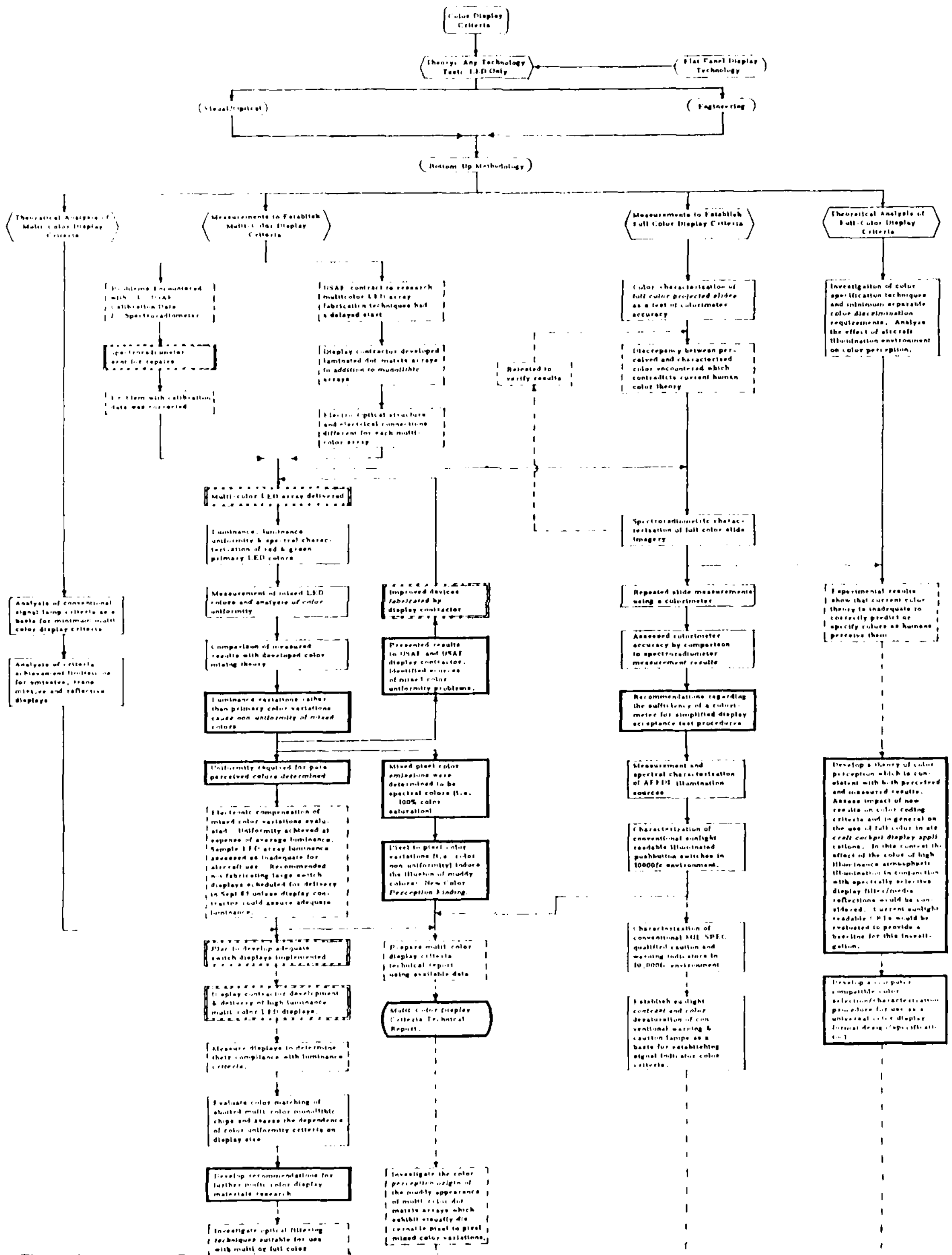
Multi-Color Experimental Investigations

The principal objective of the color criteria research conducted was to generate design information for use in guiding research on the fabrication of multi-color light emitting diode (LED) arrays under a parallel dot-matrix display development effort conducted by Optotek Limited of Ottawa, Canada, under a program jointly supported by the Canadian Department of Industry, Trade and Commerce and the USAF Flight Dynamics Laboratory, Crew Systems Development Branch. Based on the nonuniform mixed color performance of a preliminary multi-color array fabricated by Optotek, a general theory was developed to account for the spatial nonuniformity in terms of potential variations in the primary color chromaticity and luminance values of individual pixels. The fabrication process used on the first array demonstrated that a monolithic chip with separate red and green primary color LEDs was feasible but because its LED junctions were not electrically isolated (i.e., a common cathode and anode metalization connected all red and green LED contact points), the source of its nonuniformity could not be evaluated.

The research program conducted by Optotek resulted in a number of sample arrays being delivered to the USAF for evaluation of their overall electro-optical performance. The tests and subsequent data analyses performed by Burnette Engineering revealed that in each case the primary color chromaticities of the individual pixels in the arrays were constant (i.e., subject to the one nanometer error tolerance of the spectroradiometric measurements conducted) and that luminance uniformity variations were the source of the observed mixed color variations. The application of this finding and the associated luminance uniformity recommendations in combination with the fact that the LED array fabrication processes which influence the primary color chromaticities are virtually independent of those which influence spatial luminance uniformity, resulted in a progressive improvement in the successive arrays delivered.

The first arrays exhibited what appeared to be "muddy" mixed orange colors, that is colors which appeared to be dark and desaturated. Spectroradiometric tests on the individual LEDs revealed that the mixed colors were actually characterized by chromaticity coordinates that should have produced the perception of highly saturated spectral mixed colors. Moreover, examination of the arrays under a microscope revealed that when magnified the individual pixel colors did appear pure but that a noticeable pixel to pixel variation in color existed just as the objective test data had indicated. As the mixed color uniformity deviations of pixels in the successive sample arrays improved from 4.1 nm to 3.3 nm, the "muddy" color effect disappeared. The corresponding reduction in luminance uniformity needed to produce this result was a reduction from a coefficient of dispersion of about 10% to one of 5.5%. While the experiments did resolve the design criteria issue, the reason the human perceives the small magnitude spatial variations in spectrally pure colors as "muddy" remains unknown.

Color uniformity was the only major problem encountered with the Optotek LED displays which could be considered unique to the dot-matrix array media. Some potential problems, such as a change in color as a function of viewing angle due to the red and green junctions being separated by up to 10 mils in height in the superimposed junction LED chip structure, did not materialize. The high refractive index of GaP ($n \approx 3.43$) may be responsible for this result since only light



Color Display Criteria
Theory: Any Technology Tests: LED Only
Flat Panel Display Technology
Visual/Optical
Engineering
Bottom Up Methodology
Theoretical Analysis of Multi-Color Display Criteria
Measurements to Establish Multi-Color Display Criteria
Measurements to Establish Full Color Display Criteria
Theoretical Analysis of Full-Color Display Criteria
Multi-Color Display Criteria Technical Report

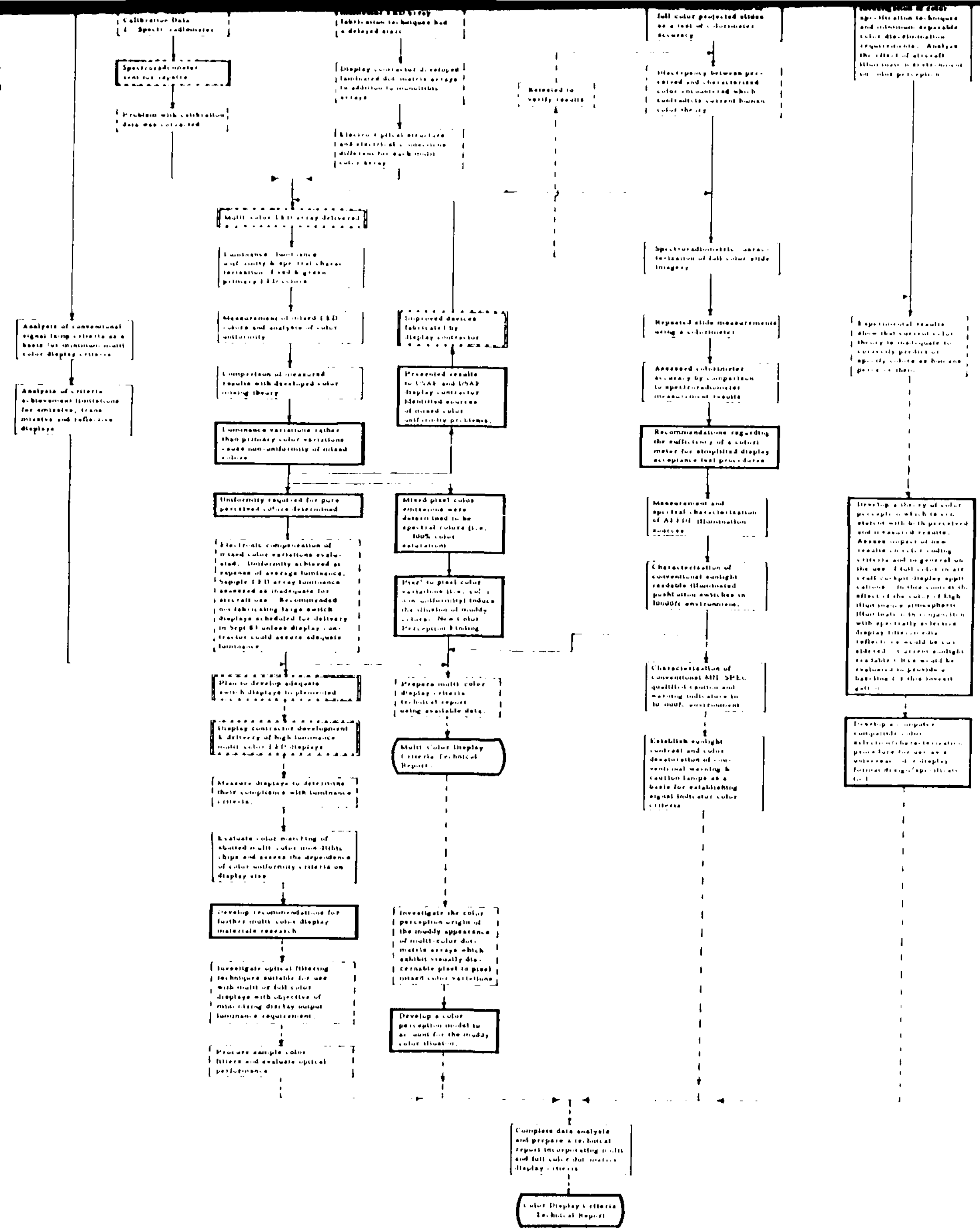


Figure 5.1 Color Display Criteria Block Diagram

hitting the inner LED surface at angles less than 17° to the surface normal is emitted. As a consequence, only a 3 mil maximum distance from the blocking edge of a 10 mil high LED could actually be differentially obscured for the bottom color as compared to the top color if the display were viewed at an angle approaching 90° (i.e., viewed nearly parallel to the surface). Since LED material of about 3 mils width typically surrounds the Optotek 8-9 mil diameter light emitting junction areas, obscuration occurs only if an opaque mask or metalization covers this region of the LED surface.

Another potential problem with color dot-matrix displays is electrical or optical coupling between pixels. In the case of the Optotek samples, red light could be observed under a microscope in the areas separating the pixels, however, the magnitude of this optical coupling was too small to be noticeable when the array was viewed with the unaided eye. Moreover, the preferential coupling of red light in this region did not appear to influence the perceived mixed color. This is presumably the case because the coupling constitutes a fixed percentage of the luminance of the LED responsible for producing it and the eye always sees the color-shifted area-averaged result of mixing the pixel aperture color with the color of the area immediately surrounding it. In the Optotek display the pixels were spaced on 16 mil centers and area averaging occurs over an approximately 15 mil diameter area (i.e., for an assumed 28 inch pilot viewing distance). It could therefore be expected that in lower resolution displays, say at 30 pixels/inch resolution the effect of background optical coupling could become observable. Since the luminance of optically coupled light drops rapidly with distance from its point of origin a problem cannot, however, be predicted with certainty for lower resolution displays.

Electrical coupling which can be a problem for some types of dot-matrix display implementations could not be observed on any of the multi-color LED array samples tested. The fact that the LED emits light only when forward biased and blocks current passage when back biased generally prevents the possibility of electrical coupling at a level that can be observed. Defective array LEDs with high reverse bias leakage currents can produce current paths which could result in making electrical coupling legible, however, these are typically found and eliminated as a part of the display assembly process.

Other aspects of the multi-color LED arrays that were evaluated included. the structure of the LED array and the optical geometry of its pixels, the techniques used for making electrical and mechanical bonds to the ceramic substrate, nd the metalization applied to the array and its interconnection technique . Each of the display samples exhibited good quality workmanship and crystal damage due to saw cutting to achieve inter column electrical isolation was typical of that encountered on previous single color arrays. To avoid influencing the optical tests no encapsulant or optical enhancement layers were employed. Since each of the sample displays was fabricated using single monolithic chips, where the pixel geometry and spacings are defined by photographic mask processes, the single color LED patterns were as expected very precise in their dimensional characteristics. To achieve good visual performance for a multi-color display using the superimposed LED junction technique in addition requires that the overlayed patterns of red and green pixels be in registration with one another. This was achieved in all of the arrays tested.

As a related and equally important issue, it was only possible to indirectly assess the ability to form continuous resolution mosaic display surfaces by four edge abutting multi-color LED array chips. In concept, the added problem associated with achieving this goal for multi-color arrays that is not present for single color arrays is the need to make provisions for interconnecting the additional electrical lines to the second color LED junction. In practice, the abutment problem actually depends on the array implementation employed. If the GaP substrate is doped to give it conductive properties which allow it to serve as a common cathode, then the red and green anodes can be formed in epitaxial layers on opposite sides of the chip with vias formed and metalized to pick up the cathode connection on the desired side of the chip. Since the cathode metalization carries the common high current it is in general preferable to make this connection on the bottom (red emitter) side of the chip where the high current can be transferred to the underlying ceramic metalization design. Doing this complicates the hidden connections to the ceramic since both the cathode and red LED anode contacts must be made and fed out to the driver circuits. The top surface (i.e., viewing surface) green LED electrical connections are simplified in this instance.

The preceding example is only one of four different implementations successfully demonstrated by Optotek using their multi-color sample arrays. Some of these possibilities exclude either common anode or common cathode drive and require that all four leads both be interconnected between abutted chips and separately fed out to permit independent drive. Although one of the four lead geometries was successfully implemented by Optotek, the resulting connection techniques did not appear to be amenable to 4-edge abutment. Subsequent to the time period of the present program an array consisting of 10 two and three edge abutted arrays was fabricated by Optotek. Its performance is described in another report.[16]

A final major issue assessed during the present effort was the luminance output performance of the multi-color arrays. In general the green luminance levels were found to be higher than those of the red LEDs, but both were too low to permit achieving the necessary 2:1 contrast ratios considered to be needed for typical aircraft cockpit applications in a 10,000 foot-candle illumination environment.

Complete formal documentation on the tests performed during this effort could not be completed within the scope of the present program owing to the higher priority placed on providing performance feedback and fabrication process improvement recommendations to the on-going USAF multi-color LED array development program. A summary of the results obtained is contained in an article on multi-color display criteria prepared as a part of a subsequent effort.[17]

Multi-Color Concepts

The only current uses of color that are sanctioned in military aircraft cockpits are to provide warning, caution and advisory indications using signal annunciators, illuminated switches or painted markers and in a very limited number of aircraft to provide full-color image enhancement for projected film map displays. In an attempt to determine criteria for multi-color displays that would make them capable of performing the functions of conventional aircraft cockpit signal lamps in addition to the functions normally performed by electronic displays, the legibility capabilities of conventional signal indicators and illuminated switches were analyzed. As a starting point for this analysis military specifications were reviewed to determine the stated requirements for both the daylight and night viewing cases. Warning and caution annunciators and switches were also measured to verify their compliance with their respective military specification requirements and to determine unspecified characteristics such as color desaturation in a high illuminance viewing environmenments.

Test results for the aircraft annunciators and switches showed that in all instances they met the legibility portion of the specifications in effect at the time the displays were made. The review of the specifications revealed, however, that a functional requirement inconsistency exists in the signal indicator specification between daylight and night legibility requirements which makes it difficult to believe that the pilot's information requirements can be fully satisfied by simply meeting the specifications. More specifically it was noticed that the master caution and warning annunciators which need only achieve a contrast ratio of 1.0 to pass the specification under daylight viewing conditions are required to produce a minimum luminance of 15 foot-Lamberts (fL) at night. Since instruments dimmed for night viewing have white symbol luminance levels between 0.02 and 0.1 fL with much lower panel reflected luminances, signal lamp contrast ratios greatly in excess of 1,500 occur during night flights. This either means that the night lighting requirements for these indicators greatly exceed the level needed to provide the desired attention-getting effect or that the daylight requirement, which in reality is only just sufficient to make the display legible in direct sun light, is inadequate for attention-getting purposes. Based on this assessment, it is recommended that signal indicators be light sensor controlled at reduced but still attention-getting luminance levels at night and provide contrasts greater than ten in day light.

Comparisons between the functions performed by fixed information format signal annunciators and switches with the objectives of multi-color electronic displays resulted in the conclusion that achieving minimum legibility requirements for multi-color electronic displays would entail the use of character sizes and contrasts which as a minimum are equal to those of single-color electronic displays. If the function performed by the display were restricted to an on/off depiction of a single color format, as is the case for conventional lighted indicators, then the smaller legend character heights and contrasts which apply to signal lamps and illuminated pushbutton switches could be employed for multi-color electronic displays as well. It is, however, the highest cognitive use to which a display is employed at any time for a particular aircraft cockpit installation that dictates the legibility requirements that need to be applied. Using contrast as an example, a display used exclusively to depict numerics and "on/off" signal annunciations could have a minimum contrast ratio (i.e., the character emitted luminance divided by "off" character luminance) of 1.0 for 0.3" high characters or 1.5 for 0.2" high characters. Adding alphabetic characters 0.2 high to the display during one of its mission segments would increase the contrast requirements for annunciations, numerics and alphabetic characters to 2.0. In the same sense, introducing graphics with a still larger symbol/character set capability would entail a minimum sunlight legible contrast of 2.7 for all information presented on the display.

The preceding requirements are those needed to achieve sunlight readability for single color displays, but apply equally as minimum requirements for color or multi-color displays. Although color contrast is often cited as a possible justification for reducing luminance contrast, in reality a display image must be made legible with respect to the reflected luminance of the "off" display screen before color contrast can become effective. Since high ambient illumination threshold and comfort level legibility test results show that white, yellow, orange, green and red characters and symbols have equal legibility requirements (i.e., equal on to off character contrasts), with blue requiring a 20 to 30% higher contrast due to the myoptic focusing of blue, there is no basis in fact for believing that color contrast will provide a perceptual advantage until minimum luminance contrast requirements have first been met. As a practical consideration, it should be noted that the visible background color provided by the band-pass filtering of current green P-43 phosphor CRT displays actually appears to be the color of the internal cockpit surfaces reflected specularly by the filter's antireflective coating. Achieving adequate luminance contrast on these displays therefore usually provides a reasonable color contrast between the narrow bandwidth green image and the wide bandwidth color reflected by the display filter. Since current cockpit contrast requirements for single color electronic displays are based largely on the satisfactory performance of P-43 CRT "single color" displays, the luminance contrast requirements already include the benefits of the color contrast between the image and its background.

The final multi-color criteria issue investigated that will be highlighted here is the effect of color desaturation in high illuminance viewing environments. Since signal indicators are the only color source in a cockpit having both broad pilot exposure and known pilot acceptance, their color performance in high ambient environments was investigated to establish a basis for assessing the performance of multi-color displays intended to perform the signal annunciation function. Since many of the conventional indicators only just meet the contrast ratio of one requirement, and even then only with the sun at angles of greater than 30° from the normal to the display surface, the emitted luminance, ΔL, which is colored by the filter and the reflected luminance, L_D, which is dominated by the neutral density diffuse reflectance of the indicator's matte finish front surface, can be used to approximately predict the measurable color desaturation effect using the standard color mixing equations. Spectroradiometric measurements of master caution, fire warning and hidden legend illuminated pushbutton switches showed that the luminance weighted mixing of the reflected ambient color with the optically filtered emitted color gave a good prediction of the directly measured desaturated color chromaticity coordinates. Thus while the aviation red and yellow colors are specified in a narrow band along the edge of the spectral locus (i.e., as measured in the dark), achieving the contrast ratio of one in high ambients yields an excitation purity of approximately 50% (i.e., halfway in towards the ambient illumination chromaticity coordinates from the spectral locus of the xy chromaticity diagram).

Although it would be very convenient to be able to apply the foregoing result directly to multi-color electronic displays as minimum criteria for signal annunciation color purity requirements, this is not in fact possible. As already mentioned, the diffuse matte finish front surface of conventional signal indicators results in most of the incident ambient illumination being reflected with essentially no change in its color. As a result of this design feature, the front surface of these indicators are perceived as light grey or white in high ambient environments whether the indicator is "on" or "off". When the indicator is "on" the light emission color is perceived as being behind the visible white surface reflected light. Since this depth perception effect is visually distinguishable to an observer, it is also evident that the full color mixing assumed by the previously described color desaturation calculations and which would be measured does not actually occur, and the emitted color will actually appear much more saturated than the color mixing results would predict. Time did not permit seeking published human vision results or to conduct the visual perception experiments that would clarify how this situation should be handled. It is possible that the depth separation of the colors could be complete but it is more likely that some mixing does occur, if only due to the poor optical quality of the eyes' optical media and the resultant perception of the scattered light which this produces. The subjective impression created when viewing these devices is that the color desaturation due to the white light veiling luminance occurs but its desaturation effect on the color perceived is quite limited.

The practical impact of the preceding observation is that no transfer of signal indicator lamp derived color desaturation criteria to multi-color electronic displays is currently possible. The optical designs appropriate for making the relatively low luminance outputs of multi-color electronic displays legible, require that the filter cover plates used be transparent with a very low front surface reflectance. Consequently the high front surface reflectance optical design used on conventional signal indicators cannot be applied to most of the multi-color display concepts currently being used or which are under development. The transparent filter cover plate design results in the incident light being transmitted to display surface where upon reflection it appears to eminate from the same display depth as the emitted light.

Color mixing as originally described applies in this ease to all but the small percentage of the light intercepted and directly reflected by the optical filter's antireflection coated surfaces and by the optical filter media.

FULL COLOR DISPLAY

Full-Color Experimental Investigations

The objectives of the research on full-color were from the outset quite limited. Since no full-color dot-matrix displays were available for test, the experimental effort was to be limited to assessing the problem of achieving reasonably accurate measurements of color for use in display qualification and acceptance test procedures. Although a spectroradiometric system allows accurate measurement results to be achieved, the system is typically quite complex, very expensive, and requires either the direct supervision or operation by highly trained personnel to achieve the desired result. Conversely the use of a colorimeter: (1) typically permits straight forward measurement procedures to be used with the chromaticity coordinates and illuminance of the color provided as direct display readouts; (2) allows reasonably rapid succession of readings to be taken; (3) requires a relatively small investment to be made; and (4) places only modest requirements on the operator for training. All of these virtues commend the colorimeter for use as a measurement device suitable for testing signal indicators, integrally illuminated panels and for the measurement of test patterns depicted on color displays (i.e., when the colorimeter is equipped with luminance measurement optics).

In spite of all of the positive attributes of a colorimeter, past comparative tests between colorimeter and spectroradiometer systems have resulted in the conclusion that the available colorimeter models are not sufficiently accurate to, for instance, permit the acceptance testing of white integrally illuminated panels. The current tests were performed to determine if the source of the inaccuracy could be identified and to then either provide a test procedure to circumvent the problem or determine what design measures might be taken to make the device useful in the defined measurement context.

The results of this effort showed that the colorimeter does have accuracy problems but that the approach does have some promise. The problem with the device accuracy was found to be two-fold. First, the optical filters used to selectively attenuate and integrate the light stimulus to produce the red, green, and blue tristimulus values that are used to generate the illuminance and chromaticity value display readouts can introduce an absolute measurement error. The source of this error is the inability to precisely replicate the necessary standard tristimulus spectral response characteristics. The technique used involves the combination of the spectral responsivity characteristic of the colorimeter's photomultiplier detector with each of four separate optical color filters in order to match the standard X (λ), Y (λ) and Z (λ) tristimulus value spectral distributions (i.e., two filters, a red and a blue are typically used to determine the value of X (λ) which has two spectral peaks). For a particular article under test this source of error would result in an essentially fixed offset error in the chromaticity values which could, on an individual test article basis, be accounted for through calibrations against a spectroradiometer.

The second source of colorimeter error is an apparently inherent instability in the gain-sensitivity characteristics of the photomultiplier detector tubes that are used to sense the light coupled into them. The problem is therefore a common one in that the photopic filter characteristics of standard photometers using these tubes match the colorimeter Y (λ) characteristic. Luminance and illuminance reading errors for this type of photometer are typically not capable of being reduced below about 1 percent for relative readings and 5% for absolute readings. Since the X and Z tristimulus values exhibit similar reproducibility errors, the calculated chromaticity coordinates suffer from the combined effect of independent fluctuations in all three measured tristimulus values.

The errors resulting from this second source of colorimeter error cannot be compensated. The magnitudes of the 5% absolute calibration errors are such that the human visual system could detect chromaticity changes that the colorimeter could not detect. Conversely if the error magnitudes could be held to the 1% relative error limit, then the capabilities of the human visual system to perceive chromaticity changes would be approximately matched by the colorimeter.

The test called out for evaluating the chromaticity of integral white lighted instruments in Mil-L-27160C uses a photometer with photopic, blue and red filters to verify that the desired white color is being achieved. The equipment calibration calls out a comparison with a spectroradiometer which results in defining an altered set of chromaticity coordinate bounds which are applicable to the photometer being used. This technique is equivalent to the colorimeter measurement value offset compensation previously mentioned. Since a colorimeter is just a photometer with automatically sequenced trichromatic filters and a built-in capability to calculate the chromaticity coordinates, it should be possible to substitute a colorimeter for the photometer in this application without degrading the accuracy of the measurements.

To achieve still greater accuracy using the colorimeter approach, that is accuracy sufficient to with confidence distinguish color difference a human can perceive, an alternative to the photomultiplier detector tube would be needed. The recent increases in the size and hence the ultimate sensitivity of silicon wafer detectors may provide the solution to this problem. While these detectors are less sensitive than the photomultiplier tube and therefore would probably be limited to higher output device tests (i.e., signal lamps and displays), they possess exceptionally good long term stability and provide in that sense a much higher potential for achieving the needed accuracy in a colorimeter application.

As a part of the colorimeter chromaticity measurement accuracy experiments, color slides projected onto the back of a translucent viewing screen were used as color light sources to make some of the colorimeter/spectroradiometer measurement comparisons. The slides used portrayed aircraft weapons status information in color coded pictorial formats suitable for generation on a color graphics electronics displays. The slides had originally been prepared for and used in an investigation entitled "Information Processing in Advanced Informational Display" which was conducted by Captain Stollings under the direction of Dr. John Reising for the Air Force Flight Dynamics Laboratory during 1982.

Four slides representative of the set used by Captain Stollings and designated by him as A2, B14, C16 and C12 as a part of his experiment were tested. The colors incorporated in the slides were as follows: (1) A2 had black alphanumeric characters on a yellow background, (2) B14 had black and white coded bombs on a pictorial aircraft outline with a blue background, (3) C16 had the same aircraft with yellow and olive coded bombs on a blue background and (4) C12 had the same aircraft with a red center pod and green coded bombs. All of the aforementioned colors and the blank screen with no slide inserted were characterized both with the colorimeter and spectroradiometrically.

The interesting feature of this test was that in spite of the variety of colors actually perceived, all but one of the chromaticity points when plotted on a Kelly Chart (i.e., a 1931 CIE color mixture diagram with colors as designated by Kelly of the NBS superimposed[18]) would indicate that only yellow-white, yellow or yellow-orange should have been perceived. The one exception was the red coded area of slide C12 which had chromaticity coordinates corresponding to the perception of reddish-orange, rather than the deeper red hue actually perceived. The significance of this result in relation to color criteria for electronic displays is that the chromaticity coordinates and luminance of a color do not suffice to provide a unique characterization of the color that will be perceived. The practical ramifications of this result will be considered as a part of the subsection entitled "Full-Color Theory" after some relevant color perception relationships have been introduced.

Full-Color Theory

The original goals of the full-color display design criteria investigation were even more limited than those of the multi-color investigation. The intent of the effort was to gather information which would improve the capability to: (1) anticipate the changes in the colors perceived as the illumination environments encountered by pilots in military aircraft cockpits change, (2) predict minimum separable color discrimination requirements and (3) specify colors for the purpose of providing definitive descriptions of them.

The results of foregoing investigations were described in a presentation given at the 1984 National Aerospace and Electronics Conference and in a journal article published in the proceedings of that conference[17]. Since there would be no benefit to reproduce those results here, the reader is referred to the article for further information on this portion of the investigation results.

The principal problem which has in the past and continues today to confound the development of color display design criteria is the limited understanding which exists of how the human perceives color. Based on the current investigation, it is known that the Munsell variables: value (i.e., relative luminance), hue and chroma (i.e., color saturation) provide a system in which perceived colors have been defined in relation to one another. The difficulty occurs when an attempt is made to relate this human based color reference system to directly measurable quantities such as luminance and the xy chromaticity coordinates to form a complete color description. Based on the analysis conducted on the evidence gathered, it was concluded that it is the difference between the luminance and chromaticity coordinates (L_i, x_i, y_i) of a color in a scene being viewed and those for a reference color (L_r, x_r, y_r) to which the human is adapted that determines the human's color perception of sensed light radiation. In other words, if the reference color of the light to which an observer is adapted can be changed without changing the color spectrum or chromaticity coordinates of the particular object being observed, then the perceived color of the object will not appear constant but instead will appear to change. The problem then is that the human can attribute different perceived colors to an object that has an invariant absolute spectral distribution or equivalently is characterized by a fixed set of chromaticity and luminance coordinates as a result of changing the spectral content of light elsewhere in the observer's instantaneous field of view which in turn alters the color of the reference light to which the observer is adapted.

Although the foregoing relationships can be demonstrated for a variety of visual scene illumination conditions and are in general consistent with both the Munsell and Dominant Wavelength/Excitation Purity methods of characterizing colors; the actual mechanisms responsible for the color adaptation and a method for predicting the reference color luminance and chromaticity variable values still remain to be determined. In many practical applications where natural reflective object scenes are being viewed, the reference coordinates appear to be simply the mean area averaged chromaticity coordinates and luminance levels that are present in the reflected object scene. It is not clear, however, that this is true in general, since subsequent work on video grey scales (i.e., the Munsell value scale axis in color space) has shown that they originate from an ability of the human to selectively adapt to different spatial areas of the visual field simultaneously. It is therefore to be expected that color adaptation will also be spatially selective although this has not yet been experimentally demonstrated.

In conclusion, to understand the perception of colors and to be able to relate this human cognitive attribute of electromagnetic radiation to measurable physical quantities, it is necessary to be able to determine the color or colors to which the observer is adapted. In quantitative terms this amounts to being able to identify the luminance level and chromaticity coordinates to which the observer is adapted at any point in time. In relation to the adaptation point it is also necessary to be able to determine the relationship between the perceived Munsell value level differences and their respective measurable luminance level differences, and to determine the relationship between the perceived hue and chroma differences and their corresponding xy or uv chromaticity coordinate differences. Since the relationship between the Munsell value and relative luminance is well established for reflective colors, this appears to be a good place to start conducting research to determine the adaptation relationships which control color perception.

Based on the history of this issue, the foregoing research would also appear to be long overdue. Following the development of the xy chromaticity system for characterizing light radiation in 1931, there followed a series of experiments to apply the newly developed system. The first of these developed a direct relationship between the Munsell color system of perceived colors and the measurable xy chromaticity coordinate system variables[19]. Based almost exclusively on the perceived threshold chromaticity difference experimental results of MacAdam in 1942[20], a variety of attempts have been made to make an algebraic transformation of the xy chromaticity coordinate system so as to produce new chromaticity coordinates in terms of which equally perceptible color differences could be represented as equal distances in the new space which is called the UCS or uniform chromaticity (i.e., uv coordinates) system space. Although a great deal of time and effort has subsequently been expended mathematically manipulating the xy chromaticity system, with a recent 1976 revival of the effort (i.e., which included luminance) resulting in the definition of the 1976 L uv system the results still leave a great deal to be desired. During this process there seems to have been little or no effort expended to try to determine how these chromaticity coordinate systems actually relate to human's perception of colors or even whether the system is well suited for that purpose (i.e., the system was developed to aid in achieving reproducable colors when mixing drugs, paints and colorants which it does quite well under the highly controlled stable illumination conditions specified for this type of work).

The Kelly color designation chart was originally developed for use in standardizing the color names for signal lamps. It was however developed using data for standard Munsell reflective chip colors under a NBS Standard Source "C" (daylight) illumination condition, with all but a small (nominal 2°) area of the field of view, where the test chips were placed, reflecting the Illuminant "C" spectrum (i.e., this was apparently a standard viewing condition which also applied for MacAdam's experiments, for instance). Although a change in the light source would have resulted in new color name boundary locations on the xy chromaticity chart, this fact was apparently not known to either Kelly or his contemporaries. The fact that those responsible for formulating the xy chromaticity system and for that matter those who have since supplied standardized illumination systems for use with it in color matching applications, were not familiar with the fact that perceived color depends on the adapting field color is not particularly surprising. These people worked almost exclusively with reflective materials which are expected to change their perceived colors, in some cases dramatically when the source illumination spectrum changes. This large color change masked the much smaller perceptual color changes.

Although verification of the perceived color changes observed by the author have subsequently been found in the literature on color television[21], much of the work that has been carried out on electronic displays using the xy or uv chromaticity systems and in trying to achieve uniform color difference spaces appears to have ignored this very important relationship. Cases in which the perceived color dependence on adaptation to the reference color is ignored, result in associating colors directly with chromaticity chart xy or uv coordinates as was done by Kelly. Until this error is resolved and a correct model of this aspect of color perception is developed, there is little possibility that a valid space having equally perceptible colors will be defined. It would also appear to be more appropriate to base such a development on the Munsell color system rather than on MacAdam's data which held luminance constant while determining threshold chromaticity differences.

FURTHER RESEARCH

Little can be added here to the recommendations for further research already described earlier in this section. The principal problem with the continued development of design criteria for color displays is the lack of a working understanding of color which would permit predicting perceived colors in general illumination and spatial color distribution environments. The author believes that an understanding of the human color adaptation process of which spatially selective grey scale adaptation is a special case[22], is necessary in order to achieve this goal. Further research should therefore be aimed first at this fundamental color perception issue.

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APPENDIX A

LUMINANCE UNIFORMITY

Two methods are used in this report to characterize the pixel to pixel variations in luminance present on a display when all of the display pixels are requested to provide the same luminance level. The variations result from physical differences in the pixels, their contacts, their drive circuitry and so forth.

Selecting the maximum and minimum emitted luminance, ΔL_{max} and ΔL_{min}, respectively, the maximum luminance uniformity deviation can be defined in normalized form as

$$U_{L\,max} \stackrel{\Delta}{=} \frac{\Delta L_{max} - \overline{\Delta L}}{\overline{\Delta L}} \qquad \text{(A.1)}$$

and the minimum luminance uniformity deviation can be defined as

$$U_{L\,min} \stackrel{\Delta}{=} - \frac{\Delta L_{min} - \overline{\Delta L}}{\overline{\Delta L}} \qquad \text{(A.2)}$$

where $\overline{\Delta L}$ is the mean luminance for the set of emitted luminance measurement values $\{\Delta L\}$ taken.

The shortcoming of this luminance uniformity characterization approach is that no information regarding the shape of the emitted luminance value distribution is derived from it and a few errant pixels can make the display performance appear much worse than it actually is.

An alternative measure of luminance uniformity is the luminance distribution's coefficient of dispersion, D, which is also a normalized metric. The coefficient of dispersion of a distribution is defined as the standard deviation, S_L, divided by the mean value $\overline{\Delta L}$ of the distribution, given in equation form as follows:

$$D \stackrel{\Delta}{=} \frac{S_L}{\overline{\Delta L}} \qquad \text{(A.3)}$$

In the present report the standard deviation is calculated using the equation

(A.4) $$S_L = \sqrt{\frac{\Sigma \Delta L_i^{\,2} - n\,\overline{\Delta L}^{2}}{n - 1}}$$

The shortcoming of this method of characterization is that it does not give the extreme values of the distribution. As a consequence of the shortcomings of the two methods of characterization, both techniques have been applied in this report.