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STUDY OF HEAD-UP DISPLAYS FOR HELICOPTER/STOL AIRCRAFT

FINAL REPORT
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By
P. Yiotis
T. Gold
W. Clark

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By
Sperry Gyroscope Division
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FOREWORD

This study was sponsored by the Navigation and Instrumentation Branch, Avionics Division, in the Naval Air Systems Command, Department of the Navy, Washington, D.C., under Contract No. N00019-69-C-0202. This document, Publication No. 70-1329-00-00, constitutes the final report of the contracted program. It was prepared by the Sperry Gyroscope Division, Sperry Rand Corporation, Great Neck, N.Y., with substantial assistance supplied by engineering personnel of the Sperry Flight Systems Division, Phoenix, Arizona. Technical cognizance and guidance for this project has been exercised by Mr. William King of the sponsoring agency.

The technical consultation assistance furnished by the organizations and personnel listed in Appendix F of this report is gratefully acknowledged. In particular, the contributions of the Sikorsky Aircraft, Vertol, and Farrand Optical Companies were significant in the successful completion of this program.

SECTION I

INTRODUCTION

A. THE OPERATIONAL PROBLEM

Helicopters, and to a somewhat lesser extent, STOL aircraft, operate over a broad flight spectrum. They have many of the characteristics of a conventional, fixed-wing airplane at higher speeds, with additional capabilities and problems resulting from low speed operation. These low speed problems are associated not only with the flight control characteristics and wind effects unique to this class of vehicle, but also with the extensive low altitude operations enabled by the low speed capability. Increasingly, hazardous, close-support, tactical missions involving low altitude maneuvers are being consigned or planned for helicopters under both day and night combat conditions. These missions include assault transport, supply transport, medical evacuation, and Search and Rescue (SAR) operations where landings are made in remote, unprepared areas. The landings are often negotiated at steep descent angles where rough, dense terrain or enemy ground fire is encountered.

During the terminal and other low altitude phases of these missions, frequent transitions are made between VFR and IFR conditions as the helicopter moves through smoke, haze or fog. The helicopter's low speed also permits operation in lower visibility conditions than are possible for fixed-wing aircraft. Such operations with frequent visibility changes and the pilot's natural desire to use real world cues when they exist is a powerful reason for a Head-Up Display (HUD), which provides control information integrated with the real world. In addition, a compelling need exists in many current helicopter systems to provide a capability for the detection, acquisition and continuous orientation of the terminal target of interest, through visual and aided-visual optical display means.

Both helicopter and STOL aircraft are subject to many of the demands imposed on conventional, fixed-wing aircraft in the cruise and high speed flight regimes. Navigation, low level terrain following and terrain avoidance, weapon delivery, station keeping, and air-to-air refueling are typical of these military mission phases. Weapon delivery, in particular, reflects a number of deficiencies and problems in current helicopters which can in part be overcome with a properly designed HUD. In summary, the operational problems related to the display and control tasks encountered by helicopters and STOL aircraft cover all areas related to conventional fixed-wing aircraft, plus a group of more difficult problems peculiar to the helicopter/STOL classes of vehicles.

B. PROGRAM OBJECTIVES

The Naval Air Systems Command (NASC), recognizing the helicopter/STOL operational problems, contracted the study program described in this report to verify that a HUD can facilitate the solution of these problems and thereby improve the effectiveness of these vehicles. The likelihood of such a favorable conclusion, in the first instance, is the basis of the Navy's decision to initiate the investigation. Augmenting this broad goal, the following three more specific objectives were established by NASC for the systems analysis effort conducted:

- Survey and establish potential applications (current and near future) of HUD to helicopter and STOL aircraft.
- Assess the effectiveness of each potential HUD application.
- Evolve practical HUD systems for specific vehicles and missions.

As indicated by these objectives, the investigation conducted was rather broadly based; HUD configurations were developed for a large number of helicopter applications. The recommended designs encompass a broad spectrum of display complexity, as might logically be anticipated by the diverse requirements of different vehicles. Although a single, universal HUD configuration is obviously impractical, the study did establish that some degree of display commonality between helicopter types is feasible, particularly as related to the optical projector unit(s) and symbol format designs.

The successful completion of this study program is viewed as an important first step in the evolution of practical, optimally designed HUD equipment for helicopters. It provides NASC with an objective basis for helicopter avionic system synthesis and display specification and provides the design information required for contracting any future development of a HUD flight test evaluation model. It is further conceived that the results of the investigation could profitably be used by the other services and will be made available to prime contractors of helicopter and STOL weapon systems for study and use in display equipment specifications.

C. PROGRAM PHILOSOPHY AND GROUND RULES

Before undertaking a large-scope study of this type, certain ground rules and guidelines were established affecting the activity and results of the program. These ground rules, listed below, reflect a philosophy of emphasis and limitations on the effort expended so as to yield the maximum practical benefit to the Navy.

(1) Study to be specifically directed to real applications as represented by operational and developmental Navy/Marine helicopter and STOL aircraft, including bi-service and tri-service vehicles. Research vehicles, principally of the VTOL type, are not to be considered in this study.

(2) Appreciable effort to be expended on the design tradeoff analyses of optical projection systems. This emphasis was established because the projector unit represents the most critical tradeoff problem in the specification of a HUD.

(3) Avoid the use of any precepts in HUD format design, as may reflect widely accepted principles applied in past fixed-wing aircraft applications.

(4) Limit system evaluations and tradeoffs to the exercise of best engineering judgments associated with design optimization and effectiveness assessments. Quantitative system cost and effectiveness evaluations associated with the decision to incorporate a HUD element in any given vehicle and/or the formulation of a detailed specification for such a vehicle, are not to be conducted. Such evaluations are logically conducted by the weapon system manager as part of a higher level, avionic system definition effort and are, therefore, beyond the scope of this study.

(5) Emphasis to be placed on establishing compelling needs, if any, for HUD in helicopters. Accordingly, the display is to be viewed not only in its conventional role of a repeater device for real-world-oriented flight control, but in a broader context of enabling a significant extension in helicopter system capability.

(6) Design studies to reflect practical solutions where the realities of the actual cockpit and sensor availability are considered. Low cost and weight shall be treated as high priority factors in all design tradeoffs.

(7) Various levels of display system complexity are to be established bounded by maximum and minimum goals, which are consistent with both the established display requirements and relative sophistication of the existing avionics system - from advanced, highly instrumented to simply equipped system configurations.

(8) Establish to the maximum extent possible, a symbol format, which is common for different helicopter and mission applications for each distinct operational flight mode, in order to standardize pilot training.

SECTION II

SUMMARY

A summary of the investigation (in terms of program scope and course of action, specific HUD applications, and significant technical results achieved) and a synopsis of the conclusions reached are presented in this section. The comprehensive nature of the study dictated that a carefully planned, systems analysis approach be employed to ensure the development of valid, practical results yielding the greatest benefit possible to the Navy.

A. OUTLINE OF STUDY

The study of HUD for helicopters consisted of the following distinct but closely interrelated phases:

- Operational Surveys - The purpose of these surveys was to establish operational problem areas in which HUD could be effectively employed. The information was obtained from research of the relevant literature and conferences with helicopter pilots and engineers in the military services and airframe manufacturing organizations.

- Aircraft and Equipment Data - The pertinent flight characteristics, cockpit configuration data, and relevant equipment complements for the helicopter models being considered were accumulated. This information was obtained from flight handbooks, installation manuals, manufacturers' literature and engineering data secured from the aircraft manufacturers.

- Systems Analysis - This critical phase in the program led to the application of the HUD, and the selection of the functional modes and the display formats for each of the applications. Mission analyses, information requirements studies and display/control analyses were performed to accomplish these selections.

- Optical Studies - Optical configurations were studied to establish the classes of HUD projector designs that are suitable for installation and use in helicopters. Final recommendations for projector designs for each application were made from among these possible alternates.

- Electronic Studies - Electronic, digital processing techniques applicable to helicopter HUD systems were studied. Electronic interfaces with sensors, data processing, and symbol generation requirements for the HUD were considered in this phase. The electronic and physical characteristics of the equipment required for the HUD were estimated.

- Cockpit Layout Studies - Cockpit configurations for some of the aircraft were studied with scaled layouts, as a basis for establishing the feasibility of installing the HUD equipments recommended for these aircraft.

- Final Evaluations - All HUD candidate systems developed were reviewed in relation to the various helicopter models and missions. A specific HUD system was then selected for each helicopter and mission.

B. SCOPE OF APPLICATIONS

The scope of the possible applications of the HUD was determined by the classes of vehicles and the types of missions considered. Six classes of helicopters and STOL aircraft in the current Navy/Marine operational inventory were investigated as listed with their manufacturers.

- H-1 Series (Bell)
- H-2 Series (Kaman)
- H-3 Series (Sikorsky)
- V-10 (North American)
- H-46 Series (Boeing Vertol)
- H-53 Series (Sikorsky)

The specific models of the vehicles considered are shown in the matrix presented in Figure 2-1. Although the CH-3C, E and the HH-53B, C aircraft are in the Air Force inventory, they have been listed because the HUD has particular relevance to their type of missions. The OV-10A is the only operational STOL aircraft in the current Navy inventory. The Hawker Siddeley Harrier V/STOL fighter, now being supplied to the Marine Corps, has not been specifically considered in this study because it is already equipped with a HUD as part of an integrated navigation/attack system. In addition, all research V/STOL vehicles were excluded from consideration in this study because they represent flight control test beds, only, with no tactical operational capability.

Helicopters and STOL aircraft may be used for the following classes of missions:

- Transport
- Search and Rescue
- Recovery
- Observation
- Reconnaissance
- Antisubmarine Warfare
- Mine Countermeasures
- Close Support
- Utility
- Medical Evacuation

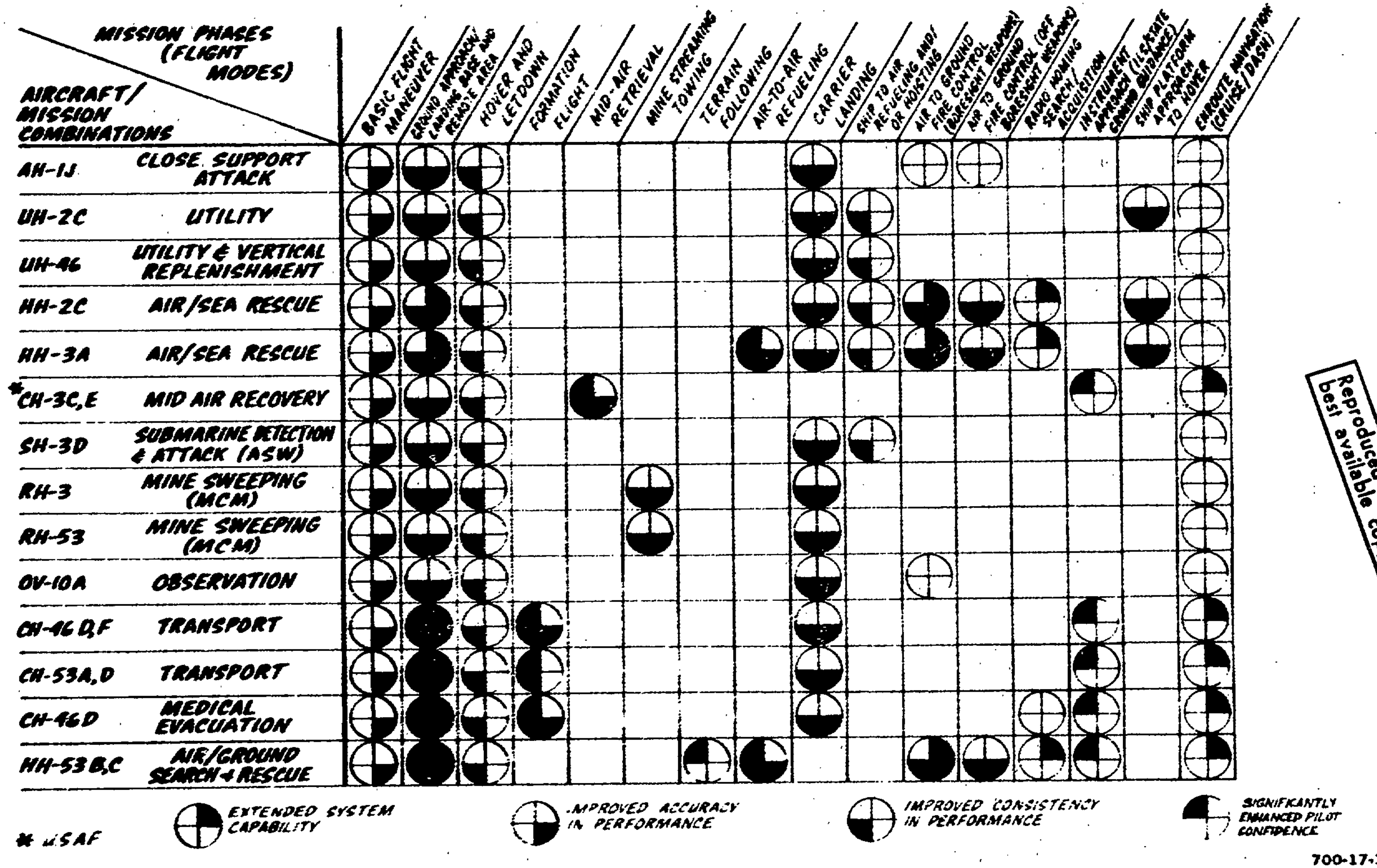

Figure 2-1
Applications of HUD to Specific Aircraft/Missions

Transport missions cover the delivery of men and/or materiel to sites located in friendly areas or to a hostile environment for assault or vertical replenishment of supplies. Search and rescue operations involve locating downed pilots on land or at sea, frequently in hostile environments, and bringing these personnel to safety. The recovery operation covers mid-air recovery of special equipment being parachuted from high altitudes. Observation involves visual target detection and acquisition from the air, and relaying this information to suitable weapon systems. Ground-to-ground weapon delivery effectiveness can also be assessed and controlled with observation aircraft. Reconnaissance missions relate to the acquisition of large amounts of intelligence by all types of sensors for storage and subsequent analysis. Antisubmarine Warfare (ASW) covers all airborne means for detecting, locating and destroying enemy underwater craft. Mine countermeasures are the means for sweeping underwater mine fields to free the mines, which float to the surface so that they can be detected and destroyed. Close support is the use of airborne weaponry for tactical support of ground operations. Utility missions involve the transport of select personnel such as VIP's or special equipment to specific sites with minimal preparation. Medical evacuation is the emergency removal of wounded personnel from forward areas to sites at which suitable medical attention is available.

C. SPECIFIC HUD APPLICATIONS

A decision regarding the utility of a HUD for any particular combination of aircraft and mission ultimately depends on the effectiveness criteria, which are selected to evaluate utility. Furthermore, the HUD has relevance to a specific critical flight operation(s) involved in any aircraft and mission. The matrix in Figure 2-1 was developed to present an overview of the evaluation performed on this basis. The vertical entries are the combinations of aircraft models and missions, while the horizontal entries are a summary of the flight operations involved in any of these missions. A component or entry in the two-way matrix, in the form of a circle, indicates that a particular flight operation is pertinent to that row representing the aircraft and mission. The circles are subdivided into four quadrants, each indicating one of four effectiveness criteria which have been used as a basis for evaluating utility of the HUD.

- Extended System Capability - Flight operations made practicable through the use of a HUD, but which could not otherwise be performed at an acceptable level of performance under a wide range of situations.

- Improved Accuracy in Performance - Augmenting the precision with which critical flight operations such as basic flight maneuvers, approach for landing, and fire control, can be performed manually by pilots.

- Improved Consistency in Performance - Reducing the variability in performance obtained in replicated maneuvers of a particular type. Variability includes that produced by a single pilot, as well as variability arising from differences among pilots.

- Significantly Enhanced Pilot Confidence - Increasing the confidence of the pilot in executing hazardous operations such as terrain following and instrument approaches. Some key factors that affect pilot confidence are: assurance that his system(s) is performing satisfactorily, advising of marginal or deficient performance, minimizing the probability of surprises for the pilot, and providing suitable backup capability in the event of system failures.

When a quadrant of a circle entry is filled in black (Figure 2-1), the HUD is considered an effective addition to the aircraft for that particular operation, based on the criterion indicated by the quadrant. The multi-quadrant entries represent recommended applications of the HUD based on several effectiveness criteria. These are generally the more cogent applications. Note that the last three criteria (augmented accuracy, consistency and pilot confidence) all contribute to improving flight safety, which is measured statistically by the complement of the accident rate.

Some of the entries in Figure 2-1 are blank circles, i.e., without reference to effectiveness criteria. These entries refer to aircraft and operations that cannot presently be conducted with the HUD due to the absence of suitable sensors in these aircraft. Avionic growth in these aircraft may lead to HUD applications for the operations indicated. Other more specialized potential applications of the HUD, which are not included in Figure 2-1, are presented in Appendix E.

D. SIGNIFICANT TECHNICAL RESULTS AND CONCLUSIONS

The HUD will, with varying degrees, improve the effectiveness of helicopter systems. As such, it deserves serious consideration in future helicopter avionic system development relating to both new and existing vehicles. Whether a HUD is established as a simple flight control and attitude orientation instrument to assist pilots with minimal training, or whether such instrumentation is specified for more critical flight operations such as weapon delivery, mid-air retrieval of space capsules, etc, display systems of varying costs and complexities are available to suit the application. A wide range of 12 practical system and equipment configurations has been conceived in this study for this purpose.

The most compelling needs for HUD are associated with the following critical helicopter problems uncovered in the operational surveys conducted.

(1) Control difficulties during rapid, steep VFR approaches as may be necessitated by enemy gunfire, rough and dense terrain, etc.

(2) Loss of ground target (after initial sighting) under adverse detection conditions due to lack of acquisition and continuous orientation capability.

(3) Approaches under poor visibility conditions.

(4) Inadequate gun/rocket fire control performance.

These problems are principally associated with the following tactical combat operations:

- Remote Area Landing - Problems (1), (2), (3)
- Gun/Rocket Fire Control - Problems (2), (4)
- Search and Rescue - Problems (1), (2), (3)

With respect to equipment design, display information and symbol formats are developed for each of the significant flight modes or mission phases analyzed. Four specific optical projector designs are recommended for various vehicle and mission combinations. The key performance and physical characteristics, developed with the aid of computer, ray-trace solutions, are provided for each design. Two of the projectors consist of on-axis refractive optics with Cathode Ray Tube (CRT) image sources. The other two projectors comprise simpler on-axis reflective optics with electromechanically driven reticles. All projectors are designed for overhead mounting. A hand-gripped aimsight featuring a stabilized servo-driven reticle has also been designed in preliminary layout form and is recommended for certain applications. A unique computer solution approach to the stabilization of this aimsight reticle has been formulated.

Recommendations are also presented on the basic design approaches to be employed in the electronic processor unit. Three processor types (one analog and two digital) are described principally in terms of selection tradeoff criteria. In addition, a digital processor centered about a special-purpose computer specifically designed for synthetic symbol displays, is described in considerable detail. This type of computer with its dual program control, exclusive solid-state memory, and instruction repertoire is presented as an efficient, promising approach to stroke-written symbol displays such as a HUD. This processor design assumes even greater advantage in certain helicopter applications, where the computer is functionally extended to execute certain specialized, display-related arithmetic calculations associated with aimsight stabilization and visual kinematic targeting.

Five kinematic targeting techniques are recommended for ranging and/or full orientation of a target with a HUD. The value of such targeting has been established for a multitude of helicopter applications, where the specific technique to be employed depends on the tactical operation, terrain and weather conditions, and the on-board avionic complement. This low cost alternative to systems employing direct range sensing has been made practical by the advent of efficient, small-scale digital computers. Equations have been fully developed, and preliminary programming analyses have been conducted to test the feasibility of each targeting system conceived.

A number of visual and aided-visual weapon delivery system concepts, involving the use of fixed and moveable optical projectors, are presented for consideration by the Navy and helicopter system managers. For visual delivery, a somewhat more simply equipped system is synthesized for improved fire control performance. An even simpler gunship system is advanced in which a more heavily instrumented leader gunship or observation (hunter) craft transmits, via voice communication, only sensed target altitude to the attack gunships for improved HUD fire control. The functional extension of the moveable aimsight from visual to night combat operations, in which pictorial LLLTV or IR is presented on the aimsight via a CRT, is also recommended.

SECTION III

DISPLAY DESIGN CRITERIA AND REQUIREMENTS

The essential design criteria and requirements associated with the design of HUD systems for the Navy/Marine operational helicopters and STOL aircraft considered in this study are presented in this section. Although frequent references are made to various missions and associated operational modes, the criteria and requirements are largely discussed in a general manner since each related extensively to many of the display formats and equipment designs presented in Sections IV, V and VI. The HUD designs synthesized in these sections take full account of these criteria and requirements and the concepts on which they are based.

A. BASIC VISUAL AND DISPLAY CRITERIA

The HUD is essentially a visual flight device, in which the pilot extracts information from the real world by visual means and combines it with processed data display by the HUD. The basic psychological advantages in using visual cues from the real world may be attributed to the following. The information from the real world has a richness in content and a high degree of organization for perceptual assimilation. The pilot has had lifelong experience in handling information in this form. The fact that flight by visual reference is not necessarily superior for all phases of a mission does not devalue the utility of the external visual field. The pilot also has a high degree of confidence in what he perceives visually. The "Mark I eyeball" is an effective means of increasing the subjective reliability of a flight maneuver. The fact that optical illusions in flight are as compelling as they are when they occur may be attributed to this factor.

The fact that the HUD is also effective for instrument flight is based on the advantages of visual flight. In almost all instrument flight, there is a transition to visual flight. A compatible Visual Flight Rules (VFR)/Instrument Flight Rules (IFR) display is therefore a compelling requirement to permit a smooth transition between the two modes of flight. The rapid, accurate evaluation of isolated visual cues such as single lights or landmarks in relation to a total situation dictates that the display be presented in a format overlaying the real visual world. Only a HUD has this attribute. Furthermore, there is sometimes the requirement for a smooth transition from visual to instrument flight such as in an aborted instrument approach, or in flight in mixed weather. Again, the HUD is particularly suited to this task. The visual flight mode discussed in the preceding assumes night/VFR operation and daylight.

Precise criteria for the assignment of information to the HUD can be established on the basis of the foregoing. When head-up flight is considered advantageous, what information should be included in the HUD? The criteria which are considered to be the most significant are as follows:

- Information that enhances the precision of visual flight control.

  Example: Providing HUD information that augments the pilot's ability to control the flight path of the vehicle in relation to the aiming point on the helicopter landing area.

- Information that improves the ability of the pilot to assess an existing situation when information from the external visual field is available.

  Example: The display of the helicopter velocity vector direction in the HUD will enable the pilot to observe the relationship between the flight path of the vehicle and a terrestrial obstacle during terrain following.

- Information that enhances instrument flight, through either a more favorable perceptual arrangement of displayed information in a three-dimensional context, or where transition from instrument to visual flight must be accomplished rapidly and smoothly.

  Example: Tracking a ground radar target defining a destination may be more easily accomplished with the target and a quickened flight control response element displayed in the HUD. Visual acquisition of the target may then be accomplished smoothly and a transition to visual flight control effected with continuity in the display/control procedure.

- Information that must be sampled frequently on a real-time basis during head-up flight control.

  Example: Ground speed must be controlled closely during approach to the hover condition. If tight flight path control is being achieved with a HUD, it is reasonable to include speed control information in the same display. Frequent shifts in visual attention between the cockpit panel and the HUD are thereby avoided.

The frequency criterion should be distinguished clearly from importance of the information. Information that has appreciable time rates of change, and a variation in mean value, must be sampled frequently if the variable is to be controlled. Continuous control of an error in a tracking task represents the extreme case for this type of information. However, variables such as engine temperature are quasistatic though extremely important to the success of the mission. The significance of advising the pilot of a change in engine temperature due to malperformance does not itself warrant inclusion of this information in the HUD.

One additional general precept must be considered among the criteria for assignment of information to the HUD. It is highly undesirable to have more information than absolutely essential displayed in the HUD; additional projected elements may occlude and/or confuse the pilot's view of the real world.

The guidance, control and assessment information, which the pilot may require in the performance of the flight operations delineated in the matrix of Figure 2-1, is shown in Figure 3-1. The entries in this matrix involve two classes of information, that which is essential and that which is desirable.

From the information requirements in Figure 3-1 and the criteria for presentation of information in the HUD described in the preceding paragraphs, the HUD configurations presented in Section IV for each mode of operation were developed.

The visual functions in flight that are augmented by the HUD are summarized below.

- Improved flight control
- Easier transition from instrument to visual flight
- Quicker visual acquisition of targets
- Precise entry of target data acquired visually
- Safer transition from visual to instrument flight

	PITCH	ROLL	HEADING	HEADING ERROR	TURN RATE	FLIGHT PATH ANGLE	GROUND TRACK	GROUND SPEED	AIRSPEED	WIND	VERTICAL SPEED	POSITION (EARTH REF.)	ALTITUDE BAROMETRIC	ALTITUDE ABOVE TERRAIN	SELECTED GLIDE SLOPE	VERTICAL ERROR IN POSITION	LATERAL/LONG. ERROR IN POSITION	TARGET RANGE	TARGET BEARING & ELEVATION
BASIC FLIGHT MANEUVERS	▲	▲	▲	△	△	△	△	△	▲				▲	△					
FIELD APPROACH & LANDING	▲	▲	▲		△	△	△	△		△				▲	▲	▲	▲	△	
HOVER & LETDOWN	▲	▲			△		▲	▲		▲	▲			▲		▲	▲		
FORMATION FLIGHT					△	△			▲							▲	▲	△	△
MID-AIR RETRIEVAL	△	△			△	▲			△	▲					▲	▲	▲	▲	▲
MINE COUNTER-MEASURES	▲	▲	▲				▲	▲		△				▲		▲	▲	△	△
TERRAIN FOLLOWING	▲	▲				▲	▲	△	▲			△	△	▲				▲	▲
AIR-TO-AIR REFUELING					△	▲			▲							▲	▲	△	△
SHIP-TO-AIR REFUELING						△				▲	△			△		▲	▲	△	△
CARRIER LANDING	▲	▲	▲		△	△		△		△				▲	▲	▲	▲	△	
AIR-TO-GROUND FIRE ON-BORESIGHT	▲	▲	▲			▲	▲	▲					▲						▲
AIR-TO-GROUND FIRE OFF-BORESIGHT	▲	▲	▲				▲	▲											▲
RADIO HOMING SEARCH	▲	▲	▲			△			▲				▲						▲
EN ROUTE NAVIGATION	△	△	▲				▲	▲	△	△		▲	△					▲	▲
APPROACH/HOVER OVERSHIP	▲	▲			△	△		△		▲	▲			▲		▲	▲	△	
INSTRUMENT APPROACH	▲	▲	▲	▲	△	▲	▲	▲		△				▲	▲	▲	▲	△	

▲ INFORMATION IS ESSENTIAL
△ INFORMATION IS DESIRABLE

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Figure 3-1
Information Required for Conduct of Helicopter Flight Operations

B. ACQUISITION AND DESIGNATION CRITERIA

The tactical, close support nature of helicopter operations makes it highly advantageous, and often imperative, for the pilot to be presented with a positional orientation of his vehicle relative to ground targets of interest. This, of course, necessitates a self-contained system of acquisition which for low flying helicopters is best achieved visually, or in the case of night operations, through aided-visual means. Since the HUD bridges the gap between cockpit-generated information and visual information from the real world, it has been established as a necessary element in helicopter acquisition systems.

The following four classes of external visual and display information associated with the acquisition process have been considered from the very specific standpoint of extending the capability of helicopter weapon systems with a HUD.

- Acquisition (V_A) - Visual information acquired for storage in a memory system on the aircraft or transmitted to another aircraft or a ground base. A typical example involves a discrete HUD acquisition providing elevation and azimuth angle data. This information, when combined with sensed or derived range, yields a full three-axis orientation of the detected ground target.

- Designation (V_D) - Visually designating the location of a target to the pilot by a symbol suitably oriented in the HUD to facilitate visual detection by the pilot. Examples are a hostile target or the estimated location of a downed pilot who is to be rescued.

- Designation/Acquisition (V_{DA}) - Designating a target in the HUD for subsequent visual acquisition. Any difference between the designated and true positions of the target is erased by updating the designated information after the target has been acquired by overlaying the HUD symbol on the target. An example is updating the initial orientation of a target for terminal weapon delivery.

- Acquisition/Control (V_{AC}) - Display of steering guidance in the HUD for precise flight path control associated with an acquired target. Examples are terminal navigation and landing letdown in remote areas and air-to-ground fire control.

In another sense, a pilot executes a more basic form of visual acquisition/control (V_{AC}) by directly using visual information acquired from the real world to control the aircraft. The overlay of a HUD deviation symbol on the aim point in a landing approach, and a reticle symbol on a ground target during weapon delivery, are examples of this class of external visual and display information.

C. FIELD OF VIEW

The extent of the visual field to be covered by the images projected in a HUD for helicopter (field of view) depends upon the flight regime of the vehicle, the flight maneuvers to be executed, and the external visual references required to conduct the operations. Under VFR, the pilot has fairly complete visual access to the environment around his aircraft, limited only by the attitude and heading of the vehicle, and the visual cockpit cutoff angles. The field of view requirements for VFR are, therefore, determined by the relationships among the display images, the orientation of the aircraft, and the location of visual objects in the real world to be used in conjunction with the HUD. Consider, for example, a visual approach to a landing pad at the prescribed descent angle, using a deviation image to measure displacement from the reference path and a flight path marker to show the direction of flight (Figure 3-2).

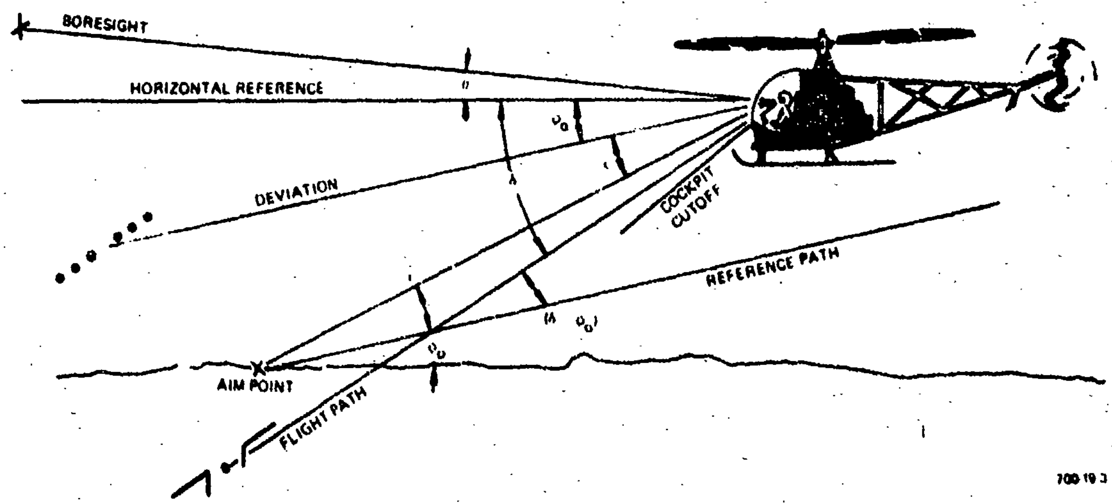


Figure 3-2
Vertical Viewing Angles in Visual Landing Approach

The required field of view is determined by the range of orientations of the deviation bar and flight path marker in the HUD and the landing aim point on the ground for the attitudes and positions of the aircraft that may be involved in the approach maneuvers. In this case, the aim point must be contained within the field of the HUD, because HUD imagery is being used to overlay and/or overfly this point. In other VFR situations such as clearing an obstacle, it may be sufficient to observe the visual target (obstacle) in the real world beyond the limits of the HUD, and to execute maneuvers in relation to the target, which ultimately move into the HUD field. In VFR, therefore, not all key visual elements in the real world need be viewed through the HUD to permit effective flight control and/or monitoring in relation to these elements. The HUD augments the information derived from the visual world in VFR, and it need not present a complete display of the visual situation.

Under IFR, however, the surrogate images representing, say, the landing area or a ground target with a known location, must be presented in the HUD in their correct visual position with respect to the aircraft. This is essential to make IFR flight compatible with VFR, to provide effective displays for mixed or limited visibility weather, in which transitions between instrument and visual flight must be smooth. The field of view requirements under these conditions are generally larger than for visual flight only.

There are several additional considerations involved in defining the visual field angles to be specified for the projection system of a HUD. The installation of the HUD in a cockpit is designed to minimize field requirements by optimizing the orientation of the center of the HUD field. Thus, if the lower limit of the field is farther below the boresight line of the aircraft than the upper limit is above this reference, the center of the HUD field should be depressed below the boresight line. The HUD optics may be made moveable, either in discrete steps to fixed positions, or continuously adjustable to cover different fields with respect to the aircraft for various flight modes. As an example, the HUD may be in an up-orientation for flight and in a down-orientation for approach and landing. Special flashing surrogate symbols may be oriented at the edges of the HUD field to designate elements that are beyond the limits of the field. These symbols may serve as adequate indicators for control until the targets move into the HUD field. This technique is useful for operations in both VFR and IFR.

In most HUD projector designs, the pilot's eyes are behind the exit pupil. This optical situation provides the pilot with dual overlapping monocular fields, displaced laterally due to the separation between the eyes (interpupillary distance). The common field in the overlapping region is seen binocularly by the pilot. The field that is mapped by the image generator in a HUD is generally larger than the instantaneous field seen by the pilot in one head position. The pilot can therefore extend the useful field of view in the HUD with some head movement. Some of these visual considerations related to the design of HUD systems are described in Reference 12.

As an example of the required orientation of the HUD images in the vertical plane, consider the approach for landing shown in Figure 3-2. The desired approach angle to the aim point is ϕ_o, and the maximum angular deviation from the reference path is ϵ. If γ is the flight path angle of the aircraft, and this is to intercept the reference path at an angle proportional to ϵ,

$$(\gamma - \phi_o) = a\epsilon$$

where

$(\gamma - \phi_o)$ = Intercept angle

a = Constant greater than unity

The flight path marker has a maximum depression below the horizontal reference of

$$\gamma_1 = \phi_o + a\epsilon$$

which corresponds to a depression below the boresight line of

$$\theta_{\gamma_1} + \gamma_1 = \theta_{\gamma_1} + \phi_o + a\epsilon$$

where θ_{γ_1} is the pitch of the aircraft at a flight path angle γ_1 equal to $\phi_o + a\epsilon$. When the aircraft is below the reference path, the intercept angle is $(\phi_o - \gamma)$, which is also made equal to $a\epsilon$. Under these conditions, the flight path marker has the minimum depression, at an angle of

$$\gamma_2 = \phi_o - a\epsilon$$

which corresponds to a depression below the boresight of

$$\theta_{\gamma_2} + \gamma_2 = \theta_{\gamma_2} + \phi_o - a\epsilon$$

where θ_{γ_2} is the pitch of the aircraft at a flight path angle γ_2 equal to $\phi_o - a\epsilon$. These required field limits for the path marker pertain to a single approach path ϕ_o. The deviation image is oriented at depression angles $(\theta_{\gamma_1} + \phi_o)$ and $\theta_{\gamma_2} + \phi_o$ for the same situations above and below the reference path. The required field of view for the HUD and its orientation in the aircraft are determined by this type of analysis covering the full range of approach angles ϕ_o.

As an example of field of view requirements in azimuth, consider the final approach situation shown in Figure 3-3. The aircraft is approaching the landing pad by coupling to a reference path that permits a landing into the wind at heading H_W. The initial lateral angular deviation of the aircraft from the reference path is δ, and the desired intercept angle of the ground speed vector (path marker) is λ, which is assumed proportional to δ (i.e., λ equal to $b\delta$). The relationship among airspeed, ground speed and wind is shown by the vector diagram in Figure 3-3. The associated sideslip angle of the helicopter at the approach speed is shown as β.

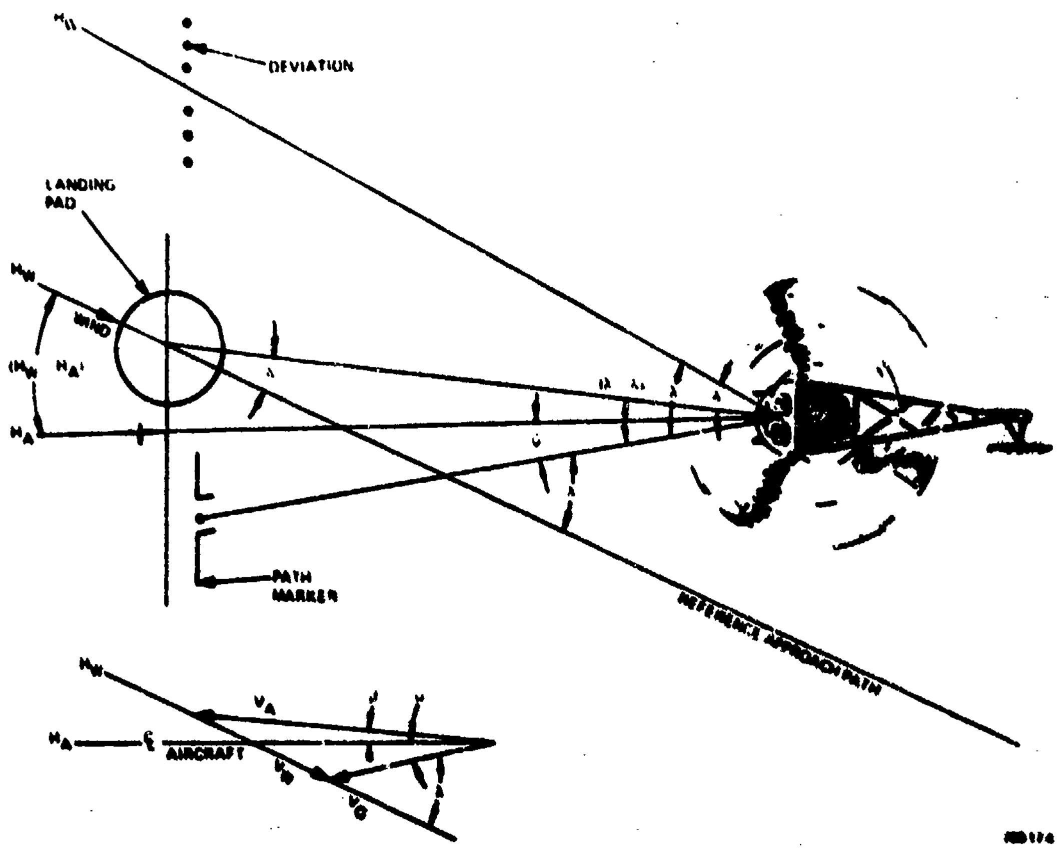


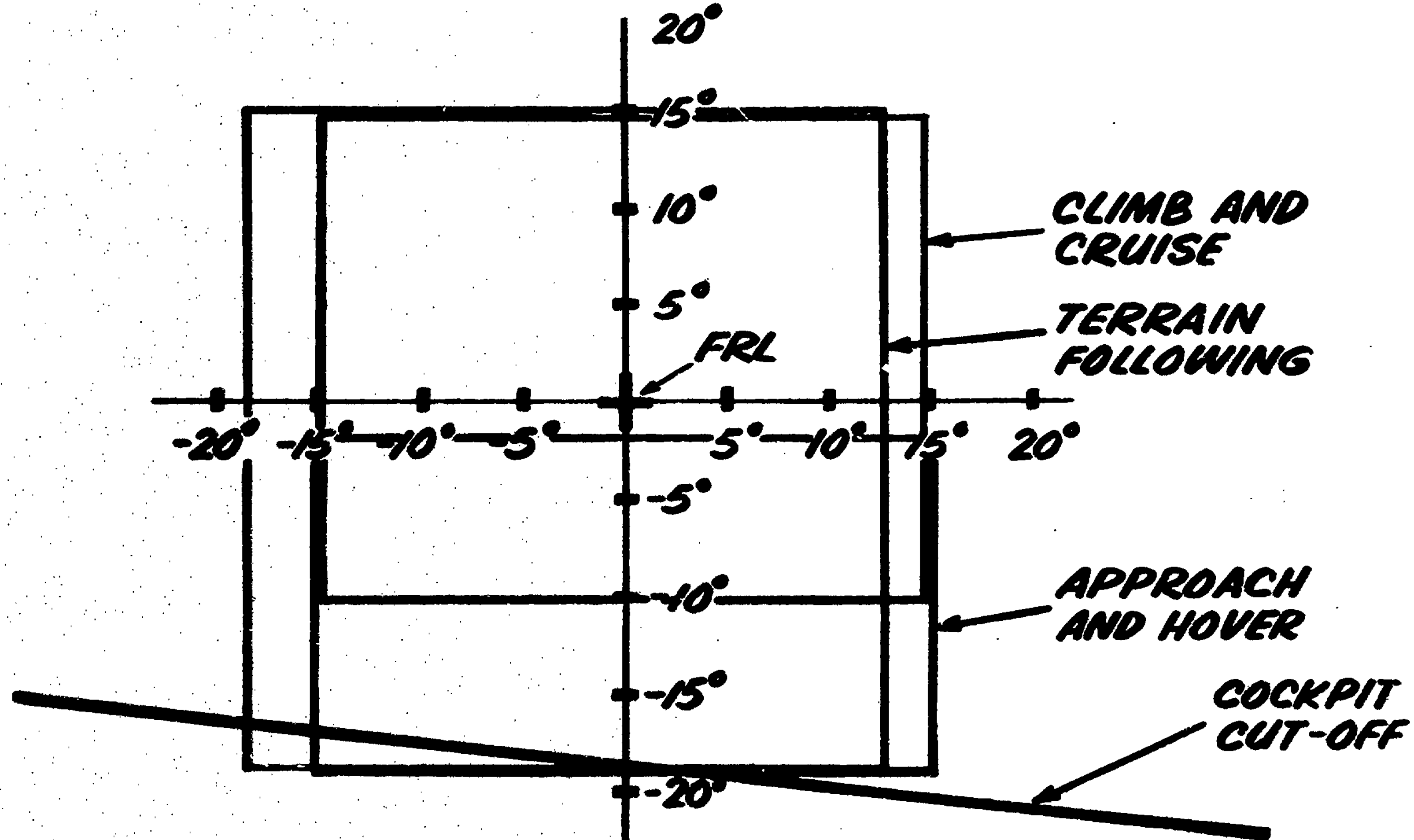
Figure 3-3
Horizontal Viewing Angles in Visual Landing Approach

The half-field angle required for the HUD under these conditions is either ψ or $(\lambda - \psi)$, whichever is greater. The angle λ is determined by the maximum deviation angle, δ, from which ψ can be determined from the vectorial speed relationships.

The results of an analysis of the characteristics of the H-53 aircraft as applied to field of view requirements for a HUD for both VFR and IFR operations are presented in Figure 3-4.

D. ON-BOARD AVIONIC SENSORS AND COMPUTERS

The avionic complements that presently exist in each of the helicopters studied are summarized in this paragraph. This survey was made to ensure that the HUD designs formulated and recommended for each application account for the realities of available sensed or computed data. A summary of the current avionic complements is presented in Table 3-1. By way of contrast with advanced fixed-wing tactical aircraft into which HUD has been incorporated, helicopters are relatively simply equipped. Furthermore, much of the equipment is not within the state of the art of achievable accuracy performance, and in some cases, reliability. In fact, the Navy is planning to replace some of the equipment listed in the table with units of more advanced design. Of particular significance to the introduction of HUD in helicopters, is the accuracy of attitude data. This is important in a display of this type, which is largely real world oriented. Without reasonably accurate attitude data as may be required for the flight operation involved, the effectiveness of a HUD is seriously impaired and its installation may not be justified. Accordingly, for certain critical operational flight modes, the substitution of a higher performance Attitude Heading Reference System (AHRS) for the existing VG/DG's is indicated. The availability of a Doppler radar is also of interest in HUD system design. All the vehicles covered, with the exception of AH-1 and OV-10, carry this equipment. In addition to enabling the presentation of a path marker symbol on a HUD, Dopplers also provide the velocity sensing necessary to implement a number of kinematic targeting systems described in Subsection III.H.



700-17-5

Figure 3-4
Field of View Requirements for VFR/IFR HUD for H-53 Aircraft

TABLE 3-1

AVIONIC COMPLEMENT FOR VARIOUS HELICOPTERS

Vehicle \ Complement	Radar Altimeter	Doppler Radar	ILS	TACAN	LF NAVAID	Hover Indicator	TAS Transducer	UHF Direction Finder	ADC	VG	DG
CH-53D	AN/APN-171 (hr)			AN/ARN-52 (R_C, ψ_{TACAN}, R_A)	AN/ARN-59 (ψ_{LF})	Flt Dir Ind (AFCS Outputs)				✓ (θ, ϕ)	MA-1 (ψ_m)
CH-46D	AN/APN-117 or AN/APN-171 (hr)			AN/ARN-52 (R_C, ψ_{TACAN}, R_A)	AN/ARN-59 (ψ_{LF})					✓ (θ, ϕ)	MA-1 (ψ_m)
HH-3A	AN/APN-117 (hr)	AN/APN-130A (V_C, β, V_H, V_D, V_V, ψ_{BEST}, R_{BEST})		AN/ARN-52 (R_C, ψ_{TACAN}, R_A)	AN/ARN-56 (ψ_{LF})		✓ (V_T)			✓ (θ, ϕ)	MA-1 (ψ_m)
CH-3C, E	AN/APN-150 (hr)		AN/ARN-58 (Δh, Δy)	VOR-101 AN/ARN-65 (R_C, ψ_{TACAN})	AN/ARN-59 (ψ_{LF})	AFCS Ind (AFCS Outputs)				Lear 5000T (θ, ϕ)	J-4 (ψ_m)
HH-3C, E	AN/APN-150 (hr)	AN/ASN-64 (V_C, β, V_F, V_H, V_D, ψ_{BEST}, R_{BEST})	AN/ARN-58 (Δh, Δy)	VOR-101 AN/ARN-65 (ψ_{TACAN})	AN/ARN-59 (ψ_{LF})	AFCS Ind (AFCS Outputs, (V_H, V_D, V_V)	✓ (V_T)	AN/ARA-25 (ψ_{TGT})		Lear 5000T (θ, ϕ)	J-4 (ψ_m)
AH-1G, J										✓ (θ, ϕ)	AN/ASN-43 (ψ_m)
SH-3D	AN/APQ-117 AN/APN-171 (hr)	APN/130 APN/182 (Future) (H, V_H, V_D, V_S, β, ψ_T, ψ_D, V_V)		ARN-52		Hover Ind (V_H, V_D, + V_V, or AFCS Null; Cable Info plus V_V)	✓ (V_T)			AN/ASN-50 (Late Models) (θ, ϕ)	MA-1 (ψ_m)
UH-2 HH-2	AN/APN-117	AN/APN-130 AN/ASA-13		✓	✓	✓		AN/ARC-52		✓ (θ, ϕ)	✓ (ψ_m)
OV-10										✓ (θ, ϕ)	✓ (ψ_m)
CH-46F	AN/ASQ-105*										
CH-53D	AN/ASQ-104*										

*Self-Contained Navigation System (SCNS) ✓ Sensor exists, designation not known.

The two noteworthy exceptions to the on-board flight data limitations noted in the previous paragraph are the CH-46F and CH-53D helicopters for which advanced self-contained navigation systems (Level I of IHAS) are provided. The flight variables and associated signal format that are available for inputting to a HUD are presented in Table 3-2. The data tabulated consists of signals currently outputted within the AN/ASQ-104 system (CH-53D) and those signals for which expansion provisions are made in the system (principally the navigation computer set) to readily output.

TABLE 3-2

SIGNALS AVAILABLE FOR HUD FROM AN/ASQ-104

Signal Name	Signal Number	Format	Update Rate (to TV's)	Range	Accuracy
Smoothed Radio Altitude - $h_{r_{TV}}$	• 0-2	Digital	10(2)	0 to 1000 ft	
Smoothed Radio Altitude - $h_{r_{VSD}}$	• 0-20	Digital	10(5)	0 to 1000 ft	
Velocity Vector Elevation Angle - θ'_{TV}	• 0-7	Digital	10(5)	-45 to +45 deg	
Drift Angle - β_{TV}	• 0-8	Digital	10(5)	-180 to +180 deg	
Elevation Angle - θ_{VSD}	• 0-17	Digital	20(20)	-45 to +45 deg	
Vertical Drift Angle - ξ_{BV}	• 0-19	Digital	10(10)	-45 to +45 deg	
Drift Angle - β_{VSD}	• [illegible]	Digital	10(10)	-45 to +45 deg	
True Heading - $\psi_{T_{VSD}}$	• 0-21	Digital	10(5)	0 to 360 deg	
Lateral V-Director Command - ξ_{CH}	• 0-22	Digital	10(10)	-45 to +45 deg	
Indicated Airspeed - V_i	• [illegible]	Digital	2(2)	-50 to +250 kn	
Vertical V-Director Command - ξ_{CV}	• [illegible]	Digital	10(10)	-45 to +45 deg	
Vertical Velocity - V_v	• [illegible]	Digital	5(5)	[illegible]	
LSS Collective Command - [illegible]	• [illegible]	Digital	10(10)	-100 to +100 ft	2.5 ft
LSS Lateral Command - [illegible]	• [illegible]	Digital	10(10)	-15 to +15 deg	0.25 deg
LSS Directional Command - [illegible]	• [illegible]	Digital	10(10)	-30 to +30 deg	0.25 deg
LSS Longitudinal Command - [illegible]	• [illegible]	Digital	10(10)	-15 to +15 deg	0.25 deg
Steering Error Output 1 - e_{SE1}	[illegible]	Digital	10(10)	[illegible]	[illegible]
Steering Error Output 2 - e_{SE2}	[illegible]	Digital	10(10)	[illegible]	[illegible]

TABLE 3-2 (cont)

SIGNALS AVAILABLE FOR HUD FROM AN/ASQ-104

Signal Name	Signal Number	Format	Update Rate (to HR's)	Range	Accuracy
Roll Angle - ϕ	* 1-17	Digital	(400)	-180 to +180 deg	VG - ±1.0 deg (1σ) AJN-73 - ±13.2 min (1σ)
Elevation Angle - θ	* 1-18	Digital	(400)	-45 to +45 deg	VG - ±1.0 deg (1σ) AJN-73 - ±12 min (1σ)
Magnetic Heading - ψ_m	1-30	Digital	(400)	-180 to +180 deg	±0.33 deg
Climb Command Angle - γ_{cb}	* 1-23A	Digital		-45 to +45 deg	0.30 deg
Bearing Base, Checkpoints, Destination - ψ_B	0-Cont	Digital	10	0 to 360 deg	
True Airspeed - V_T	0-Cont	Digital	3	0 to 250 kn	
Drift Velocity - V_D	* 0-21	Digital	2(2)	-30 to +30 kn	
Heading Velocity - V_H	* 0-23	Digital	2(2)	-30 to +30 kn	
Doppler Altitude - h_D	1-6	Digital	(14.7)	0 to 3000 ft	±3% h + 2 ft (Nom)
Doppler Heading Velocity - V_{HD}	1-1	Digital	(2.7 or 30)	-30 to 250 kn	±0.2% VG + 0.2 kn
Doppler Drift Velocity - V_{DD}	1-2	Digital	(2.7 or 30)	-100 to +100 kn	±0.2% VG + 0.2 kn
Doppler Vertical Velocity - V_{VD}	1-3	Digital	(30)	-3000 to +3000 fpm	±1% V_V + 0.2% VG or 25 ft/min
Ground Speed - V_{GS}	0-Cont	Digital	2	0 to 250 kn	
Roll - ϕ	0-50	Synchro		±45 deg	±6 min (1σ)
Pitch - θ	0-52	Synchro		±45 deg	±6 min (1σ)
Ground Track - ψ_{GT}	0-Cont	Digital	10	0 to 360 deg	
Heading Velocity - V_H	0-[illegible]	DC		±50 kn	±(1% VG + 0.1 kn)
Drift Velocity - V_D	0-[illegible]	DC		±50 kn	±(1% VG + 0.2 kn)
Vertical Velocity - V_V	0-[illegible]	DC		±3000 fpm	±(1% VG +0.2% VG or 25 ft/min)
Baro Altitude - h_B	0-Cont			-1000 to 25,000	
Normal Acceleration - N_Z	* 1-7	Digital		-1.0g to +2.0g	±0.01g
Lateral Acceleration - β*	* 1-9	Digital		-1.0g to +1.0g	±0.01g

*Provision for expansion from capability Level I (SCN).

E. COMPUTED BASIC FLIGHT PARAMETERS FOR HUD

Some of the information presented in the HUD cannot be obtained directly from existing sensors. The orientation of the horizon line, which indicates attitude in the HUD, can be based directly on the output of a vertical gyro. On the other hand, flight path angle and flight director commands, which orient the flight path marker and the flight director image in the HUD, must be derived by computation from more basic information. Some of the key flight parameters which must be derived by processing other sensor data are shown in Figure 3-5. The sensor sources are shown in the blocks to the left, while the computed outputs lead to the display generator on the right.

As an example of the types of computation involved in the data processing, consider the smoothed radar and barometric attitude signal obtained by mixing radar altimeter and pressure altitude signals. Consider two successive sampled pressure altitudes $H_{P_{n-1}}$ and H_{P_n} and the associated radar altitudes $H_{R_{n-1}}$ and H_{R_n}. If, in general, ΔH_P is defined as:

$$\Delta H_P = H_P - H_R$$

then

$$\Delta H_{P_{n-1}} = H_{P_{n-1}} - H_{R_{n-1}}$$

and

$$\Delta H_{P_n} = H_{P_n} - H_{R_n}$$

A smoothed value of ΔH_P for the two samples is

$$\overline{\Delta H}_P = 0.9\left(\Delta H_{P_{n-1}} + 0.1\ \Delta H_{P_n}\right)$$

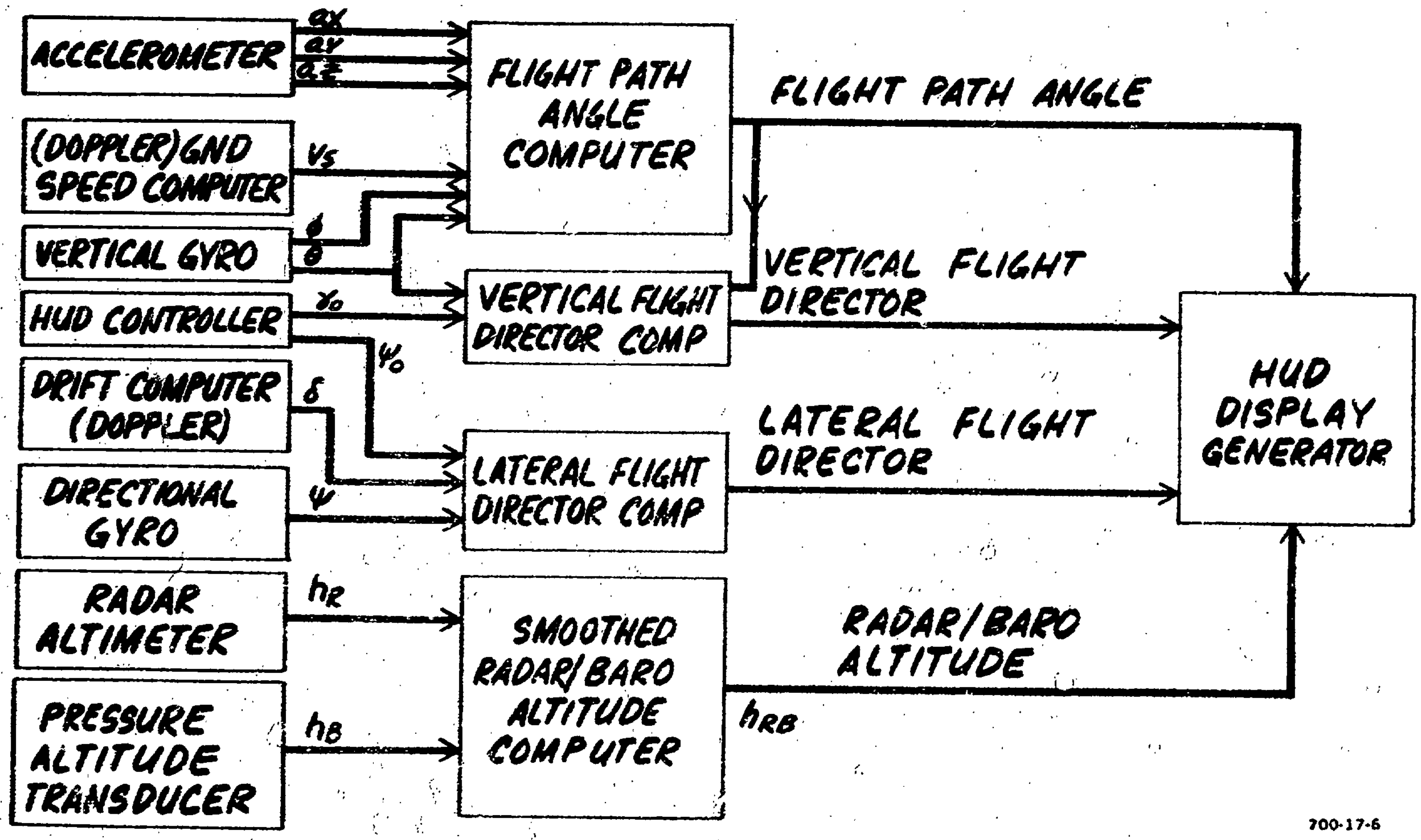


Figure 3-5
Computed Basic Flight Parameters for HUD

The associated smoothed value of radar and barometric altitude $H_{R/P}$ is then given by

$$H_{R/P} = H_{P_n} - \overline{\Delta H}_P$$

F. GROUND GUIDANCE SYSTEMS

An effort was made early in the program to uncover the currently employed systems and developmental ground guidance systems likely to be adopted by the Navy/Marines for future operations. The purpose was to ensure compatibility in HUD terminal approach operation with these aids. Many such radio guidance systems were uncovered, both operational and developmental, intended primarily to aid in remote area landing and in detecting the position of downed aircrews in SAR operations. These systems include:

- ILS - Used in standard IFR approach to base
- GCA - Used in standard IFR approach to base
- Portable Field TACAN - Used in night/IFR approaches to remote areas. However, system provides lateral directional guidance only. Vertical path control is presently conducted essentially open loop via airspeed and rate of descent from an initial point established by radar vectors from remote ground stations. A more positive, accurate means of acquiring and orienting the touchdown point, either visually or through video sensors, is indicated.
- PRC-90 UHF Radio Transceiver - Provides voice communication link and homing signals for direction finding during SAR operations.

- PRC-95 Radio Transceiver - Operates with TACAN-equipped search aircraft to pinpoint location of survivor. Provides distance measurement and bearing information.

- TALAR - Portable ILS developed by Air Force.

- RATS - Remote Area Terminal System developed by Sperry Flight Systems Division.

- ACLS - Automatic Carrier Landing System.

- STATE - Simplified Tactical Approach Terminal System developed by Honeywell for remote area landing guidance. Provides elevation and lateral deviations to aircraft for descent angles between 3 to 30 degrees. Slant range provided up to 10 nautical miles.

Other guidance aids uncovered include a hand-held laser beacon developed by Sperry Gyroscope with applicability to helicopter night operations. However, time did not permit an adequate in-depth study of all these aids as they would affect specific HUD utilization and design. Accordingly, they were treated rather generally in this study.

G. OFF-BORESIGHT, STABILIZED AIMSIGHT CONCEPT

1. General Requirements and Implementation Approach

One of the more compelling optical display requirements established in this study for tactical helicopters reflects the use of a small field, moveable aimsight for use in visual acquisition and/or tracking of ground targets. Conceptually, the directional sight is a generally well understood device having been applied in military aircraft for some time including helicopter gunships. In its simplest form, the sight projects a fixed, collimated reticle image, which the operator manually positions to overlay a ground target, either instantaneously or continuously. In helicopter applications, this motion generally covers a wide range of azimuth and elevation angles. The angular orientation of the reticle line-of-sight, relative to aircraft axes, is directly sensed through appropriate pickoffs.

There are two basic approaches to aimsight design: a hand-gripped unit and a helmet sight. These designs and the relative merits of each are described in Section V. Either type unit can, if properly designed, be used to implement the acquisition and tracking requirements established in this study. Accordingly, the system concepts described in this paragraph and Paragraph H of this section are applicable to both designs.

Characteristically, helicopter-installed aimsights are used to direct off-boresight firing of gun turrets via a ballistics lead computer. In addition, aimsights have been employed in the AH-56 helicopter and certain fixed-wing, hunter aircraft to control the position of a radar and laser range finder toward the sighted target. Such ranging devices, however, are lacking in every Navy operational helicopter as evidenced by the sensor complement summary presented in Paragraph D of this section. This deficiency poses a number of operational problems and otherwise limits the effectiveness of certain key helicopter missions. To alleviate these problems, therefore, a number of kinematic targeting techniques, by which range and other offset target orientation data are computed from aimsight-derived angle data and certain flight variables, have been conceived. These kinematic targeting systems and the specific helicopter operations for which they apply are described in Paragraph D of this section.

Helicopters are inherently well suited in accommodating effective use of hand-gripped aimsights. All Navy/Marine helicopters provide for a two-man cockpit crew, of which the copilot/gunner is relatively unburdened and has considerable latitude to make frequent and effective use of the aimsight. In terms of space accommodation, the relatively large cockpit and absence of cockpit ejection associated with all helicopters negates any serious installation difficulty for the hand-held sight. Helmet-mounted sights, of course, can readily be accommodated in helicopters and fixed-wing aircraft. In fact, they constitute the only practical means at present for off-boresight acquisition in single-place tactical aircraft.

A preliminary layout design of a hand-held aimsight is presented in Section V. The unit features a servo-driven, rather than fixed, reticle to enable earth stabilization of the reticle image in accordance with the requirements for such stabilization described in Paragraph G.2. of this section.

Implicit in any projected reticle aimsight, of course, is the visual nature of its application. However, the operational and technical feasibility of extending aimsight utilization to the aided-visual display of IR/LLLTV pictorial video during night combat operations is discussed in Appendix E. These video sensors are under active consideration for near-future introduction into a number of helicopters. The presentation of raster scan video would logically be accommodated by substituting a miniature CRT for the two reticle servos otherwise required for strictly visual operations.

2. Aimsight Stabilization

a. Basis of Requirement

Attitude stabilization of aim reticles or other real-world-related symbols is generally acknowledged to be a highly desirable, if not necessary, feature of HUD. In the case of aimsights, it enhances acquisition and tracking performance by eliminating from the operator the burden of filtering the adverse effects of short term vehicle disturbances. The effectiveness of such stabilization to cancel the effects of attitude motion has been clearly demonstrated in weapon delivery displays (both head-up and panel mounted) employed in fixed-wing aircraft. However, before recommending costly stabilization for off-boresight aimsights in helicopters and undertaking the task of deriving the associated equations, investigations were first conducted to establish a reasonable or compelling need for incorporating this function in the aimsight design.

These studies revealed that high frequency attitude and translational motion effects as induced by wind gust, vehicle control inputs for maneuver and trim adjustment, and other atmospheric disturbances are no less severe for helicopters as is the case for fixed-wing aircraft. For example, flight tests conducted by Sperry Flight Systems Division on an H-3 helicopter yielded typical responses of ±2.0 degrees in pitch and roll to 20- to 25-knot wind gusts with attitude hold disengaged as would be the case in maneuver flight. Somewhat larger transients of about ±4.0 degrees were encountered in yaw under the same wind and disengaged autopilot conditions, because of the tendency of helicopters to rotate into the wind. Characteristically, oscillation levels in helicopters are roughly the same in any given axis over the entire speed regime - from hover to maximum. In the case of constant path flight with attitude hold engaged, Sperry flight tests yielded somewhat improved damping in the attitude response to gusts with amplitudes approximately one-half that incurred without attitude hold. In either case, the amplitudes and associated natural frequency of oscillations are both sufficiently large to suggest that aiming or tracking performance with an unstabilized optical sight is poor.

Even under the most ideal conditions of constant speed, straight and level flight in smooth air, and three-axis attitude hold engaged, CH-53 flight test data supplied by NATC indicates perturbations of about 0.2 degree rms in pitch and yaw and 0.5 degree rms in roll, with peak excursions of between 2 to 3 times these values. Significant translational effects are also experienced in helicopters as in fixed-wing aircraft, particularly with respect to vertical velocity response during wind shear transition. However, because of their relatively low incidence of occurrence, display stabilization for these transients, although relatively simple in its implementation, is not recommended.

Interviews conducted with several helicopter pilot/gunners confirmed the anticipated difficulties of visually locking an unstabilized gunsight reticle onto a ground target - both with a fixed, boresight projector and swiveable off-boresight aimsight. This problem is discussed more fully in Subsection IV.H. It is more acute for the more demanding task of continuous tracking of a ground target under maneuver conditions than it is for one-shot, single-point acquisitions.

b. Coordinate Conversion Equations Required for Stabilization

The stabilization of an off-boresight aimsight, the optical center (line of sight) of which is manually positioned in yaw and elevation relative to aircraft axes, presents a significantly more complex function than that associated with more conventional, boresight-oriented, HUD projectors. The optical axis of the latter unit is generally fixed in its installation and always lies in the X-Z plane of the vehicle. Thus, whereas relatively simple coordinate transformation relationships exist for stabilizing a symbol in fixed projectors, the stabilization of an off-boresight aimsight projection poses a wholely different situation and a more formidable mathematical problem.

In fact, it is clear from the transformation equations derived in this study that effective off-boresight reticle stabilization by means of computer solution would be impractical were it not for the advent of efficient, small scale avionic digital computers. The only known practical technique previously devised and first employed in bomber aircraft during World War II was to piggyback mount the optical sight onto a vertical gyro. This mechanization approach is rather cumbersome, however, and reflects a brute-force solution to the problem.

This approach has a number of deficiencies when compared to a digital computer implementation approach in the current state of the art; these deficiencies include larger weight and size which adversely affect cockpit installation and operability of the unit. Verticality accuracy of the gyro mount design, unless extensively compensated for drift, is significantly less than that provided by advanced AHRS, and will very likely prove to be unacceptable under maneuver conditions. Relative cost is an unknown factor requiring detailed analyses. However, preliminary indications are that the costs are comparable if it is assumed that the stabilization functions are processed in an existing computer provided for other purposes. Perhaps the most serious shortcoming of the gyro mount approach is the unavoidable tendency of the operator to inadvertently jerk the hand-held aimsight as a result of body motion caused by sudden aircraft transients and maneuvers.

In electing to pursue the computer solution approach, a search of the literature failed to produce any previously developed coordinate conversion equations that relate attitude motion to appropriate earth stabilization signals for the aim reticle. Accordingly, the desired equations were derived (Appendix A) as part of this study. These equations are believed to be unique in their solution and application, since no published evidence has been uncovered as to their actual or proposed implementation in air and surface craft.

The equations derived in Appendix A are predicated on the sampled data stabilization loop design described in Subsection III.H.2.c. Five expressions, which are ultimately yielded, transform incremental attitude changes in each of the three aircraft axes to X-Y displacements of the aim reticle from the central Line-Of-Sight (LOS) axis of the optical sight. The processing of these compensating signals via a computer forms part of a minor feedback loop of the overall tracking system. The X-Y aimsight axes noted above are fixed and orthogonal to the optical centerline, irrespective of the means employed to generate and display the aiming symbol (i.e., CRT or servoed reticle). The stabilization formulae derived also assume an aimsight gimbal arrangement with azimuth rotation about the Z-axis of the vehicle and elevation rotation in a plane which contains the selected azimuth and is perpendicular to the X-Y lateral plane of the vehicle. The line-of-sight, of course, by virtue of its cockpit installation, is assumed to be oriented within a spherical sector centered about the longitudinal axis and ahead of the aircraft. The equations derived do not constrain the size of the sector although the visual cutoff angles of cockpit windows would establish practical operational bounds.

The use of sampled, incremental changes or perturbations in attitude for computing the stabilization data contrasts with the stabilization functions employed in fixed, boresight-oriented HUD where absolute values of attitude are the relevant independent variables. The latter holds because the aircraft boresight, about which coordinate transformations are made, is located within the display field. Hence, within the boundaries of the display field of view, a continuous system exists in which earth-oriented symbols are linearly related to the aircraft axes as a function of pitch, roll, relative bearing (sometimes referred to as heading error) and elevation angles.

The aimsight stabilization concept and associated equations advanced in this section are not to be confused with another, well understood form of LOS stabilization which transforms the two LOS orientation angles from vehicle to stable earth coordinates. This latter stabilization function is also recommended for a number of helicopter aimsight applications (Appendix B).

To ascertain the practicality of a computer solution for aimsight stabilization, a preliminary programming analysis is contained in Appendix D in which several avionic computer models were used to estimate time and memory space requirements. The results indicate that the implementation of this function is well within the time capacity of current, high speed machines to perform in conjunction with other possibly required functions such as symbol generation for a fixed HUD projector, kinematic targeting solutions, and simple fire control ballistics equations.

c. Operation, Loop Dynamics and Stability Considerations

The basic operation and loop dynamics of a unique, visual acquisition and tracking system recommended for a number of helicopter applications are described in this subsection. To assist in the understanding of an important new filter concept for improved stability of the system, it is useful to first examine the three most common operational methods of utilizing a stabilized aim circle in airborne HUD.

(1) In a fixed, boresighted optical projector, where the aim symbol is automatically and continuously locked-on to a ground target from position data derived either from ground guidance (e.g., ILS) or from self-contained, on-board systems (e.g., radar/inertial navigation or Doppler/kinematic ranging). In this case, the symbol is stabilized over the entire frequency bandwidth of attitude motion - from zero to maximum.

(2) In a fixed, boresighted optical projector, where the aim symbol is positioned by either fixed elevation and azimuth angles in earth coordinates or in the case of gun and rocket weapon delivery, by computed quantities representing an impact-point position on the ground. In this case, the pilot typically controls the vehicle path to overlay the symbol onto the ground object of interest - either for instantaneous acquisition or continuous tracking. Since the helicopter response of relative

aircraft-to-target angular position to attitude oscillations is virtually zero over the entire range of sinusoidal frequencies, full attitude compensation is required as in the case in Paragraph c.(1).

(3) In a moveable, off-boresight projector, the aim symbol is nominally positioned at the optical center and is correlated to the real world only through the sighting action of the copilot. In this case, the copilot acquires and/or tracks the target of interest independent of the pilot's control of vehicle path. Since the copilot cannot distinguish between the effects of vehicle-to-target relative motion and vehicle attitude changes on symbol position, only the high frequency components of attitude (above the response cutoff of the human operator) can be used in automatically stabilizing the aim symbol.

The frequency separation concept noted above for the aimsight yields a distortionless mixing of complementary signals. This concept, which is sometimes referred to as "dual period filtering" in multi-input control systems, is intended to optimize the performance and stability of the tracking loop. As conceived, the filtering would consist of simple, high-pass, lead networks to which the three attitude variables would be applied (Figure 3-6). With the real world target as the reference, the primary loop comprises the human operator and the aimsight itself, with the position of the reticle symbol representing the primary feedback signal. A second feedback loop provides the attitude stabilization function. It is essentially comprised of a digital computer that operates on the filtered attitude data and yaw/elevation angular positions of the optical boresight to calculate the ΔX, ΔY reticle

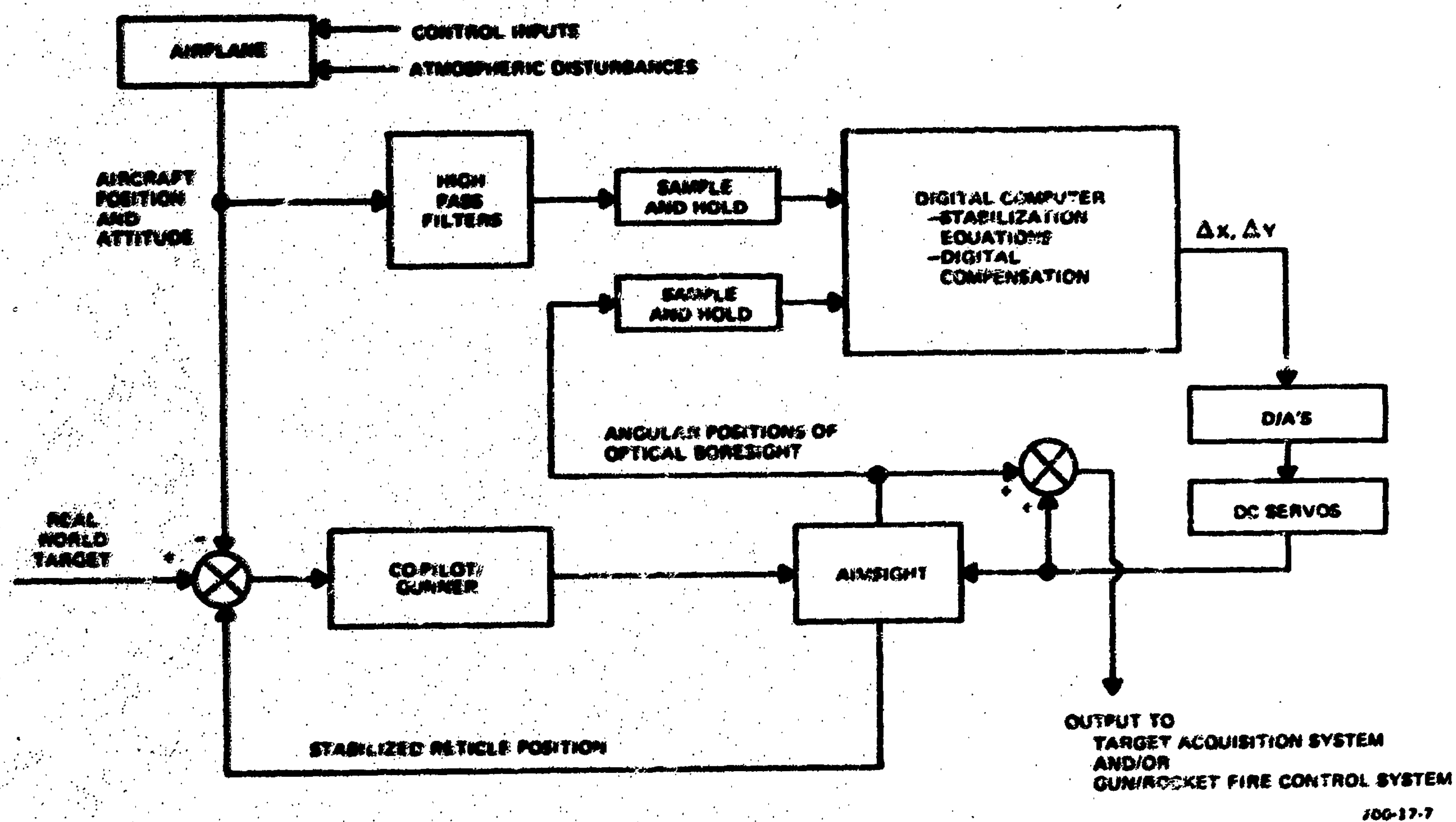


Figure 3-6
Aimsight Reticle Stabilization - Simplified Block Diagram

displacement signals in accordance with the equations noted earlier in this subsection. The computer output interface would typically include appropriate data registers, digital-to-analog converters, and driving servos for positioning the reticle. No attempt was made in this study to recommend a specific detailed design of the input/output computer interface, since the optimum design depends on detailed cost and performance analyses and on loop stability considerations affecting the various block transfer functions. For the output interface, for example, many implementation forms are deemed possible, including the use of direct, non-linear digital servos. However, from preliminary analyses, it is considered likely that the dc linear servo approach noted in Figure 3-6 will prove to be the lowest cost approach most amenable to the requirements for jitter-free symbol motion and provision for sharp attenuation at cutoff discussed later in this paragraph.

Operationally, aimsights inherently lend themselves to close-in monocular viewing. A small field of view is permitted by virtue of the tracking nature of the operation. For helicopter applications, a 2-3/8-inch aperture with ±5-1/2 degrees reticle motion in X, Y is recommended as the best tradeoff satisfying such characteristics as viewing distance, size constraints, and peak excursions of high frequency attitude transients. The aim circle, of course, is limited at the field extremities so that it is always in view. Additionally, while the aimsight is designed for monocular viewing, the operator's other eye is sighting on the real world outside of the optical field and therefore could pick up the target if it were to move beyond the display field, such as may result with a large, rapid change in attitude during a maneuver. In such an event, the operator would adjust his aimsight accordingly to re-acquire the target within the display field.

During tracking, the operator's task at all times is to overlay the aim reticle over the target, irrespective of the relative position of the reticle to the optical boresight center. Consistent with this action by the operator, the high pass filter in attenuating or "washing out" the low frequency components (including the average dc value) of attitude aligns the reticle to the optical center axis under steady-state conditions. The effect of both these actions is shown in Figure 3-7. To assist in understanding the system, a simplifying assumption is made here that the vehicle-to-target position orientation is constant (e.g., vehicle is motionless or in a steady-state turn with the target at the center of turn). Four display sequence of events (A, B, C, D) are shown where each display is properly oriented vertically with respect to the real world target. In the original situation (Point-A), steady-state tracking conditions prevail where the pilot is maintaining the aim circle on the target at the optical center of the field. At Point-B, a step function transient in roll angle is assumed to occur where the sighthead center is displaced with the vehicle and the aim reticle automatically displaced from the optical boresight to remain superimposed on the target. Point-C (a short time later) depicts the simultaneous effects of the high pass filter in slowly moving the aim circle back toward the optical center and the operator adjusting the aim-sight assembly downward so as to continue to overlay the aim circle on the target. At Point-D, the process of Point-C is completed - the aim circle, optical boresight and target are restored to the original desired condition of Point-A, but under a new set of steady-state attitude conditions.

This automatic centering example illustrates, by simple intuitive analysis in the time domain, what a stability analysis in the frequency domain would conclude; namely, that the lead networks enhance loop stability. Without the filter in the example, the aim circle after being initially displaced would have instantaneously been repositioned to the optical center and off the target until the operator responded to re-acquire the target. To augment this example for a high frequency transient, consider the case of a very low frequency attitude oscillation such as may occur with a natural phugoid longitudinal oscillation

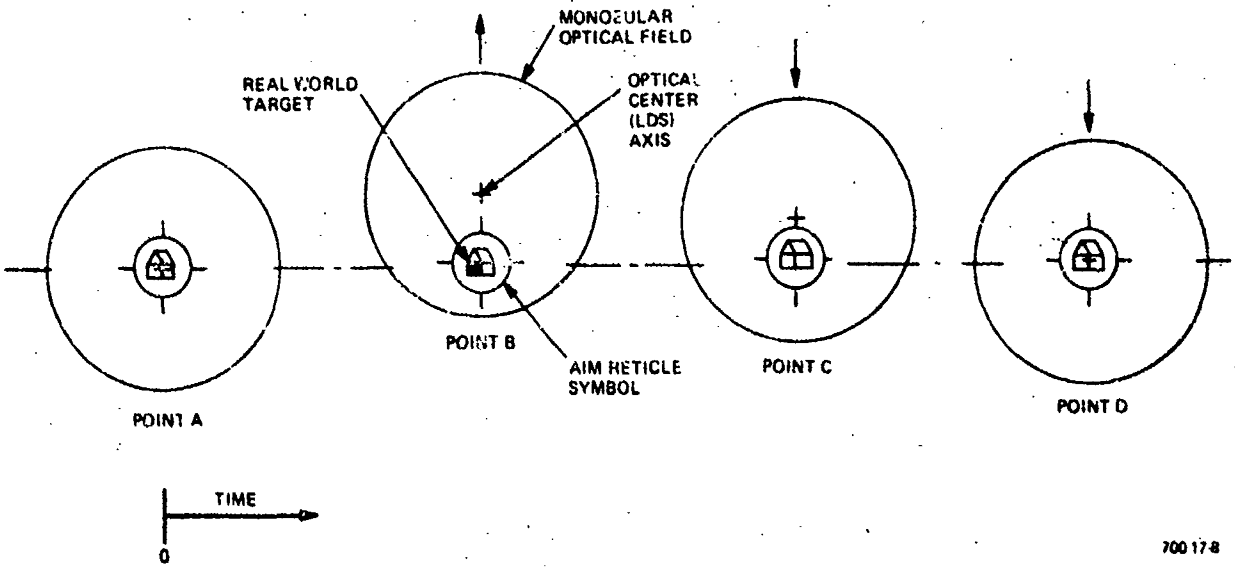


Figure 3-7
Effect of Attitude Filtering on Visual Target Tracking
with Stabilized Aimsight

at typically 0.1 radian per second in a STOL aircraft. In this case, the pitch signal is highly attenuated resulting in negligible automatic compensation. The operator manually tracks this oscillation himself since its frequency is well within his response ability.

There are two basic modes of stabilized aimsight operation involving different data outputting requirements. The first comprises continuous tracking for fire control of gun turrets, where the turret is essentially slaved to the aim reticle. In this mode, the aim reticle position data, which is transmitted to the gun turret servos via a lead computer, is oriented in aircraft axes. Hence, no further conversion processing is required. The second mode involves discrete or continuous acquisition for target and own-aircraft orientation purposes. In this case, the aim reticle position is first converted from aircraft-to-earth-stable coordinates before application to the computer. In both cases, the reticle position is represented by the algebraic sum of the angular positions of the aimsight center axis and the ΔX, ΔY displacements of the reticle from this axis.

No effort was made in this study to conduct a rigorous stability analysis of this non-linear tracking system. Such an analysis, of course, is required to establish the dynamic design of the system including the specific digital compensation, if any, to be incorporated in the computer. However, the following system parameters were briefly considered as a useful prelude to any final system design and stability analysis effort.

- Attitude High Pass Filter - The design of this filter is essentially dependent on the transfer function established for the operator. The human transfer function includes a reaction time delay (transport lag), dynamic compensation characteristics, and neuromuscular lag (Reference 2). The gains and time constants to be established for each of these functions depends on the specific tracking operation involved. Of specific interest in the lead network design is the break frequency at unity amplitude ratio and the attenuation versus frequency slope (or slopes if a second, lower break frequency is incorporated). Based on the simplifying assumption that an operator can track a 1/3-Hz sinusoid with acceptable phase lag, it would appear that the upper break frequency of the network does not exceed 2 radians per second, with 1.5 radians per second considered to be a reasonable value.

- Helicopter Natural Frequencies - An important system design parameter is the frequency bandpass of attitude information to be processed. This relates directly to the short-period, natural frequencies of the aircraft and the associated attenuation characteristics in three frequency regions. For example, the short-period, natural frequencies and damping factors for an H-3 helicopter equipped with a Sperry Hover Augmentation System (HAS) are approximately as follows:

  Pitch - $\omega_n \cong 3.5$ rad/sec, $\zeta \cong 0.6$

  Roll - $\omega_n \cong 5.0$ rad/sec, $\zeta \cong 0.5$

  Yaw - $\omega_n \cong 4.5$ rad/sec (with heading hold), $\zeta \cong 0.5$

  Each dynamic element of the attitude compensation loop must be designed to preserve the fidelity of all relevant attitude frequencies. For the H-3 example cited above, the range of frequencies to be passed is estimated to be from 0 to 5.0 radians per second for pitch, and 0 to 6.5 radians per second for roll and yaw.

- <u>Processor Sampling Rate</u> - In establishing sampling rates for non-linear systems containing digital computers, tradeoffs are usually conducted between system accuracy/stability performance and computer cost/time. Since sampling rates of 10 times the maximum signal frequency of interest are commonly used, this ratio was selected for use in the computer programming analyses of Appendix D, yielding a sampling frequency of

$$6.5 \text{ radians/second} \times \frac{1 \text{ cycle}}{2\pi \text{ radians}} \times 10 \cong 10 \text{ samples/second}$$

- <u>Low Pass Output</u> - Experience in digital loop design indicates a need for a low pass function at the computer output - either independent or part of the positioning servos. For the example noted in the preceding paragraph, the response break should occur at about twice the 6.5-radians-per-second signal frequency or about 2.0 Hz. Ideally, the attenuation slope should be quite sharp - at least -40 decibels per decade. This low pass cutoff enhances system stability by filtering signal noise and smoothing the ripple frequency of the outputted data caused by data sampling.

H. KINEMATIC TARGETING TECHNIQUES

1. Discussion of Concept and Requirements

It is clear from the tabulations presented in Tables 3-1 and 3-2 that the avionic complements of operational helicopters are relatively limited when compared to advanced, fixed-wing tactical aircraft. In particular, range sensors are notably absent in all helicopters. Although the lack of radar and laser range sensors is understandable in terms of their high cost and weight, it nevertheless has limited the effectiveness of certain helicopter missions. This limitation assumes the following basic forms.

- Deficiency in the accuracy of the predicted impact point in gun and rocket fire control because of estimated nature of slant range data. Flight tests conducted by the Army in helicopter air-to-ground range estimation confirmed the severity of the problem (Reference 1).

- Inability of the helicopter system to acquire and continuously orient the vehicle to a ground target* in three dimensions.

In pursuing this HUD study, several low cost optical sighting techniques were considered as possible solutions to the range measurement problem. Stadiometic ranging is one such well known method, but was judged to be impractical for helicopter operations because target sizes are generally unknown in preflight planning. Optical range finders constitute another technique; however, these range finders are difficult to install and provide only limited utility. They are not only constrained in directivity, but assuming a boresight-oriented installation, cannot be effectively used when the vehicle is headed straight in toward a target at a high closing range rate.

The most practical method conceived for deriving target range and orientation data uses an optical HUD projector(s) as part of what are termed "kinematic targeting" systems. Kinematic targeting is not an altogether unfamiliar concept. Having been applied before in military aircraft. However, some of the systems and operational techniques advanced in subsequent paragraphs are believed to be of a novel nature,

*The term "target" as used herein denotes any ground object of interest, including enemy targets.

made possible by the capabilities of modern digital computers. These systems involve the use of the acquisition and designation criteria discussed in Subsection III.C.

Basically, these systems use triangulation methods to initially derive and store the desired range and/or orientation data at some point in flight. This is immediately followed by a continuous updating of the derived variables as the aircraft proceeds in its flight. Either the target or own-aircraft may be oriented in absolute earth coordinates given the position of the other. Alternately, relative orientation may be derived in terms of range/bearing/altitude. The system operates on two-axis, LOS angle data, ground referenced flight velocity data, and altitude stabilization data to effect a computer solution of one or more triangles. A HUD optical projector (either fixed or moveable aimsight type) is used to obtain the LOS angle data through visual acquisition of the target. Velocity data is required to derive the distance traversed after each point of acquisition. Doppler radars represent the most practical source for this data because of their extensive application in helicopter navigation and flight control systems. Three-axis attitude data, required for coordinate transformation and aim circle stabilization purposes, is most practically supplied by an AHRS of reasonably high performance (i.e., 1/2 degree, 2-sigma verticality accuracy under dynamic maneuver conditions).

Although no operational helicopter currently contains equipment providing such performance (including the ASN-50, ASN-73 AHRS incorporated in Self-Contained Navigation System - SCNS), the retrofit of an AHRS of advanced design as a substitute to the presently installed AHRS or separate VG/DG's does not appear to be too costly. Several companies are known to be developing a next-generation, two-gyro AHRS characterized by high performance and low cost. The last element required in the kinematic targeting systems is a small-scale, digital computer to execute solutions of the aim circle stabilization, coordinate transformation and triangle geometry equations. Such a computer can be implemented either separately or as an integral part of the HUD processor. The feasibility of the latter integrated approach, which has been confirmed by the programming analyses of Appendix D, is accordingly recommended because of its minimum cost advantage.

A kinematic targeting system, as roughly outlined in the preceding paragraphs, compares quite favorably in cost to systems employing narrow-beam radar and lasers for direct range sensing. This assumes, however, the prior existence of a Doppler radar in the vehicle to be equipped with the kinematic targeting system. The opitcal sighting unit and a high performance AHRS element have no impact on relative cost, since they are required in both ranging systems. This leaves, for comparison, the cost of a radar and laser sensor against that of the additional memory and other hardware required in the HUD processor to implement a kinematic ranging solution. Indications are strong that the latter approach is appreciably cheaper; however, this lower cost must ultimately be traded off against the superior performance and operability of a direct sensing ranger.

A rigorous accuracy analysis was not attempted in this study on any of the kinematic targeting systems conceived. Such a task was deemed too formidable because of the multitude of different sensors (and associated accuracies) that exist among the various helicopters considered. Furthermore, any meaningful accuracy analysis must reflect equipment accuracies achieved under actual flight conditions, and not necessarily the specified values. In addition, since the precision of visual acquisition has a significant impact on overall accuracy, simulation testing using the stabilized aimsight concept described in Subsection III.G is deemed to be a necessary first step in obtaining this accuracy data. However, a cursory error analysis was conducted for two hypothesized flight conditions in which all error contributions were conservatively established. As indicated by the results, acceptable accuracy performance can be realized, which on a statistical basis would far exceed that afforded by simple estimation. In addition, what was intuitively obvious (i.e., that the accuracy of attitude and heading data supplied by the AHRS is far more critical than any errors incurred in Doppler-generated ground velocity) was confirmed.

Five basic kinematic targeting techniques, each of which is appropriately recommended for various operational flight modes and tactical situations, are described in Subsections III.H.3 and III.H.7. These techniques involve the mandatory or optional use of a stabilized aimsight device described in Subsection III.G. This implies the existence of short time periods during which the aimsight stabilization equations of Appendix A would undergo continuous computer solution (as in the case of gun turret firing on a continuously tracked target), concurrent with the solution of the kinematic target ranging and orientation equations. The targeting schemes presented in Subsections III.H.3, III.H.6 and III.H.7 enable the optional use of a conventional, fixed HUD projector on which a suitable aim circle is displayed for acquisition purposes. In this case, earth stabilization of the aim circle reflects attitude-dependent functions that have been extensively applied in past HUD designs and are much simpler than those associated with off-boresight, aimsight stabilization.

All the kinematic targeting systems and equations conceived, which involve the use of the moveable aimsight, are applicable to aided-visual sensor operations under night/IFR conditions, as well as under day/VFR conditions. This application can be accomplished by displaying the IR/LLLTV pictorial video on the aimsight to enable the desired target detection and acquisition. This concept is discussed more fully in Appendix E. The only requirement for achieving a common set of system equations and compatible operation between visual and aided-visual modes is that the video scan presentations be unstabilized, i.e., the video sensor LOS be slaved to the aimsight central optical axis so that the projected video image is properly superimposed onto the real world in a one-to-one relationship.

2. Application in Helicopter Operations

The need for an acquisition system that enables ground target and own-aircraft orientation has been established for the following helicopter operations. Some of these operations are current; whereas, others are proposed for future introduction in helicopter systems.

- Target Orientation (Relative to continuously updated aircraft position)

  Air-to-ground fire control
  Remote area landing
  Downed airman rescue
  Hunter/killer
  Special stores drop
  Air-to-ground bomb delivery

- Own-Aircraft Orientation

  Enroute navigation
  Paradrop
  Mine sweeping

Five basic end purposes are associated with the target and own-aircraft orientation functions to be applied in these helicopter operations.

- Acquisition and retention of targets susceptible to loss of visual contact
- Designation of acquired target to other aircraft
- Own-aircraft geographic position update

- Derivation of target range and altitude for fire control ballistics computation
- Derivation of optimal, two-axis steering guidance to target for presentation to pilot.

The ability to execute these functions either improves the reliability of the associated operation, or extends the present capability of the helicopter system. As an example supporting this conclusion, consider the first objective listed above relating the possible loss of visual contact of a target. The importance of this problem, and the need for a solution, is best exemplified by some of the tactical situations experienced in Vietnam. Often, target detection characteristics are such that the ability to immediately acquire and store a target can often spell the difference between success or failure of an operation. Such marginal visual targets fall into two general classes:

- Targets which are of a momentary or discontinuous visual nature as may be caused by

  Flashing lights

  Occlusion of target by rough or dense terrain features at different points in flight (e.g., personnel and small clearings)

  Small movements of enemy targets in dense terrain to escape detection subsequent to initial sighting

  Mixed IFR/VFR (flight into sporadic cloud or fog formations)

- Targets that remain available usually, but are difficult to discriminate continuously (hence susceptible to detection loss after initial sighting) because of

  Small size (e.g., downed airman on land or sea)

  Low ambient illumination (e.g., VFR at dusk or night)

  Poor target contrast relative to terrain or water background

Most of these adverse target conditions relate to day/VFR operations in which targets are detected by direct visual means. Only the mixed IFR/VFR and the low illumination conditions are amenable to improved target detection capability with IR/LLLTV aided-visual means.

3. <u>Offset, Two-Axis, Single-Plane Targeting Solution (Discrete Acquisition Method)</u>

One effective method of kinematic ranging or full targeting involves two discrete visual acquisitions while the aircraft is flown toward the target along a straight ground track passing through the target. This approach is recommended for situations where:

- Terrain is sufficiently rough to preclude the use of directly sensed absolute altitude above the ground.

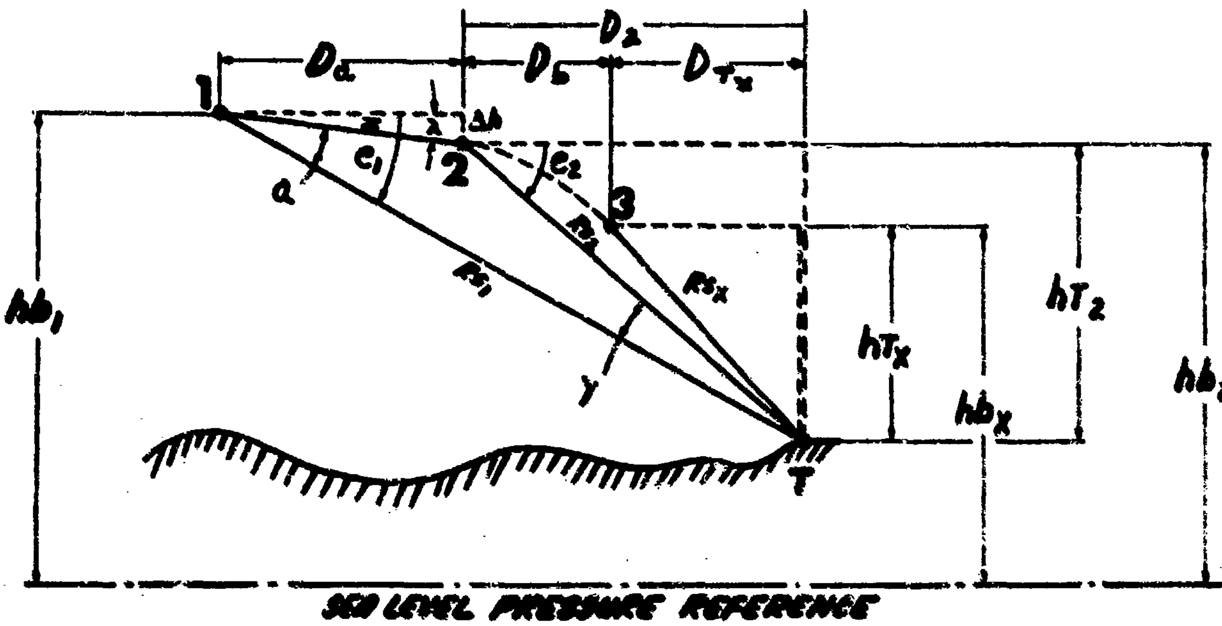
- Target location is predetermined or clearly observable at a distance allowing pilot to plan and execute an immediate straight-in approach toward the target, thereby minimizing exposure time to enemy fire.

- Pilot is limited to this technique, involving the use of a fixed-HUD projector, because an off-boresight aim-sight is unavailable to copilot for offset targeting.

By controlling the aircraft on a straightline course through the target between visual sightings, the principal condition is satisfied for the solution of an oblique triangle located in a vertical plane perpendicular to the earth's local horizontal. The geometry of this kinematic problem is shown in Figure 3-8. This two-axis solution represents a special case of the general off-boresight, three-axis solution described in Subsection III.H.4, and, as such, comprises a simpler set of calculations. The equations to be solved are derived in Appendix B. Preliminary programming analyses relating to computer implementation of these equations are contained in Appendix D.

Visual acquisition of target (T) is made at Positions 1 and 2 in the aircraft trajectory by means of a stabilized projected aim circle (Figure 3-8). With each "pickling", the depression angles (e_1, e_2) and barometric altitude (hb_1, hb_2) are sampled and stored. In addition, time integration of Doppler-derived ground speed is initiated at Position 1 yielding the distance traversed (D_a) at Position 2. During flight between Positions 1 and 2, the pilot has the freedom to establish any vertical path profile he desires. The only vertical path variable affecting the solution is any resulting change in altitude (Δh).

Immediately upon execution of the second acquisition, slant range (RS_2) and target altitude (hT_2) from Position 2 to the target are derived via the once-only solution of triangle (1, 2, T). Subsequent update processing to be performed as the aircraft continues its flight depends on the tactical operation involved and the specific data required. In the case of gun and rocket fire control, only target altitude (hT_x) or slant range (RS_x) associated with present position (Position 3 in Figure 3-8) is required for ballistic prediction. The aircraft trajectory after acquisition has no constraints in its vertical profile, but laterally is assumed to adhere to the previously established straightline course to the target. However, other operations such as search and rescue may require full three-dimensional target orientation to enable additional



POSITION 1 – POINT OF FIRST VISUAL ACQUISITION

POSITION 2 – POINT OF SECOND VISUAL ACQUISITION

POSITION 3 – AIRCRAFT PRESENT POSITION

POSITION T – TARGET LOCATION

COMPUTED VARIABLES (REFER TO APPENDIX B FOR DERIVATION)

- ***ALTITUDE ABOVE TARGET (h_{tx})***
- ***SLANT RANGE TO TARGET (R_{sx})***

Figure 3-8
Offset, Two-Axis Kinematic Targeting Geometry
(Discrete Acquisition Method)

go-around maneuvering before completion of the flight operation. This orientation can be expressed in any one of several possible horizontal coordinate systems such as polar (range, bearing), Cartesian (Army grid), or geographic (latitude, longitude). The vertical dimension in all cases would be represented by absolute altitude. Equations defining this three-dimensional orientation for subsequent off-course maneuvering are presented in Appendix B as part of the general, three-axis kinematic targeting technique described in Subsection III.H.4.

A rigorous accuracy analysis was not attempted in this study on any of the kinematic targeting designs conceived. A limited analysis, however, was made on one error effect associated with the two-axis solution approach but not incurred in the general three-axis solution described in Subsection III.H.4. This error relates to the constraint imposed by the solution for constant course flight between the two visual acquisitions. The analysis indicates that for most practical altitude and range approach conditions, accuracy of the computed target altitude and range is largely impervious to expected lateral positional deviations from the required straightline ground track. For example, for one reasonable set of acquisition geometry conditions examined, a deviation drift of 3 degrees results in a rather small 0.2-percent error in computed slant range. Such lateral path performance over relatively short distances is deemed to be within the abilities of experienced helicopter pilots to achieve with visual tracking control of the instantaneous velocity vector in azimuth, suitably stabilized in heading.

An optical display design that enables the pilot to simultaneously perform the acquisition and flight control functions is described in Subsection IV.H. A fully earth stabilized aim circle is recommended to ease the acquisition and control tasks, not only during attitude transients, but in flight conditions where a standoff roll attitude bias is maintained during straight-ahead flight and when small, banked turn corrections are made to align the velocity vector onto the target.

4. Offset, Three-Axis, Two-Plane Targeting Solution (Discrete Acquisition Method)

The most versatile technique conceived for kinematic targeting, free of any impositions on operational techniques and tactical conditions, uses two discrete off-boresight visual acquisitions of the ground target. The geometric relationship of this approach involves the solution of two orthogonal triangles oriented in the three earth coordinates.

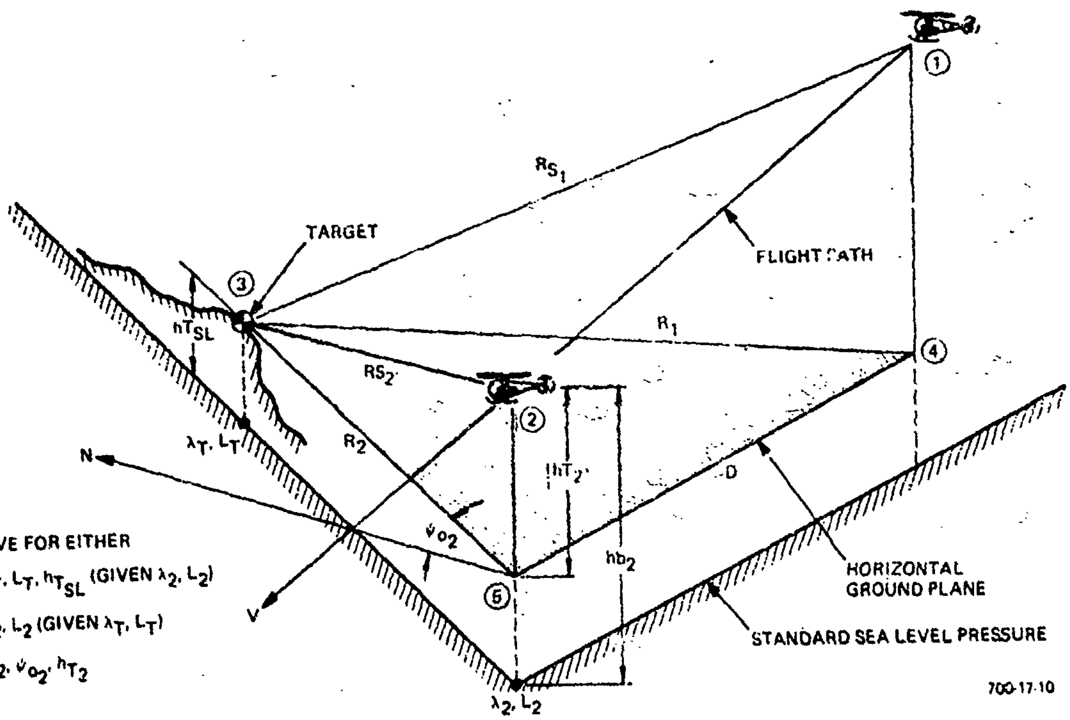
Whereas the two-axis kinematic solution described in Subsection III.H.3 uses a fixed, on-boresight projector, the three-axis solution necessitates the use of an aimsight. Two basic orientation modes of interest are associated with three-axis kinematic solutions; namely,

- Own-aircraft orientation where the sensed aircraft position is updated from known coordinates of the memory point.

- Target orientation where the absolute coordinates of a target are computed from a known position of the own-aircraft.

As a correlated extension of target orientation, relative coordinates in terms of range, bearing and altitude above the target may be continuously computed either directly from, or independent of, absolute target coordinates. The equations defining these three orientation modes are derived in Appendix B. Preliminary programming analyses relating to computer implementation of these equations are contained in Appendix D.

A simple representation of the flight geometry is shown in Figure 3-9. Visual acquisitions are made at Points 1 and 2 from which earth-oriented depression and relative bearing angles are derived. In addition, the horizontal distance (D) between Points 1 and 2 is derived from Doppler-generated ground speed data. Generally speaking, there is



SOLVE FOR EITHER

$\lambda_T, L_T, h_{T_{SL}}$ (GIVEN λ_2, L_2)

λ_2, L_2 (GIVEN λ_T, L_T)

R_2, ψ_{o_2}, h_{T_2}

Figure 3-9
Offset, Three-Axis Kinematic Targeting Geometry
(Discrete Acquisition Method)

no restriction in either the horizontal and vertical flight paths between the two acquisition points, although as a practical matter a straightline course is likely to be followed. Immediately upon execution of the second acquisition, horizontal range (R_2), bearing ($\psi\sigma_2$), and altitude above target (hT_2) are computed from triangles (3, 4, 5) and (2, 3, 5) and stored. From this data, one of the following is subsequently performed:

- Aircraft latitude (λ_2) and longitude (L_2) at Point 2 are computed and the on-board navigation system updated.

- Target latitude (λ_T), longitude (L_T), and elevation above standard sea level (hT_{SL}) are computed and stored.

- Range, bearing and altitude above target are continuously computed as the aircraft continues its flight.

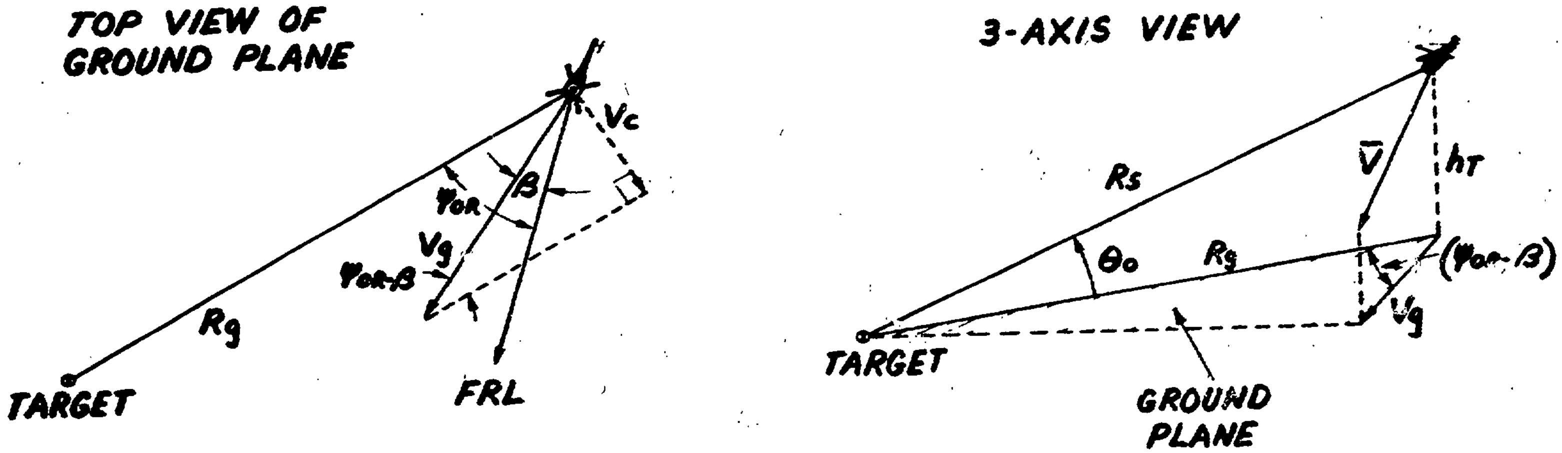
5. Offset, Three-Axis, Two-Plane Solution (Continuous Tracking Angular Rate Sensing Method)

Another, more commonly known method of kinematic targeting uses angular rate sensing of the optical LOS in bearing to derive the desired orientation data. A continuous computer solution is effected providing instantaneous range, bearing and altitude to the target during the flight period in which the operator is tracking the target. This technique yields relative coordinate data, as its use is generally intended. The data could be sampled at some appropriate point for use in calculating either target or own-aircraft position in absolute earth coordinates. However, the discrete acquisition method of Subsection III.H.4 is preferred for this purpose because it is more accurate.

The principal application of angular rate targeting is in off-boresight, gun-turret, fire control for immediate suppressive fire support where the tactical situation does not permit the time-consuming, two-discrete acquisition technique. The geometry and equations of the kinematic solution are shown in Figure 3-10. To achieve a reasonable degree of accuracy, both the flight velocity and bearing angle rate must be of sufficiently high magnitudes. An accuracy analysis defining such reasonable thresholds is required; hence, the extent of the operational constraints imposed is undetermined.

The elements of the system are the same as that required for the systems described in Subsections III.H.3 and III.H.4; namely, a stabilized aimsight, Doppler radar for sensing ground velocity vector, AHRS and a digital computer. The stabilized aimsight is as described in Subsection III.G with the associated processing equations given in Appendix A. Relative bearing (ψ_{OR}) and elevation angle (θ_o) referenced in stable earth coordinates are computed in accordance with the equations derived in Appendix B, paragraph 1.c. Range is solved in accordance with the V-equals-RW relationship governing angular motion of a radial line. Ground speed (V_g) is resolved to obtain the normal tangential velocity (V_c), where the effects of high fr[illegible]uency heading motion on the ($\psi_{OR-\beta}$) term are cancelled. Angular veloc[illegible] ($\dot{\psi}_{OR}$) is derived by the sampling process within the computer. Actually, only the low frequency components of the sampled ψ_{OR} variable are used in the rate derivation. This is enabled by virtue of the aimsight stabilization function that washes out the high frequency components of attitude motion including that of heading. The radius vector, or ground range (Rg), is then computed followed by slant range (Rs) or altitude (hT) solutions in accordance with the equations presented in Figure 3-10.

Computer programming analyses covering the aforementioned processing are presented in Appendix D. Time and memory space estimates are presented for several computer models; all estimates are based on a 5-second computation rate.



1 COMPUTE EARTH STABILIZED ψ_{or}, θ_o VARIABLES (REFER TO APPENDIX B.1)

2 $V_c = V_g \, SIN \, (\psi_{or} - B)$

3 $R_g = \dfrac{V_c}{\psi_{or}}$

4 $R_s = \dfrac{R_g}{COS \, \theta_o}$ OR $h_t = R_s \, SIN \, \theta_o$

WHERE

V_g = GROUND SPEED

B = DRIFT ANGLE

700-17-11

Figure 3-10
Offset, Three-Axis Targeting Geometry
(Continuous Tracking, Angular Rate Sensing Method)

6. Target Overflight Method of Partial Orientation (Ranging)

A method exists for obtaining continuous slant range to a land target in which an overflight procedure is performed just prior to the planned terminal maneuvers about the target. This method represents a low cost alternate to the offset discrete acquisition techniques of kinematic targeting (Subsections III.H.3 and III.H.4) which involve a relatively complex set of arithmetic processing functions. Primary use of the target overflight technique of ranging is conceived for visual gun and rocket fire control, where a Doppler radar and/or digital computer are assumed to be unavailable to execute the more sophisticated offset targeting solutions.

The operational procedure and associated geometry are shown in Figure 3-11. The helicopter is first flown over the observed target at any desired course. At the instant the vehicle passes directly over the target, the pilot "pickles" the sensed valves of both radar (hT_1) and pressure altitude (hb_1) data. The difference between these quantities yields the pressure altitude (hT_{SL}) of the target above standard sea level. As the helicopter is maneuvered into a boresight, dive-attack configuration, altitude above the target (hT_x) is continuously derived from the vehicle, which for the purpose of gun and rocket trajectory solution against clearly visible targets is sufficient. (Full, three-axis target orientation is required for the marginal target discrimination conditions outlined in Subsection III.H.2.) Slant range is easily derived from the hT_x altitude data through use of a projected, stabilized, aim-circle display. In the case of a fixed optical projector, the derivation involves a bootstrap control loop design in which the target depression angle (e) is continuously sensed as the pilot maintains the lead-driven aim circle on the target. This angle (e), together with altitude (hT_x), enables a relatively simple solution (e.g., divide servo) of a right triangle to obtain slant range (RS_x). Where a moveable, optical aimsight is used in off-boresight firing, the same right triangle solution is executed. This system, however, is not of a bootstrap type

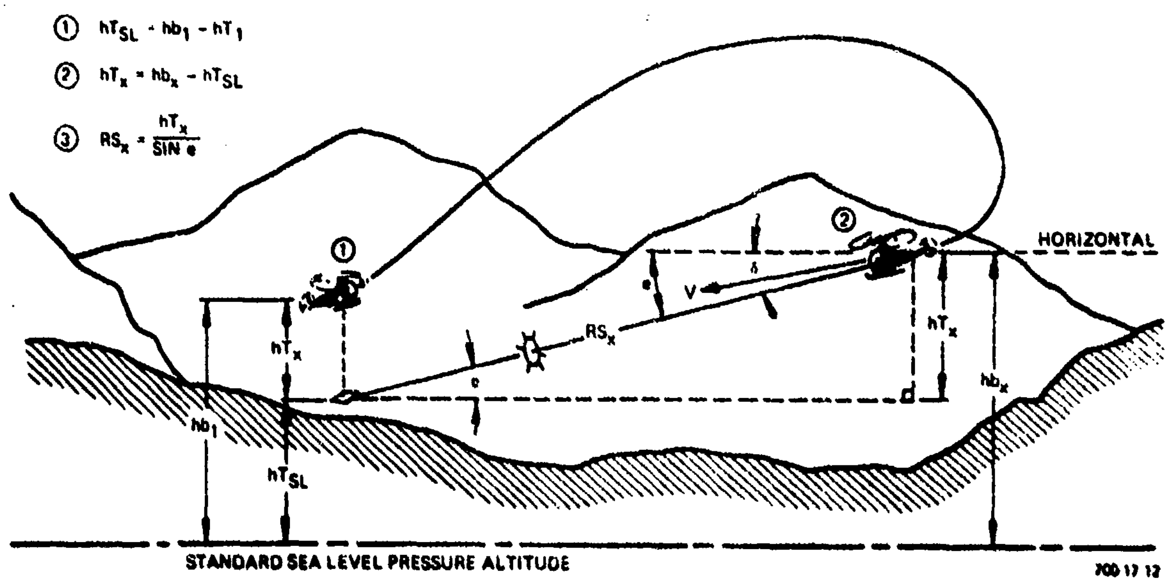


Figure 3-11
Target Overflight Ranging Geometry

in that the position of the aim reticle is independent of the computed, range-dependent, lead angles. The availability of a moveable aimsight in this case presupposes that computer hardware is also provided to perform the necessary aircraft-to-stable-earth coordinate conversion function (and attitude stabilization to a much lesser degree of importance).

Target overflight can, of course, be used in any one of several helicopter missions (e.g., close support attack, observation, SAR, etc) to fully orient a target in three coordinates, given a self-contained navigation system on-board the vehicle. No optical display(s) is required for this purpose. Similarly, overflight of a checkpoint can be used to update the own-aircraft coordinates.

Such simplified orientation systems (partial or full) suffer, however, from a number of operational disadvantages when compared to offset targeting in that the following conditions must be met:

- Adequate time exists to execute overflight
- Tactical situation safety permits overflight
- Terrain immediately around target is relatively flat

As a practical matter, it is not anticipated that the Navy would establish target overflights as a standard primary procedure for any of the missions covered in this study. Rather, overflight maneuvers are viewed only as an option to the pilot to be undertaken during safe situations of opportunity and under good visibility conditions. Additionally, they could be established as a backup mode of target orientation, to be used in the event of certain equipment failures (e.g., Doppler radar) in a primary offset targeting system, if such were provided.

One exception to these limitations envisioned is during radio homing flight in remote areas (e.g., Medivac, SAR) under limited night visibility conditions. The helicopter can be expected to pass over the portable omni-transmitter before a positive visual contact and identification is made. If the crossover were to occur at a sufficiently low altitude to minimize the size of the vertical cone of confusion, then the pilot could "pickle" altitude and navigation coordinate data during the to-from needle swing so as to provide a reasonable approximation of the radio position. This position would be stored and subsequently designated on a forward-looking headup and/or panel mounted-display to localize the pilot's attention during the next pass and thereby assist in the visual or aided-visual acquisition.

7. Partial (Ranging)/Full Orientation Over Water

The level nature of water (and flat desert terrain) enables a more simplified set of kinematic targeting procedures than those established earlier in this section for flight over land. The techniques described in the following paragraphs are based on the use of radar-sensed altitude to provide a continuous measure of altitude relative to the target. This, of course, assumes both the availability of a radar altimeter and conditions of adequate signal return providing reasonably good precision. Otherwise, the kinematic targeting methods of Subsections III.H.3, III.H.4 and III.H.5 would best apply.

Where only slant range to a target is required (i.e., partial target orientation) such as in gun and rocket fire control, the mathematical solution is identical to that described in Subsection III.H.6 for the target overflight method except that the overflight procedure is not required. This applies to both boresight and off-boresight weapon delivery. This method of ranging (involving continuous display acquisition) is not only operationally superior to multiple discrete acquisition methods, but would probably yield more accurate results. It is therefore recommended for visual fire control where conditions do not dictate the retention of target position, even if a primary offset kinematic targeting system centered about a Doppler radar were available.

Where full target orientation in three-coordinates is required because of adverse target detection conditions, only a single, discrete visual acquisition is required to initially orient the target. Either a fixed or moveable projector can be used for this acquisition, which provides elevation and bearing to the target. Ground range is obtained through the solution of a right triangle located in the earth's vertical plane, where the vertical leg is represented by radar altitude sampled at the instant of acquisition. Subsequent updating of relative aircraft-to-target position is performed in accordance with any one of the methods and associated equations presented in Subsections III.H.3 and III.H.4. By way of contrast with overland operations, it is only in this terminal continuous update phase of the kinematic targeting process that a Doppler radar, or other suitable flight velocity sensor, is required.

SECTION IV

OPERATIONAL ANALYSIS AND DISPLAY SYNTHESIS

The recommended HUD designs for each of the established mission phases or modes (in terms of information content, symbol format and data processing requirements) are presented in this section. In conjunction with each display design, a discussion of the current operational procedures and problems associated with each flight mode is presented. A matrix-tabulated summary of the HUD symbols selected for each mission phase is presented in Figure 4-1.

A. BASIC FLIGHT

The basic flight regime in a helicopter involves moderate pitch attitudes, within ±10 degrees, and moderate flight path angles. The flight maneuvers involved are climbs, descents, turns and, predominantly, level flight with a fixed ground track. Airspeed must be controlled at all times. Enroute navigation is a primary function in basic flight involving combinations of the maneuvers noted.

The HUD is useful in basic flight under visual conditions, both day and night, and under instrument conditions. The means for accomplishing flight control tasks are the same under these diverse conditions when the HUD is involved, and simultaneous, compatible reference to the display and the external visual world can be realized.

	Attitude Scale-Pitch	Attitude Scale-Roll	Heading Index	Flight Path Marker	Air Speed Readout	Lateral Drift Image	Longitudinal Drift Image	Altitude Readout	Deviation Bar	Director Image	Boresight Image	Landing Site Image	Special Images
BASIC FLIGHT MANEUVERS	X	X	X	X	X			X					
FIELD APPROACH & LANDING	X	X	X	X	X			X	X	X	X		
HOVER & LET DOWN	X	X	X			X	X	X	X		X		
MID-AIR RETRIEVAL	X	X	X	X	X				X	X	X		
MINE COUNTER MEASURES	X	X	X					X			X		X
TERRAIN FOLLOWING	X	X	X	X	X			X			X		X
AIR-TO-AIR REFUELING	X	X			X				X		X		
CARRIER LANDING	X	X	X	X	X			X	X	X	X		
AIR-TO-GROUND FIRE-ON BORESIGHT	X	X		X									X
AIR-TO-GROUND FIRE-OFF BORESIGHT	AIM	SIGHT	ONLY										
RADIO HOMING SEARCH	X	X		X				X		X			X
EN-ROUTE NAVIGATION	AIM	SIGHT	ONLY										
INSTRUMENT APPROACH	X	X	X	X	X			X	X	X	X	X	

700-17-13

Figure 4-1
Summary of HUD Images for Each of Mission Phases

A comprehensive HUD configuration, made possible through the use of electronically generated imagery on a CRT, which is then collimated, is shown in Figure 4-2. Attitude is presented by the orientation of the horizon line, which is a horizontal reference line that represents the trace of a plane normal to the vertical at the present aircraft altitude. It is space stabilized in pitch and roll to maintain its horizontal orientation at zero elevation angle. Auxiliary pitch lines provide surrogate horizontal references should the horizon line leave the field of view of the HUD. The heading index on the horizon line represents a reference heading in the proper visual relationship with the actual heading of the aircraft. When the nose of the aircraft moves 1 degree to the left, the heading index moves 1 degree to the right. Auxiliary heading indices are also positioned on each of the pitch lines.

The horizon line and heading index represent an external visual reference to the pilot from which he can obtain pitch, roll and heading information as in visual flight. These images continuously overlay their counterparts in the real world, such as the true horizon and a visual heading reference near the horizon if this exists. The images are perceptually associated with the real world, by virtue of collimation and space stabilization. The boresight image (cross) indicates the extension of the boresight line of the aircraft to its intercept on a reference sphere in space. The direction of the velocity vector of the aircraft in space is indicated by the flight path marker, in the form of a miniature airplane. If the direction of flight were to remain constant, the aircraft would strike the ground at the point indicated by the center of the path marker image. The aircraft is descending in Figure 4-2 because the path marker is below the horizon line. The angular separation between the path marker and the horizon line is a direct visual readout of the flight path angle.

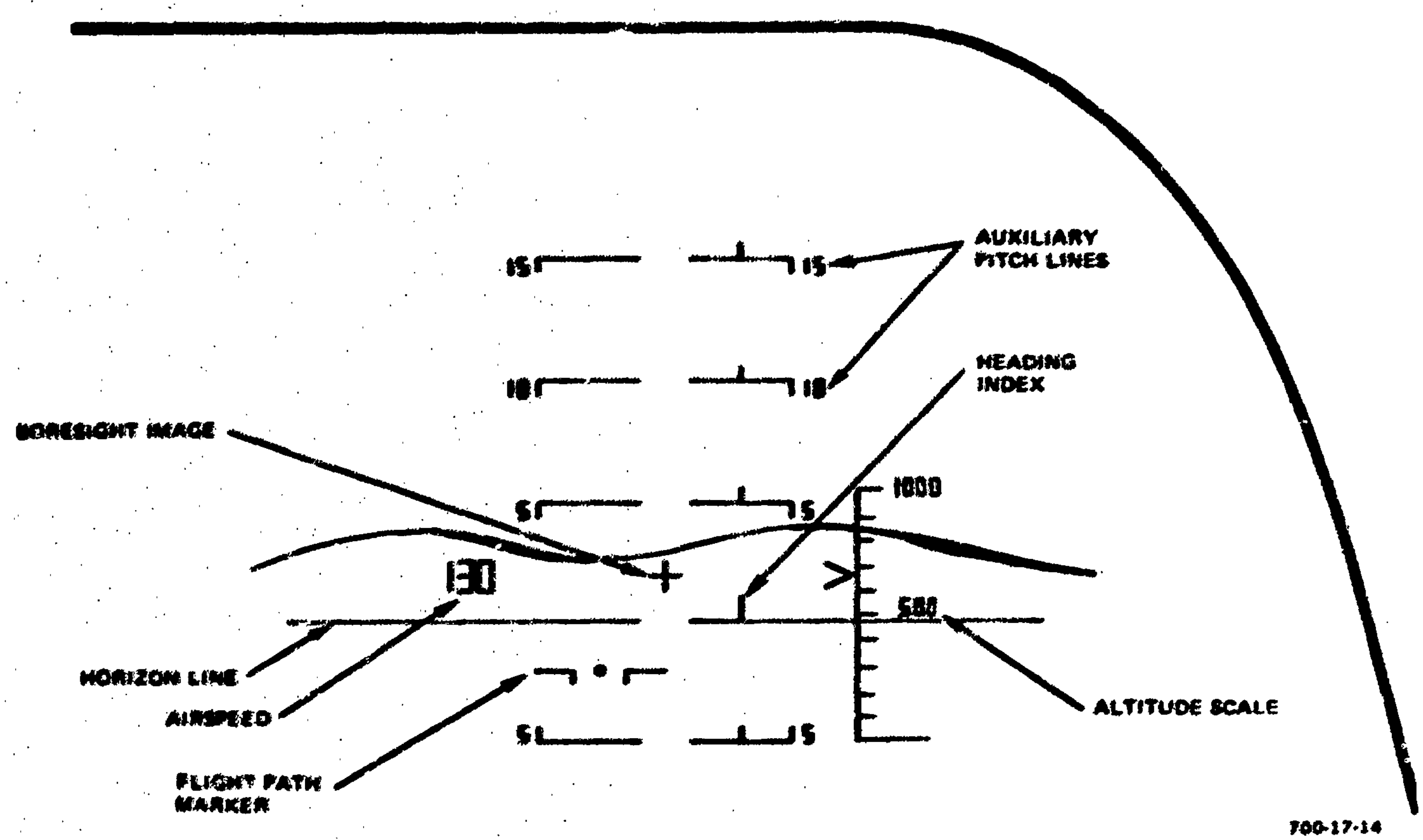


Figure 4-2
HUD Configuration for Basic Flight using CRT Image Generator

9-6

The altitude scale on the right side of the display provides the pilot with a readout of his radar or barometric altitude. This scale is read against the V-index, which is to the right of the boresight marker. Airspeed is presented in a numerical readout oriented to the left of the boresight marker opposite the altitude index. This display is suitable for both vertical and running takeoff, and climb-out, as well as for en-route maneuvers.

A similar display for basic flight, generated by electromechanically driven reticles for HUD images (Figure 5-3, System "B") in lieu of an electronic CRT, is presented in Figure 4-3. This system provides more freedom in generating symbol shapes and alphanumerics, but is limited by the kinematics of the reticles and the multiple optical channels required. A configuration for aminimal electromechanical system for basic flight (Figure 5-3, System "A") is shown in Figure 4-4. This simplified system lacks a path marker and an altitude scale, but includes a settable deviation bar slaved to the horizon line. The deviation image therefore maintains fixed elevation and depression angles with respect to the horizon.

B. APPROACH AND LANDING

Approach and landing operations with a helicopter are varied because of the extraordinary flexibility of the vehicle with regard to the range of flight path angles and speeds that can be achieved. Field landings may be made on prepared runways or landing pads, as well as in cleared remote areas. Visual approaches may be made during daylight and at night; instrument approaches may be performed if suitable terminal guidance is available. Conventional running landings may be made with touch-down and roll-out, or the helicopter may transition from an approach to a hover over the landing area, followed by a letdown to final contact with the ground. Approaches are normally made into the wind, and the transition to a hover makes this possible on any runway, regardless of the

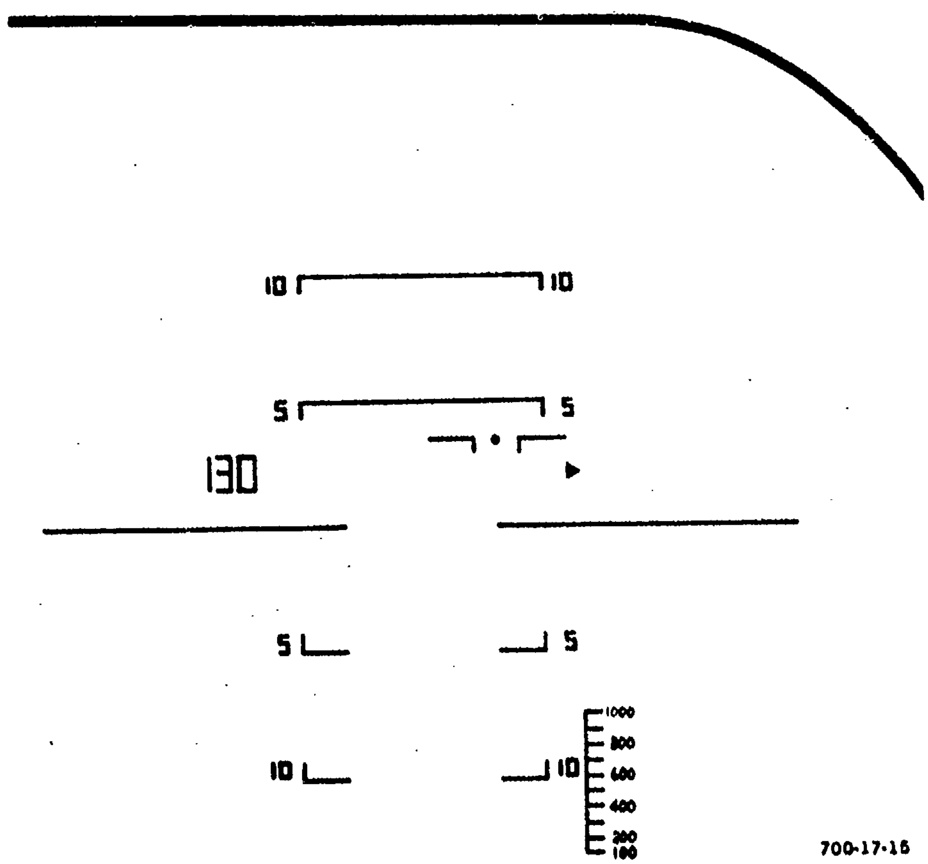


Figure 4-3
HUD Configuration for Basic Flight using
Electromechanically Driven Reticles

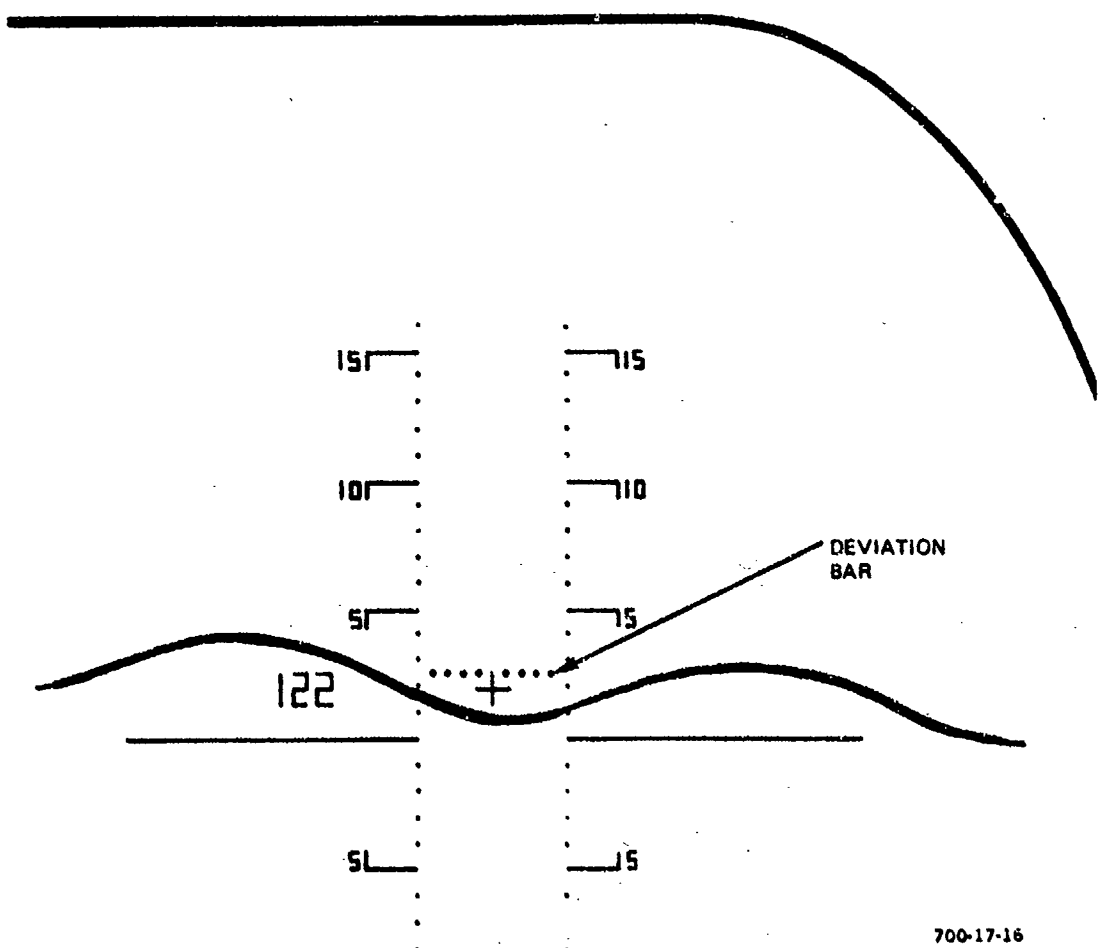


Figure 4-4
HUD Configuration for Basic Flight using Simplified
Electromechanical System

direction of the wind relative to the runway, i.e., crosswind condition. Vertical landings in cleared areas surrounded by obstructions such as tall trees present special situations which can be handled only by a helicopter or VTOL aircraft. Landings to secured sites surrounded by hostile approach zones often dictate the approach patterns to be followed to minimize exposure to ground fire. Helicopters are also required to land on moving aircraft carriers or platforms on other types of ships.

Visual approach and landings are by far the most frequent. Referring to Figure 4-5, the helicopter enters the final approach gate into the wind at Point 1 from an initial approach pattern determined by navigational and tactical considerations. There is a straightline descent between Points 1 and 2 accompanied by a steady reduction in airspeed. At Point 2, the helicopter flares to a level flight path during which the speed is reduced further until a hover is established over the landing area at Point 3. This is followed by a letdown to contact at Point 4. Ranges of airspeed, altitudes and flight path angles associated with these maneuvers are shown in Figure 4-5.

The application of a complete HUD system based on a CRT image generator leads to the configuration shown in Figure 4-6. The horizon line, auxiliary pitch reference lines, flight path marker, and airspeed and altitude readouts serve the same functions as in basic flight. The deviation bar is space stabilized with respect to the horizon line at a depression angle equal to the desired approach angle. The angular displacement of a deviation bar from the aimpoint or the landing site is therefore the angular deviation of the position of the aircraft from the desired approach path (Reference 10). The deviation bar, therefore, provides an optical guidance system with high precision and good resolution for final approach. If the angular subtense of the circular delineation of the landing area is made equal to the width of the deviation bar when the aircraft is at the flare position, the pilot has a direct readout of

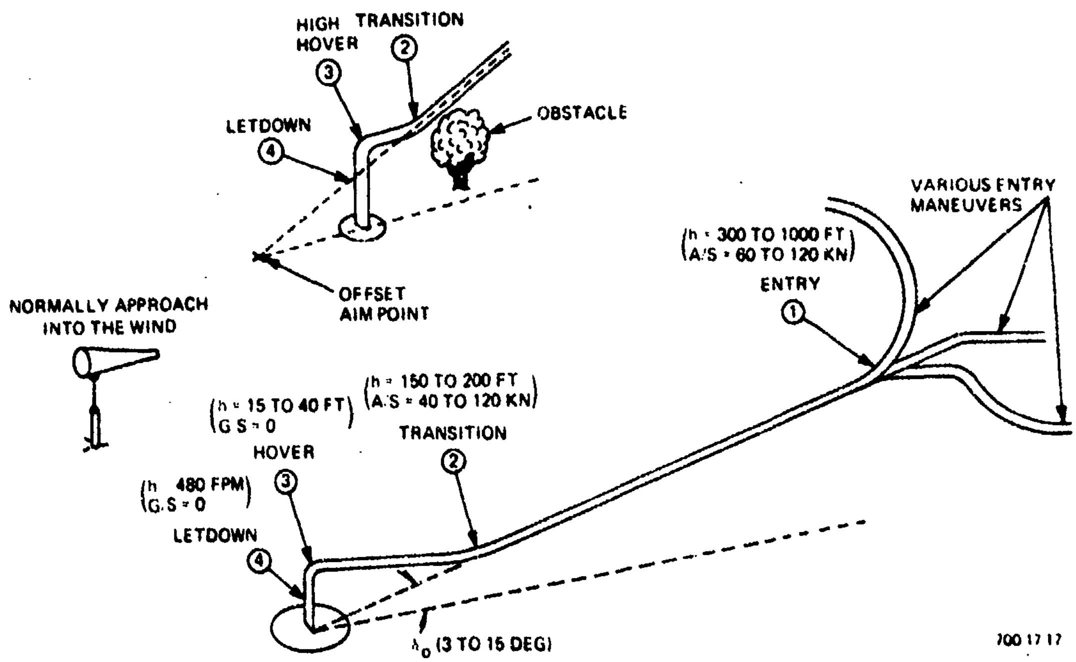


Figure 4-5
Helicopter Flight Patterns in Approach to a Hover

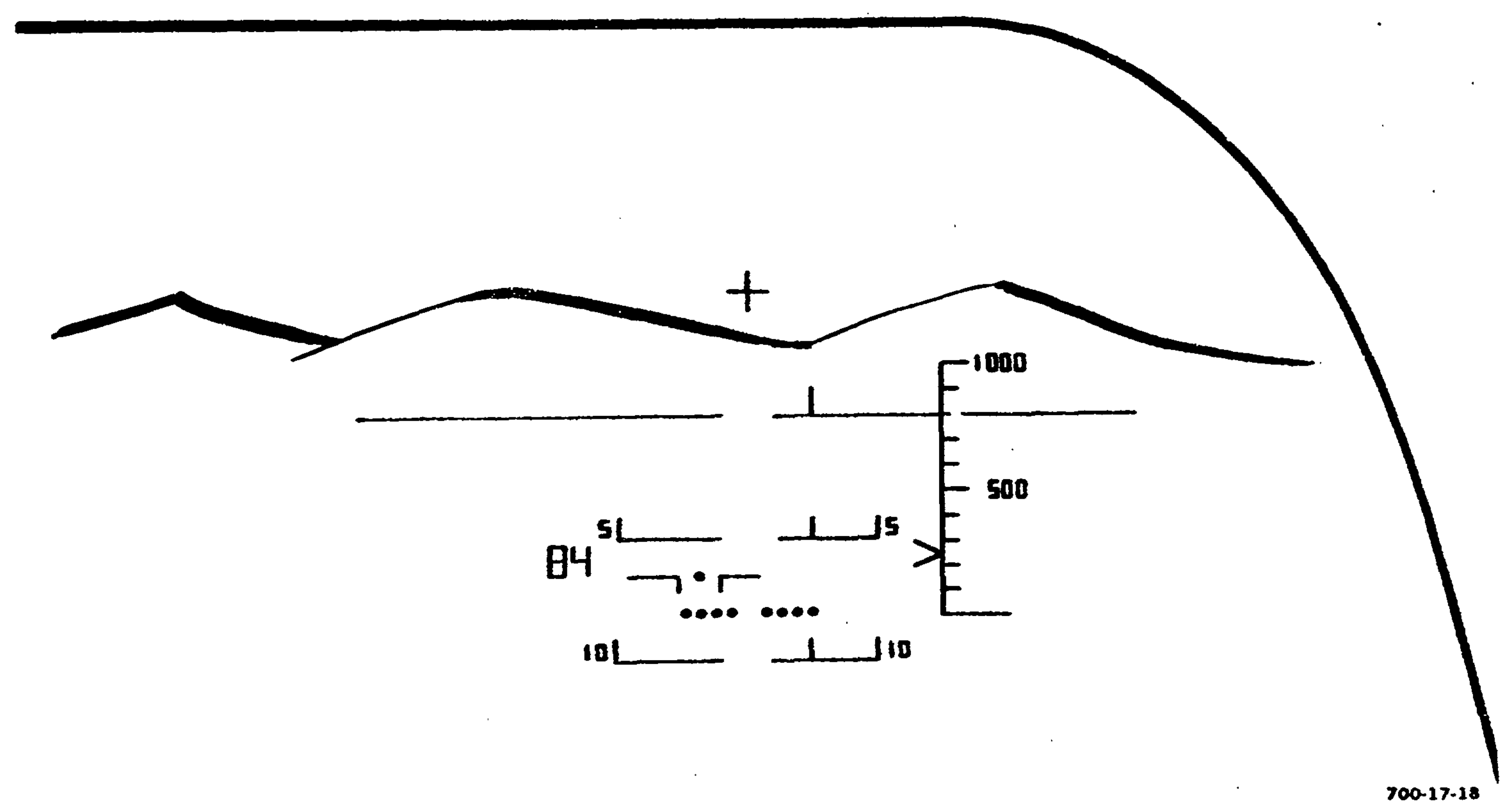


Figure 4-6
HUD Configuration for Landing Approach using CRT
Image Generator

time to initiate the flare. This technique obviates dependence on the altitude readout for orientation for flare. The reduction of ground speed to zero at the hover point must be accomplished visually by reference to the ground.

The HUD provides the means for visually coupling the aircraft to the straight descent path between Points 1 and 2 in Figure 4-5. The coupling is visual because it requires reference to the aimpoint on the ground. When the deviation bar is above the aimpoint, indicating that the helicopter is high, the pilot must position the flight path marker below the aimpoint, i.e., undershoot, to erase the error in position. The amount of undershoot and its variations in time are introduced at the discretion of the pilot, providing extreme flexibility for the introduction of non-linear techniques. The maneuver must end with both the deviation bar and the path marker superimposed on the aimpoint, indicating zero error and zero error rate. If the pilot makes the undershoot angle (path marker orientation below the aimpoint), proportional to the position error (deviation bar above the aimpoint), he is maintaining a linear first-order control loop, in which there is always an asymptotic approach to the on-course, i.e., no overshoot.

The path marker can also be used as a flight director, in which continuous tracking of the aimpoint with the path marker provides direct, closed-loop control without reference to the deviation bar (Reference 10). If the means for obtaining flight path angle is subject to steady-state errors, these errors may be eliminated by using a lead network with transfer function $\tau S/(\tau S + 1)$ to modify the flight path function in the director mode. This network, which is a high pass filter, at frequencies ($\omega \ll 1/\tau$), is a differentiator that wipes out steady-state values at low frequencies ($\omega \ll 1/\tau$).

The approach along a linear track between Points 1 and 2 of Figure 4-5, terminating at the aimpoint, is not suitable for an approach over a high obstacle. The aimpoint is not visible to the pilot in the approach because of the obstruction. In this situation, a surrogate or offset aimpoint (Figure 4-5) must be used to establish the linear approach path prior to the flare to the hover point over the landing area.

If ground track information is available to position the path marker laterally, coupling to a desired approach in azimuth may be accomplished using techniques similar to those described for control in elevation. Stabilizing the deviation bar in heading at the orientation of the desired approach path in azimuth provides lateral angular deviation information for the pilot. Director functions can be introduced in azimuth as in elevation for quickened flight control.

A simplified visual approach and landing display generated by electromechanically driven reticles is shown in Figure 4-7. The path marker provides flight director functions in both azimuth and elevation; there are readouts of altitude and airspeed. All ancillary display images (such as attitude, heading and deviation) have been eliminated.

For instrument approaches with ground guidance systems (Subsection III.F), the display shown in Figure 4-8 is recommended. The navigational information, which indicates the orientation of the aimpoint in space, is processed and used to position the ellipse, which is a rendition of the circular landing pad or landing area in perspective. This image overlays the real landing area when the latter becomes visible, making a smooth transition from instrument to visual flight. In all other respects, this display is identical to the HUD designed for visual approaches (Figure 4-6). The displays are thereby made completely compatible, and the techniques involved in their use are identical. This maximizes the transfer of pilot training from visual to instrument flight.

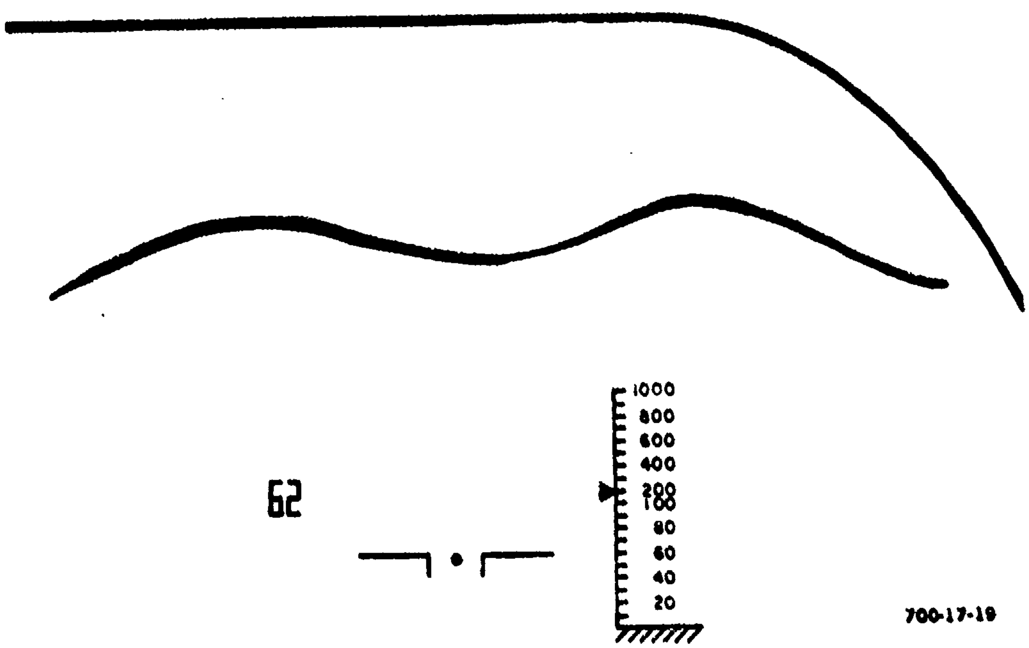


Figure 4-7
HUD Configuration for Landing Approach
using Electromechanically Driven Reticles

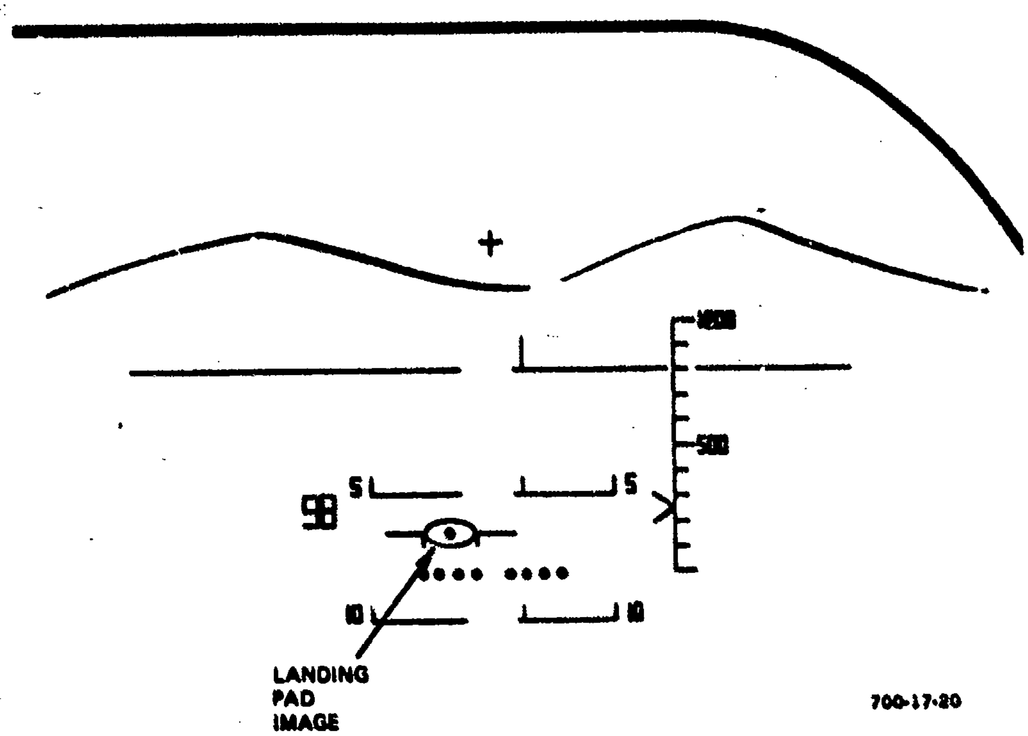


Figure 4-8
HUD Display Configuration for Instrument Approaches

The helicopter approach to a moving carrier or landing platform on a ship is complicated by the velocity of the platform and the wind over the deck. The relationships among the velocities involved are shown in Figure 4-9. The velocity of the helicopter with respect to the ground V_{HG} is

$$V_{HG} = V_{HA} + V_W \tag{4-1}$$

where

V_{HA} = Velocity of aircraft with respect to air

V_W = Wind velocity

The velocity of the helicopter with respect to the carrier V_{HC} is

$$V_{HC} = V_{HG} - V_C \tag{4-2}$$

where

V_C = Velocity of the carrier

Substituting for V_{HG} in Equation (4-2)

$$V_{HC} = V_{HA} + (V_W - V_C) \tag{4-3}$$

But $(V_W - V_C)$ in Equation (4-3) represents the wind over the deck V_{WD} (Figure 4-9). Therefore

$$V_{HC} = V_{HA} + V_{WD} \tag{4-4}$$

As indicated by Equation (4-4), when the velocity of the helicopter with respect to the air is in the same direction as the wind over the deck (as indicated by a windsock), the velocity of the helicopter with respect to the deck is in this same direction. Flying the helicopter in the direction of the windsock, therefore, provides a direct approach to the moving deck without drift over the deck. The HUD in the landing mode may

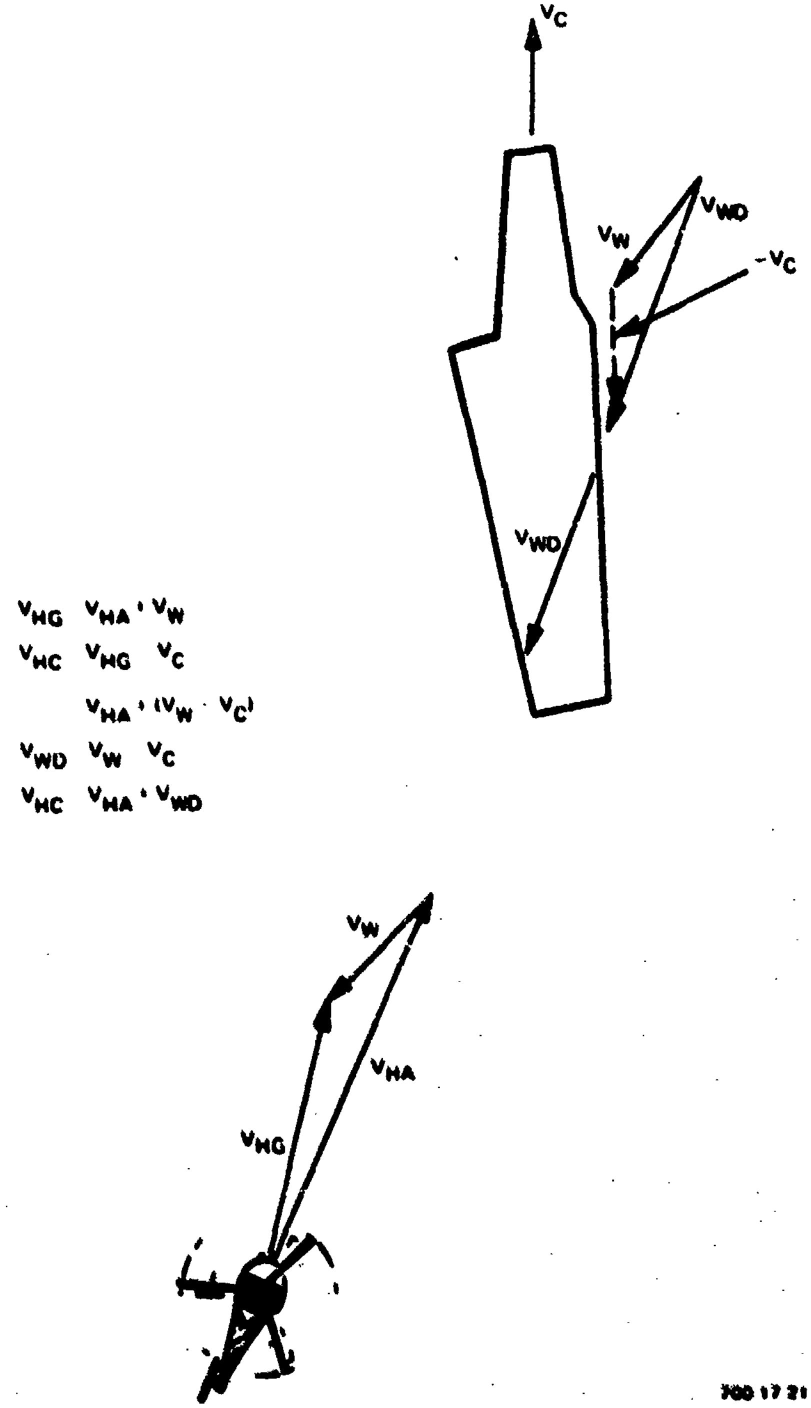


Figure 4-9
Velocity Relationships for Helicopter Approach to a Moving Platform

be used to implement an approach of this type without compensating for the drift of the helicopter, as long as the approach is made with zero yaw or in the direction of a known remote relative wind. Coupling to the desired descent path may be accomplished as with a stationary landing site, using airspeeds for path marker or flight director functions. The deviation bar provides a valid indication of displacement of the aircraft from an approach path, which moves with the landing deck.

C. HOVER AND LETDOWN

Hovering over a ground point is presently accomplished visually by reference to prominent terrestrial features in the area such as trees, large rocks, and man-made structures. The pilot attempts to maintain the visual bearing to these points constant. He can detect lateral and longitudinal velocities of his vehicle by motion parallax cues, i.e., changes in the angular subtense between objects as the position of the helicopter changes. Altitude and attitude rate can also be monitored visually by reference to the ground at the low altitudes involved. The presentation of ground speeds, altitude and rate of climb and descent on the instrument panel, based on radar and/or inertial data, provides ancillary information, which the pilot may use to considerable advantage. However, the divided visual attention between the outside world and the cockpit panel makes the task difficult for the pilot and compromises the safety of the operation. With or without cockpit displays, the accuracy and facility with which a pilot can hover his aircraft over a fixed point is largely dependent on his skill and experience.

Since external visual reference is primary in the hover, the HUD can be employed to considerable advantage in this maneuver. Consider the display in Figure 4-10. The heading of the aircraft is determined by the direction and magnitude of the wind, the difference between heading and wind direction being determined by antisymmetrical effects produced by the main rotor, tail rotor and aerodynamic yawing moments on the fuselage.

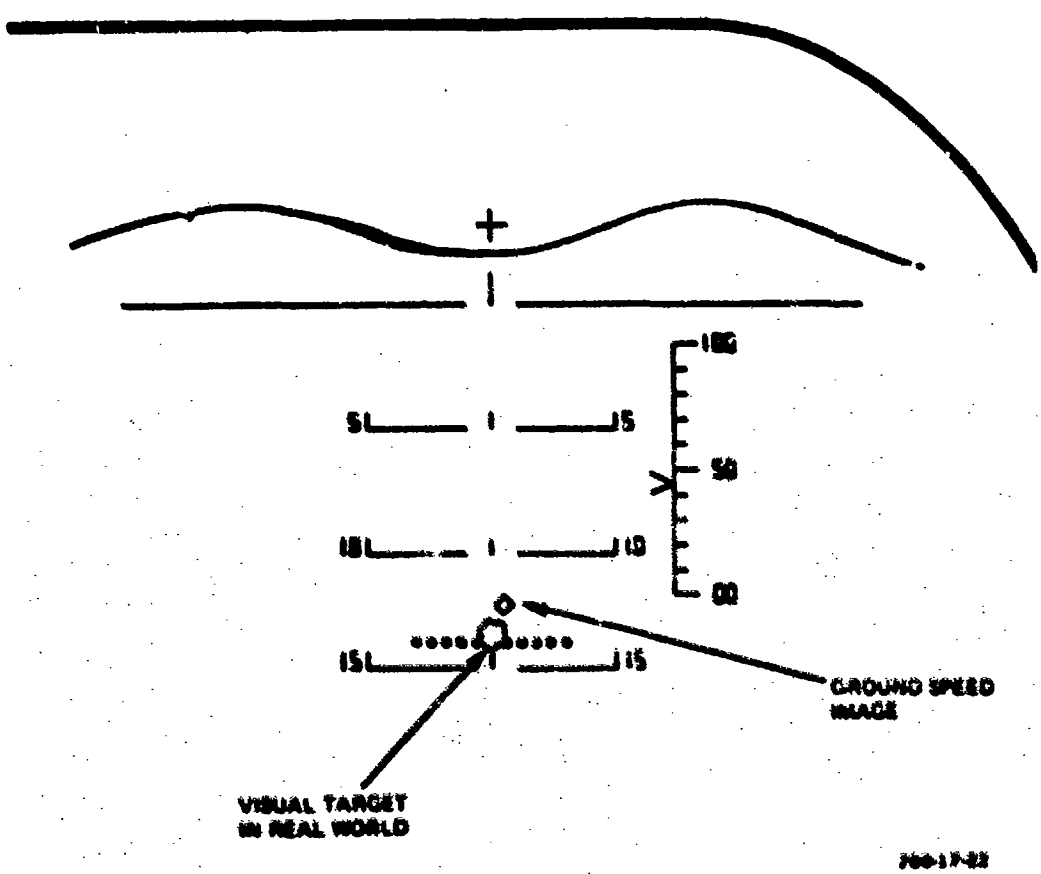


Figure 4-10
HUD Configuration for Hover and Letdown
using CRT Image Generator

The deviation image is slewed to position in which it overlays a convenient visual target when the aircraft is in its correct hover position at the correct altitude. Subsequent lateral differences between the deviation image and the target indicate a lateral displacement of the aircraft from the hover point. A vertical difference between the deviation image and the target can be caused by a longitudinal displacement of the aircraft and/or a change in altitude. The altitude indication, based on radar altimetry, can be used to monitor vertical position. The lateral and vertical displacements of the diamond-shaped, ground-spied image from the center of the deviation image represent lateral and longitudinal helicopter ground speeds, based on Doppler radar data. The diamond image leads the deviation image in lateral and longitudinal displacements from the target produced by any drifting of the helicopter from the hover point. A vertical shift of the deviation bar without a displacement of the diamond from the bar is due to a change in altitude. This is an additional clue to the pilot to corroborate his altitude indication.

The diamond image can be used together with the target to couple the aircraft to its horizontal position over the hover point. If a longitudinal or lateral displacement has developed, overlaying the diamond on the target produces a ground speed that is proportional to the displacement, but in the opposite direction. Continuous tracking of the target with the ground speed image produces a closed loop, first-order system, in which error rate is made proportional to the error. The diamond image behaves as a visual flight director. Non-linear operation is also possible in this flexible scheme, since the pilot may overfly or underfly the system to provide the response characteristics he considers desirable.

A simplified HUD configuration for hover based on the electromechanical image generating System "B" in Figure 5-3 is shown in Figure 4-11. Deviation information is absent in this display, and drift velocities are presented as departures of the path marker from the boresight circle. The hover display in Figure 4-11 is, from the standpoint of specific imagery, compatible with the basic flight display in Figure 4-3.

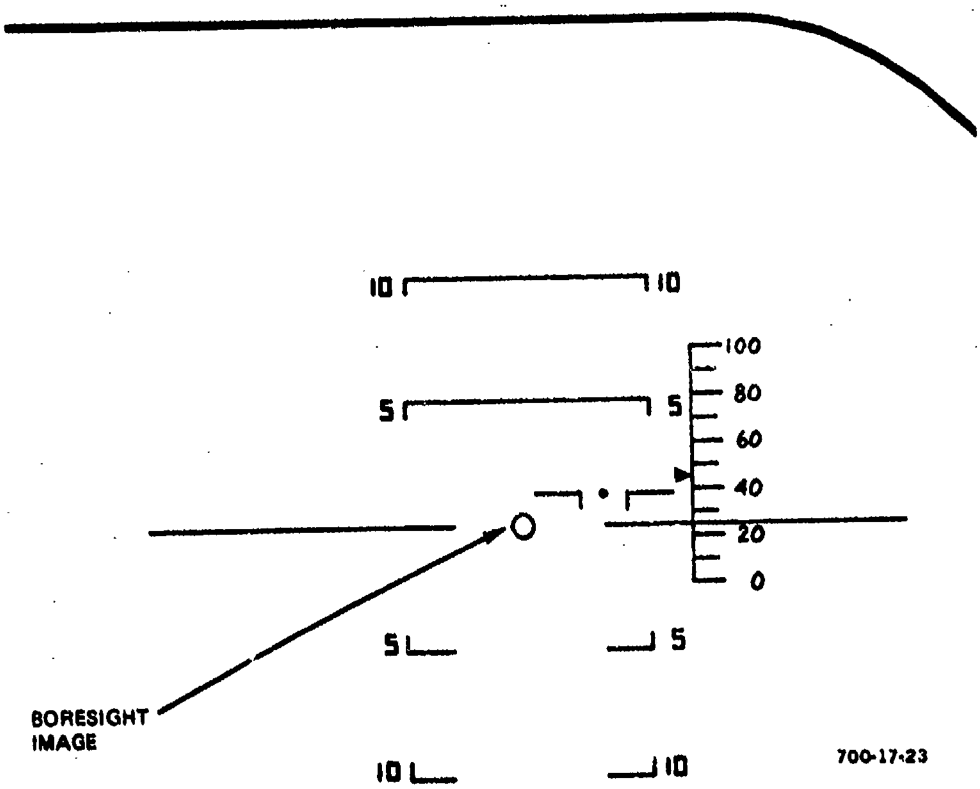


Figure 4-11
HUD Configuration for Hover and Letdown
using Electromechanically Driven Reticles

This requirement is a result of the limited flexibility for changing imagery when reticles are used to generate the images. Position information must be obtained by raw external visual reference when this display is used for hovering.

Letdown from the hover may also be accomplished with the display in Figure 4-10. In the letdown mode, the diamond image is made a letdown command image. Its depression from the horizon line is made proportional to the rate of descent of the helicopter. Overlaying the letdown image on the target makes the rate of descent proportional to the altitude of the aircraft, i.e.,

$$-k\dot{h} = \frac{h}{R}$$

or

$$\dot{h} + \frac{1}{kR} h = 0$$

where R is the distance from the hover point to the target. This provides a first order closed loop system for reducing the altitude to zero at substantially zero sink rate. The same type of letdown control may be accomplished with the electromechanical HUD system (Figure 4-11), using the path marker as a letdown command symbol.

D. TERRAIN FOLLOWING

Terrain following is a high speed flight operation at low altitudes to penetrate a hostile region with minimal exposure to enemy defenses. The terrain clearance altitude is selected as small as practicable, consonant with maintaining a satisfactory level of flight safety. There is a tradeoff between increased exposure to enemy counteraction at the higher altitudes and the increased hazard of impact with the ground (clobber) at lower terrain clearances. In terrain following, maneuvers are executed in elevation only at sensibly constant ground track. Therefore, the aircraft trajectory conforms to the terrain contour to the extent possible with the characteristics of the guidance provided by the forward-looking radar system and the dynamics of the aircraft.

Flight control during terrain following can be performed with an Automatic Flight Control System (AFCS) or manually with flight director commands. With the AFCS, a manual backup mode is generally required to provide a high level of system reliability. The flight director can also be used to monitor the performance of the AFCS. A high level of precision in flight control is required for terrain following, whether the control mode is automatic or manual.

In addition to control, however, the pilot must have the means for assessing his situation in the real world at all times, whether the flight is being conducted in visual, instrument or mixed weather conditions. Assessment is the means for assuring the pilot that his flight control performance is satisfactory when, in fact, it is, and advising him when the performance is submarginal. Assessment is not simply a go/no-go matter which may be resolved by simple signals such as warning lights. The human pilot requires sufficient information so that he can assess the total situation at all times and effectively exercise his prerogatives for decision-making as commander of the aircraft. The assessment function is particularly important in both low-level and high-speed flight and during approach and landing. These maneuvers are conducted in close proximity to the ground, where failure to recognize a hazardous situation and initiate appropriate recovery measures can be catastrophic.

The perceptual capabilities of the pilot make the situation for the assimilation of visual information from the real world extremely favorable. Human capabilities for pattern recognition with the type of visual information available during approach and landing are unparalleled. Furthermore, the pilot subjectively has more confidence in what he perceives directly, as contrasted to an instrument display with sensor and processed data inputs. The eyes, more often than not, believe what they see. This is the reason that optical illusions are so compelling. Consequently, the real world provides the pilot with two assessment features that panel instruments cannot rival: perceptual ease of assimilation and subjective confidence that the information is reliable. The HUD exploits these advantages provided by the visual world.

The HUD configuration recommended for terrain following is shown in Figure 4-12. The horizon line, pitch reference lines, heading indices, flight path marker, airspeed readout and boresight line serve the same functions as in a basic flight mode.

The terrain carpet is a perspective rendition of the topography in front of the aircraft, based on data obtained from the forward-looking radar system. Consider the typical situation shown in Figure 4-13. The forward-looking radar data is processed to determine the critical terrain element (T_n) in each of the five range gates (ΔR). The critical terrain element is defined as the point in range within the interval ΔR, having the maximum algebraic elevation angle ϵ. When the elevation angles are negative, as for the first three range gates in Figure 4-13, ϵ corresponds to the minimum depression angle. Therefore, the critical terrain element represents the terrain point that must be cleared if the aircraft were to fly safely on a straightline through the range gate from its present position.

In the HUD, each critical terrain element is presented at its true elevation angle ϵ so that it overlays its terrain correlate in the real world under visual flight conditions. These form a series of horizontal lines in space (Figure 4-12). The length of each horizontal line is inversely proportional to the range of the terrain point it represents. When the ends of the successive terrain elements are joined by straight lines, the series of trapezoids comprising the terrain carpet is generated. The terrain carpet represents a true perspective of a series of planar pathways in space, with constant width, laid between successive critical terrain points. The altitude scale on the right of the display provides the pilot with a readout of his actual altitude above the ground below the aircraft, as determined by a radar altimeter, for example.

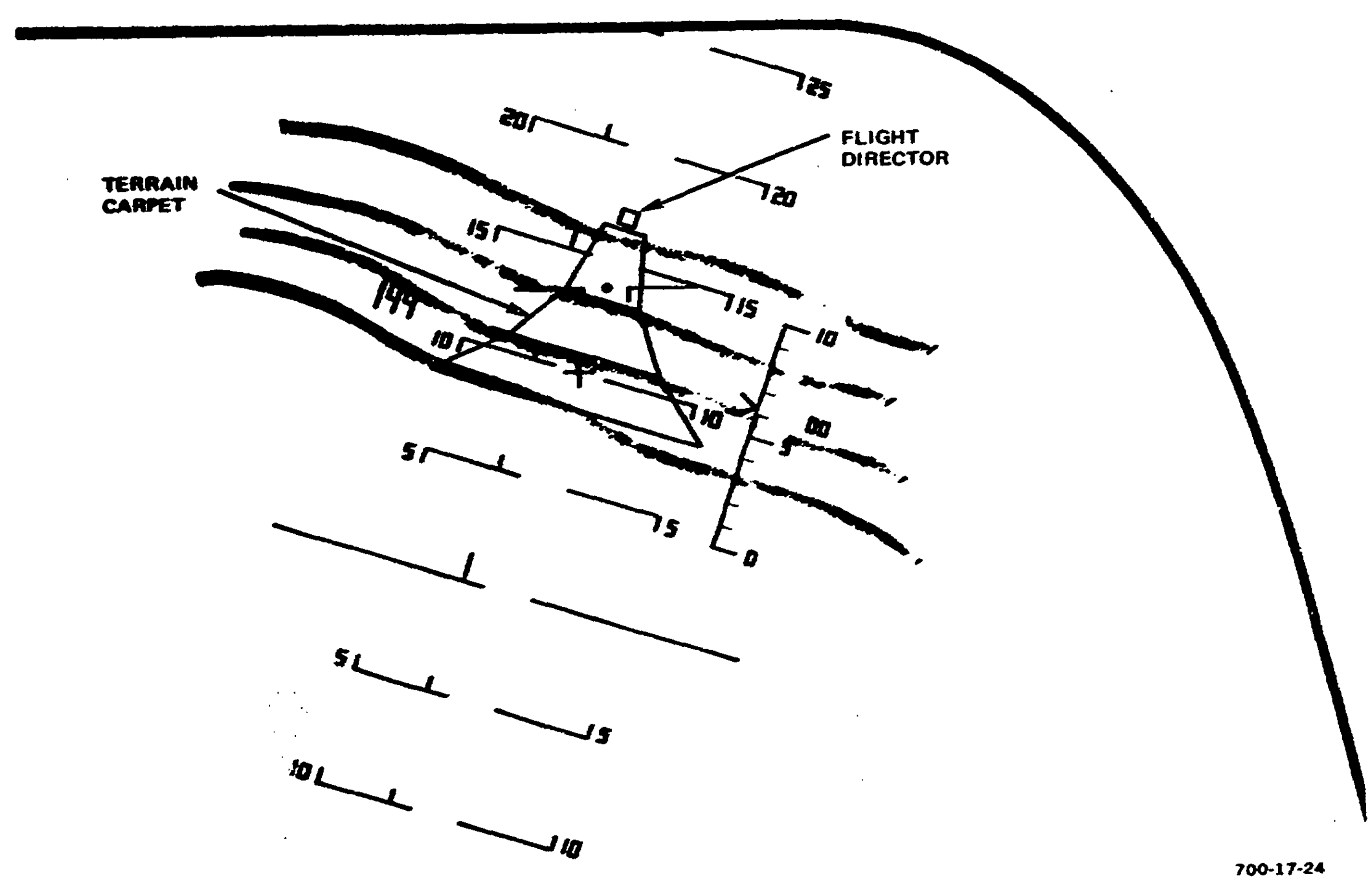


Figure 4-12
HUD Configuration for Terrain Following

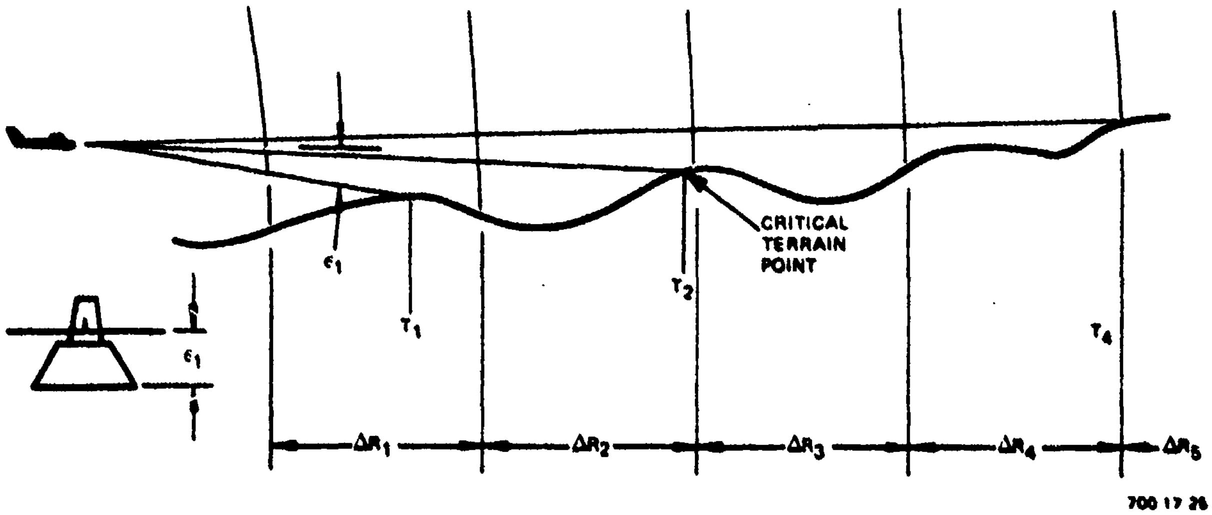


Figure 4-13
Data from Forward-Looking Radar System

The flight director image (Figure 4-12) presents vertical flight commands to the pilot. The pilot responds to these commands by "flying" the path marker to the square, and the commands are satisfied when the center of the path marker and the square are superimposed. Therefore, the director image moves in relation to the path marker acting as a null position. The relative motion between the two depends on the quickening dynamics used in the command generating system. The flight director can also be used to monitor the performance of the AFCS. On this basis, the flight director remains in the null position, i.e., the path marker and director image are superimposed, as long as the AFCS is responding properly to the command flight path angle input.

In summary, the display elements in Figure 4-12 continuously change in size, shape and position so that they always indicate:

- How the critical features in the real world appear
- What the aircraft is doing
- The flight control commands

A flight simulation study of this form of display for terrain following has been performed in a fixed base simulator (Reference 11); the salient conclusions were:

- The HUD assists the pilot materially in monitoring the conduct of low-level, high-speed flight missions.

- The display helps the pilot to recognize active and passive malfunctions in the autopilot and flight director systems and to recover safe control of the aircraft under these emergency conditions.

- The terrain carpet and the flight director are the primary display images that make higher levels of performance possible under these conditions.

E. MID-AIR RETRIEVAL

The mid-air retrieval operation involves the helicopter recovering stores descending by parachute, as shown in Figure 4-14. There is a small engagement chute above the main chute, which must be captured by a rectangular, webbed rig or window (18 feet x 11 feet) which is erected on the underside of the helicopter. The target has a rate of descent which may vary between 1200 and 1800 feet per minute. In the CH-3 aircraft, which has provisions for this mission, the maximum rate of descent of 2500 feet per minute based on autorotation is a consideration in planning and executing the maneuver. The engagement chute is black with a single brightly colored gore that delineates the direction from which the helicopter should approach the target. Flight control in azimuth involves a homing maneuver in which the pilot establishes a suitable ground track that compensates for any drift of the target. Helicopter speeds are between 50 and 60 knots.

The kinematics of the motions in elevation are shown in Figure 4-14. Assume that it is desired to engage the target at a small descent angle (γ_o) with respect to the target. If the target has a descent velocity (V_T) to produce a relative velocity (V_{AT}) of aircraft with respect to target at the desired intercept angle (γ_o). The relationship among the three velocities involved is

$$V_{AT} = V_A - V_T$$

Note that the flight path angle of the aircraft is γ, which is larger than γ_o, to compensate for the velocity of the target (V_T).

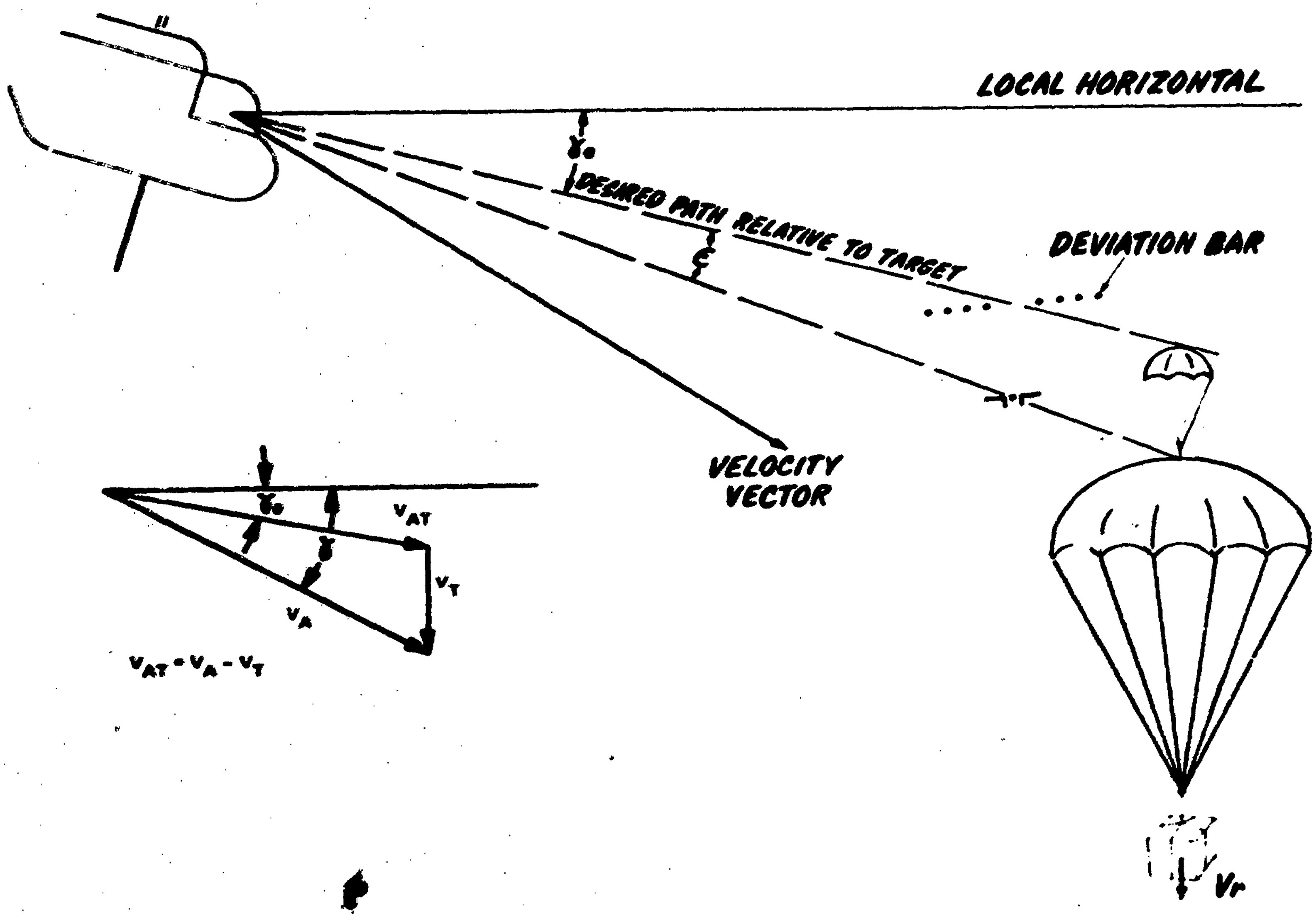


Figure 4-14
Motions Involved in Mid-Air Retrieval Maneuver

The HUD may be used to facilitate the intercept maneuver in the vertical plane. A deviation image space stabilized at a depression angle (γ_o) indicates to the pilot his angular deviation from the desired path relative to the target. This desired path is a moving reference line which is descending with the target. When the deviation image is above the intercept point on the target, the aircraft is high. Conversely, a low deviation image indicates that the aircraft is low.

The problem of establishing a suitable trajectory to the target is thereby made comparable to landing an aircraft on a runway visually through the use of a HUD, as described in Reference 10. The deviation bar may be used by the pilot in its raw form to provide position information, while the pilot changes flight path angle to superimpose the deviation bar on the intercept point on the target. The correct flight path angle also maintains the bar on the target, i.e., both zero error and error rate will have been established. A HUD display format suitable to this type of operation is shown in Figure 4-15.

If flight path information is available, this may be used in the HUD in a number of ways to further simplify the control task for the pilot. A direct indication of the flight vector of the aircraft in elevation may be presented in the form of the path marker (Figure 4-16). The pilot can then use the position of the path marker, which is a measure of error rate, to assist him in nulling the deviation image against the target. Alternately, the flight path information may be used to quicken the control situation (Reference 10), so that the HUD presents flight director information to the pilot. The pilot maneuvers the aircraft to maintain a continuous overlay of the target by the single director image, similar to a path marker, in a tracking task. The aircraft then establishes and maintains the proper trajectory in space in a closed loop control operation.

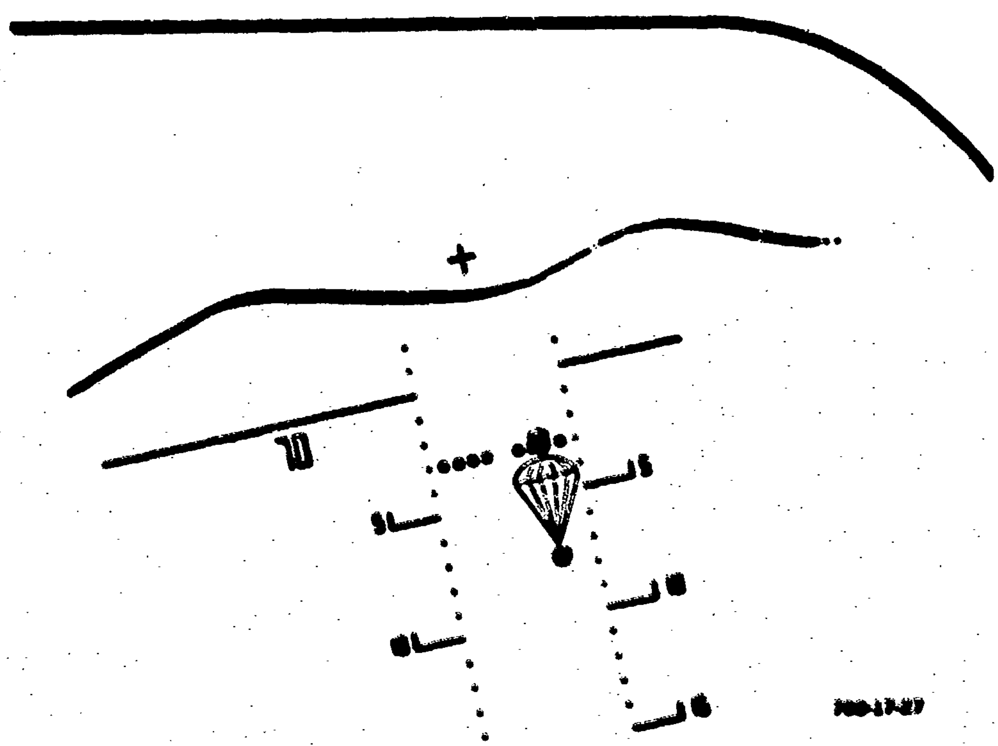


Figure 4-15
HUD Configuration for Mid-Air Retrieval

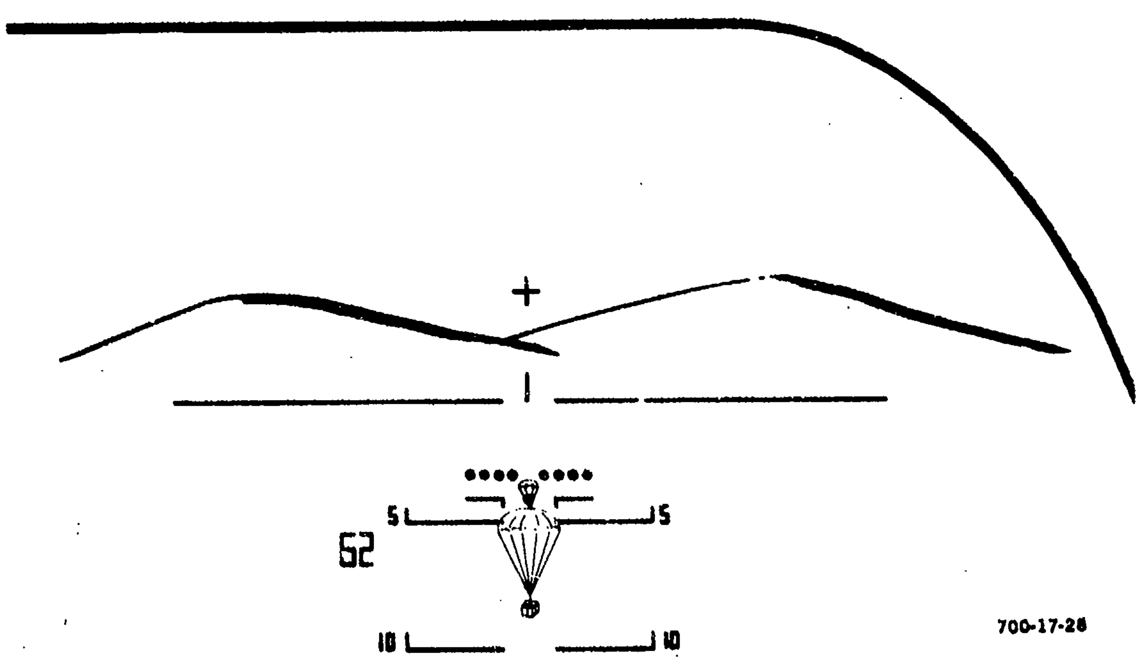


Figure 4-16
Alternate HUD Configuration for Mid-Air Retrieval

F. AIR-TO-AIR REFUELING

In the air-to-air refueling operation, the helicopter must be flown to engage its probe with the drogue trailing from the tanker aircraft, which is usually a large fixed-wing vehicle such as the C-130. The helicopter must subsequently maintain an accurate station with respect to the tanker during the refueling procedure, followed by disengagement of the two aircraft. The tanker navigates to the helicopter, homing into the area with Automatic Direction Finding (ADF) equipment. Prior to the approach of the helicopter to the tanker, the helicopter is flying at about 90 knots, while the airspeed of the tanker is about 130 knots. The drogue of the tanker trails from the wind of the tanker. The drogue line has markers at 10-foot intervals to provide a visual reference of the length of line extended to the helicopter pilot.

The probe-drogue engagement is always performed visually, during day and night operations. A spotlight on the helicopter illuminates the drogue and its hose line at night. The pilot controls the aircraft and effects the engagement, while the co-pilot acts as a safety monitor. Successful engagements are the result of a smooth trajectory to the mean position of the drogue, which has some oscillatory motion produced by unsteady airflow. Pilots are advised to avoid chasing the higher frequency drogue motions. After engagement, the pilot maintains station by visual reference to the aft fuselage of the tanker, using a salient cue such as the insignia on the fuselage. The orientation of the insignia in the pilot's visual field provides the most usable guidance available.

The HUD can be used to increase the ease and consistency with which probe-drogue engagements can be implemented and maintained in this type of operation. Assume that the wing of the tanker aircraft has two prominent marks equally spaced about the centerline of the drogue line in the spanwise direction. A HUD configuration such as that shown in Figure 4-17 is recommended. This horizontal angular subtense of the deviation bar is made equal to the subtense of the two marks on the wind when the

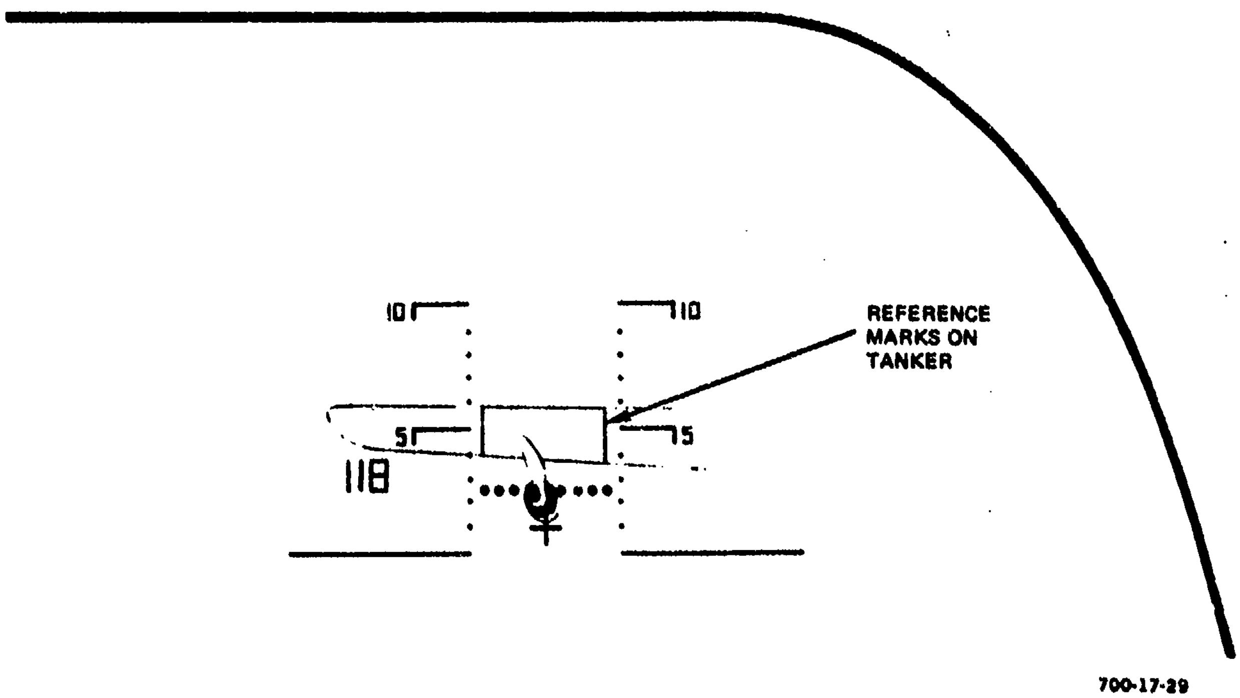


Figure 4-17
HUD Configuration for Air-to-Air Refueling

helicopter is in its correct longitudinal position with respect to the tanker. The deviation bar is also space stabilized at a fixed elevation angle with respect to the horizon line. The elevation angle corresponds to the desired position of the helicopter in the vertical plane, when the deviation overlays a suitable target, such as an engine pod. Therefore, the single deviation bar is sufficient to provide an accurate approach to the tanker, as well as to permit accurate station keeping. When the helicopter first approaches the tanker from behind at the approximate altitude, the deviation image is high above the wing, and its lateral subtense will be greater than the angular separation of the wing markers. The angular separation between the wing markers increases as the helicopter approaches the tanker until it is equal to the subtense of the deviation bar at the correct range. The pilot must adjust his altitude during this approach until the deviation bar overlays the elevation target when the helicopter is at the correct range. The pilot can execute these maneuvers with the HUD without diverting his visual attention from the drogue, which is in the same viewing region. Both engagement and station keeping are effected with the same set of visual cues on the tanker. This provides an optimal transition between the two critical stages in the operation.

G. MINE COUNTERMEASURES

Mine sweeping is an operation in which the helicopter flies in the pattern of successive parallel paths, reversing direction in each pass (Figure 4-18), at low altitude and speed. The helicopter tows a sweeper and cutter rig that frees moored mines, which subsequently float to the surface so that they may be detected and destroyed. The helicopter is in a distinct nose- down attitude due to the large rotor thrust in the forward direction required to overcome the drag of the trailing rig in the water. In the RH-3 aircraft, for example, the pitch is 12 to 15 degrees nose-down, which is distinctly uncomfortable for the pilots.

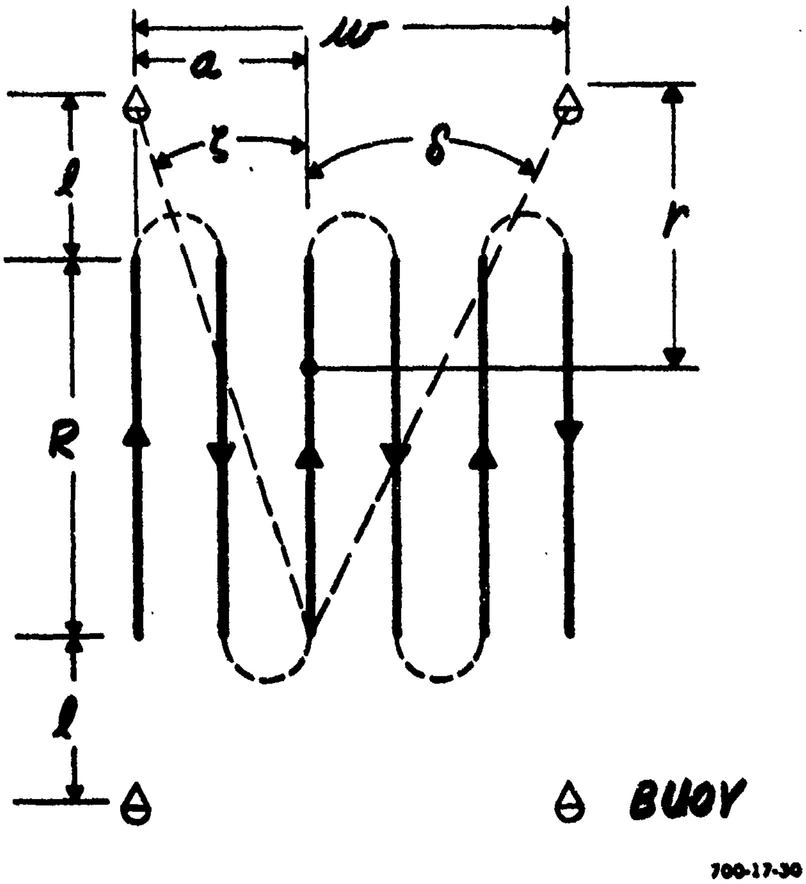


Figure 4-18
Grid Pattern for Mine Sweeping Operation

In the RH-53 aircraft, these nose-down attitudes are reduced to 7 to 8 degrees. Precise navigation is required under these demanding flight conditions in close proximity to the water, if the area is to be cleared effectively. Pilots consider these operations more difficult than an ASW hover on the water at one spot.

Mine sweeping is a daylight, visual contact operation. The accuracy of the sweeps currently depends on the skill and experience of the pilot in visually orienting the aircraft in relation to buoys which are strategically positioned for guidance, as well as any landmarks that may be available in the area. The tracks are 1 to 2 miles long in a field sweep, and about 1800 feet of line are being towed. Speed control is maintained by monitoring cable tension, which can be read out from a cockpit indicator. This cable tension is determined by the drag of the rig in the water, which is a function of the towing speed. Altitude is controlled automatically at about 50 feet, with altitude sensing accomplished by a radar altimeter. The pilot monitors this altitude by external visual reference to maintain a high level of safety in the operation.

The HUD can be used to increase the precision with which the pilot can sweep an area and to lower his workload in this demanding series of maneuvers. Referring to Figure 4-18, assume that it is desired to sweep the area defined by the rectangular dimension w and R. Consider four buoys positioned laterally at the extremities of the area to be swept, and longitudinally at distance (ℓ) from the ends of the tracks. Assume further that the distance (ℓ) is selected so that the angles (ζ and δ) are small for all positions on all legs of the sweep. Each leg is defined by the lateral dimension (a) and the leg length (R). Considering any point on a particular leg at a distance (r) from the buoy base, the geometry indicates that:

$$a = r \tan \zeta \approx r\zeta$$

$$(\omega - a) = r \tan \delta \approx r\delta$$

for small angles (ζ and δ).

Eliminating r from these equations yields:

$$\frac{\delta}{\zeta} = \frac{(\omega - a)}{a} = \frac{\omega}{a} - 1$$

Therefore, the ratio of the two angles (δ and ζ) is a constant for a particular leg, independent of the longitudinal position of the aircraft on the leg. The start of a particular track occurs at a value of r equal to (R + 1), and the initial settings for the angles (ζ and δ) are determined for this value of R.

Assume that the HUD has two images space stabilized with respect to the desired track heading angle, or the reference heading associated with this ground track. These images are presented as the two vertical index markers below the horizon line in Figure 4-19. The markers are oriented at the initial values of ζ and δ, and the total angle between them exceeds the angular subtense of the two buoys before the aircraft reaches the starting range ($r = R + \ell$) for each leg of the grid. When the aircraft reaches the starting range and is correctly oriented laterally, the two markers overlay the buoys. The lateral displacement between the markers and the buoys indicates the lateral deviation of the aircraft from the desired track. The total angle ($\zeta + \delta$) is increased continually as an inverse function of range (r), determined by Doppler or inertial navigation data, keeping the ratio δ/ζ constant. On this basis, lateral deviation of the aircraft is indicated by a displacement of markers with respect to the buoys throughout the entire track over the distance (R). If the navigation data is not available, the pilot can periodically adjust the total angle ($\zeta + \delta$) manually to agree with the angular subtense of the buoys and obtain essentially the same guidance information.

Speed control for towing is maintained with the HUD through the use of the cable tension circle in the display (Figure 4-19). This image is oriented in the vertical plane of the reference heading, and its position above the horizon represents a deficiency in tension in the cable, while position of the circle below the horizon represents excessive tension.

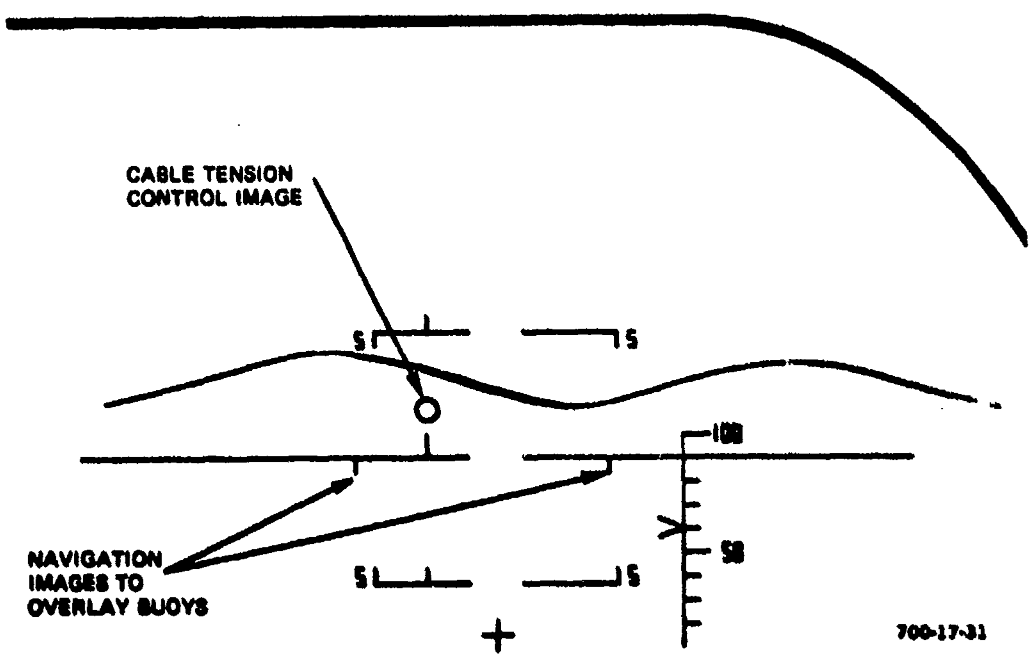


Figure 4-19
HUD Configuration for Mine Countermeasure Mode

This sensing has been selected to make the direction of motion of the cable tension image agree with the nose of the aircraft as the tension is adjusted to its correct value. The nose of the aircraft goes down as tension is increased, so that the circle is also moving down to the horizon. A similar relationship exists as tension is reduced to the desired value. Altitude is monitored by means of the readout of the altitude index on the scale on the right side of the display. The boresight image (cross) and the supplementary pitch lines at ±5 degrees complete the mine countermeasure display.

H. AIR-TO-GROUND FIRE CONTROL

1. Discussion of Helicopter Weapon Delivery Systems

Currently, helicopter and STOL weapon delivery systems consist almost exclusively of the firing of guns and rockets onto ground targets. This applies to all such operational vehicles including the AH-1/UH-1 series gunships, HH-2/HH-3/HH-53 series armed search and rescue helicopters, and the OV-10 STOL observation aircraft. The principal exception to this form of weapon delivery relates to the dropping of depth bombs by SH-3A, D helicopters against visually detected submarines close to the water surface. However, this method of submarine attack is rarely employed because the opportunities encountered for such an attack are quite limited. Homing torpedoes remain the primary weapon employed by ASW helicopters. If visual depth bomb delivery were ever adopted as a primary ASW attack doctrine by the Navy, a HUD would likely be required. Some of the ramifications of such a system, including CEP performance and submarine velocity sensing requirements, are discussed in Appendix E.

A number of special weapon delivery concepts, proposed or planned for helicopters, are presented in Appendix E. Perhaps the most noteworthy of these concepts is the high speed delivery of special bomb stores (e.g., FAE, MTW, napalm, anti-personnel) currently under study at

NATC, Patuxent, Maryland. Other concepts uncovered include recoilless rifle fire support, air-to-air intruder attack, and a system enabling a more accurate, pin-point drop of electronic personnel detectors at speed. All of these operations as presently conceived would use a HUD. However, no display analyses were made on these applications because of the preliminary, largely undefined or proprietary nature of the system requirements. Accordingly, the emphasis in display design was placed on air-to-ground fire control - still the primary helicopter weapon delivery mode.

Moving as well as fixed targets were considered in the study. Since certain land and water targets can assume speeds of up to 40 knots, this reflects a kinematic lead (i.e., allowance for target motion during projectile time of flight) that cannot be neglected. Since helicopters are not equipped with attack and MTI radars, sensing of target speed or relative aircraft-to-target speed must be accomplished visually. In most impact-point delivery systems, this is achieved by a simple estimation of target speed where the pilot anticipates future target motion by aiming the reticle ahead of the target. In fire control systems that compute kinematic lead as part of a total lead solution, target tracking is employed to derive relative angular velocity, and range is estimated. This approach, which is termed "lead computing sight", is used primarily in air-to-air gunnery. This system, and others such as vector rate sight, which requires absolute target velocity data, are described in Reference 3 together with their mathematical relationships. (Discrete visual acquisition techniques cannot be effectively employed in deriving target velocity.) However, the value in implementing total-lead-solution systems in helicopters is highly questionable, both because of the errors incurred in estimating or computing target range or velocity and the unlikelihood that high speed moving targets would be encountered in helicopter missions. The data deficiency noted is particularly adverse in boresight weapon attacks where a large range closure rate is experienced.

The only exception to this conclusion relates to the firing of off-boresight gun turrets by SAR vehicles against water surface craft. In this situation, whether the helicopter is hovering or at speed, range can be accurately and continuously computed from sensed radar altitude, and relative velocity derived from LOS tracking. The LOS angular tracking rate would normally be sufficiently large in off-boresight firing to yield an accurate solution.

Actually, the specific airborne fire control systems and associated trajectory equations that may be provided in any helicopter is beyond the scope of this study. Of interest in this study is the impact of the weapon delivery system on the display processing and format design. Except for new concepts such as the Honeywell Hotline System, little or no difference exists in the display format between an impact-point solution and one extended to include a kinematic lead for moving targets. In both cases, the pilot controls the sight or aircraft path to overlay a suitable image (e.g., aim circle) over the target. Also of interest in a study of this type is the development of new target acquisitions and ranging concepts which:

- Are essentially independent of the fire control equations.
- Specifically make use of HUD optical projector and digital computer elements.
- Alleviate the need for pilot estimation of range.

Such concepts are described in Section III of this report.

Armed H/STOL aircraft provide for the firing of boresight and/or off-boresight weapons. Boresight armaments include guns, rockets, and in some cases missiles, all of which at the present time are aimed and fired by means of a single, manually depressed gunsight reticle. Off-boresight weapons are comprised exclusively of gun turrets, rotatable in elevation and azimuth. Computed lead correction is simply mechanized from airspeed and estimated range data to account for the effects of aircraft motion and ballistic deflection.

2. Current Operational Techniques and Problems

In order to gain a first hand understanding of the operational techniques and problems associated with air-to-ground fire control, a number of interviews were held with Marine and Army helicopter pilots with Vietnam combat experience. Among the AH-1/UH-1 gunship pilots, there was unanimous agreement that the vulnerability of the helicopter to enemy fire is of compelling and overriding concern to them. Consequently, every effort is made to attack the enemy immediately and rapidly to minimize exposure.

There was general acceptance of the two- and three-axis discrete acquisition techniques for target ranging described in Subsections III.H.3 and III.H.4. Even in situations requiring an unplanned fast attack, it was felt that at least the copilot/gunner could execute the two acquisitions required prior to the weapon release. However, other targeting techniques that unduly expose the helicopter such as target overflight or station-keep tracking of a moving target to derive target speed were deemed unacceptable.

A straight-in dive attack with boresight weapons is the most effective and, therefore, the primary weapon delivery mode. This capability is currently provided in the AH-1 G, J and UH-1B gunships and OV-10 observation aircraft. Armed SAR vehicles (operational and developmental) are provided only with chin- or belly-mounted gun turrets for protective fire support. A typical dive attack profile is described as follows for the AH-1G Cobra. This gunship enters the dive toward the target slowly during which a predetermined speed/dive angle configuration is established. Dive angles of up to 60 degrees are possible although a more shallow attack is often used to allow more firing time on the target. A dive speed of about 140 knots is typical for the Cobra, which contrasts to about 60 to 100 knots for the earlier model UH-1B gunship. The pilot has complete control in the firing of the 2.75-inch FFARS rockets; the copilot can only control the firing of the minigun turret. A "canned" solution is used by the pilot in boresight gun and rocket fire control by means of a manually depressed reticle on the fixed gunsight. Rocket release altitude is typically 1500 to 2000 feet depending on the dive angle and consistent with the 2100 meter burnout range of this armament. These release conditions allow about 15 to 20 seconds of firing. Minigun firing commences somewhat later in the dive since its maximum range is 750 meters. During a turning breakaway, the gun turret is used by the copilot for suppressive fire support. Such off-boresight fire control whether conducted during breakaway, or suddenly at targets of opportunity, usually takes one of two forms. One involves area suppression in which the firing is dispersed to cover a finite area. The other reflects a firing pattern that rings a specific target point. Continuous, pin-point aiming at a target is seldom attempted for reasons presented later in this subsection.

The depressable gunsight reticle provided in the Cobra is a low cost representation of an impact-point fire control system, which is generally accepted as the best technique for air-to-ground fire control. This type of system, where the aim circle represents the anticipated point of projectile impact, was assumed, therefore, in the formulation of the display design described later in this subsection. (The Honeywell Hotline fire control concept may ultimately be accepted by the armed services as a superior approach. Unfortunately, however, since public disclosure of this system occurred at the completion of this study, it could not be adequately treated as relating to its possible introduction in helicopter gunships and its impact on HUD design requirements.) The most commonly employed technique in Vietnam is to continuously overlay the impact-point reticle on the target. Strafing or walk-in of the reticle line of fire through a fixed target is also possible, but not preferred. Helicopter pilots, however, do sometimes walk-in a rocket line of fire, but invariably for area coverage only. A number of pilots have also indicated that if confronted with a fast moving land or sea target, they might employ a strafing run rather than aim and fire continuously ahead of the target as indicated in Subsection IV.H.1.

The opinions of each pilot/gunner interviewed were solicited as to the problems and limitations that exist in current helicopter fire control systems. The following represents a composite of the principal problems, on which opinion was virtually unanimous.

- Gun Calibre - The 7.62-millimeter calibre of the gun turrets is deemed ineffective. Gunners want a gun calibre large enough to literally "chop down trees". (This limitation is unrelated to HUD specification.)

- Range Sensing - Fire control performance is adversely affected by the lack of accurate slant range to the target. A HUD can alleviate this problem by means of the kinematic ranging techniques discussed in Section III.

- Computation of Projectile Trajectory - A more precise solution of anticipated projectile trajectories (involving the sensing of additional parameters such as inertial velocity, wind, sideslip, etc and the implementation of more exact ballistic deflection equations) is required.

- Gunsight Reticle Stabilization - A need exists in both fixed- and moveable-optical sights to stabilize the aim reticle for the effects of vehicle attitude motion. Under most conditions, gunners have considerable difficulty maintaining the reticle on a fixed point target.

- Night Combat Operations - Aided-visual approaches, (IR/LLLTV) are being introduced in several helicopters to extend both close support and armed SAR operations to dusk and night conditions. The moveable optical aimsight constitutes one candidate means for accommodating the display and orientation control of these sensors.

The Army AH-56 Cheyenne with its rather sophisticated avionic system was designed to overcome some of these problems. The system includes an inertial reference set and a laser ranger.

3. Target Orientation/Ranging Techniques

A number of kinematically derived target orientation and ranging techniques are described in Section III. Specific recommendations for these techniques and other undescribed targeting methods for each known operational attack mode are presented in the following paragraphs.

- Boresight Weapon Delivery - Mode No. 1

  For low altitude situations requiring an immediate attack on targets of opportunity.

  (1) Off-boresight, two-point discrete acquisition by copilot followed by computation and storage of target position.

  (2) Continuous computation of target bearing/range/altitude while aircraft maneuvers for straight-in attack.

  (3) Target designated on pilot's HUD for re-acquisition (update) if necessary and impact point continuously computed.

(4) During pull-up and turn, copilot/gunner provides off-boresight suppressive fire support. Range data used in this fire control mode can be either that continuously derived in item (2) above, or data independently derived using continuous angular rate sensing method.

- Boresight Weapon Delivery - Mode No. 2

For situations involving dive attacks on known targets from relatively high attitudes.

(1) On-boresight, two-point discrete acquisition by pilot along flight velocity plane followed by computation and storage of target position.

(2) Continuous computation of target range used for impact point solution.

- Off-Boresight Weapon Delivery

For situations requiring immediate suppressive fire support (e.g., sudden appearance of target).

(1) Continuous angular rate sensing method used for target impact point solution.

Another method of targeting over land makes use of filtered radar and barometric altitude data, the equations for which are presented in Subsection III.E. The method is analogous to that presented in Subsection III.H.7, covering the special case of flight over water. Slant range is computed, typically by means of a divide servo, from smoothed absolute altitude and depression angle of the sighted target. This ranging approach represents a low cost, though less precise backup than the approaches outlined for each aforementioned attack mode. It's use is envisioned in situations where:

- Insufficient time exists for two discrete acquisitions
- Magnitude of relative bearing angle rate too small to enable sufficiently accurate computations of range
- Digital computer is unavailable or has malfunctioned thereby obviating kinematic ranging solutions
- Terrain along approach path to target is reasonably smooth

Still another target ranging method is one similar in principle to the hunter/killer weapon delivery systems recently developed by the Air Force. The concept advanced herein is a simplified version of these systems intended to improve gunship fire control performance under day/VFR conditions with a minimum of additional avionic hardware over the present complement. This concept is compatible with the coordinated operations of Forward Air Controllers (FAC), flying observation aircraft and attacking gunships. In current Vietnam operations, the FAC informs the gunships either visually or by radio of the location of a detected target. In the system conceived, voice communication would be extended to include two key tactical parameters; namely, altitude of target above standard sea level and average wind velocity. The system concept is shown in Figure 4-20. The observations aircraft is heavily instrumented; whereas, the gunship is rather simply equipped with:

- HUD (replaces existing fixed gunsight)
- AHRS (replaces existing VG/DG's)
- True Airspeed (TAS) sensor
- Keyboard data entry panel
- Calibrated pressure altitude sensor

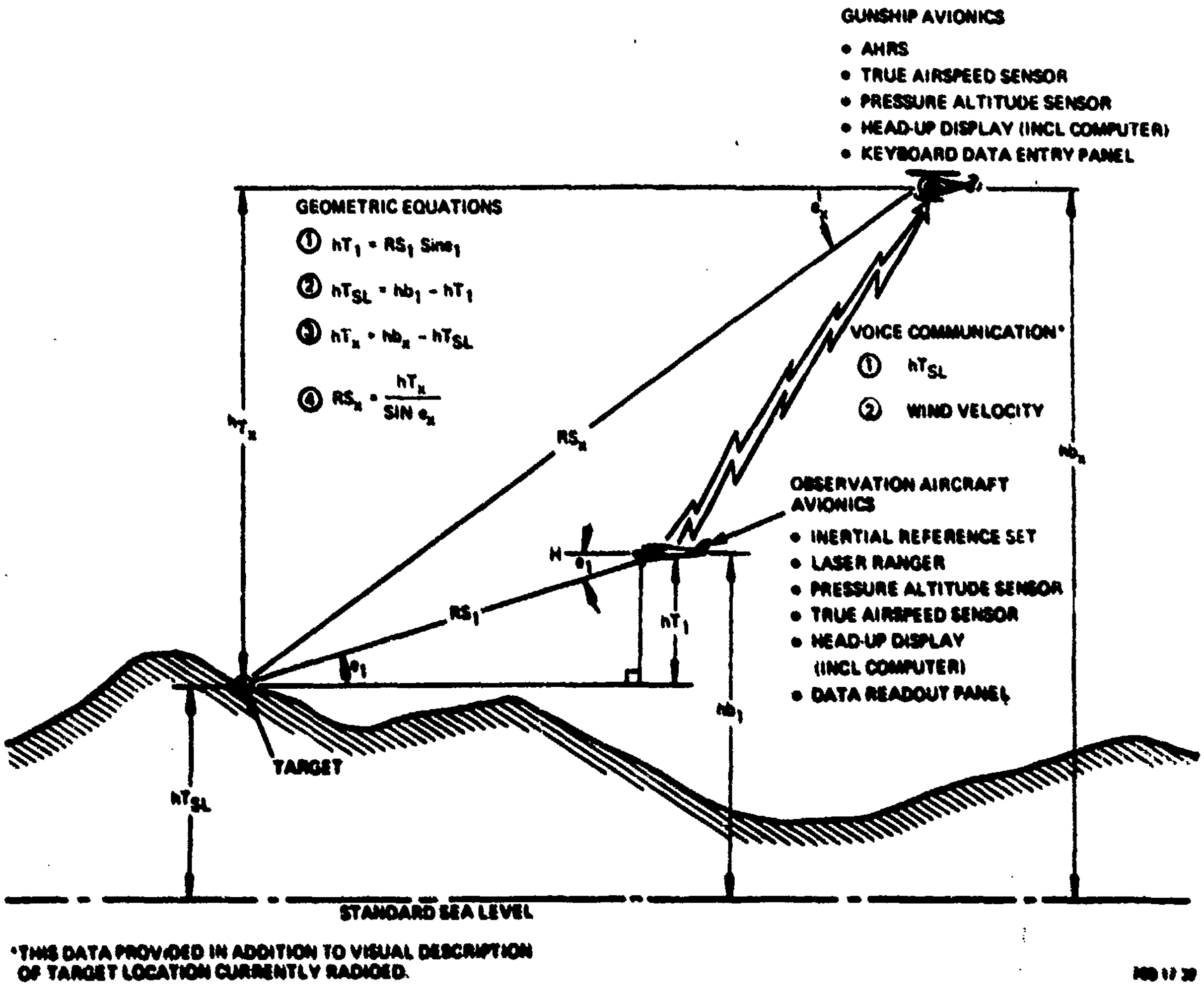


Figure 4-20
Simple Hunter/Killer Method of Target Ranging

The observation aircraft would typically be equipped as indicated in Figure 4-20. Other avionic system complements are possible to obtain the desired tactical data. The laser range and optical HUD projector is used, by means of discrete acquisition, to derive altitude above the target (hT_1). Acquisition accuracy is enhanced by the availability of precise altitude data from the inertial platform. At the instant of acquisition, pressure altitude (hb_1) is also sampled enabling the subsequent calculation of target altitude above sea level (hT_{SL}). The inertial reference set provides ground velocity data, which, together with sensed true airspeed, enables the calculation of wind speed and direction. Suitable filtering of the velocity data is required to provide an average readout of wind data. The calculations associated with the aforementioned functions are relatively simple and would logically be accommodated in a single computer. Such a computer could also be shared with the HUD processing functions.

The targeting vehicle can be represented by many fixed and rotary-wing aircraft, including the OV-10. It is not inconceivable that the flight leader gunship itself could be appropriately equipped to perform the targeting function either in a primary role or as a backup to an observation aircraft.

The copilot/gunner of the attacking gunsight enters the received data into the lead computer via a keyboard control panel. When the target is visually spotted, the attack can then commence. The wind data together with the on-board sensed true airspeed is used in the calculation of predicted ballistic deflection. A calibrated pressure altitude sensor, identical to that installed on the observation craft, enables the continuous computation of altitude above the target (hT_x). (Low cost, production pressure altitude sensors accurate to ±15 feet at sea level, are known to exist in the Air Force inventory.) Slant range is then derived for use in impact point solution, through the method described in Sub-Section III.H.6, in which the aim circle on the HUD is continuously overlayed on the target. Pressure altitude is also used in conjunction with a relatively low-performance, body-mounted accelerometer (Z-axis) in the computation of broadband vertical velocity - a parameter also required for impact point solution. Finally, an AHRS provides altitude data of moderate precision for use in earth stabilization of displayed data and in fire control computation. As in the case for the observation vehicle, it is reasonable to assume that a single computer can accommodate all the calculations noted above and the necessary HUD symbol generation and other processing functions.

This two-aircraft ranging system, if implemented, would likely require that a backup means of weapon delivery be provided on each of the attack gunships in the event the lead observation aircraft is disabled or a malfunction occurs in the avionic system. The low cost, filtered radar and barometric altitude approach described earlier in this paragraph is deemed appropriate for this purpose.

4. <u>On-Boresight Fire Control Display</u>

The design and operation of a HUD symbol format recommended for helicopter air-to-ground fire control with boresight weapons are described in this subsection. The design, which is predicated on an impact-point solution of the fire control problem, includes a target acquisition capability for use just prior to the weapon release period. The configuration is applicable for presentation on a fixed-projection unit only.

Since the acquisition and attack functions, in the recommended display, are both executed during a single pass over the target, operational simplicity is of utmost importance. The acquisition mode of the display design is in accordance with the kinematic targeting method presented in Subsection III.H.3, involving two discrete visual "picklings" of the target. The display for the various phases of a dive attack is shown in Figure 4-21. In the acquisition display submodes,

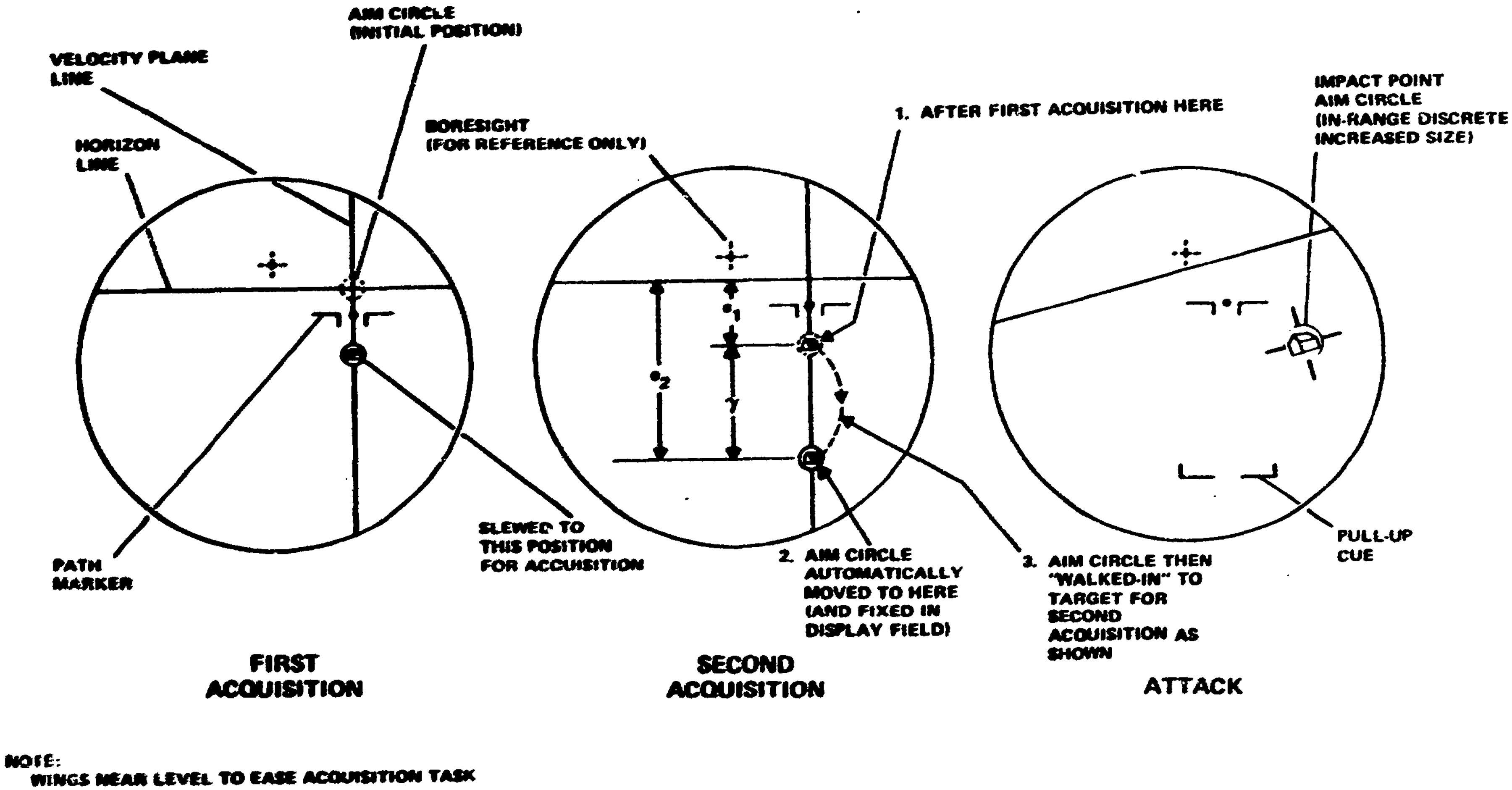


Figure 4-21
Air-to-Ground Fire Control Mode
(Boresight Guns/Rockets)

the cues consist of a path marker, azimuth velocity plane line, aim circle, horizon line and pitch scale. The velocity plane line, aim circle and path marker are all tied together and positioned laterally from boresight by drift angle augmented by high frequency heading data for the purpose of stabilizing the images to the real world. Early in the pass, the pilot heads in toward the target by aligning the velocity plane line onto the target. Maintaining the lateral path on the target is consistent with current attack procedures and simplifies the acquisition task considerably; to do otherwise, results in an increasing relative bearing angle where the target rapidly moves away laterally in the display field. It is rather difficult to accurately acquire such a target while in a banked turn. The pilot is required to continuously maintain his lateral flight path on the target between the two acquisition points in order to minimize lateral deviations from an ideal straightline path established in the computer targeting solution. Although this flight situation implies an essentially wings-level condition, the pilot is permitted to establish small roll attitudes even at the points of acquisition to correct for path deviations. With respect to the vertical plane, the pilot is not constrained to any path and resulting altitudes between the two acquisition points.

Prior to the first acquisition, the aim circle appears on the horizon line. When the helicopter has been maneuvered so that the velocity plane line overlays the target, the pilot manually slews the aim circle downward to capture and "pickle" the real-world target. This direction of slew is preferred since the target is also moving downward in the field. As an alternate approach, the pilot can slew the aim circle to a position just below the target and "walk-in" the then fixed-circle cue to the target for acquisition. The acquired depression angle (e_1) and other angles shown in Figure 4-21 are the same as that presented in Figure 3-8. All of the angles shown for both acquisitions are measured in a vertical plane perpendicular to the earth's local horizontal. This is effected by appropriate pitch and roll stabilization of the velocity line and aim circle so that the velocity line is always perpendicular to the horizon line. The velocity line tied to the path marker facilitates the acquisition task and the lateral path control requirement previously stipulated.

Immediately upon execution of the first acquisition, the aim circle is automatically repositioned downward in the field by a predetermined number of degrees. This enables the pilot as he continues his flight to "walk-in" the aim circle to the target for the second acquisition. The magnitude of this differential depression angle (identified as "γ" in Figure 4-21) should be sufficiently large to assure an acceptable systematic accuracy in the solution of the oblique triangle geometry equations derived in Appendix B. A fixed value of γ would constitute the simplest design approach. However, further analysis may indicate that a variable γ is warranted where this angle would be computed as an adaptive function of the sighted depression angle (α_1) and smoothed radar altitude at the point of first acquisition. The objective in this latter, more sophisticated approach is to ensure, irrespective of the attack conditions established by the pilot, that adequate target distance (and hence time) exists at the second acquisition point for the firing of weapons during the attack phase.

Upon completion of the two acquisitions, the attack format shown in Figure 4-21 is presented on the display. In this submode, the symbols consist simply of a path marker, horizon line/attitude scale, aim circle, and a pull-up or breakaway cue. The aim circle in this case is automatically positioned in elevation and azimuth from computed lead angle data representing the predicted point of projectile impact at all times. During the attack phase, the pilot controls the aircraft path to continuously overlay the aim circle onto the visual target. Weapon release is indicated by a sudden increase in the size of the aim circle, which is effected with the receipt of an in-range discrete. Earth-stabilized fins are placed on the aim circle to enhance the ability of the pilot in properly sensing two-axis deviations from the target, thereby assisting him in his steering task for target overlay. Since gun and rocket projectiles are not free-fall devices like bombs, the display of a vertical trajectory (impact) line is an invalid proposition. The path marker incorporated in the display is not a controlling element; rather, it is presented for flight status purposes only. The pull-up cue moves up from the bottom of the display field as the helicopter closes in on the target. Breakaway is commanded when the pull-up cue arrives at the path marker. In advanced weapon delivery systems for tactical aircraft, the pull-up command is computed as a function of several flight parameters to ensure a safe breakaway maneuver.

I. SEARCH AND RESCUE

1. General SAR Mission and Systems

Search and rescue is one of the most important and difficult missions assigned to helicopters. Increasingly, high mission performance goals are being established by the Navy and Air Force for combat rescue operations under all weather conditions. In addition to providing more effective location-finding communications systems, major emphasis is being directed toward providing full night/IFR low level capability with appropriate detection, terrain avoidance, and automatic approach and hover control systems. Of particular importance and interest is the Air Force's current development (PAVESTAR) of a full night rescue vehicle. Ceiling and visibility play an important part in the execution of an SAR mission as it is accomplished today in Vietnam. Without full night capability, unless the SAR helicopter can safely search with visual reference to the terrain, the mission is delayed until more favorable conditions exist. Ocean searches can be accomplished in poor weather or night conditions; however, as in operations over land, visual detections and identification of the rescue must be made for recovery. The positive establishment of such a visual (or aided-visual) reference is an operational doctrine that must always be satisfied before the helicopter is committed to a final descent to hover.

In analyzing the SAR mission profile, it is clear, as is the case with most tactical missions, that the critical terminal phase represents the greatest potential for HUD applicability. Although applicable to current VFR operations, the need for head-up flight control is deemed most compelling for the advanced limited and full night rescue system where the pilot is required to simultaneously perform the following functions:

- Basic flight control
- Terminal approach navigation (both vertical and lateral steering)
- Low altitude terrain avoidance
- Visual detection of rescuee

It is, of course, possible to appropriately divide these functions with a two-pilot crew using appropriate head-down instrumentation. What is recommended in Subsection IV.I.2, however, is a concept that integrates these functions in the command pilot's HUD to satisfy the pilot's innate desire to look out the windshield during low altitude, low visibility flight and to augment the copilot's primary task of detection achieved with panel-mounted instrumentation.

A generalized SAR flight profile is shown in Figure 4-22. Initial notification of a downed airman is made via voice communication to an HC-130 search aircraft orbiting an assigned station covering a specified area. The HC-130 immediately proceeds to the scene and, after establishing voice contact, obtains a description of the surroundings. Meanwhile, the SAR helicopter(s) alerted for the rescue operation is directed to the vicinity of the downed airman, from TACAN position or geographic coordinate data relayed by the HC-130 command ship. The helicopter(s) dashes to the general area at between 5,000 to 10,000 feet of altitude whereupon a search doctrine is adopted consistent with the crew's prior knowledge of the rescuee's situation. For example, if it

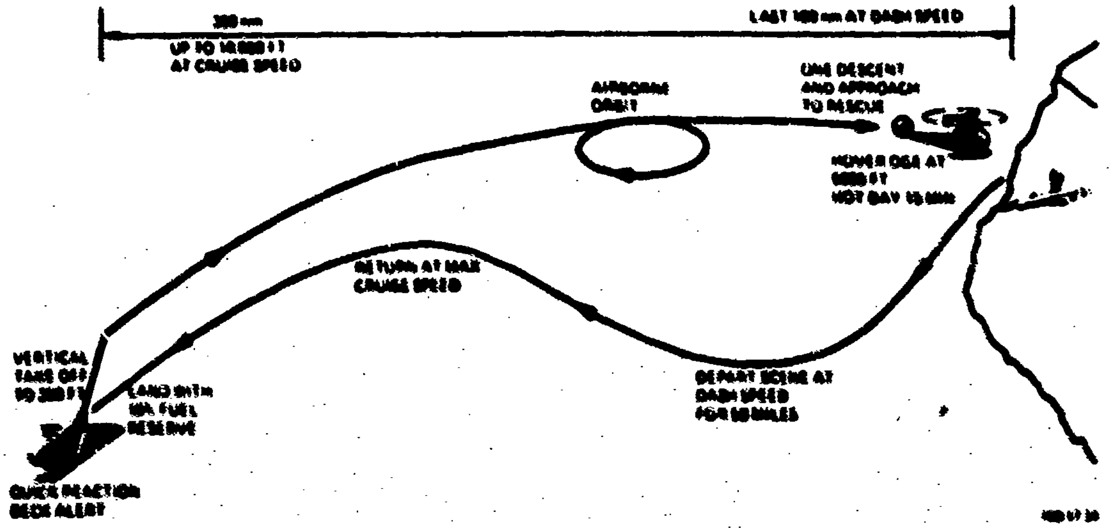


Figure 4-22
US Navy SAR Flight Profile

is known that the rescuee is in the vicinity of a river, a contour search is initiated. Upon locating the general area, a rapid spiral descent to about 2000 to 3000 feet is executed. Generally, at this point the helicopter crew has established voice contact with the rescuee. The task now is to pinpoint the position. This is achieved by homing in on the rescuee's personal survival radio signals ("beeper"), in which the helicopter flies over the survivor during the first pass. The location is noted -, the ADF instrument needle swing. Invariably, in such rescue operations over enemy-held territory (especially the rough, dense terrain of Vietnam) radio homing is the only means available for localization since the rescuee is either difficult to detect or he cannot freely expose himself for a sustained period of time. It is because of this adversity in detection, especially under limited visibility conditions, that a means for acquisition and storage of the airman's position be provided upon the initial sighting.

It is desirable that the initial overpass be made at as low an altitude as possible, since ADF portable radio transmitters are not very useful at high elevation angles. Hence, a radar-directed, terrain-avoidance system is under active consideration. Durin, one or more overflights, visual or aided-visual detection is attempted. When visual detection occurs, communication is again established for identification and approach guidance purposes via voice and electronic homing (and sometimes flares and SDO-5E flasher light guidance). After assessing the tactical situation in terms of terrain, wind, enemy threat, etc, the final approach course and descent angle conditions are selected, and the rescue is effected at a 150- to 200-foot hover.

The Navy's concept for an advanced SAR helicopter system calls for a full night/IFR weather capability under minimum visibility conditions of 125-foot ceiling and 1/4-mile range. One of the principal mission performance goals stipulated for such a system is the rapid detection, identification, and acquisition of the rescuee so that a fast descent and a single approach to hover can be accomplished. To meet the desired mission goals, a more sophisticated avionics system is conceived; this system is comprised of more extensive and improved communication and navigation, terrain-avoidance, and detection elements. For example, in the area of UHF direction finding where UHF voice transceivers (e.g., portable ground transmitter PRC-90) and ADF (e.g., ARA-25 or ARA-50) provide voice communications and identification and homing bearing signals, recent developments are being considered to provide range finding as well. Although these radio systems provide some degree of capability in locating a survivor without visual contact, both the Navy and Air Force still insist on visual contact before a final committment is made to go into a rescue hover - especially in a known defensive environment. Visual contact is indispensible for the rescuee who does not possess a locating aid. Where enemy action is not a factor in a night rescue, the use of flares or overt and covert lights is the obvious answer. In hostile territory, the use of image intensifiers, either direct-view or via LLLTV with covert illumination (infrared or ultraviolet), is dictated and has been incorporated in the Air Force PAVESTAR program. These devices, both forward looking for approach and downward looking for hover, enable aided-visual detection and acquisition, only, and do not solve the communication and identification problem.

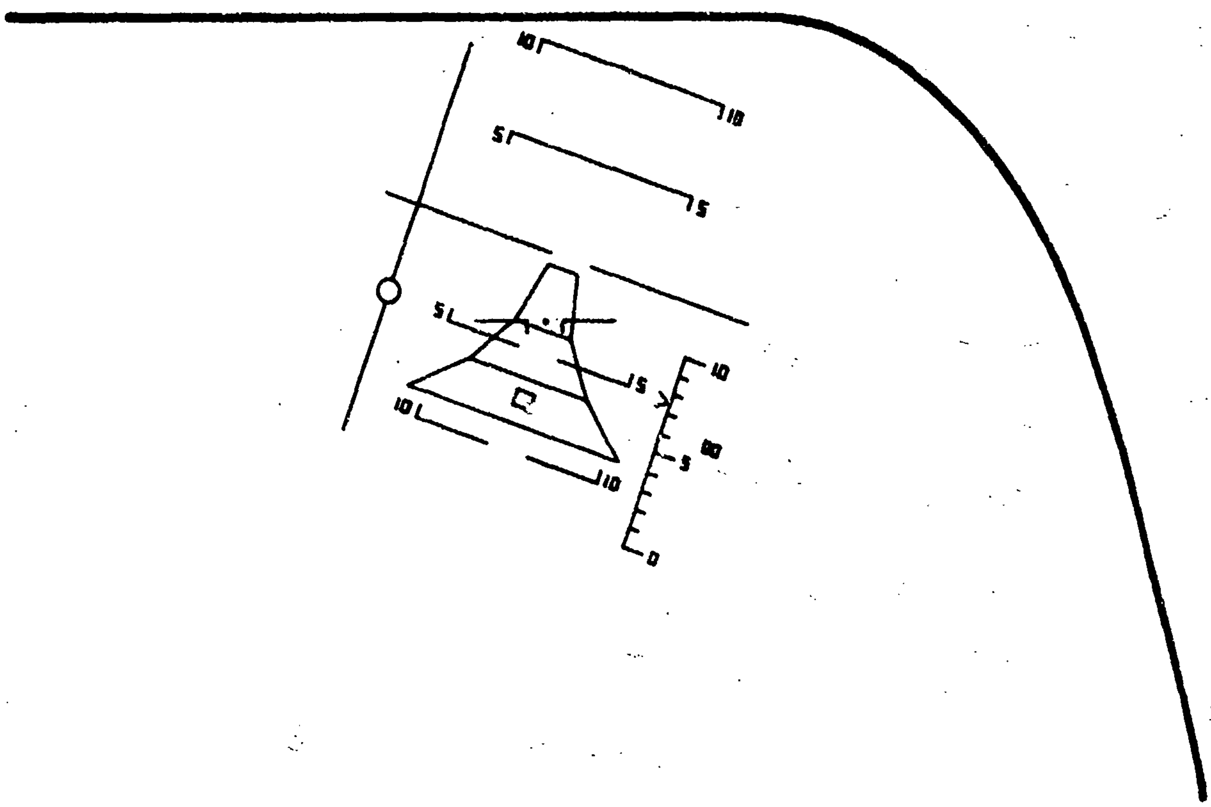
The detection problem, when coupled with critical low altitude maneuvering and approach flight under dusk or night conditions, establishes an important if not compelling need for a HUD. The need for head-up flight control by the command pilot is accentuated when enemy defensive fire is encountered. In the following paragraphs, in which the recommended display is described, a concept is defined for an interchange of designated position data between direct head-up eyeball detection by the pilot and aided-visual detection by the copilot on the panel-mounted TV monitor. The probability of initial detection is most certainly enhanced if the command pilot is controlling through the windshield, since his viewing field is considerably greater than that provided by a pointed TV camera. In addition, under certain dusk and moonlight conditions, earlier detection through direct visual contact may be effected because of the superior resolution characteristics of the eyeball to that of 525-line TV system. Direct visual detection of lights is also superior to that of LLLTV under relatively dark conditions because of the higher viewing contrast.

2. Radio Homing Search and Acquisition Display

The HUD format recommended for low altitude homing search and acquisition flight at night is shown in Figure 4-23. This format embodies all the symbols comprising the terrain-following display of Figure 4-12 and, in addition, includes a constant bearing line and aim circle. The range-gated, peak-elevation data used to generate the terrain carpet lies along an earth-stabilized vertical plane passing through the ground velocity vector. This data generally can be extracted as one azimuth segment from the terrain-avoidance radar, providing wider azimuth coverage. Prior to the terminal phase of a homing operation, where lateral maneuvers are required in low altitude search and holding patterns, the pilot relies on his primary terrain-avoidance display (i.e., forward-looking shades-of-gray or TCPPI panel-mounted presentation). However, during homing at close distances, straight-ahead flight is normally conducted - hence, the selection of a terrain-following display.

A radar terrain-avoidance system has been specified to provide the night VFR/IFR weather capability desired in SAR operation. In day VFR operation, it is likely that the terrain-avoidance system will be deactivated, thus blanking the terrain carpet and director images from the display.

When communications have been initially established and homing signals are being received, the helicopter immediately heads-in toward the transmitter location. To enable visual head-up homing control, a



700 17 36

Figure 4-23
Radio Homing Search and Acquisition

vertical bearing line image, which is a true representation of constant bearing in the real world for all elevation angles, is provided. Lateral steering guidance is effected by flying the path marker to overlay the bearing line. The bearing line and connected earth-stabilized aim circle shown in Figure 4-23 also serve to assist in the task of detection and acquisition. The line localizes the region to which the controlling pilot should devote his attention for finding the survivor. If a detection is made at a sufficiently large distance, acquisition of the position for subsequent designations is negotiated in the following manner. The bearing signals that normally position the line are deactivated from the display, and the bearing line is locked coincident with the path marker by a pilot-activated discrete. The pilot then proceeds to effect two discrete acquisitions at different points in the flight in much the same manner as that described for air-to-ground fire control in Subsection IV.H.4. The bearing line is continuously superimposed on the rescuee in azimuth by the control of lateral path. The aim circle is then slewed in elevation until a total two-axis capture is achieved. The pilot may elect to quickly execute the second acquisition by the slewing process rather than the walk-in technique described in Subsection IV.H.4, if he is concerned about losing sight of the survivor (or light) because of terrain or visibility conditions. Aircraft path control is used for lateral alignment of the aim circle because acquisition via two-axis slew control of the circle is deemed too difficult for the controlling pilot.

Alternate methods of detection and acquisition are available, reflecting either redundant or substitute means to the technique described above. Time line analyses and simulation may prove night SAR acquisition using HUD to be unsatisfactory or too formidable a task for the controlling pilot, active and concerned as he is in basic flight control, navigation, terrain avoidance, voice communication and possible enemy defensive fire. One obvious method of acquisition, although not very accurate and lacking the necessary positive detection, is to "pickle" the geographic coordinates of the ground transmitter during the point of overflight. Another is to assist the copilot in aided-visual detection by rapidly slewing the aim circle in elevation to the approximate position of the detected or suspected survivor position and designating this location to the copilot's LLLTV display for a more positive detection and accurate cursor acquisition. Designation would logically be accomplished by automatic positioning of the cursor and/or reorienting the camera look angle in elevation. Similarly, during the homing and detecting phase, when the copilot is viewing the TV monitor, he may designate a suspected position on the pilot's HUD for confirmation purposes. The designated image would appropriately comprise a synthetic symbol such as a square, although a TV raster encompassing a small circular or square field of 3 degrees in size properly superimposed - 1:1 onto the real world has been conceived. The objective in all these and any other arrangements of data interchange between head-up and head-down electronic displays, is to extract the greatest benefit in combined visual and aided-visual capability to improve the odds of detection.

To summarize, the HUD recommended for day and night homing search operations encompasses the information necessary for basic flight control, terrain avoidance, lateral terminal navigation, and detection and acquisition. After detection, identification and acquisition have been effected, the pilot would then either immediately proceed with the final letdown approach or maneuver around for a new approach at perhaps a new course. The display shown in Figure 4-8 would be presented on the HUD for an IFR instrument approach where the aim point is designated from the stored acquisition data. Without approach landing guidance, however, indications are that a panel-mounted VSD presenting LLLTV with superimposed flight situation symbol data will be the primary control/display mode. The HUD, if incorporated, would represent a backup. The display of terrain-avoidance radar data, either head-up or head-down, would be of little value in the last 1/4 mile of the approach because of the blind radar return envelope associated with such radars. When the vehicle finally enters into a hover, the HUD reverts to the configuration of Figure 4-10. It is likely that a HUD hover display will be relegated to a backup status, since a downward looking TV and automatic hover system is planned for horizontal position control and stabilization during night/IFR operations.

SECTION V

OPTICAL PROJECTOR DESIGN STUDIES

Experience has clearly demonstrated that the optical projection unit represents the most difficult tradeoff problem in the specification of a HUD. An appreciable effort was expended in this area leading to the synthesis of specific projector configurations, optimally designed for helicopter applications.

A. INITIAL DESIGN ANALYSES

Early in the study program, Sperry contracted the Farrand Optical Company for consultative engineering and design series on the critical projector element. The overall purpose in contracting this support was to ensure that the optical designs recommended for helicopters represented not only practical, realizable solutions, but the latest advancements in the state of the art as well.

Farrand's first task consisted of preliminary design analyses on three candidate optical system approaches to HUD application in helicopters:

- On-axis refractive (with internal folding mirror)
- On-axis reflective
- Off-aperture reflective

As part of the initial effort, Farrand was encouraged to seek new design concepts so as to yield substantial increases in field of view over that previously attained for an equivalent set of size, weight, performance and cost characteristics. (This goal was established early in the program as an anticipatory requirement for helicopter HUD.) Emphasis, in the design studies, was directed at achieving reductions in weight from that associated with current state-of-the-art designs.

The results of this effort are contained in the Task I report submitted by Farrand (Appendix C). The report presents a summary of the tradeoff analyses and comparative evaluations conducted on each of the three optical projection configurations, where the major advantages and disadvantages of each approach are discussed. The designs analyzed and subsequently established for each of these configurations reflect two important innovations. The first makes use of curved CRT faceplates as a powerful tool in maintaining good parallax correction over wide fields, thereby enabling the extension of mapped fields to at least 35 degrees and beyond with acceptable parallax errors. Actually, computer ray trace analyses indicate that in certain optical system designs, mapped fields of 40 to 50 degrees with acceptable performance may be possible with the curved faceplate approach. These faceplates are all of spherical curvature shape for compatibility with the lens design. The curvature is concave for the on-axis refractive and off-aperture reflective systems and convex in the case of the on-axis reflective system. The use of a concave image plane surface for the refractive and off-aperture reflective system also yields as a by-product advantage the elimination of the first two lens elements immediately adjacent to the CRT image surface. There is no essential difference, other than a constant of proportionality, in the transfer function of CRT beam deflection to yoke current between flat-face and curved-face tubes.

The only potential problem concerns the need for a dynamic focusing arrangement with the concave faceplate to alter the beam focus as a function of deflection angle and thereby maintain acceptable spot size. However, based on preliminary investigations and discussions with CRT manufacturers, this problem doesn't appear to be serious and can be satisfactorily solved with relatively low cost circuit implementation. One positive method of eliminating the need for dynamic focusing with concave faceplate designs uses a fiber optic faceplate with a convex inner surface and the required concave outer surface. Such a faceplate, which allows for independent curvature on both the front and rear surfaces, might also be used to advantage in correcting mapping errors. The fiber optic approach, however, is quite expensive and results in some sacrifice in brightness.

As an interrelated and essential adjunct to the curved faceplate concept, a second innovation was developed by Farrand, which, with the aid of programmed computer ray trace solutions, optimizes the mapping match between the CRT and optics to significantly reduce distortion errors. Although the process (and associated equations) conceived as applicable to both flat and curved faceplate CRT's, it is especially important in the design of wide field optical systems of 35 degrees and larger, in which relatively large distortions (i.e., image position mapping errors) are usually incurred.

Essentially, the new mapping formulation recommended involves changing the maximum beam deflection angle in order to alter the mapping function previously employed by Sperry and Farrand on past 25-degree field HUD developments. (Refer to the end of Task I report in Appendix C for equations describing this earlier function.) Although largely developed during the Task I effort, the new mapping concept is described under the Farrand Task II report also contained in Appendix C. The rather spectacular reductions in mapping errors achieved at the extremities of 35-degree field systems are shown by the computer-generated data tabulated in Figure 4 of the Task II report.

Each of the three candidate model systems were error optimized for mapped fields up to 35 degrees, and the three principal geometric CRT parameters of axial length (K), diameter (2P), and maximum deflection angle (ϕ_{MAX}) were established. The basic CRT and optics mapping equations remain unchanged from those previously employed; only the tube geometry noted above and deflection sensitivity as represented by the constant-C are altered.

The second phase of Farrand's effort involved a comprehensive effort in quantifying the principal physical and performance design parameters for each of the three selected optical system types analyzed during the Task I phase. In each of the three system types, data was developed in family-drawing format covering a wide range of overall system characteristics and goals relating the aperture, field of view, pupil size and weight. All of the optical designs reflect the innovations discussed earlier in this section and a number of other state-of-the-art advances toward simplification and reduced weight. As a supplementally assigned task, design analyses were conducted on the use of plastic lens elements in HUD projectors. Based on a qualifying risk assessment involving accuracy and environmental restrictions, estimates of weight savings over conventional glass element designs are tabulated for each of the quantified optical designs.

The design data is contained in Farrand's Task II report. The purpose in undertaking this quantification effort was to assist Sperry in subsequent design specification tradeoffs involving specific helicopter installations, leading to the definition and recommendation of final candidate projector configurations. (Refer to Subsection V.C.)

The data provided enables two levels of tradeoff. The first reflects a gross tradeoff analysis for establishing the best optical system type for the given installation. This tradeoff selection is primarily affected by cost, weight, accuracy, transmission efficiency (as affecting required image brightness), display symbol requirements (as affecting type of image source), and cockpit installation characteristics/constraints (as affecting field of view). With regard to this latter factor, pupil-field reference drawings (Drawing No. 137151 and 137152) are provided in Appendix C; these drawings will assist the layout designer in determining the monocular and bimonocular fields over a variety of head positions and eye distances, for any selected projector configuration.

Upon selection of the basic optical system type, a second, lower level tradeoff is conducted in which a specific projector is synthesized through more refined tradeoffs between weight, size, fields of view, apertures and CRT or servo reticle size. In this case, an interpolation process is used in extracting trial sets of design parameters from the tabulated family data, until an optimal set is yielded. The number and assortment of optical models for which data was generated is quite sufficient to permit such interpolation with reasonable accuracy.

A concluding comment is in order concerning the effort undertaken to generate the aforementioned HUD optical design data. This effort has very likely resulted in the most extensive compilation of documented, published data of this type. In addition, the data is reasonably precise, since it reflects considerable computer-aided ray trace solutions of optical models, which are largely predicated on successful prior developments by Farrand. Accordingly, it is believed that this data can be of substantial benefit to avionic display systems engineers, supplementing the value derived from its use in this particular study program.

Directional aiming sights were also investigated during the initial design analysis phase. An evaluation was conducted on the relative merits of advanced, helmet-mounted sights as a class against the more conventional hand-gripped, swivable aim sights of the type presently installed in the AH-1G, J and HH-2C helicopters. The evaluation is necessarily of a limited qualitative nature because time did not permit an in-depth study of the multitude of existing helmet sight designs. At least nine companies and one government center are known to have been engaged in helmet sight development over the recent past.

The evaluation is based on Sperry and Farrand's familiarity with helmet sights derived from past in-house design studies and developments, augmented by literature reviews and interviews with helicopter systems engineers and pilots in which their experiences and/or opinions regarding helmet sights were solicited. A discussion of the advantages and disadvantages of helmet sights as conceived by Farrand is presented in the Task I report of Appendix C. A comparison between helmet sights and hand-gripped aimsights performed by Sperry is summarized in Table 5-1. Two image sources are considered for each sight: namely reticle and CRT. Electro-optic position sensing is assumed for the helmet sight rather than a mechanical head-tracker.

In any evaluation of this kind, any one factor can often dictate the selection. For example, for a single-place, fixed-wing aircraft, a helmet sight is obviously the only practical approach. On the other hand, if extremely high accuracy is required, a rigidly supported and precisely boresighted conventional aimsight may be dictated. However, based on critique of Table 5-1 a single aimsight choice for two-place helicopters is not obvious. For a simple, unstabilized reticle design, the helmet sight is preferred, particularly where target range is sensed by a pointed laser. Where a stabilized reticle is specified for improved tracking accuracy, the hand-held aimsight is preferred because of its substantially lower cost than a helmet sight/CRT combination. (The CRT is the only practical method known of displacing an aim circle image in a helmet sight.) Where a CRT directional sight is required for the presentation of IR/LLLTV pictorial video, additional flight tests appear to be required to establish the acceptability of helmet sights. It is understood that instances of disorientation have been experienced by pilots, apparently due to the visual confusion between the cockpit and display imagery occasionally being viewed simultaneously. This possibility is non-existent in the operation of a hand-gripped aimsight, simply because head motion is independent of the display.

TABLE 5-1

COMPARATIVE EVALUATION OF AIMSIGHTS

Factor	Reticle		CRT	
	Helmet Sight	Hand Sight	Helmet Sight	Hand Sight
Attitude Stabilization Capability	No	Yes (with 2 servos)	Yes	Yes
Accuracy (estimated)	7 mr	3 mr	10 mr	6 mr
Fatigue Effect of Weight/Inertia	Moderate	None	Significant	None
Instantaneous and Total Field of View	Wide	Moderate	Wide	Moderate
Bulkiness and Cockpit Space Required	Negligible	Appreciable (Except in Overhead Stow-away Position)	Negligible	Appreciable (Except in Overhead Stow-away Position)
Ease of Operation/Slew Response Time	Excellent	Fair	Excellent	Fair
IR/LLLTV Video Display	No	No	Yes (However, Disorientation is potential problem)	Yes
Use for Flight Control	No	No	Yes	No
Alignment Maintainability	Poor	Good	Poor	Good
NOTE: Cost and weight data undetermined.				

B. CANDIDATE DESIGN OF STABILIZED AIMSIGHT

Since helmet sights have already been extensively developed, no effort was made in this program to undertake new design studies on this relatively complex device. Rather, a layout design was generated of a hand-gripped sight containing a simple aiming reticle, servo stabilized for attitude motion. Based on the evaluation of Subsection V.A, this design is deemed to be perhaps the most effective approach to satisfying a number of VFR aimsight applications established in this study.

A layout drawing of the aimsight assembly is provided in Figure 5-1. A two-element on-axis reflective system is used to project an illuminated image. Simple dc servos are used to position the reticle in elevation and yaw. The 2-3/8-inch diameter aperture, ±5-1/2-degree range of reticle motion and 3-1/2-inch focal length are a result of tradeoffs involving field of view, size and weight considerations. Since the aperture permits only one eye viewing, an unsymmetrical hand-grip arrangement is preferred as shown in Figure 5-1.

An installation layout of this aimsight on the copilot's side of the H-53 cockpit is shown in Figure 5-2. Two four-bar linkages are used in the overhead mounting to provide the necessary 2 translational degrees of freedom in elevation: rotary support is used on top for rotation in azimuth. The study confirmed the feasibility of this installation, principally in terms of providing the copilot with the ability to aim the sight over virtually all possible windshield viewing angles - fore, starboard and port. Stowage of the sight, overhead and aft of the copilot, is easily achieved. Cockpit layout studies conducted on the H-3 and H-46 helicopters also confirmed that this aimsight design is fully compatible for installation on the copilot's side of each of these vehicles.

C. CANDIDATE DESIGNS OF FIXED OPTICAL PROJECTORS

The terminal design tradeoff and installation studies conducted to evolve a number of projector designs as candidates for helicopter application are described in this subsection. To produce practical, optimal solutions and otherwise contain the effort within manageable bounds, the study was principally directed to a single, specific cockpit installation: namely the CH-53. Other side-by-side heavy helicopters (the H-3 and H-46 series) were subsequently investigated to assess installation compatibility of the CH-53 candidate projectors. However, time did not permit similar investigations for the three other operational helicopter/STOL aircraft in the Navy/Marine inventory: namely the AH-1, OV-10 and H-2 series.

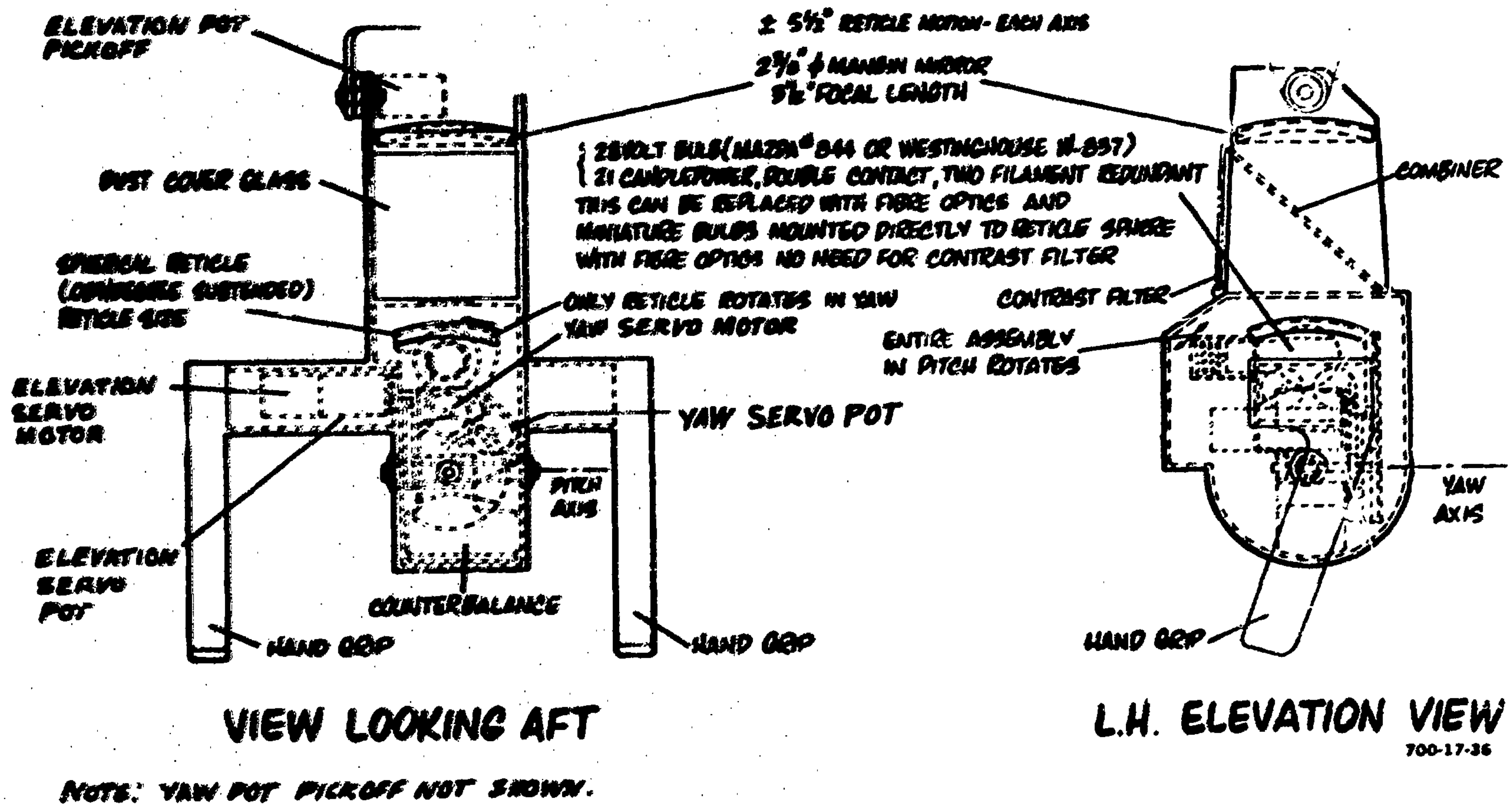


Figure 5-1
Layout of Aimsight with Stabilized Reticle

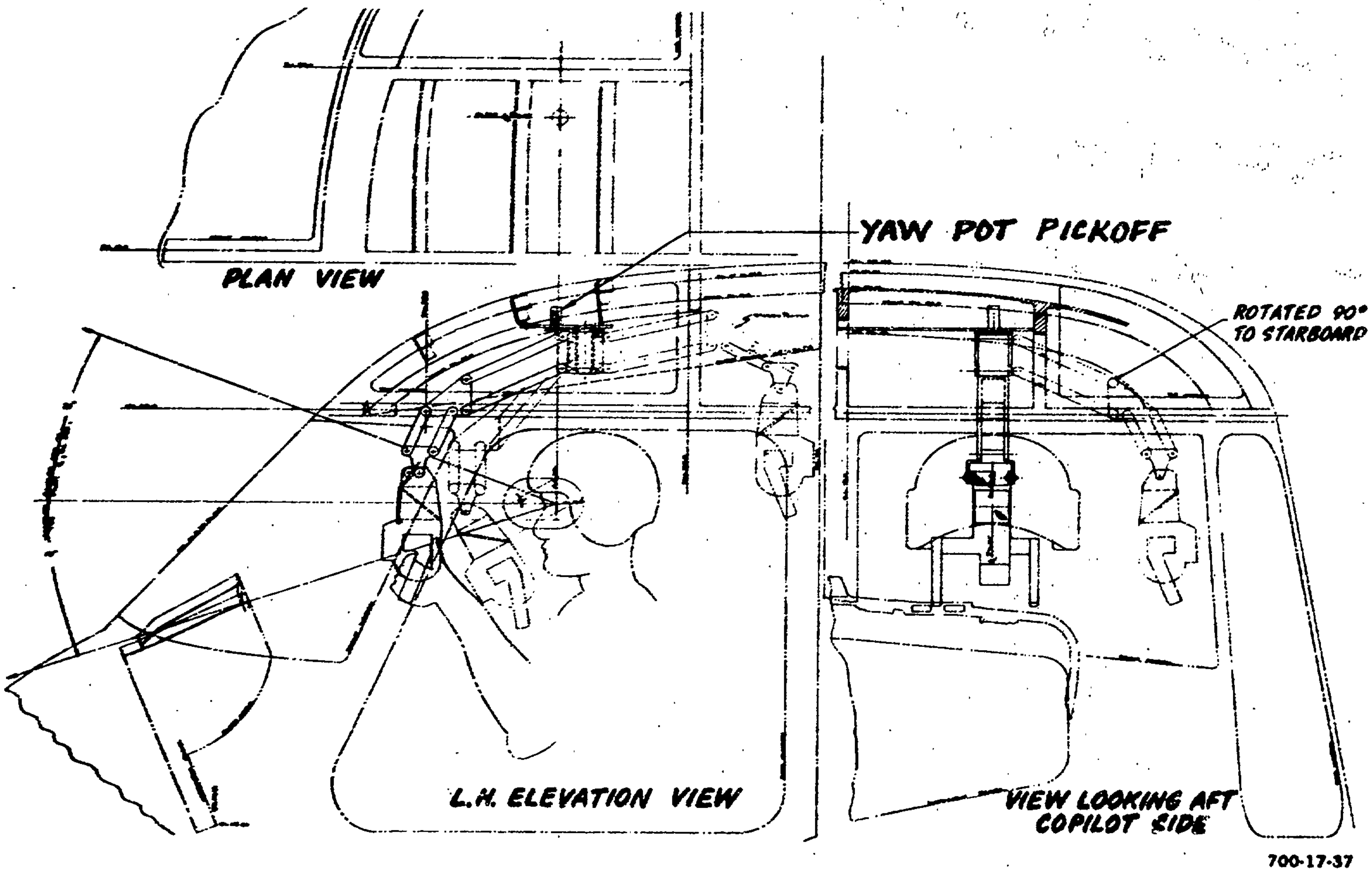


Figure 5-2
Installation of Aimsight on Copilot's Side of H-53 Cockpit

The CH-53 was selected for primary attention for the following reasons:

- Extensive multi-mission role (including armed search and rescue, assault transport, and mine countermeasures) presents many critical operational modes applicable to effective HUD utilization

- Extensive sensor and computer instrumentation, which presently exists (including SCNS in transport version), enhancing utility and effectiveness of HUD without major sensor retrofit

- Vehicle not as sensitive to increases in cost, size and weight as other smaller helicopters

The tradeoff and installation design studies conducted are essential to the generation of optimal projector configuration for any HUD application. However, to ensure that each projector configuration synthesized reflects realistic physical and performance characteristics, the detailed optical design data developed by Farrand earlier in the program in family drawing format was used (Subsection V.A). The candidate projectors encompass a range of cost and complexity levels relating to both the optical system and image source types. In addition, a range of field of view (i.e., aperture) is established, from a minimum acceptable to a maximum practical, consistent with size and weight constraints. This provides the aircraft system designer with a useful, substantive range of options from which he can proceed in formulating a final specification for a HUD projector to be actually developed.

1. Considerations and Tradeoffs

Two levels of tradeoffs are outlined in Subsection V.A as typical of procedures often employed in the design specification of HUD projectors. The first or higher level tradeoff establishes the basic optical design and image generation approaches. The second tradeoff leads to a definition of specific performance and physical design parameters for the installation of interest. It is acknowledged, however, that in the final analysis, realities dictate cost and weight as perhaps the most paramount factors, consistent with the achievement of at least minimum acceptable performance. A discussion of the higher level trade-off as related to HUD application in helicopters is presented in the following paragraphs.

a. Installation Considerations

With the exception of the rear cockpit seat in the AH-1 and OV-10 vehicles, panel mounting of optical projectors in helicopters is impractical because of limited space behind the panel and light mounting structures. Therefore, the installation of an optical projector is restricted to overhead mounting. The size and shape of the projector when installed must be such that an 8-inch (preferably 10-inch) spherical clearance from the normal eye position is yielded in accordance with military standards governing such installations. Special mounting provisions and structural reinforcement may be necessary due to the severe vibration environment of the helicopter. The severe vibration also dictates that the weight of the projector be minimized so as to produce resonant frequencies higher than the natural frequencies of vibration. For the single rotor H-3 helicopter, recorded data indicates a fundamental (1/REV) vibration frequency of about 4 to 4.5 Hz (0.20g) with a short period (5/REV) frequency of about 20 to 22 Hz (0.25g). It is estimated that with adequate structural reinforcement, a projector weight of 25 pounds will provide a resonant frequency of at least 30 Hz. Any projector mount must be designed to clamp the unit rigidly, but still permit ease of installation and removal. Finally, any projector design and installation layout must consider the helicopter cockpit MIL-STD-33574, -33575, and -33576, to the extent of their applicability as imposed by the systems manager.

b. Field of View

Large instantaneous and mapped fields of view, although often desired, are invariably limited in practice by weight, size and cost limitations. New concepts must continually be sought to effectively increase Field Of View (FOV) performance without the corresponding increases in projector size, weight and inaccuracies usually incurred. This is potentially important in helicopters because of the wide range of angle of attack and sideslip angles associated with this class of vehicle. Fixed-wing attack aircraft also require expanded vertical field coverage for delivery of high drag bombs - a requirement strikingly similar to the need for large downward field coverage in helicopters during steep descents.

Two design features were adopted for the HUD projectors synthesized in this study. In one of these features, a moveable combiner in systems of small-to-intermediate instantaneous fields of view is used to satisfy the conflicting display field locations of various flight modes in the vertical plane. This approach, termed "remapping", represents a powerful tool for reducing the instantaneous FOV requirements, and hence the aperture of the system. In fact, with this feature, an instantaneous monocular FOV as small as 10 to 12 degrees (depending upon combiner position) is provided with one of the candidate projector designs established below. The moveable combiner can be designed for operation in two or more discrete positions (e.g., HUD design for the A-7 airplane), or as a part of a continuous positioning arrangement, controlled either manually or automatically based on some tracking variable such as the velocity vector.

A key feature reflected in all the moveable combiner arrangements presented ensures that for each combiner position, the central optical axis is always oriented to pass through the normal eye position thereby obviating any need for pilot head motion to view the entire instantaneous field. This was achieved by simultaneously rotating and translating the combiner based on kinematic functions derived to yield the desired result. Although, the same principle can theoretically be applied to reorient the instantaneous field laterally, it is a much more difficult matter. Ideally, for overhead installations, the entire projector would be manually rotated on a suitable track rotated about the operator's normal eye position. However, structural obstructions exist in all helicopters examined that obviate this approach. A less imposing approach is to manually swivel the projector about its own mounting typically as a function of average drift angle. This technique was successfully implemented by Sperry in an NASC-spondored HUD flight test program on an F-8 airplane. However, this approach is also largely impractical in that existing structural members limit the swing of the project to about ±5 degrees. In addition, excessive lateral head motion is required for display viewing.

In the second field expansion feature adopted in the projectors evolved in this study, curved faceplate CRT designs and new CRT/optics mapping relationships developed in the initial design analysis (Subsection V.A) are used. This feature, which enables an efficient increase in the total field of view mapped (i.e., 35 degrees) is incorporated in candidate projectors of somewhat larger apertures providing compatible instantaneous fields of view of about 18 to 20 degrees.

c. Optical Configurations

Three basic optical system types or configurations were investigated for helicopter application in the initial analyses (Subsection V.A). The first is the on-axis refractive system which collimates light images by refraction through various lens elements. The principal advantages of this system are high accuracy, high light transmission efficiency and shorter focal lengths, which enables use of smaller sized image surfaces. This approach suffers the disadvantages of relatively higher cost and weight than an on-axis reflective system. This latter, second system collimates the light by reflection off a spherical mirror. Although the inherently simple nature of its design results in the lowest weight and cost of all known schemes of collimated projection, the on-axis reflection system is somewhat less accurate and yields relatively poor light transmission efficiency. This low efficiency dictates the use of high intensity reticles. In addition, the physical layout characteristics of the on-axis reflective system do not allow the use of short focal lengths. Consequently, larger reticles are required with a corresponding increase in projector size.

The third optical configuration considered is the off-aperture reflective system, comprising a more complex refractive lens arrangement for projection and a spherical combiner where final image collimation is achieved (Appendix D). This system was originally developed by Farrand for NASC as a panel-mounted instrument. When configured for overhead mounting, however, the offset between the combiner axis and the axis of the overhead projection optics section is insufficient to allow for adequate head clearance. Any attempt to increase the offset causes rapid increases in size and weight, making the system impractical for overhead mounting.

Based on these considerations, a number of rules can be established concerning the selection of an optical system. The display symbol requirements largely determine the type of image source to be provided (as discussed in the following paragraphs). Relatively complex symbol formats would preclude the use of reticles and favor a CRT. The CRT, in turn, with its limited brightness and/or requirement for high accuracy performance, would dictate the specification of a refractive optical system. Conversely, relatively simple display formats would logically be best accommodated by an on-axis reflective optics and reticle match.

d. Image Sources

Two basic image generation techniques are available to the HUD designer; namely, the CRT and electromechanically driven reticles. The greatest flexibility for image formatting and position control is provided by the CRT. Symbols may be overlapped and easily changed to satisfy the conflicting requirements of multiple flight modes. The CRT, however, cannot be used with an on-axis reflective optical projector because of its limited brightness (6000 foot-lamberts typical for 3-inch usable diameter). Additionally, the CRT and its associated driving circuits and power supply reflect a heavy initial investment in cost, weight and power.

Electromechanically driven reticles, on the other hand, provide low cost and weight advantages for systems with relatively simple display formats. There is virtually no flexibility in altering the format design, and the number of symbols that can be accommodated is limited. Care must be exercised in the display format design to avoid overlapping of images because of the inherent mechanical constraints; nevertheless, some symbol overlapping can be accommodated through optical mixing of images by means of beamsplitters. With the addition of each optical input channel, however, light transmission efficiency is significantly reduced necessitating ultra-high brightness reticles. Fortunately, small, low power lamps are available, which in conjunction with the current fibre-optic technology, can satisfy this high brightness performance in two or three input channel projection systems.

To assist in image source selection, a preliminary tradeoff analysis was made to establish a selection crossover point between CRT and reticle drive complexity. It was concluded that this point is represented by four positional servos plus two meter mechanisms as the driving elements in a hypothetical electromechanical projector model. The principal selection tradeoff factors considered were unit cost, weight, reliability, ease of maintenance and space limitations as related to an overhead cockpit installation.

2. Synthesis of Candidate Designs

A number of candidate projector designs, reflecting the multitude of design tradeoff considerations previously discussed, are described in this subsection. Practical spectrums of cost/complexity and field-of-view performance, in accordance with the objective of providing the avionic system designer with such options as a point of departure in his specification task, are encompassed by the designs. Two basic classes of projectors are covered; namely,

- Electromechanical reticle and on-axis reflective configurations associated with the lower end of cost/complexity/field-of-view spectrum. The specific designs recommended are best suited to accommodate a limited number of the simpler display formats established in Section IV, either individually or in combinational sets.

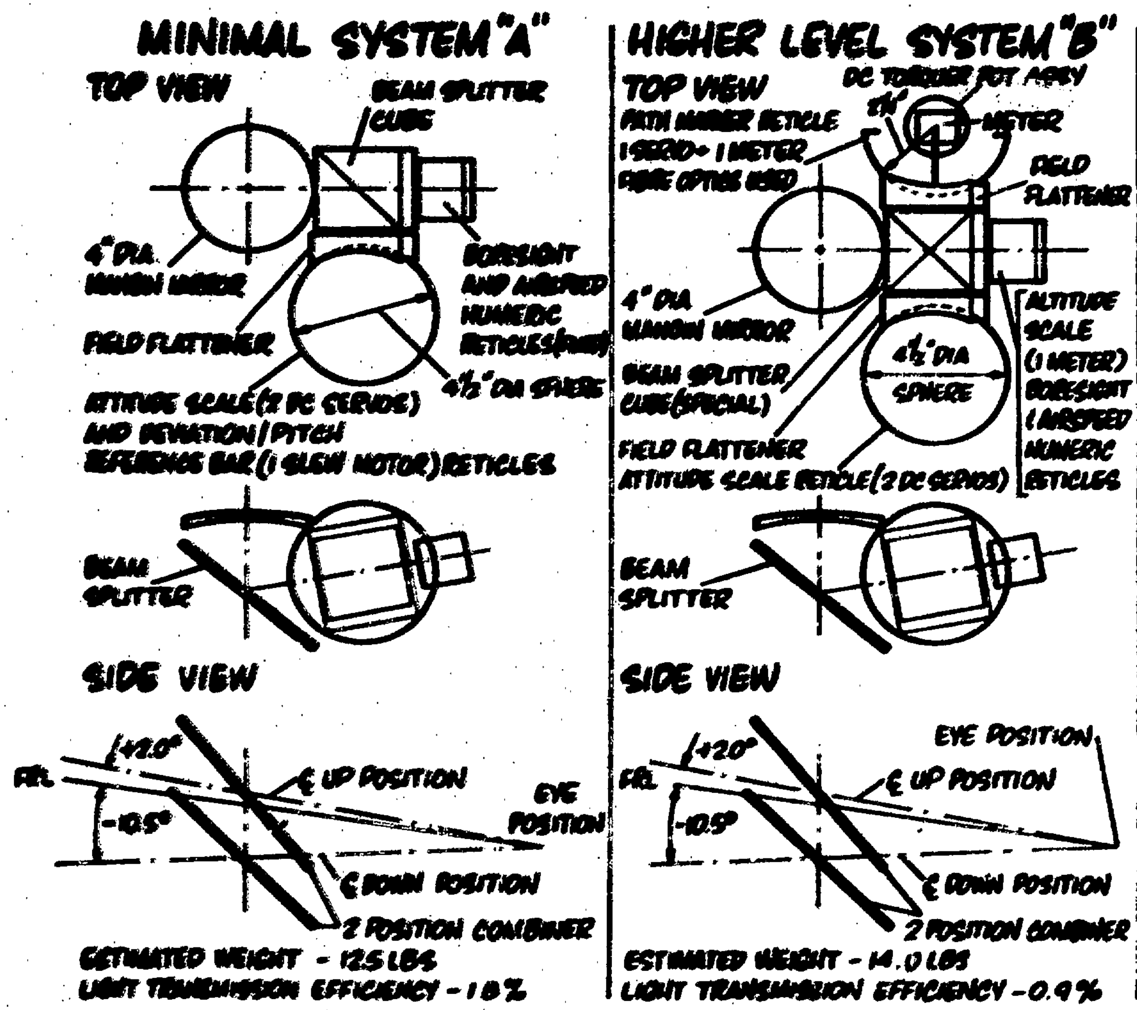
- CRT and on-axis refractive configurations largely, but not necessarily, associated with the upper end of the cost/complexity/field-of-view spectrum. Any and all of the display formats, FOV and other functional requirements of Section IV are satisfied with the relatively wide-field version of this class of projector. Narrower field versions, capable of accommodating a somewhat fewer number of these display modes, including those that can be satisfied by the electromechanical type of projector are also presented.

a. Electromechanical Projectors

Reticle-imaged gunsights constitute the simplest, first-applied form of HUD. However, as conceptual development of HUD was expanded to the contact analog with ever increasing sophistication of application in fixed-wing aircraft, the simpler reticle devices were quickly replaced by CRT's. The nature of the helicopter situation, however, dictates reconsideration of the projected reticle approach for certain helicopter applications. A simpler reticle approach to HUD design may very likely be favored over CRT versions for those helicopters that reflect a limited number of non-critical operations, a low total cost of procurement and ownership and a minimum of on-board avionic instrumentation.

An effort was undertaken, therefore, to evolve a series of low cost projectors, making use of reticles and simple reflecting optics. An evolutionary process was employed, beginning with a simple attitude/airspeed display as an aid in basic flight orientation and progressively increasing the functional complexity to some practical limit as established by the reticle and CRT cost tradeoffs and physical limitations in packaging reticle devices. In this building block approach, symbols were successively added one by one in order of importance. As a result, two projector designs were developed; the display requirements of the basic flight modes established in Section IV are satisfied by the more complex design. A third candidate design was hypothesized, but is only conditionally recommended in this report pending the results of future feasibility layout studies and cost-effectiveness analyses. This third design would functionally extend the second system to effectively accommodate the established display requirements for visual gun and rocket fire control (impact point solutions) and radio homing and acquisition during visual search and rescue.

The first two projector designs are schematically shown as Systems "A" and "B" in Figure 5-3. System "A", established as the minimal level, comprises two optical input channels; System "B" includes three such channels. In System "A", the reticle driving elements consist of two position servos and one slew motor, which, in conjunction with certain other fixed reticles, enables the display of an attitude scale, boresight, airspeed numeric and deviation/pitch reference bar symbols.



COMMON CHARACTERISTICS

- ON-AXIS REFLECTIVE OPTICS
- APERTURE - 4" DIA
- FOCAL LENGTH - 6¾"
- TOTAL MAPPED FOV - 18°
- INSTANTANEOUS MONOCULAR FOV
  - 11° FOR COMBINER UP POSITION
  - 10° FOR COMBINER DOWN POSITION
- INSTANTANEOUS BINOCULAR FOV
  - 18° FOR COMBINER UP POSITION
  - 16° FOR COMBINER DOWN POSITION
- 2 POSITION COMBINER COATING
  - 20% REFLECTANCE, 80% TRANSMISSION
- BEAM SPLITTER COATINGS
  - 45% REFLECTANCE, 45% TRANSMISSION
- RETICLE SIZE / RANGE OF MOTION
  - 2⅛" EACH AXIS COVERING 18° MAPPED FIELD

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Figure 5-3
Electromechanical Projectors

In such a system, the servos would typically operate from pitch and roll synchro signals inputted from a remote vertical gyro or AHRS; no other signals are required. In addition, there are no processing requirements; hence, the projector is the only HUD unit to be provided.

System "B" expands on System "A" through the addition of one servo and two meter mechanisms for reticle positioning. Thus, this configuration closely approximates the four-servo/two-meter configuration established in earlier tradeoffs as a crossover point between CRT and reticle drive cost versus complexity. The symbols added in this system consist of a path marker and altitude scale. The deviation reference bar and associated slew motor are deleted.

The salient physical and performance characteristics of each of these relatively small field projector designs are tabulated in Figure 5-3. The designs were predicated on a rather tedious and somewhat difficult design tradeoff in which the geometry and constraints associated with CH-53 cockpit installations were a major factor. The physical configuration of the two projectors is shown in the CH-53 installation layout of Figure 5-4. As shown in Figures 5-3 and 5-4, an adjustable combiner arrangement that enables the pilot to manually position the combiner in either one of two discrete, detented positions in the vertical plane is provided. This has the effect of shifting the central optical axis and associated instantaneous field. When the combiner is switched between positions, the mapped field is also repositioned electrically thereby preserving the proper relationship of image to real world viewing angles.

The up-position is best suited for display operation during high speed flight and hover modes. For the H-53, orientation of the optical centerline 2.0 degrees above the vehicle FRL is recommended.

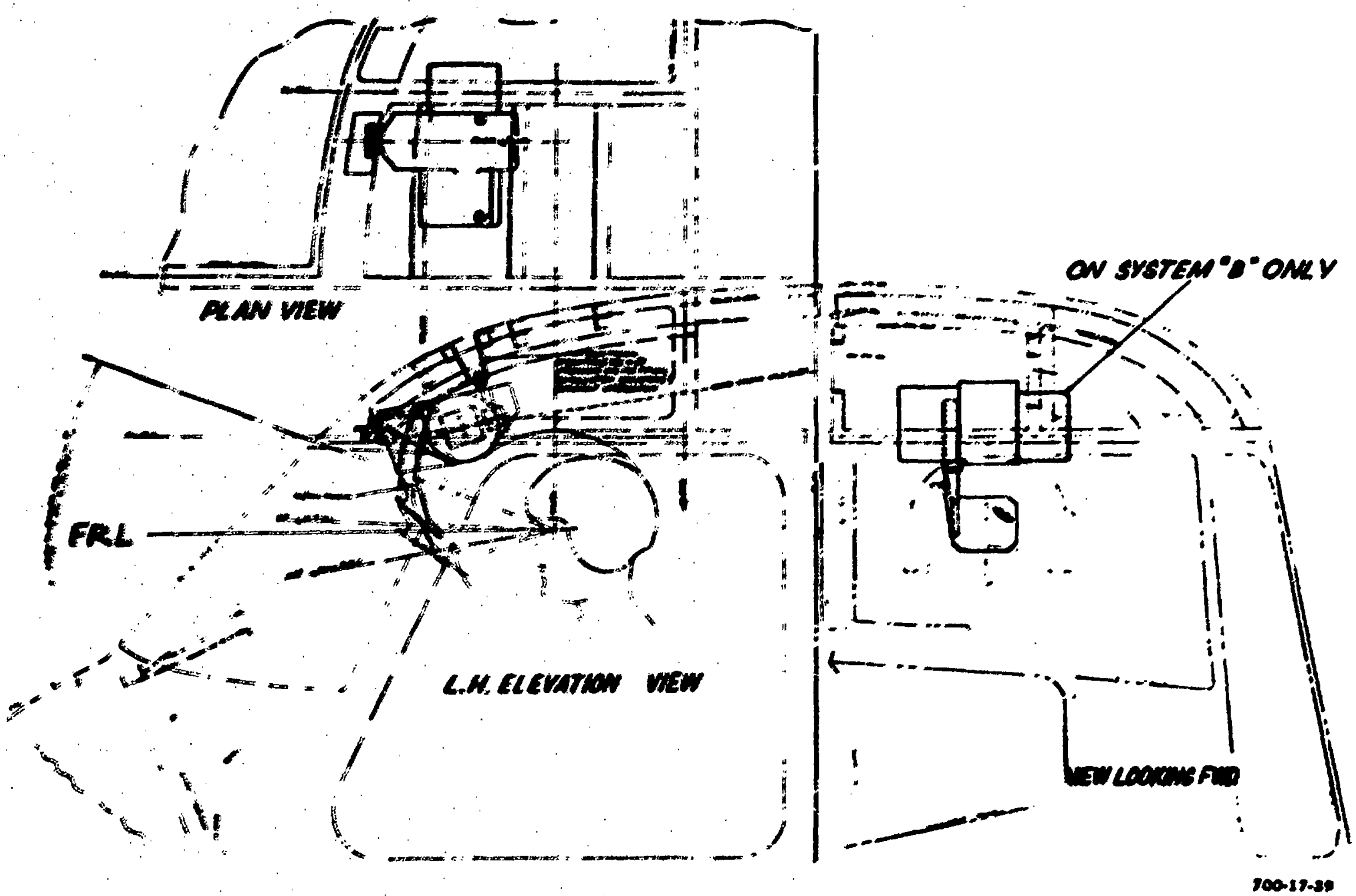

Figure 5-4
Installation of Electromechanical Projector
in H-53 Cockpit

The lower or down-position would be selected during descents to enable viewing the field of interest. In this case, a 10.5-degree depression of the optical centerline below the RFL is recommended. The selected positions reflect a judicious compromise of many conflicting FOV criteria so as to provide optimum display field coverage among the various flight modes of operation.

The major elements of Systems "A" and "B" are described in the following paragraphs. Multicolor display capability is afforded by multiple reticle projectors; however, the selection and allocation of color to each of the images outlined below was not attempted in this study.

• Optics - Systems "A" and "B" are on-axis reflective type projectors, in which a 4-inch diameter (effective aperture) spherical mirror is used in conjunction with a selected 6-3/4-inch focal length. A beam splitter is located immediately below the spherical reflector (often referred to as a Mangin mirror) as shown in Figure 5-3. Light from the reticles is partially reflected off the beam splitter and is collimated by the spherical reflector. The collimated light then passes through the beam splitter and is partially reflected off the combiner to the pilot's eye. A dichroic-coated beam splitter was selected with equal 45-percent reflectance and transmission properties. The combiner is coated to yield 20-percent reflectance and 80-percent transmission. In System "A", optical mixing of the two-reticle channels is achieved by a conventional beam splitter cube. In System "B", however, a special beam splitter cube was conceived to enable the mixing of light rays of three input channels. This concept, in which two orthogonally oriented, coated surfaces are incorporated within the cube, was investigated with optical manufacturers and determined to be both technically viable and practical in terms of cost. However, this beam splitter cube has a light transmission of approximately one-half that of the conventional beam splitter cube.

The focal plane of the Mangin mirror is a spherical surface with a radius of 6-3/4 inches. Due to physical limitations, the moveable reticles are designed with spherical image planes of 2-1/4-inch radii. Therefore, a field flattener with the appropriate negative power is required to optically increase the radius of the spherical image plane to minimize the optical errors.

• Attitude Scale and Deviation Bar Symbols - A spherical configuration, similar to that commonly employed in conventional Attitude Director Indicator (ADI) instruments, has been selected in the design of the attitude scale reticle assembly for Systems "A" and "B". This configuration is actually a thin-walled section of a 4-1/2-inch diameter sphere with 2 degrees of freedom. The surface of this spherical section is the attitude reticle itself. The reticle (i.e., projected symbol) configuration is shown in Figure 5-5. Each of the symbol segments is interconnected as a package to one of several miniature lamps through a fibre-optic bundle. In this particular design, the use of fibre-optics is necessitated to compensate for the low transmission efficiency of the optics to ensure adequate display brightness. Based on the increased efficiency in light transmission afforded by fibre-optics, the design synthesized results in 45,000 foot-lamberts at the reticle surface where relatively low power, low heat dissipating lamps are used.

In System "A", the center of the spherical section is cut out so that a separate sector containing the deviation bar reticle may be independently positioned vertically relative to the attitude bars. Positioning of the deviation bar is accomplished by a small dc slew motor, controlled by the pilot via a conveniently located, remote slew switch. The pilot visually sets the position of the deviation bar against the projected attitude scale in the display field. A simpler, mechanical shaft arrangement with a manually operated knob and dial readout was considered but rejected for two reasons: The mechanical configuration to provide the required differential movement without interfering

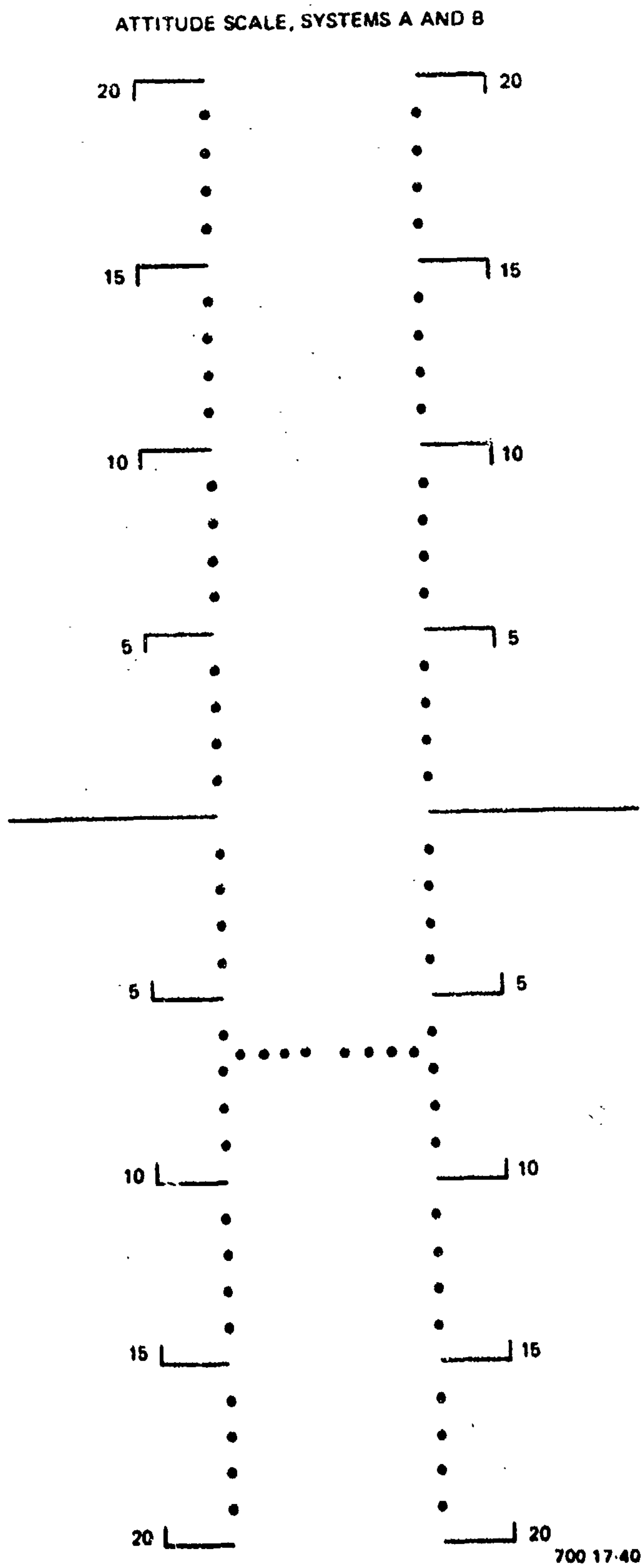

Figure 5-5
Attitude Scale/Deviation Bar Reticle Configuration

with the motion freedom of the sphere in pitch and roll is rather awkward and complex; display operability would be adversely affected by requiring the pilot to reach above his head and direct his vision onto the rear of the projector.

DC motors are used by the pitch and role positioning servos to reduce gearing and power requirements. These servos are shown in Figure 5-6. The pitch axis, which is on the inside, is driven by a direct-coupled, dc torque motor. The optical reticle light packages are mounted within the spherical section. The feedback synchro element is mounted opposite the reticle to help balance the assembly. The entire reticle and pitch servo assembly is rotated about the roll axis by the roll dc servo motor via a single gear pass. This assembly rotates optically about the aircraft boresight when the combiner is in the up-position; hence, the display is properly correlated to the real world. However, when the combiner is in the down-position, the reticle optical roll axis is no longer the aircraft boresight; therefore, in this case, the attitude scale cannot be displayed. Actually, this doesn't pose any disadvantage in that when the display field is depressed to accommodate viewing of the velocity vector and aim point, attitude cannot be read out since the boresight is beyond the total mapped display field.

The error effects of improper rolling of the deviation bar is another matter and, therefore, must be compensated. Since this symbol is formatted as a dotted horizontal bar and only vertical deviation guidance is provided, errors introduced in the lateral positioning of this symbol are unimportant. However, errors in the vertical axis must be compensated so that the deviation bar is correctly oriented vertically relative to the real world aim point of interest. The error compensation function required is shown in Figure 5-7. When the combiner is rotated to the down-position, the optical boresight and all the images are displayed downward by some angle (V). (In the figure shown, the deviation bar is assumed to overlay the real world aim point.)

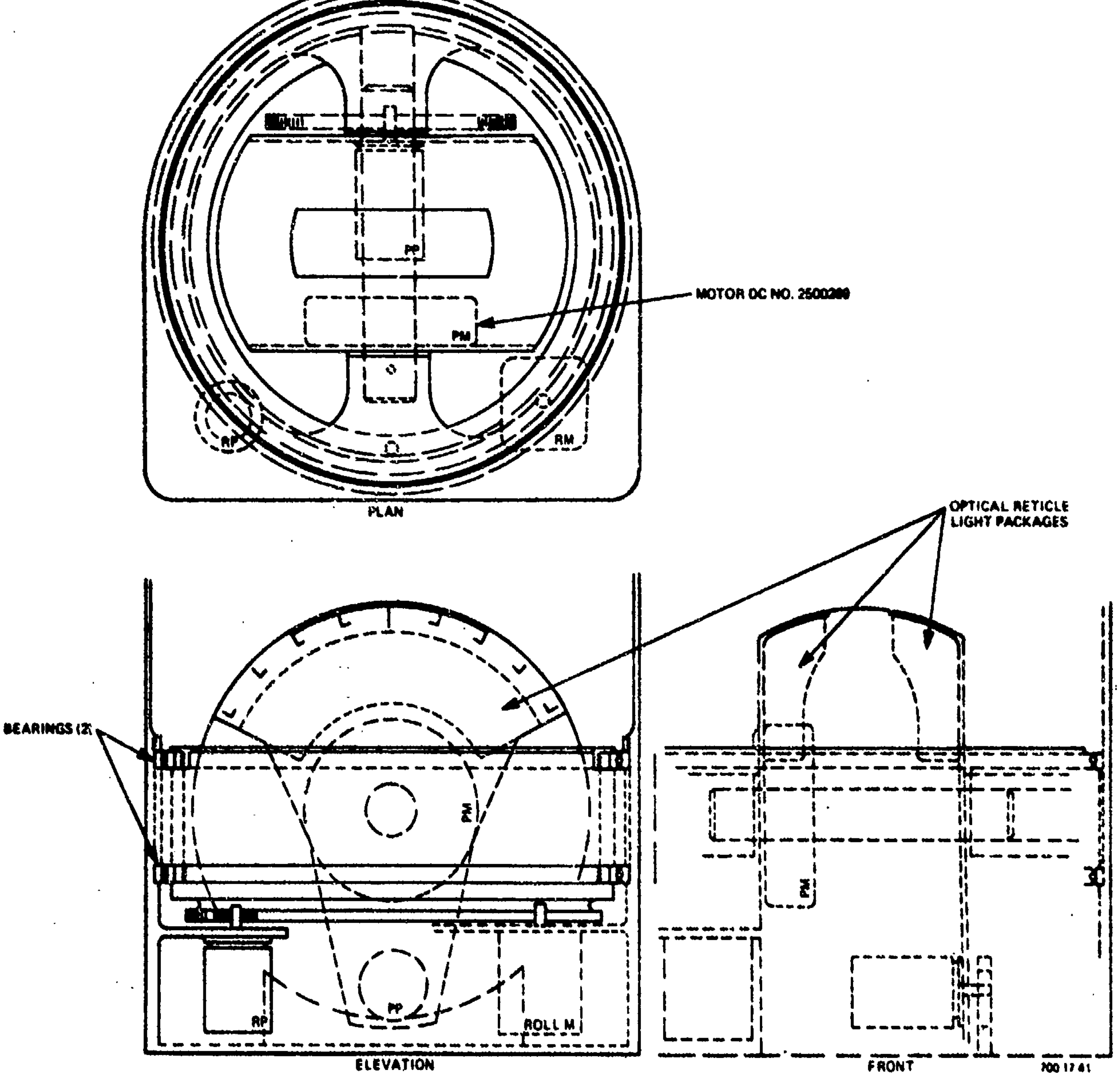

Figure 5-6
Mechanical Layout of Attitude Sphere
Reticle Assembly

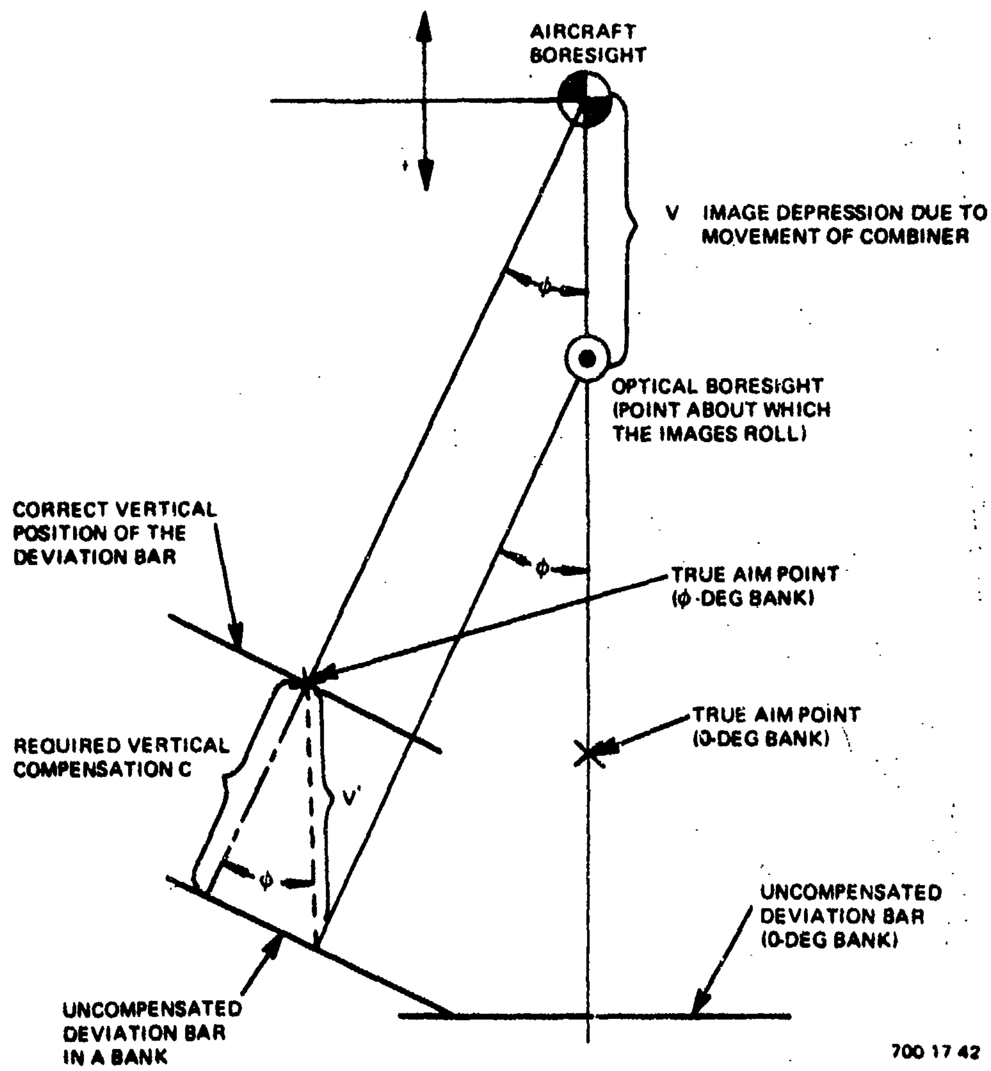

Figure 5-7
Roll Compensation Geometry
for Deviation Bar Reticle

By constructing the line (V') parallel and equal to V, a right triangle is formed, one leg (C) of which is the required vertical compensation in a bank angle of ϕ. Solving this triangle,

$$C = -V \cos \phi$$

A simple, proven implementation scheme for this compensation function is shown in Figure 5-8. Lead-lag networks are used for servo stabilization instead of tachometers, in order to minimize cost, weight, power and heat dissipation.

• Boresight and Airspeed Numeric Symbols - The boresight and numerical airspeed images are injected in the second optical input channel. A field flattener is not required since these image-generating devices are small and each may be placed within the image plane independently. The boresight symbol is displayed in the combiner up-position only and is extinguished when the combiner is down. The boresight symbol is a separate fibre-optic light package.

• Altitude Scale Symbol - The altitude scale image generator, provided in System "B", only, is incorporated in the second optical input channel on a side opposite that of the airspeed numeric. The assembly is comprised of a fibre-optic light package potted in a drum which is 1.25-inch diameter by 0.4-inch wide. The drum is driven by a meter movement that is of a high torque, closed-loop type in which a separate coil is provided for feedback to the driving amplifier. The recommended altitude scale configuration (Figure 5-9), which covers a range of 0 to 1000 feet, has a scale factor break at 100 feet for increased readout resolution below this altitude.

• Path Marker Symbol - In System "B", a flight path marker reticle assembly is incorporated for projection through a third optical input channel. The reticle is configured as a hollow sector of a 4-1/2-inch diameter sphere. It has 2 degrees of freedom with a total range of

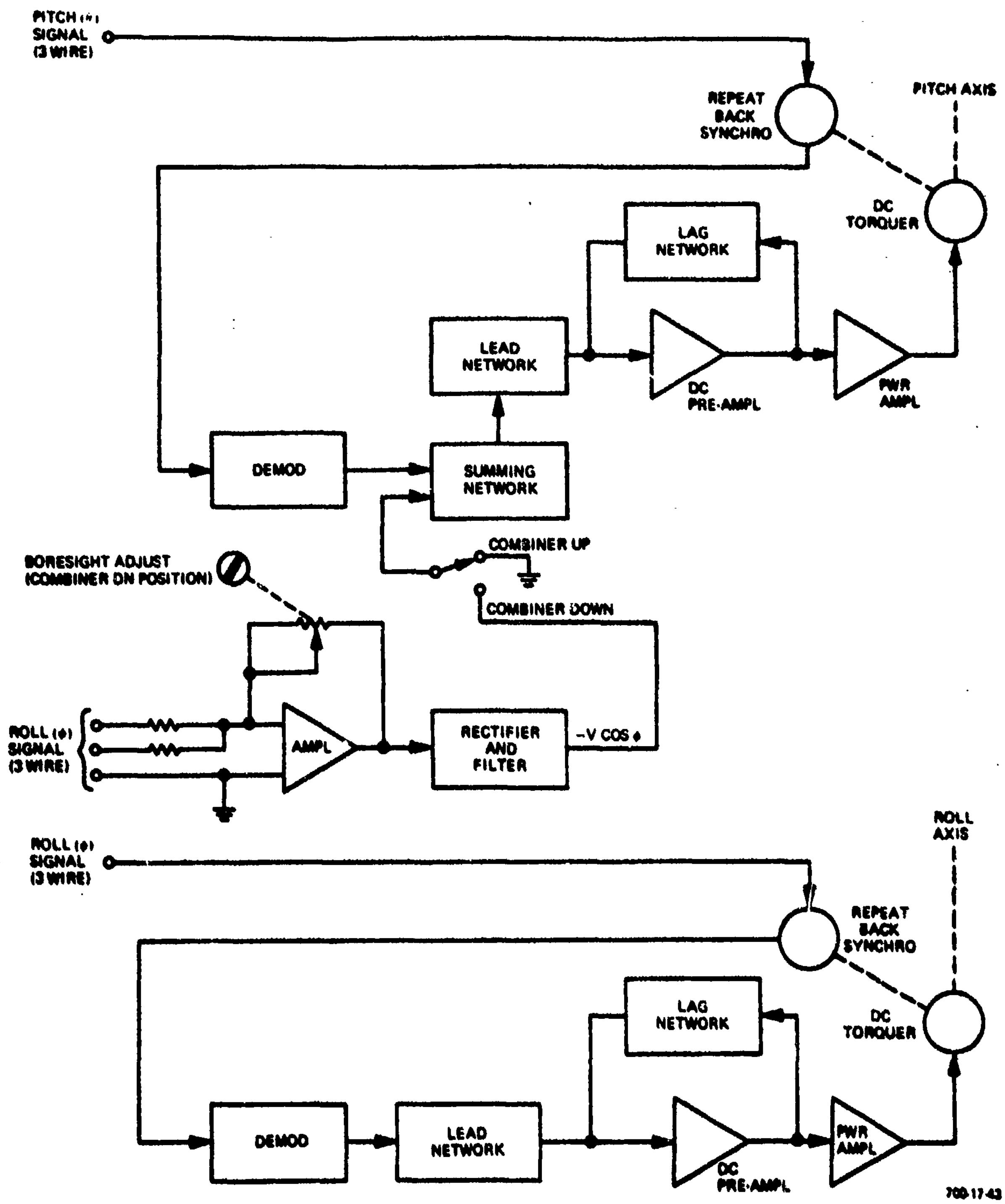

Figure 5-8
Attitude Sphere Servos Block Diagram
(Reticle Projector Systems A and B)

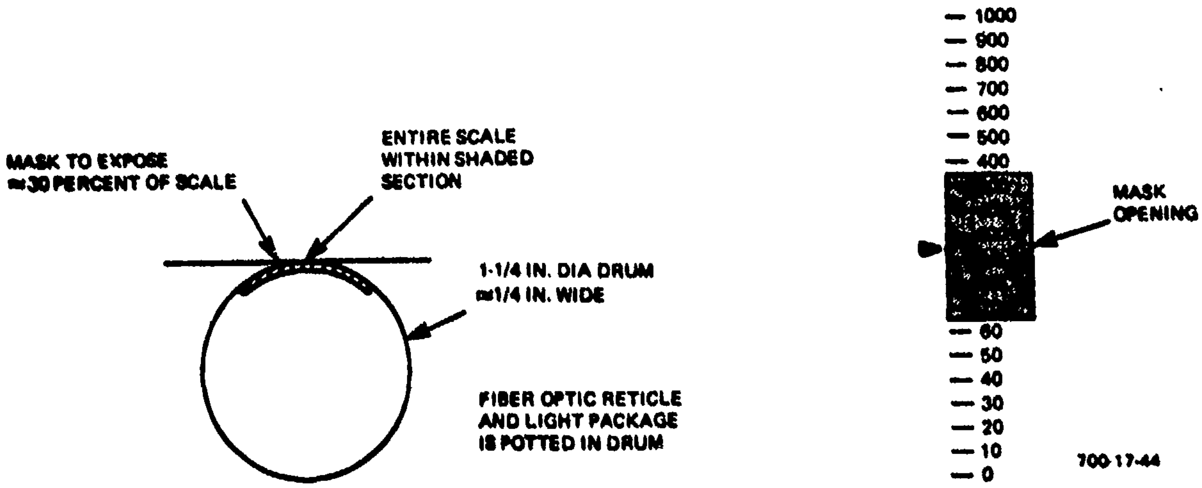

Figure 5-9
Altitude Scale Reticle Configuration

±9 degrees of real-world-related motion in each axis. The reticle, with its fibre-optic light package, is rotated in elevation by a special high torque meter mechanism. The reticle assembly and associated meter mechanism are rotated in azimuth by a dc servo, in which an integrated, compact dc torquer-potentiometer unit is used. A simplified sketch of the entire flight path marker reticle assembly is provided in Figure 5-10. A field flattener, identical to that used for the attitude sphere, is required to minimize optical distortions.

A third electromechanical projector system, noted earlier, has been conceived, but not investigated for feasibility and cost effectiveness. The design comprises five positioning servos and two meters - a level of complexity just above the four-servo/two-meter level hypothesized as equivalent to that of a CRT design. In this concept, System "B" is used essentially as described, and two servos are added within the attitude sphere. The display reticle configuration of the sphere is also altered to provide a center sector that is independently driven in the vertical axis similar to that provided in System "A" for the deviation bar. The display reticle in this center section comprises an aim circle image connected above and below by a straight line extending over the entire mapped field and representing a vertical plane perpendicular to the earth's local horizontal. Thus, one of two added servos would rotate this composite aim circle image (and the entire sphere itself) in azimuth; the other servo would position the aim circle vertically independent of the attitude scale. The objective here is to position the aim circle in response to appropriately computed lateral and elevation commands to satisfy any one or more of the following operational functions under day/VFR conditions only:

> <u>Landing</u> - Two-axis deviation or director to be selected (If simple deviation is selected, the aim circle would supplant the deviation bar incorporated in System "A".)

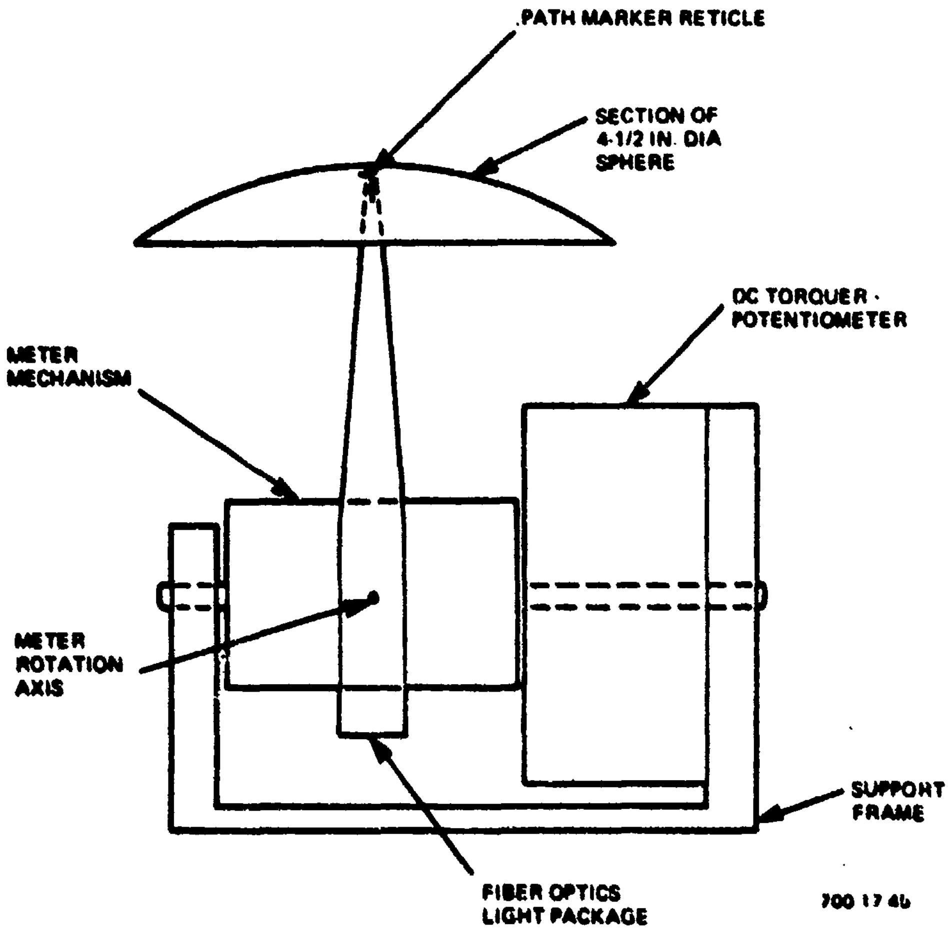

Figure 5-10
Flight Path Marker Reticle Assembly

Gun and Rocket Fire Control - Two-axis acquisition followed by computed impact point

Search and Rescue - Two-axis acquisition followed by two-axis director for terminal steering and final approach

Where a deviation mode is used in landing or during the acquisition phase of fire control and homing search operations, the new vertical axis servo would revert to a slew mode for manual positioning of the aim circle. Operation under good visibility conditions only has been stipulated for this display because a designated target symbol cannot be accommodated. The display of a designated ground target or aim point under limited or zero visibility conditions is deemed essential.

b. Cathode Ray Tube Projectors

Two overhead-mounted, CRT projectors were synthesized as candidates for the H-53 helicopter. On-axis refractive optics with internal folding mirrors are used in these projectors. The mirrors bend the central axis so that the included angle is approximately 102 degrees. For the H-53 installation, the 4-1/4- and 5-1/2-inch aperture sizes selected represent practical limits yielding a minimum acceptable instantaneous FOV on the one hand, and on the other hand, a maximum realizable instantaneous field that satisfies the requirement for clearance outside an 8-inch spherical radius from the normal eye position. The system designers can select an aperture size anywhere in between these limits, using the family drawing data of Appendix C to establish the principal design specifications.

The installation geometry, projector configurations, and mounting design are shown in Figures 5-11 and 5-12. In both cases, a moveable combiner arrangement has been designed to effectively extend the vertical field by reorienting the position of the central optical axis in

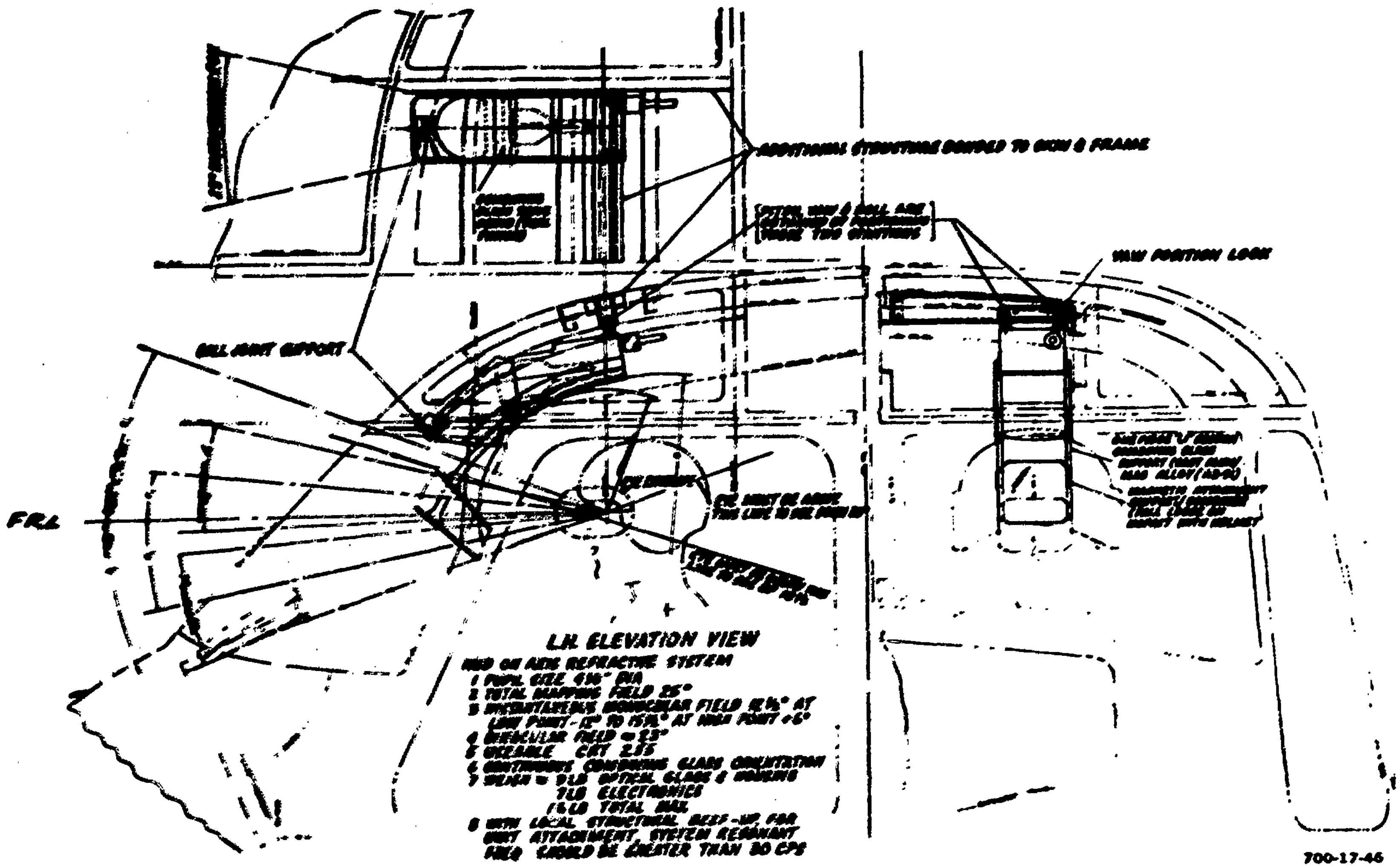

Figure 5-11
Installation of CRT Projector
with 4-1/4-inch Aperture in H-53 Cockpit

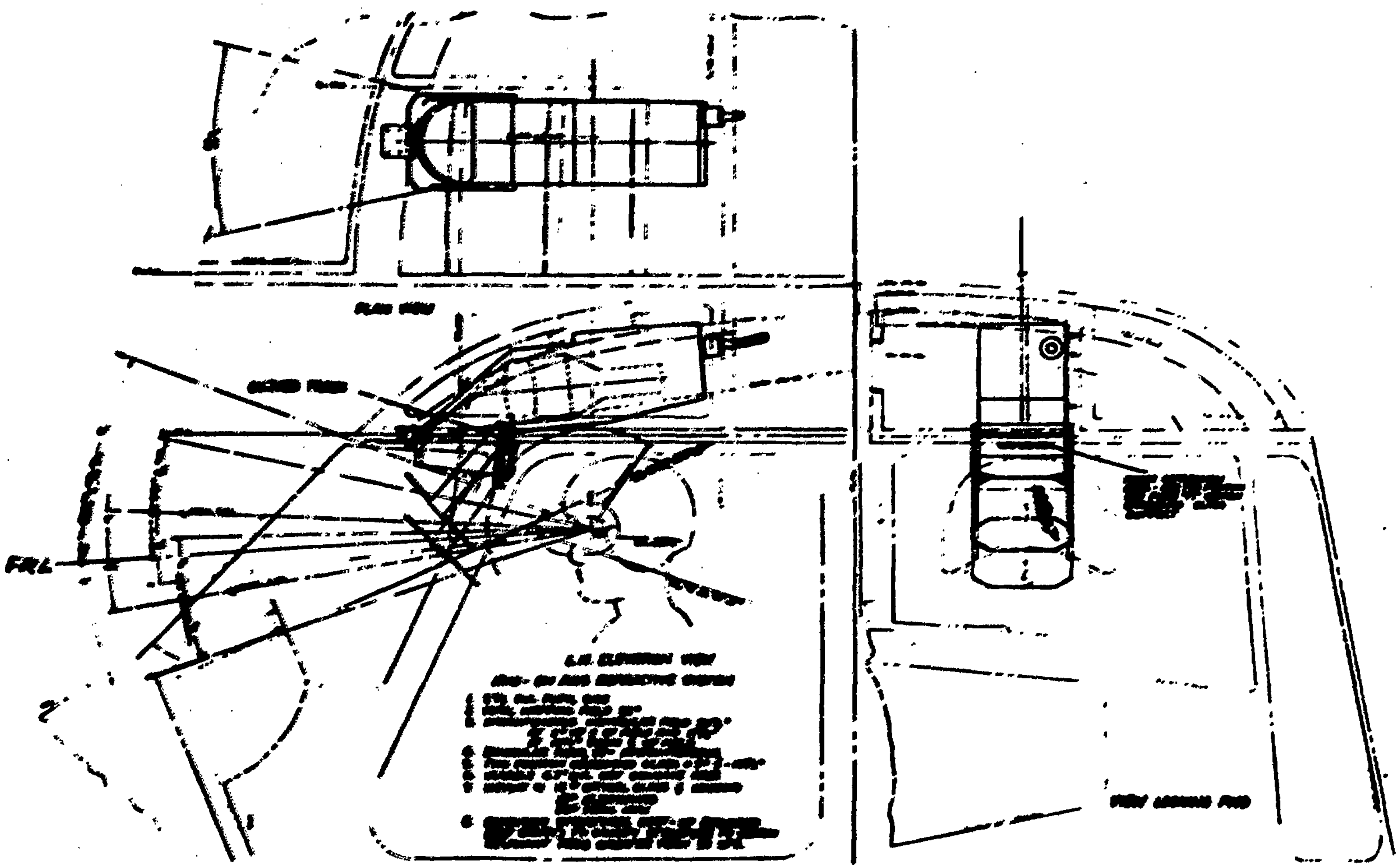

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Figure 5-12
Installation of CRT Projector
with 5-1/2-inch Aperture in H-53 Cockpit

the forward field of view. In the 4-1/4-inch aperture design of Figure 5-11, a mapped field of 25 degrees is provided on a 2.55-inch usable diameter, flat-faced CRT. This mapped field is compatible with the average instantaneous fields of 14 degrees monocular and 23 degrees binocular provided, in terms of the head motion required to view the extremities of the mapped field. The design philosophy established in both projector designs is to scale the total mapped field to the instantaneous fields so that only reasonable head motion is required to view any edge of the mapped field. Certainly, very little would be gained in providing a 35-degree total mapped field with the 4-1/4-inch aperture projector.

In the 4-1/4-inch aperture design, a continuous motion combiner mechanism, which enables the positioning of the optical field center anywhere from 12 degrees below to 6 degrees above the FRL of the M-53, has been developed. Although the design can be adapted for simple manual positioning control, greatest operational benefit would be derived if a servo were used to automatically position the combiner, typically as a function of a suitably computed and smoothed angle-of-attack signal defining the vertical velocity vector of the vehicle. Increasing value with decreasing aperture size is assumed in the servoed combiner concept. The 4-1/4-inch aperture projector, in addition to providing a minimum acceptable instantaneous field of 12.5 degrees (at the maximum down-position of the combiner), essentially satisfies the 10-inch spherical radius clearance goal recently established via applicable military standards (Figure 5-11).

In the larger 5-1/2-inch aperture design of Figure 5-12, a mapped field of 35 degrees is provided on a 4.7-inch usable diameter curved CRT faceplate. This larger field is fully compatible with the 19-degree average monocular and 27-degree binocular instantaneous fields of view provided. Because of these larger fields and head clearance considerations, a simple two-discrete position combiner arrangement, in which the optical center is oriented either 10.5 degrees below, or 2.0 degrees above, the vehicle boresight is recommended. The 5-1/2-inch aperture design essentially satisfies the 8-inch spherical radius clearance goal, which existed prior to the recent change to a 10-inch radius.

c. Compatibility of H-53 Projectors for H-3 and H-46 Installation

The results of installation studies conducted to test the compatibility of the candidate H-53 projectors to the H-3 and H-46 series helicopters are presented in the following paragraphs.

• H-46 Series Helicopter - Generally, to accommodate any of the projectors, some of the panels on the overhead console must be relocated aft to reduce the lateral span of the console. In addition, the structural overhead mounting design for any of the projectors is facilitated by the proximity of the primary rotor support structure. The 4-1/4-inch aperture CRT projector fits within the cockpit and provides 10-inch clearance from normal eye position. No structural reinforcement is required. The 5-1/2-inch aperture CRT projector also fits within the cockpit and provides 9-inch eye clearance. However, some reinforcement of the aircraft structure is probably required.

Both of the electromechanical projectors (A and B) can be accommodated without need for structural reinforcement. Projector-A provides an 8-inch eye clearance when installed on the pilot's side and about 7-1/2 inches of such clearance on the copilot's side. Projector-B provides a 7-1/2-inch clearance on either side.

• H-3 Series Helicopter - The 4-1/4-inch aperture CRT projector is readily accommodated in the H-3 with no structural reinforcement required and with a 10-inch eye clearance yielded. The 5-1/2-inch aperture unit can also be installed but with only an 8-inch eye clearance.

Additionally, extensive structural modifications are required, including the removal of a major lateral frame of the airframe structure. Both electromechanical projectors can easily be accommodated, providing a 9-inch eye clearance without need of any structural reinforcement.

SECTION VI

ELECTRONIC PROCESSOR DESIGN STUDIES

A. DESIGN CONSIDERATIONS

The design of a HUD electronic processor for helicopter applications is based on much the same specification criteria as those commonly considered in previous HUD developments for fixed-wing aircraft. The more important of these criteria are as follows:

- Data Inputs (except roll angle)

  Number of Inputted Variables
  Analog or Digital Format

- Roll Input

  Synchro or Digital Format

- Number and Types of Symbols Required
- Number of Symbols Rolled
- Complexity of Calculations Required
- Required Accuracies

The impact of these design considerations on the processor design approach to be selected for any given application is discussed in the following subsection.

B. CANDIDATE PROCESSOR DESIGN APPROACHES

The selection of the two basic classes of HUD processors is directly related to the type of image generation source incorporated in the projector unit. The first class comprises an analog computer (not unlike the relatively simple flight-director, flight-path-angle, etc, computers) used in conjunction with conventional panel instruments. Such a processor would logically be used with projectors of the electromechanically driven reticle type. The second processor type is essentially of a digital nature, primarily used for generating symbols on a CRT image source. The digital processor is also favored, either as an alternate or auxiliary function to that of symbol generation, to implement the processing requirements for kinematic targeting associated with the use of a stabilized aimsight projector. In examining various digital processors, calligraphic or stroke writing methods of generating symbols was assumed. Dot generation techniques, in which a television raster scan is used to construct symbol images, were not considered in this study.

1. Analog Processor

Because of its low cost, an analog computer type of processor is recommended for operation with HUD projectors of the electromechanically driven reticle type (e.g., projectors described in Subsection V.C.2.a). Characteristically, this type of HUD processor would operate on a largely analog data interface to compute the necessary reticle positioning signals; symbol generation circuits are not required. Although analog inputs are supplemented by digital format signals in certain of the helicopter applications examined, any avionic system supplying an extensive digital interface to the HUD would tend to favor a digital approach to the processor design. Because of the limited number of symbols that can be practically accommodated by electromechanical reticle projectors, complexity of an analog processor is rather minimal. Based on the applications studied, relatively simple processing requirements can be expected to an extent indicated in Figure 3-5. Computation complexity much beyond this level would tend to make the analog processor too costly and impractical relative to a digital computer approach.

Recent strides in product development of linear microcircuits and analog circuit modules for multiply, divide and other arithmetic functions have enhanced the competitiveness of simple analog computers. In addition, low voltage power supply requirements are not particularly demanding. There appears to be no need to perform roll angle coordinate transformations of symbol positions in the processor itself. For the display design developed in this study, this function is mechanized within the projector by means of a positioning servo operating from three-wire synchro roll angle data. The principal disadvantage of the analog processor when compared to a digital processor is a lower accuracy in the derived symbol positioning data.

2. Digital Processor

A digital processor is recommended for HUD systems in which a CRT is used for image generation. Actually, two classes of such processors have been selected as candidates for helicopter applications:

- Logic Controlled
- Computer Controlled

The logic-controlled processor reflects a straightforward design approach in which hard-wired logic or Read-Only-Memory (ROM) circuits are used to control the sequence of all events including symbol stroke generation. As with a computer, there is little or no time sharing of hardware. In addition, data processing can be either of a digital or hybrid nature. This type of processor is recommended for HUD systems in which CRT symbol generation functions only are primarily involved. Computations are typically limited to either analog additions and/or multiplications or simple digital addition. The design of a hard-wired processor, which is special to any given application, is largely dependent on the input interface format and display output requirements.

The programmable, time-shared nature of the computer-controlled digital processor allows data processing and sequence control of all operations. This design is most cost effective for display systems requiring a relatively extensive symbol format repertoire and/or complex symbol positioning calculations. In addition, the programmable processor is most appropriate for executing the complex arithmetic operations associated with the various acquisition and kinematic targeting functions described in this report. As conceived, a HUD system could be extended beyond its normal display function to include these additional arithmetic functions, where an existing on-board digital computer with adequate time and memory space capacity is unavailable in the vehicle.

Significant advantages of the programmable, computer-controlled processor is its flexibility in system design and change and in growth potential. Changes in input data format, quantity and scaling as well as changes in display symbology can readily be accomplished with minimal hardware modifications. This is of particular value to the weapon system manager in that it enables display modifications, if necessary, as a result of experiences gained in flight test and actual operations.

The optimum design of a display computer as principally reflected in its structure, instruction repertoire, and memory/logic circuit elements is based not only on the specific display requirements but also on the status of a rapidly advancing state of the art in microcircuit technology. In the preliminary programming analyses conducted on various kinematic targeting functions (Appendix D), various small scale computer models reflecting a range of processing speeds were considered.

- Sperry Gyroscope - Earlier Production Core Stack Model
- Sperry Gyroscope - Advanced Developmental Core Stack Model
- Teledyne - ASN-77,78 Computer for SCNS
- Univac - 1819 Computer
- Sperry Gyroscope - Solid-State Memory Display Computer

This latter computer, which is a special-purpose machine designed by Sperry specifically for synthetic symbol displays, is described together with the input/output interface in Subsection VI.C. This computer reflects a number of efficient approaches to hardware and time utilization.

Any selection between a hard-wired logic and computer approach to HUD digital processor design will be mainly based on two factors affecting cost; namely,

- Complexity of Symbol Format
- Complexity of Arithmetic Operations

Extensive arithmetic operations would likely compel a programmable computer solution independent of symbol requirements. In terms of symbol format, however, cost analyses conducted by Sperry in the past on fixed-wing HUD's did not yield such an obvious conclusion. Generally speaking, the results indicated that for displays of relatively simple formats the straightforward, logic-controlled design is considerably less costly; whereas, for functionally more complex displays the computer-controlled design rapidly achieved cost equivalence with the straight logic design, and in the case of the A-7D HUD, actually reflected a slightly lower unit cost. In the latter case, the selection of the computer approach is favored not so much by any minimal cost advantages, but by the other inherent advantages of lower development risk, higher accuracy, greater flexibility for display change and potential for growth.

Another, less important cost factor influencing the basic digital processor design is the input interface. For example, an exclusive analog interface would favor a straightforward logic-controlled approach in which analog circuits are used in generating symbol positioning signals. Costly analog-to-digital conversion circuits and variable, read/write digital memory that would otherwise be required with a computer-controlled processor are avoided with this approach.

Of special interest in all HUD processor designs is the implementation of the roll angle coordinate conversion functions. Typically, these functions include the rolling of both the position and orientation of real-world-related symbols and usually reflect a substantial part of the processing specified for a HUD. Although it is conceivable that, on a cost basis, the various mechanization schemes noted below could influence the selection of the processor design approach, past analyses have shown the influence not to be decisive. Rather, the question usually faced by the display system designer is how to most efficiently implement the roll coordinate transformation function given a selected processor design approach. The answer largely depends on the form of the input roll data; i.e., three-wire synchro, digital angle, or digital sine/cosine of the angle. Based on relative cost and weight analyses conducted by Sperry, recommended techniques of implementing roll angle coordinate conversion for each combination of processor type and roll data format are presented in Figure 6-1. A total of four mechanization techniques are recommended:

- Analog servo
- Digital servo
- Electronic hardware
- Programmed computer solutions

The characteristic transformation equations for rolling symbol position coordinates are:

$$X_A = X_E \cos \phi - Y_E \sin \phi$$

$$Y_A = X_E \sin \phi + Y_E \cos \phi$$

where

X_E, Y_E = angular displacements in earth axes

X_A, Y_A = angular displacements in aircraft axes

ϕ = aircraft roll angle

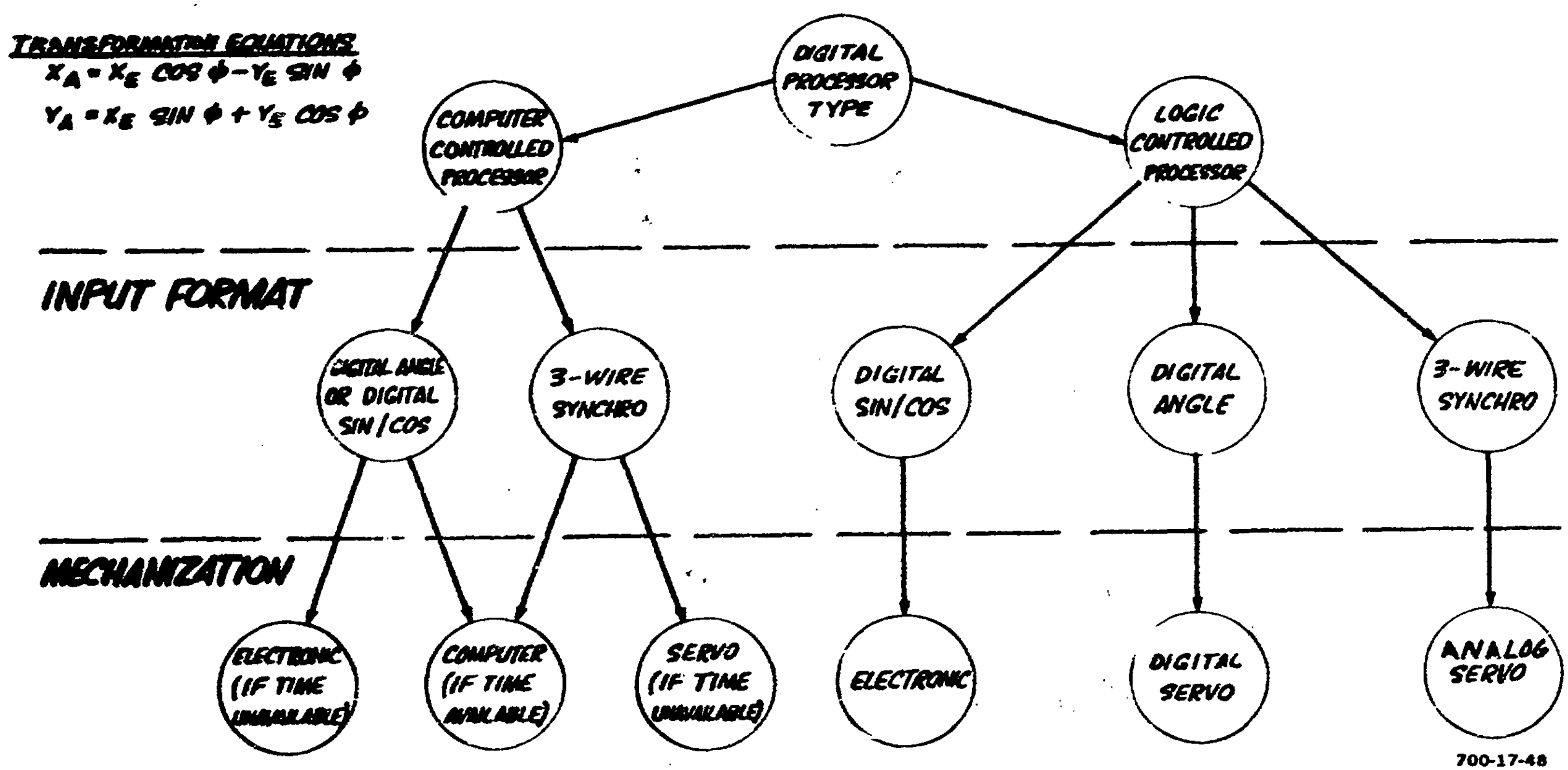

Figure 6-1
Roll Coordinate Conversion Design Criteria
(for Digital Processors)

In addition, rotation of symbol line segments with roll angle is required. Where these lines are normally vertical or horizontal on the display at zero roll angle, sine/cosine ϕ data is used directly to stroke the line properly; no arithmetic operations are required. However, where a symbol line segment is normally oblique to the CRT axes at zero roll angle, much the same set of equations presented above for symbol position rotation must be solved for each symbol line.

Considering the computer-controlled processor, if adequate time exists a computer solution is preferred for any roll input format. Experience has shown a reasonable computer time allocation for a HUD system to be 40 percent for input/output, 40 percent for processing other than roll coordinate conversion, and 20 percent for roll conversion. Assuming a symbol update rate of 50 Hz, this would limit the allocated time for roll conversion to 20 percent of 20 milliseconds or 4 milliseconds. Based on these assumptions, the number of roll conversions possible is easily derived as shown below for two of the computer models considered in this study.

	Univac 1819 Computer	Sperry Special Purpose
Time per Conversion (microseconds)	144	126
Number of Conversions (in 4 milliseconds)	28	32

The calculated time per conversion is based on ten add-times and four multiply-times required to roll a single point or oblique line stroke.

If insufficient computer time exists to execute the required roll transformations, then additional external hardware must be provided for this purpose. If the roll input is in three-wire synchro format, an analog followup servo is recommended in which a driven sine/cosine potentiometer is used to resolve the roll angle and perform the required multiplication functions. This servo, together with the associated sine/cosine potentiometer drivers, is estimated to cost about $2000 in moderate production quantities and weigh about 3.0 pounds. If digital angle or digital sine/cosine data is inputted to the HUD, then an exclusive electronic design is deemed optimum in which four digital-to-analog (D/A) converters enable the necessary multiplication functions. (If digital angle is transmitted, the computer is used to derive the sine/cosine data for application to the D/A converters.) The total hardware, including the four D/A converters (10 bit), D/A drivers, inverting amplifiers, electronic switches, and four D/A registers, is estimated to cost about $4000 in production and weigh about 0.8 pound.

In the case of the logic-controlled processor, both the analog servo and electronic hardware coordinate converters described above are recommended in accordance with Figure 6-1. However, where roll angle is received in digital format, a digital servo with a shaft encoder feedback element and a sine/cosine potentiometer output device, is judged to be the most efficient mechanization approach.

C. DIGITAL PROCESSOR WITH SPECIAL-PURPOSE COMPUTER

1. Background and Features

The computer-controlled digital processor described in this subsection is largely based on design studies conducted by Sperry prior to this program. The initial model was especially designed for operation with synthetic-symbol, avionic displays to yield maximum efficiency in cost and time execution. The processor described below, however, has been extended into a somewhat more powerful machine to accommodate the more complex arithmetic operations associated with aimsight stabilization and various kinematic targeting techniques. As such, it represents a promising candidate design for a HUD processor that can be used as a starting point in the actual development of a HUD system for helicopters.

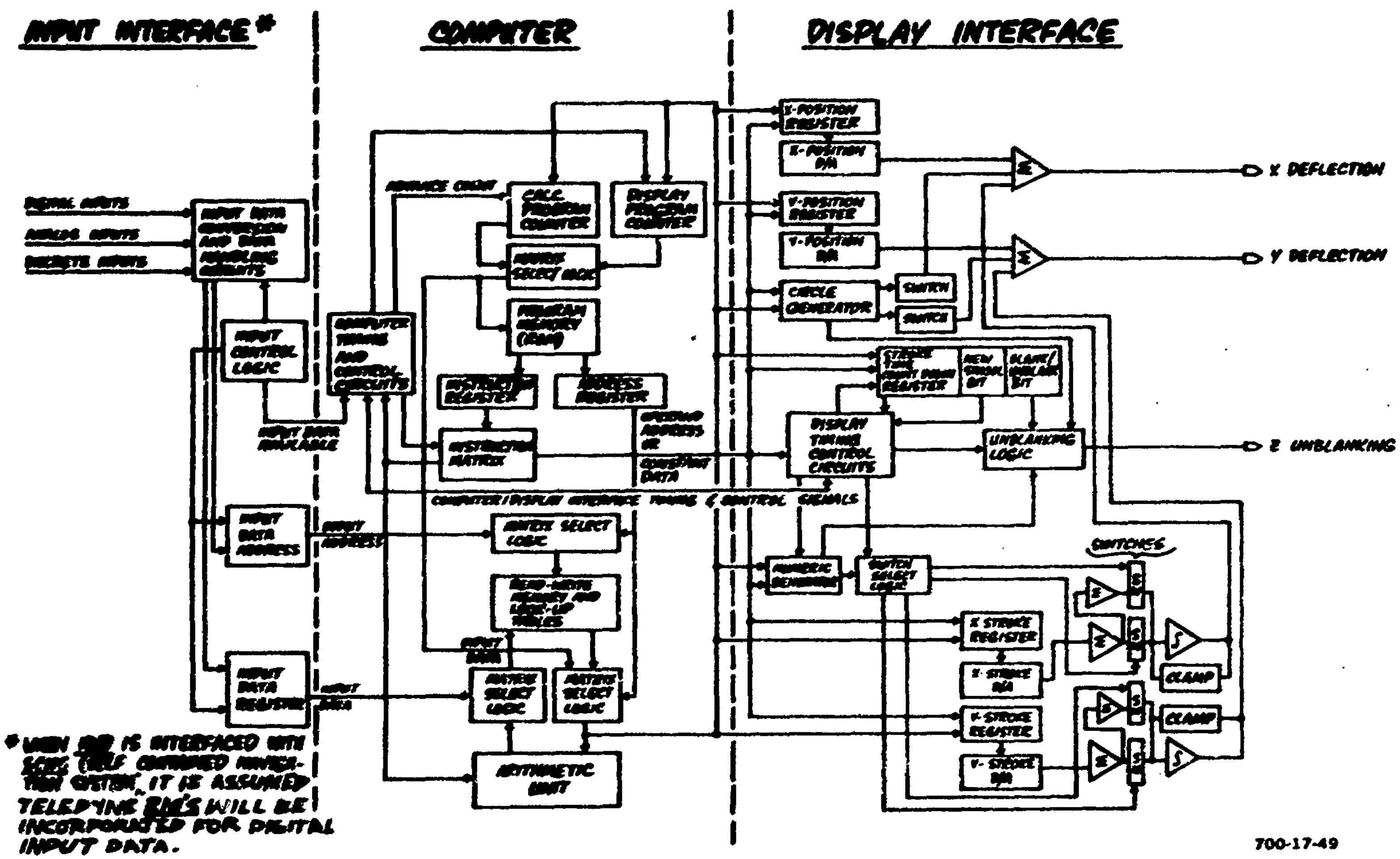

Figure 6-2
Digital Processor with Special-Purpose Computer

The key features of the special purpose computer portion of the processor are as follows:

- State-of-the-art components and design techniques
- Medium-Scale Integrated (MSI) and Large-Scale Integrated (LSI) elements employed
- Solid-state ROM and read/write memories
- Direct memory access input
- Direct parallel memory readout with display program counter control of readout data
- Design lends itself to high efficient input/output data rates

2. Functional Description

The digital processor is comprised of the following major sections:

- Input Interface
- Special-Purpose Computer
- Display Interface

A block diagram of the processor is shown in Figure 6-2. The input interface section receives all the signal inputs from the various sensor and computer sources. This data (analog, digital and discrete) is appropriately formatted, temporarily stored, and inputted to the special-purpose computer. The computer processes the input data and outputs symbol data and control signals to the display interface. This output interface, in turn, generates the deflection and Z-unblanking signals required for the CRT electronics.

a. Input Interface

The input interface section receives all the variable and discrete inputs to the processor. The interface effectively handles the data to provide full compatibility between the asynchronous operation of the computer and the inputted data. For those helicopter applications where the processor is interfaced with SCNS, it is assumed that Teledyne receiver modules will be incorporated to receive the digital input data. The essential functions of the input interface are:

- Recognition, acceptance, and conditioning of input data
- Temporary storage of data
- Time interlacing of digital data and discretes for display computer inputting
- Address structuring for direct computer memory access of all input data

The input interface informs the computer that input data is available by means of an input-data-available signal. This signal is sent to the computer after new data is inserted in the input data register and the appropriate input data address is presented to the computer. The computer, upon receipt and recognition of a new-data-available signal, employs the input address to transfer the input data into memory.

The circuits that would be required for operating on analog data are not shown in the input interface. Since wide variations prevail in the analog signal formats between various helicopters, specially designed analog interfaces are required for each application. From an examination of existing helicopter avionics, the analog interface includes a wide complement of dc-to-dc and ac-to-dc conditioning circuits, dc-to-digital conversion, and synchro-to-digital (θ, tangent θ) conversion circuits along with the associated sample and hold elements.

b. Special-Purpose Computer

The computer was especially designed to fulfill the specific requirements of high display refresh rates, high input data rates and high calculation rates often imposed on avionic display processors. Highly efficient input/output data rates are afforded by the capabilities of direct parallel memory access data input and direct parallel memory data display readout under display program control. All computer functions are performed using a parallel information transfer format. The basic characteristics of the computer are as follows:

- 16-Bit Instruction Format
- 12-Bit Data Word
- ROM - Solid State, Random Access, 2.0-microsecond Cycle Time
- Read/Write Memory - Solid State, Random Access, 1.0-microsecond Cycle Time
- 4-microsecond add
- 14.5-microsecond multiply
- Two's complement arithmetic
- Two priority interrupts

    Input data available

    Display data request

In addition to the memory elements noted above, MSI and LSI elements are extensively used in the logic design.

(1) Data Input

The computer has the capability of writing data directly into memory. This is done by employing the external input data address as the read/write memory address, enabling transfer of the input interface data to the memory and the execution of a write operand memory cycle. Prior to writing in new input data, availability must be recognized by the computer. Data availability is checked once during every computer short cycle (e.g., add) and after the completion of the operand memory cycle of a long computer cycle (e.g., multiply).

(2) Display Data Output

All display data readouts from the computer are controlled by the display program counter. When a display data request is received from the display interface and recognized by the computer, the computer disables the calculation program counter and enables the display program counter to address the program memory (ROM). The computer remains in the display program control mode until all the quantities required to paint the next symbol or symbol part have been transmitted to the display interface. After the display interface has generated the appropriate deflection and Z-axis signals to the CRT for the presently received data, the display interface sends another display data request to the computer.

The display quantities that are read out of the computer are as follows:

- X-position
- Y-position
- $\dot{X}$
- $\dot{Y}$
- Stroke time (length)
- Numeric symbol to be generated
- Circle (plus size)

The parallel readouts can be either from the output of the program memory (constants) or from the ROM (variables). In general, the only outputs that are variable quantities are symbol positions and rolled stroke magnitudes.

Since the display program contains all the symbols required in all the various display modes, it must be modified in accordance with the selected system mode. During the display program, symbol or display mode words are interrogated to determine which display data readouts are to be omitted. To inhibit a readout, the display program counter is set to an advanced starting location given in the output of the ROM memory.

(3) Arithmetic Operations

The computer is capable of performing arithmetic operations employing either the output of the program memory (ROM) or the operand memory. The program memory is used when an arithmetic operation is performed using a constant quantity (e.g., add a constant or multiply by a constant). The read/write operand memory is used for arithmetic operations involving variables. When a constant quantity is involved in an arithmetic operation, only a program memory cycle is required. This technique, which saves the operand memory cycle time, is made possible by the availability of bits in the 16-bit instruction format that was chosen to satisfy the requirements of both the display data readout and computer operation addressing schemes.

(4) Computer Instruction Repertoire

The computer instruction complement and programmed subroutines are listed below. The programmed subroutines are included for implementing the aimsight stabilization and/or kinematic targeting functions as delineated in this report.

INSTRUCTION COMPLEMENT

General	Readout
Clear + Add	Read to X-Position
Add	Read to Y-Position
Subtract	Read to X-Stroke
Multiply	Read to Y-Stroke
Left Shift	Read to Stroke Time
Extract	Read to Numeric Generator

INSTRUCTION COMPLEMENT (cont)

General	Readout
Store Accumulator	Read to Circle Generator
Store M-Register	
Jump (To Return Address)	
Jump (If Zero)	
Jump (If One)	

PROGRAMMED SUBROUTINES

Grey to Binary

Sin/Cos

Tan^{-1}

Sin^{-1}

Divide

Square Root

c. Display Interface

The display interface receives data from the computer in word-serial, bit-parallel format. In addition, identity gating signals, which, when received, are used to channel the associated data to the appropriate register, are outputted. After all the quantities required to generate a symbol, or portion thereof, have been received, the deflection and Z-unblanking signals for the CRT display are generated by the display interface. Upon completion of the writing of a symbol and symbol part, a display data request is fed to the computer requesting new data.

The display interface would typically comprise the following symbol generation circuits for most conceived helicopter HUD applications employing a CRT.

- X- and Y-position circuits to establish an X- and Y-CRT beam position from which the symbol is referenced and written

- Stroke generation circuits to generate straight-line segments

- Circle generator to generate circles of different sizes

- Numeric generator to generate the stroke patterns and Z-unblanking required for writing a numeric symbol as identified by a coded 4-bit word received from the computer. Rolled numeric symbols can also be generated.

In order to generate line strokes, direction and length parameters are required. The stroke direction is established by the normalized magnitudes of the inputs applied to X- and Y-stroke integrators. These inputs, as received from the computer, are termed X-rate ($\dot{X}$) and Y-rate ($\dot{Y}$): they are equivalent to the cosine and sine of the stroke angle, respectively. For a constant-write-speed system, the vector sum of $\dot{X}$ and $\dot{Y}$ must be constant. Stroke length is a function of the time the stroke integrators are enabled, hence, use of the term "stroke time". Stroke time data is obtained either from the computer or is generated within the numeric generator. Start/stop control of the stroke integrators is achieved by presetting the stroke time word into a counter and counting down to zero at a fixed rate.

3. Physical Characteristics

The estimated hardware characteristics of the special, computer-controlled processor are as follows.

- Input Interface - 1 Card

- Display (Output) Interface - 6 Cards

- Computer

  Logic (5-1/2 Cards)
  Memory Interface (1 Card)
  Program Memory (1-1/2 Cards)
  Read/Write Memory (2 Cards)

- Total Processor Volume

  890 cu in.

  6 in. X 9 in. X 16-1/2 in.

- Total Processor Weight - 26.8 lb

This estimated data is supplied for planning purposes only and is based on the following factors and assumptions.

- For the input interface estimate, it is assumed that pitch and roll are received in a digital format as is the case in the SCNS (ASQ-104 or ASQ-105). The one-card estimate is only for the SCNS-transmitted, digital data anticipated for a relatively extensive HUD format and related kinematic targeting processing operations. Estimates for analog signal conditioning and conversion are not included.

- Low voltage power supplies are included.

- All cards are 3-inch x 7-inch multilayer boards.

- TTL logic is employed.

- A memory size of approximately 3000 words of 16 bits each and the use of 2048 bit MOS ROM microcircuits is assumed in the program memory estimates.

- A memory size of approximately 200 words of 12 bits each and the use of 128 bit TTL read/write microcircuits is assumed in the read/write memory estimate.

- It is assumed in the volume and weight estimate that the processor chassis includes a cold wall.

SECTION VII

CANDIDATE HEADUP DISPLAY SYSTEMS

A. SYNTHESIS OF SYSTEM CONFIGURATIONS

Candidate HUD systems for application to current and future Navy helicopter and STOL aircraft are presented in this section. These systems were established based on Sperry's best engineering judgment and consideration of the multitude of factors affecting this formulation. As such, this effort brings together in sharper focus all the operational and design tradeoff analyses conducted in this study.

The HUD systems are defined in terms of principal equipment configurations reflecting the individual projector and processor equipment candidates established in Sections V and VI. The rationale as to what constitutes reasonable combinations of such equipment is effectively treated throughout this report. For example, if one or two fixed electromechanical projectors were to be specified, a simple analog processor would logically be selected as part of the system. As an added example, if a stabilized aimsight were assumed to be required, a computer-controlled, digital processor would best complement this optical unit assuming that an existing on-board computer could not accommodate the required aimsight functions. As a final example, it is felt that systems comprising dual installations of fixed, CRT projectors cannot be justified because of the associated high cost and weight and have, therefore, been ruled out.

Out of the literally hundreds of system permutations possible, 12 headup display systems have been established as candidates. These systems are defined in Figure 7-1. The HUD systems recommended in Section VIII for each of the vehicles and missions considered in this study have been selected from these twelve.

The display configurations established represent a first level of system definition. This study was not intended to prepare detailed system and equipment specifications to be recommended. For any actual application, considerably more in-depth analysis by the system manager would be required, involving more substantive cost-effectiveness evaluations and the establishment of specific operations and display requirements.

B. SELECTION CRITERIA FOR HUD SYSTEMS

The specific HUD system recommendations presented in Section VIII are based on an overall, composite consideration of many selection criteria for each of the vehicle and mission applications studied. These selection criteria are as follows:

- Allocation of crew duties
- Display requirements
  - Operational modes
  - Complexity of display formats
  - Complexity of data processing
  - Field of view
- Requirement for acquisition aimsight
- Need for dual cockpit instrumentation
- Cost and weight factors
- Cockpit configuration and space constraints
- Existing on board sensors

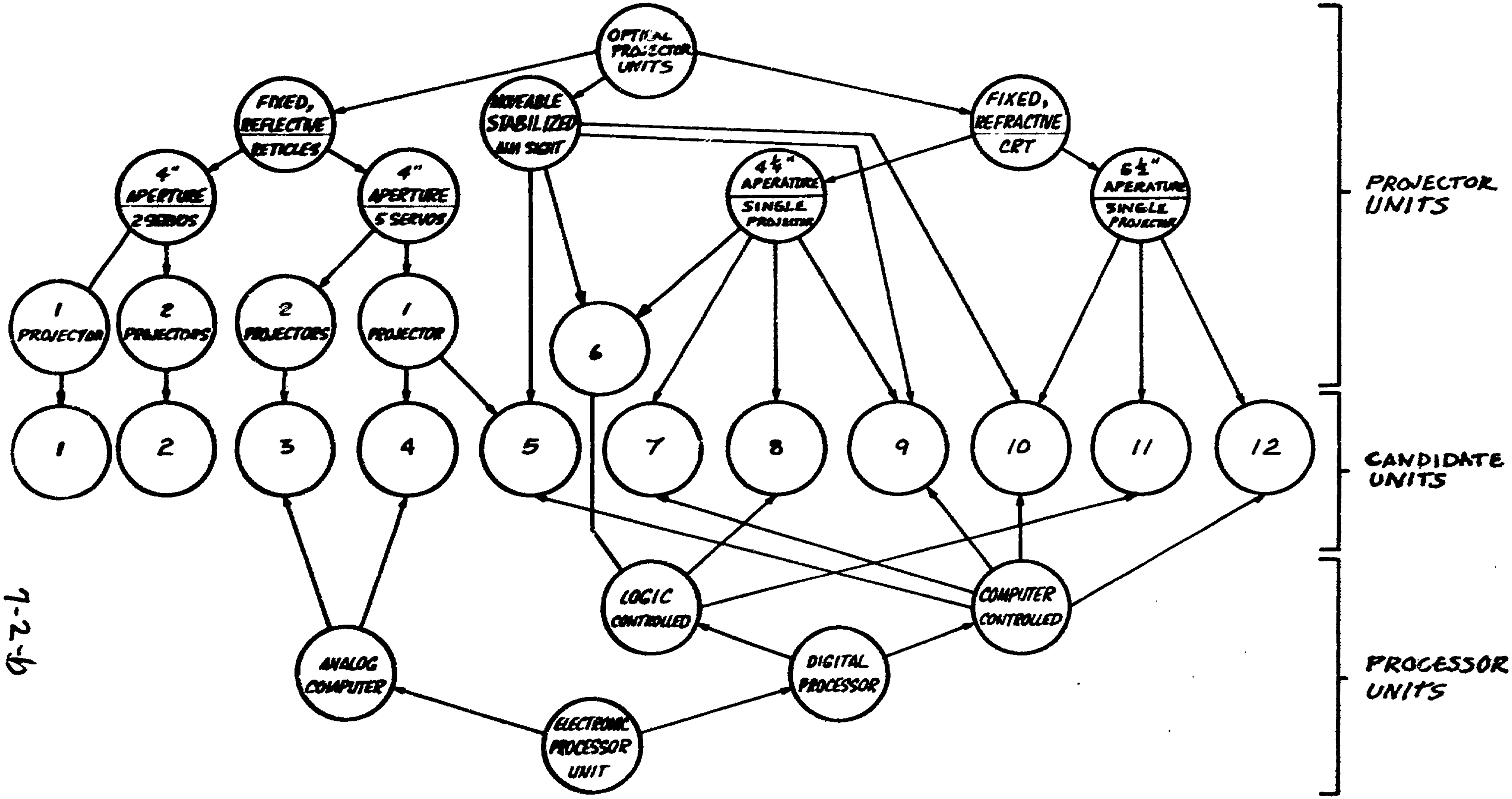

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Figure 7-1
Candidate Head-up Display Systems

- Additions/modifications to existing sensor complement
- Availability of programmable on-board digital computer with sufficient spare time and memory capabity

Each of these criteria was assessed both objectively in terms of established facts and requirements developed in this study, and where required, subjectively in the form of assumptions and judgments. Examples of the latter include the weighting applied to cost and weight factors and the likelihood that desirable additions and/or modifications to an existing helicopter sensor complement would be approved by the Navy.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The HUD will, to varying degrees, improve the effectiveness of all military helicopter systems. As such, it warrants serious consideration in future avionic system development relating to both new and existing vehicles. In fact, compelling needs for a HUD have been established for a number of critical applications, which, it is believed, will be substantiated by more thorough cost-effectiveness evaluations. In assessing the value and role of HUD for the gamut of existing helicopters and associated missions analyzed in this study, generalized conclusions are not viable, and a single, universal design is invalid. Rather, a complex of different system configurations, reflecting a wide range of cost and complexity, is involved in both the retrofit decision and design specification process. In addition, in retrofit applications, the HUD can be considered either simply as an individual element, or as part of a somewhat larger integrated avionic package, depending on the specific use intended for the display and the objectives established for improved weapon system performance and capabilities enabled by such a display.

At the present time, the most compelling needs established for HUD relate to the close support attack (gun and rocket fire control), medical evacuation and assault transport (remote area landing), and SAR missions. The major problems associated with these missions, which can be ameliorated by a properly designed HUD are as follows:

- Control difficulties during rapid, steep VFR approaches as may be necessitated by enemy gunfire, rough and dense terrain, etc.

- Loss of ground target (after initial sighting) under adverse detection conditions due to lack of acquisition and continuous orientation capability

- Approaches under poor visibility conditions

- Inadequate gun and rocket fire control performance

A. RECOMMENDED HUD SYSTEMS

Twelve HUD system configurations are established in Section VII as candidates for helicopter and STOL application. These systems reflect various combinations of equipment designs selected from among five optical projector and three electronic processor designs presented in Sections V and VI of this report. The HUD systems recommended below for each aircraft and mission application studied were selected from among the aforementioned 12 candidates based on criteria outlined in Section VII. These recommendations are based on the sensor and computer avionics presently existing on board each vehicle. Significant additions or modifications to an avionic complement would probably dictate a change in the HUD recommendations for that vehicle. Most noteworthy in this regard are the AH-1J and OV-10 aircraft, which are presently simply equipped in avionics. If any of the recommendations presented in Subsection VIII.B relating to improved visual fire control were to be adopted, a CRT projector and digital processor would be the preferred choice.

Aircraft/Mission	System No.	Description
AH-1J Close Support Attack	1	Electromechanical - 2 Servos (1 projector)
UH-2C Utility	4	Electromechanical - 5 Servos (1 projector) + Analog Processor
UH-46 Utility and Vertical Replenishment	2	Electromechanical - 2 Servos (2 projectors)
HH-2C Air/Sea Rescue	9	CRT + 4-1/4-in. Aperture Projector + Aimsight + Computer-Controlled Digital Processor
HH-3A Air/Sea Rescue	9	CRT + 4-1/4-in. Aperture Projector + Aimsight + Computer-Controlled Digital Processor
SH-3[illegible] Submarine Detection and Attack	2	Electromechanical - 2 Servos (2 projectors)
RH-3 Minesweeping	8	CRT + 4-1/4-in. Aperture Projector + Logic-Controlled Digital Processor
RH-53 Minesweeping	8	CRT + 4-1/4-in. Aperture Projector + Logic-Controlled Digital Processor
OV-10 Observation	1	Electromechanical - 2 Servos (1 projector)
CH-46F Transport	9	CRT + 4-1/4-in. Aperture Projector + Aimsight + Computer-Controlled Digital Processor
CH-53D Transport	9	CRT + 4-1/4-in. Aperture Projector + Aimsight + Computer-Controlled Digital Processor
CH-46D Medical Evaluation	2	Electromechanical - 2 Servos (2 projectors)
HH-53B, C Air/Ground SAR	10	CRT + 5-1/2-in. Aperture Projector + Aimsight + Computer-Controlled Digital Processor

B. RECOMMENDATIONS FOR IMPROVED VISUAL FIRE CONTROL SYSTEM ON AH-1J GUNSHIP

It is urged that serious consideration be given to updating the AH-1G, J gunship fire control system for improved performance with a low cost avionics package, oriented about a head-up display. The operational, display, and target acquisition concepts developed in this study (Subsection IV.H) are suggested as a baseline for such studies. There are two key functional considerations affecting system design and complexity. The first concerns the basic type of projectile trajectory prediction method to be employed. The two best known candidates are the impact point and hotline solutions. The second relates to the problem of providing the sensed data necessary for computing the trajectory solution. The two recommended approaches that follow reflect a low cost, low weight philosophy, i.e., a system that qualitatively is one step above the current AH-1 avionics, but considerably below the level of sophistication designed for the Army AH-56 (AAFSS). The lowest cost, and thus preferred, system retrofit concept is one where the flight leader or observation aircraft relays target altitude and wind velocity data to the gunship squadron (refer to Subsection IV.H.4). This enables the derivation of range and flight velocity on board each attack helicopter to satisfy the fire control solution requirements. Other than a HUD symbol generation computer, which is shared for the fire control solution, very little in the way of additional equipment is required. The most expensive sensor retrofit required would be an AHRS, preferably of advanced high performance design, to replace the existing VG and DG.

The second system alternate reflects a self-contained means for kinematic ranging and deriving flight velocity and wind. The added equipment would essentially comprise the following:

- A relatively low cost Doppler radar specifically designed for velocity sensing in the high speed regimes, and with no navigation computer function

- Pressure altitude sensor
- True airspeed sensor
- AHRS (to replace VG/DG)
- HUD (with digital computer processor)

The apparent higher priority assigned to providing night combat capability to gunships over improving visual weapon delivery performance is easily appreciated. However, a case can probably be made for the latter objective as well when the question is considered in terms of the following hypothesis. The Cobra presently carries 76 rockets, each weighing 21 pounds. It is reasonable to assume that by eliminating, say ten rockets, to accommodate additional avionic weight, this weight tradeoff may result in improved mission effectiveness. Similarly, it can be reasoned that the cost penalty incurred with added avionics would be at least partially offset by the fewer armament stores to be expended over the expected life of each gunship.

C. FUTURE STUDIES RECOMMENDED

It is recommended that additional studies be pursued on several of the concepts developed during this program. Specifically, accuracy analysis and flight simulation are required on the various kinematic targeting techniques advanced in this study to establish feasibility in terms of performance and operability. The two-angle acquisition during a straight-in approach, in particular, warrants ground-based simulation to test both acquisition performance and time adequacy. In addition, a rigorous sampled data stability analysis of the stabilized aimsight loop design developed in this study is recommended. This effort should yield the exact digital computer compensating functions required for optimum visual tracking performance. No equipment developments are recommended at this time since most of the equipment designs advanced in this report are within the state of the art - either proven or of a low development risk nature. The curved CRT faceplate concept for achieving wide fields of view is perhaps the most deserving candidate for development. However, it is Sperry's opinion that any equipment developments and flight test programs should be deferred until the studies outlined above are conducted and the results substantiate the effectiveness of these techniques.

APPENDIX A

DERIVATION OF AIMSIGHT STABILIZATION EQUATIONS TO COMPENSATE FOR THE EFFECTS OF ATTITUDE MOTION

1. STATEMENT OF THE PROBLEM

In the development of a manually rotatable aiming sight for helicopter tracking tasks (i.e., weapons delivery), one of the problems encountered is reticle jitter due to oscillations in pitch, roll and yaw. Tracking errors are introduced and the tracking task is aggravated from a human factor's standpoint by oscillations at frequencies greater than the operator's ability to correct. The need exists, therefore, to automatically stabilize the aim reticle in the presence of high frequency, low amplitude oscillations in pitch, roll and yaw. The development of the equations necessary to implement aim reticle stabilization is presented in this appendix.

2. DEFINITIONS AND CONVENTIONS

AIRCRAFT AXES AND POLARITY CONVENTIONS (FIGURE A-1)

Roll right is positive
Pitch up is positive
Yaw right is positive

These aircraft axes (not the earth's axes) are the frame of reference for this problem.

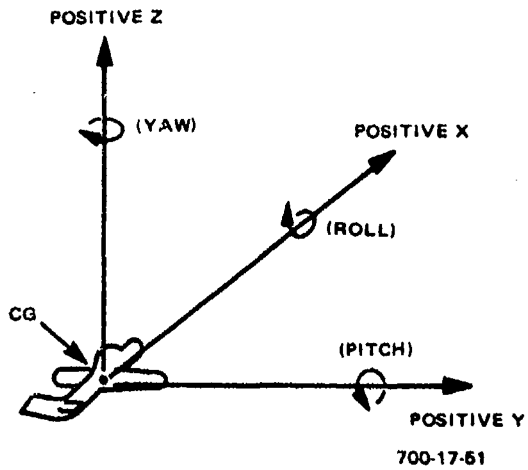
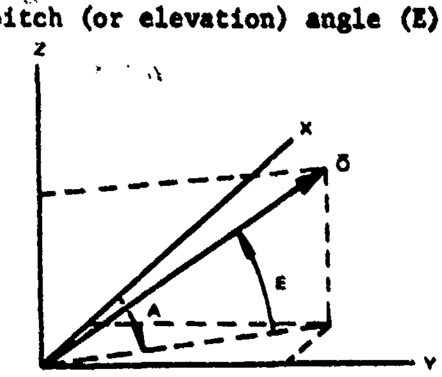


Figure A-1

THE AIMING RETICLE CAN BE POSITIONED IN YAW AND PITCH (OR ELEVATION) RELATIVE TO THE AIRCRAFT AXES.

The reticle is positioned by first rotating the sight through a yaw angle (A), and then rotating it through a pitch (or elevation) angle (E). The position of the sight is thus described by the angles (A and E) as shown in Figure A-2. The vector $\overline{O}$ is the optical line of sight. The origin of the aircraft reference frame is the aircraft center of gravity. One simplifying assumption is that the optical axis ($\overline{O}$) is pivoting around the cg. The complexity of the mathematics is significantly reduced by this assumption.



$\bar{O} = \cos A \cos E\bar{\Gamma} + \sin A \cos E\bar{\Gamma} + \sin E\bar{\Gamma}$

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Figure A-2

Another coordinate system of interest is the optical reference frame. This system is simply the aircraft system rotated through A and E. Thus $\overline{O}$ is the X'-axis, and the Y'/Z'-plane is the two-dimensional field in which the aim reticle is viewed. Therefore, the problem is — How do aircraft oscillations affect the motion of $\overline{O}$ in the Y'/Z'-plane? This seems confusing since $\overline{O}$ is and remains the origin of the Y'/Z'-plane. Think of it this way. There are really two $\overline{O}$'s. One is the physical axis of the optical sight. This axis is positioned relative to the aircraft axes by the gunner, so when the aircraft axes move, the axis moves, too. It follows every aircraft and gunner-induced movement, high and low frequencies. A second axis is the axis of the reticle that is displayed on the combiner by the optics. This axis is smarter than the other. It knows that low frequency motions are either caused by the gunner, or can be handled by the gunner, so it goes along with them. On the other hand, it does not respond to high frequency oscillations, but remains where the gunner put it. Since the not-so-smart $\overline{O}$ number 1 wants to get back where it belongs, where in Y'/Z' number 1 is $\overline{O}$ number 2? $\overline{O}$ number 2 is the smartest, so we'll let it figure out where 1 went; then it can reverse the information and give it to 1. What more can be done?

3. SYMBOL DEFINITIONS

E = Gunner-induced pitch rotations of the optical sight

A = Gunner-induced yaw rotations of the optical sight

$\Delta\theta$ = Small, high frequency rotations of the aircraft about its Y-axis (pitch)

$\Delta\phi$ = Small, high frequency rotations of the aircraft about its X-axis (roll)

$\Delta\psi$ = Small, high frequency rotations of the aircraft about its Z-axis (yaw)

Small Rotations = Less than 10 degrees

High Frequency = Greater than 1 Hz

X-Y-Z = Coordinate axes of the aircraft

X'-Y'-Z' = Coordinate axes of the optical system

α-β-γ = Direction angle (in X-Y-Z) of the subscript (i.e., $\alpha_{X'}$, $\beta_{X'}$, $\gamma_{X'}$ are the direction angles of X')

a-b-c = Direction cosines of the subscript

$\overline{O}$ = Axis of the optical sight in vector form

δ = Radius of the roll circle

ϵ = Angle between $\overline{O}$-X plane and X-Y plane

ρ = Radius of the roll circle

ν = Angle between $\overline{O}$-Y plane and X-Y plane

x_ϕ, y_ϕ, z_ϕ = Coordinate of a vector ($\overline{V}_\phi$) describing the roll motion of $\overline{O}$ (X, Y, Z)

$x_\theta, y_\theta, z_\theta$ = Coordinates of a vector ($\overline{V}_\theta$) describing the pitch motion of $\overline{O}$ (X, Y, Z)

$x'_\phi, y'_\phi, z'_\phi$ = x_ϕ, y_ϕ, z_ϕ in X', Y', Z' coordinates ($\overline{V}'_\phi$)

$x'_\theta, y'_\theta, z'_\theta$ = $x_\theta, y_\theta, z_\theta$ in X', Y', Z' coordinates ($\overline{V}_\theta$)

θ_x, θ_y = Motion of the reticle due to $\Delta\theta$

ϕ_x, ϕ_y = Motion of the reticle due to $\Delta\phi$

ψ_y = Motion of the reticle due to $\Delta\psi$

σ_1 = The sign of sine A (roll)

σ_2 = The sign of cosine A (pitch)

4. COORDINATE TRANSFORMATION

DIRECTION COSINES OF X'-Y'-Z'

The direction cosines of a vector are the cosines of the angles the vector makes with the X-Y-Z axes. The direction cosines of $\overline{V}$ in Figure A-3 are:

$a_V = \cos \alpha_V$

$b_V = \cos \beta_V$

$c_V = \cos \gamma_V$

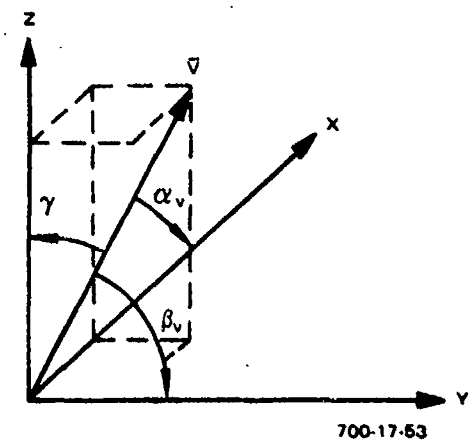

Figure A-3

The direction cosines of X', Y', and Z' are of particular interest. They are:

- Direction Cosines of X' (Figure A-4)

$a_{X'} = \cos A \cos E$

$b_{X'} = \sin A \cos E$

$c_{X'} = \sin E$

NOTE: X' is $\overline{O}$, the optical axis.

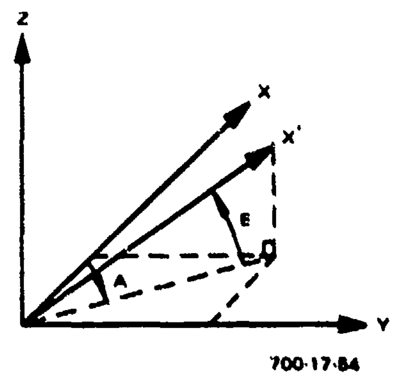

Figure A-4

- Direction Cosines of Y' (Figure A-5)

$a_{Y'} = -\sin A$

$b_{Y'} = \cos A$

$c_{Y'} = 0$

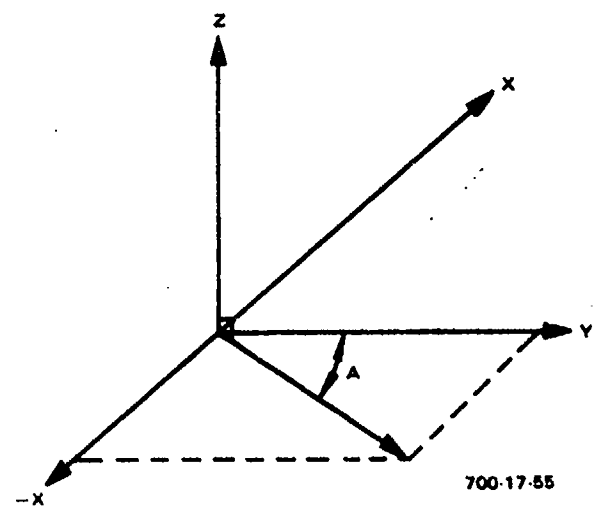

Figure A-5

- Direction Cosines of Z' (Figure A-6)

$a_{Z'} = -\sin E \cos A$

$b_{Z'} = -\sin E \sin A$

$c_{Z'} = \cos E$

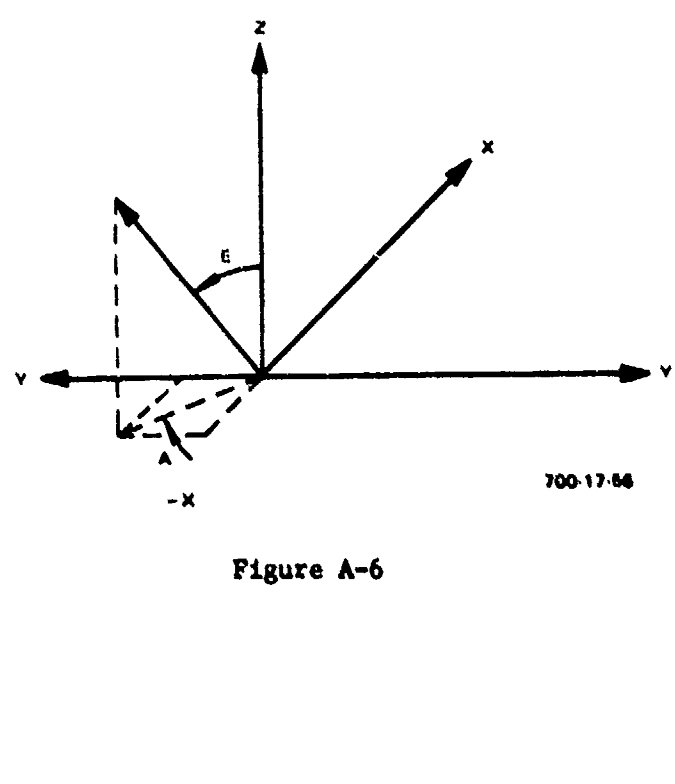

Figure A-6

TRANSFORMATION OF COORDINATES FROM X-Y-Z TO X'-Y'-Z'

Given the direction cosines $(a_{X'}, b_{X'}, c_{X'})$, $(a_{Y'}, b_{Y'}, c_{Y'})$, $(a_{Z'}, b_{Z'}, c_{Z'})$ of the X'-axis, Y'-axis and Z'-axis, respectively, of the optical coordinate system with respect to the aircraft coordinate system and given any vector $\overline{V} = x\overline{i} + y\overline{j} + z\overline{k}$ in the aircraft system, $\overline{V}$ can be transformed into optical coordinates $(\overline{V} = x'\overline{i} + y'\overline{j} + z'\overline{k})$ by the following equations*:

$$x' = a_{x'}x + b_{x'}y + c_{x'}z$$

$$y' = a_{y'}x + b_{y'}y + c_{y'}z$$

$$z' = a_{z'}x + b_{z'}y + c_{z'}z$$

This transformation is a basic tool in the development of the equations in Paragraph 6 of this appendix. The most significant items are y' and z' since these are the coordinates in the plane of the sight picture of the new location of $\overline{0}$ if, in fact, the motion of $\overline{0}$ is described by $\overline{V}$.

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*<u>CRC - Standard Mathematical Tables, 16th Edition</u>, The Chemical Rubber Company, 1967, Page 334.

5. METHOD OF SOLUTION

Consider $\overline{0}$, the vector from the aircraft cg to the aim reticle image on the combiner, as being of unit length. If the aircraft were fixed in space (this is valid since we are trying to compensate for high frequency oscillations, not solve the basic tracking problem) and rotated through 360 degrees in pitch, roll and yaw, the tip of $\overline{0}$ would describe a sphere about the cg. An incremental (small amplitude) motion of $\overline{0}$ can be approximated as a motion along the tangent to the sphere in the direction of motion.

- Roll

We will develop independent expressions for pitch, roll and yaw and superimpose the results. Consider the curve described on the sphere by a 360-degree roll regardless of the position of the sight. A circle, the radius of which is a function of A and E, is described by the tip of $\overline{0}$. The direction of motion of the tip of $\overline{0}$ is tangent to the circle and, at any instant, is perpendicular to the plane defined by $\overline{0}$ and the X-axis. In Figure A-7, the view is from the cg out the X-axis. The projection of $\overline{0}$ is seen on Z-Y; but the $\overline{V}_\phi$ is the full size vector, $\overline{V}_\phi$, describing the motion of $\overline{0}$ subjected to a small roll, $\Delta\phi$. The movement of $\overline{0}$ in the gunner's field of view is described by the projection of $\overline{V}_\phi$ onto Y'-Z' (using the transformation equation.

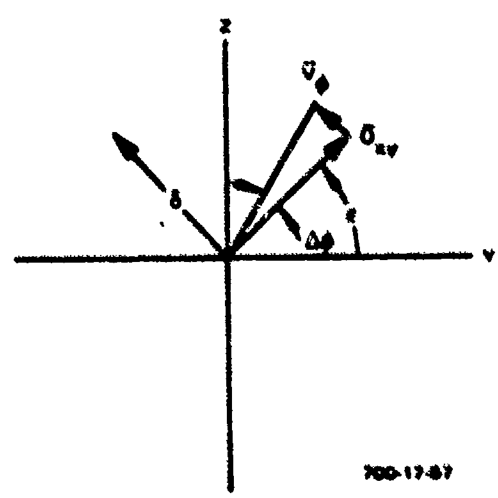

Figure A-7

The following calculations must be made:

(1) Determine the radius (δ) of the inscribed circle in terms of A and E (thus the magnitude of $\overline{V}_\phi$).

(2) Determine the angle (ϵ) the $\overline{O}$-X plane makes with X-Y plane (thus the direction of $\overline{V}_\phi$).

(3) Transform $\overline{V}_\phi$ into X'-Y'-Z' coordinates.

(4) Convert y'_ϕ and z'_ϕ into directions for $\overline{O}$ number 1 by reversing the signs.

- <u>Pitch</u>

The case of pitch is the same as that described for roll. Imagine that in Figure A-7 the view is out the pitch axis instead of the roll axis. The radius of the pitch circle is ρ, and the angle the $\overline{O}$-Y plane makes with the X-Y plane is ν.

- <u>Yaw</u>

The case of yaw is similar to that described for pitch, but simpler. Regardless of A and E, the tangent to the yaw circle is also the Y'-axis of the optical system, and the radius of the circle is simply cosine E.

6. CALCULATIONS

MAGNITUDE OF THE MOTION OF $\bar{O}$

- **Pitch (Figure A-8)**

Given

$E = 0$

$A = A$

$\Delta\theta < 10$ deg

Description of Figure A-8:

$\overline{OA}$ = initial position of $\bar{O}$

$\overline{OB}$ = final position of $\bar{O}$

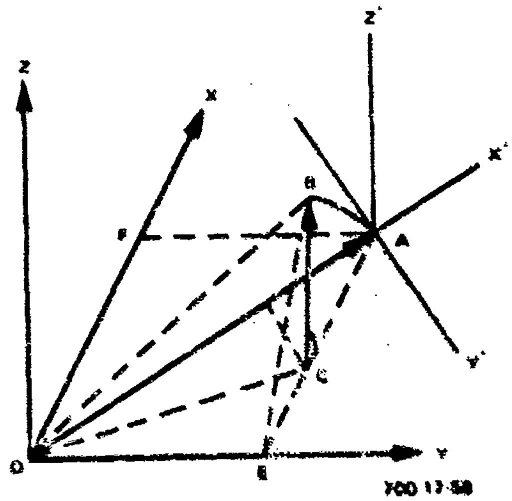

Figure A-8

$\angle FOA = A$

$\angle BEA = \Delta\theta$ (made large for clarity)

$\overline{AB}$ = path of $\bar{O}$

$\overline{AC}$ = projection of AB along the radius of the circle

$\overline{CB}$ = projection of AB along the tangent of the circle

Calculation of CB and AC:

OF = EA = EB - cos $\angle$FOA = cos A = ρ (radius of $\widehat{AB}$)

CB = (BE) sin $\angle$BEA = cos A sin $\Delta\theta$ (special case) = δ sin $\Delta\theta$ (general case)

Since $\Delta\theta < 10$ degrees a reasonable approximation is sin $\Delta\theta \approx \Delta\theta$. Therefore, CB $\approx \rho\Delta\theta$.

CB is the magnitude of motion of $\bar{0}$ along the tangent to the inscribed circle.

$$AC = EA - EC = EA - EB \cos \Delta\theta$$

Since EB = EA, AC = EB $(1 - \cos \Delta\theta)$. Using the small angle approximation of $\Delta\theta$, $\cos \Delta\theta \approx 1$. Therefore, AC $\approx$ 0. The conclusion is that for pitch rotations, the motion of $\bar{0}$ is along the tangent to the inscribed circle and is of magnitude $\rho\Delta\theta$, or

$$\boxed{\left|\bar{V}_\theta\right| = \rho\Delta\theta}$$

- Roll (Figure A-9)

Given

E = 0

A = A

$\Delta\phi$ < 10 degrees

The situation is identical to pitch. Therefore

$$\boxed{\left|\bar{V}_\phi\right| = \delta\Delta\phi}$$

and acts in a direction perpendicular to the $\bar{0}$-X plane.

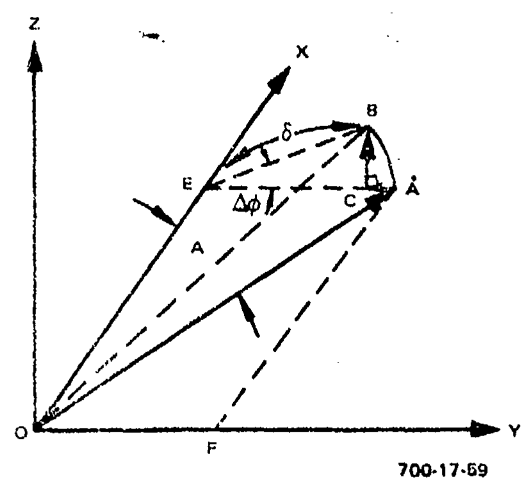

Figure A-9

- Yaw (Figure A-10)

Given

$A = 0$

$E = E$

$\Delta\psi < 10$ degrees

This situation is similar to pitch and roll; except that the radius of the inscribed circle is always cos E. Therefore

$$\boxed{\left|\bar{V}_{\psi}\right| = (\cos E)\ \Delta\psi}$$

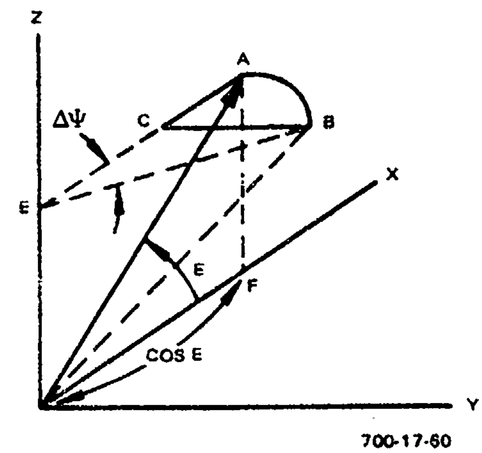

Figure A-10

MAGNITUDE OF RADII OF INSCRIBED CIRCLES

- Magnitude of ρ (Figure A-11)

$OC = \cos E$

$OB = \sin A\ (OC) - \sin A \cos E$

Therefore

$$\rho = AB = +\sqrt{1 - \sin^2 A \cos^2 E}$$

or

$$\boxed{\rho = \cos\ \sin^{-1}\left[(\sin A \cos E)\right]}$$

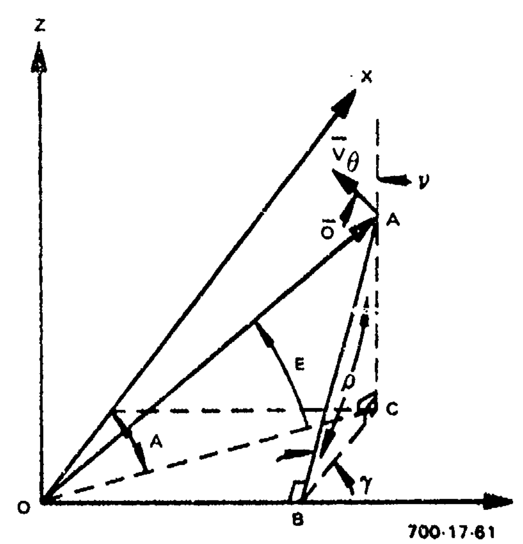

Figure A-11

- Magnitude of δ (Figure A-12)

OC = cos E

OB = cos A (OC) = cos E cos A

Therefore

$$\delta = AB = \sqrt{1 - \cos^2 E \cos^2 A}$$

or

$$\boxed{\delta = \cos\left[\sin^{-1}(\cos E \cos A)\right]}$$

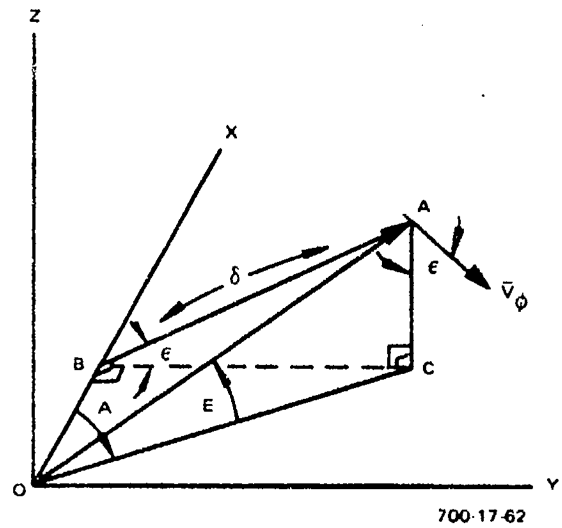

Figure A-12

DIRECTIONS OF THE MOTION OF $\overline{O}$

- Direction of $\overline{V}_\theta$ (Figure A-11)

The path of $\overline{O}$, when pitching, is in a plane perpendicular to the pitch (Y) axis; therefore, $y_\theta = 0$.

The tangent to the pitch circle makes an angle (ν) with the Y-Z plane. From Figure A-11:

$$AC = \sin E, \quad OC = \cos E, \quad BC = OC \cos A = \cos E \cos A$$

Therefore

$$\boxed{\nu = \tan^{-1}\left(\frac{AC}{BC}\right) = \tan^{-1}\left(\frac{\sin E}{\cos E \cos A}\right)}$$

The direction of $\overline{V}_\theta$ is

$$\hat{V}_\theta = (-\sin \nu \bar{i} + \cos \nu \bar{k})\ \sigma_2$$

Therefore

$$\boxed{\overline{V}_\theta = \sigma_2 \rho \Delta\theta \;(-\sin \nu \overline{i} + \cos \nu \overline{k})}$$

where σ_2 is the sign of cosine A.

- <u>Direction of $\overline{V}_\phi$ (Figure A-12)</u>

The path of $\overline{0}$, when rolling, is in a plane perpendicular to the roll (X) axis; therefore, $x_\phi = 0$.

The tangent to the roll circle makes an angle (ϵ) with the X-Z plane. From Figure A-12:

$$AC = \sin E, \; OC = \cos E, \; BC = OC \sin A = \cos E \sin A$$

Therefore

$$\boxed{\epsilon = \tan^{-1}\left(\frac{AC}{BC}\right) = \tan^{-1}\left(\frac{\sin E}{\cos E \sin A}\right)}$$

The direction of $\overline{V}_\phi$ is

$$\hat{V}_\phi = (-\sin \epsilon \overline{j} + \cos \epsilon \overline{k})\; \sigma_1$$

Therefore

$$\boxed{\overline{V}_\phi = \sigma_1 \delta \Delta\phi \;(\sin \epsilon \overline{j} - \cos \epsilon \overline{k})}$$

where σ_1 is the sign of sine A.

- **Direction of $\overline{V}_\psi$ (Figure A-13)**

The path of $\overline{0}$, when yawing, is in a plane perpendicular to the yaw (Z) axis; therefore, $z_\psi = 0$. The tangent to the yaw circle makes an angle (A) with the Z-Z plane. The direction of $\overline{V}_\psi$ is

$$\hat{V}_\psi = -\sin A\bar{i} + \cos A\bar{j}$$

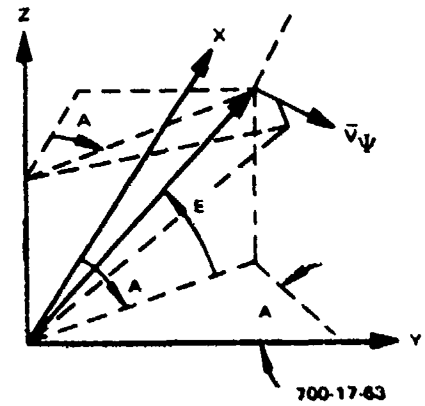

Figure A-13

Therefore

$$\boxed{\overline{V}_\psi = \cos E\ (\Delta\psi)(-\sin A\bar{i} + \cos A\bar{j})}$$

TRANSFORMATION OF $\overline{V}$ TO X'-Y'-Z'

- **Transformation of $\overline{V}_\theta$**

(1) $x'_\theta = a_{x'}x_\theta + b_{x'}y_\theta + c_{x'}z_\theta$

$$= \Big[(\cos A \cos E)(-\rho\Delta\theta \sin\nu) + (\sin A \cos E)(0) + $$
$$+ (\sin E)(\rho\Delta\theta \cos\nu)\Big]\sigma_2$$

$$= \Big[-\rho\Delta\theta \cos A \cos E \sin\nu + \rho\Delta\theta \cos\nu\Big]\sigma_2$$

(2) $y'_\theta = a_{y'}x_\theta + b_{y'}y_\theta + c_{y'}z_\theta$

$$= \Big[(-\sin A)(-\rho\Delta\theta \sin\nu) + (\cos A)(0) + (0)(\rho\Delta\theta \cos\nu)\Big]\sigma_2$$

$$= \sigma_2\rho\Delta\theta \sin A \sin \overline{V}$$

(3) $z'_\theta = a_{z'}x_\theta + b_{z'}y_\theta + c_{z'}z_\theta$

$$= \Big[(-\sin E \cos A)(-\rho\Delta\theta \sin \nu) + (-\sin E \sin A)(0)$$
$$+ (\cos E)(\rho\Delta\theta \cos \nu)\Big]\sigma_2$$

$$= (\rho\Delta\theta \sin E \cos A \sin \nu + \rho\Delta\theta \cos E \cos \nu)\ \sigma_2$$

- Transformation of $\overline{V}_\phi$

(1) $x'_\phi = a_{x'}x_\phi + b_{x'}y_\phi + c_{x'}z_\phi$

$$= \Big[(\cos A \cos E)(0) + (\sin A \cos E)(\delta\Delta\phi \sin \epsilon)$$
$$+ (\sin E)(-\delta\Delta\phi \cos \epsilon)\Big]\sigma_1$$

$$= (\delta\Delta\phi \sin A \cos E \sin \epsilon - \delta\Delta\phi \sin E \cos \epsilon)\ \sigma_1$$

(2) $y'_\phi = a_{y'}x_\phi + b_{y'}y_\phi + c_{y'}z_\phi$

$$= \Big[(-\sin A)(0) + (\cos A)(\delta\Delta\phi \sin \epsilon) + (0)(-\delta\Delta\phi \cos \epsilon)\Big]\sigma_1$$

$$= \sigma_1 \delta\Delta\phi \cos A \sin \epsilon$$

(3) $z'_\phi = a_{z'}x_\phi + b_{z'}y_\phi + c_{z'}z_\phi$

$$= \Big[(-\sin E \cos A)(0) + (-\sin E \sin A)(\delta\Delta\phi \sin \epsilon)$$
$$+ (\cos E)(-\delta\Delta\phi \cos \epsilon)\Big]\sigma_1$$

$$= \Big[-\delta\Delta\phi \sin E \sin A \sin \epsilon - \delta\Delta\phi \cos E \cos \epsilon\Big]\sigma_1$$

- <u>Transformation of $\overline{V}_\psi$</u>

(1) $x'_\psi = a_{x'}x_\psi + b_{x'}y_\psi + c_{x'}z_\psi$

$= (\cos A \cos E)(-\Delta\psi \cos E \sin A)$

$+ (\sin A \cos E)(\Delta\psi \cos E \cos A)$

$= -\Delta\psi \cos^2 E \sin A \cos A + \Delta\psi \cos^2 E \sin A \cos A$

$= 0$

(2) $y'_\psi = a_{y'}x_\psi + b_{y'}y_\psi + c_{y'}z_\psi$

$= (-\sin A)\left[-\sin A \cos E\ (\Delta\psi)\right]$

$+ (\cos A)(\Delta\psi \cos E \cos A) + (0)(0)$

$= \Delta\psi \cos E \sin^2 A + \Delta\psi \cos E \cos^2 A$

$= \Delta\psi \cos E$

(3) $z'_\psi = a_{z'}x_\psi + b_{z'}y_\psi + c_{z'}z_\psi$

$= (-\sin E \cos A)(-\Delta\psi \cos E \sin A)$

$+ (-\sin E \sin A)(\Delta\psi \cos E \cos A) + (\cos E)(0)$

$= \Delta\psi \sin E \cos E \sin A \cos A - \Delta\psi \sin E \cos E \sin A \cos A$

$= 0$

PROJECTION OF $\overline{V}'$ ONTO Y'-Z' PLANE

The projection of any vector $\overline{V}' = x'\overline{i} + y'\overline{j} + z'\overline{k}$ onto the Y'-Z' plane is simply $\overline{V}'_{yz} = y'\overline{j} + z'\overline{k}$. Therefore

$$\overline{V}'_{\theta_{yz}} = \sigma_2 \rho \Delta\theta \left[(\sin A \sin \nu)\ \overline{j} + (\sin E \cos A \sin \nu + \cos E \cos \nu)\ \overline{k} \right]$$

$$V'_{\phi_{yz}} = \sigma_1 \delta \Delta\phi \left[(\cos A \sin \epsilon)\ \overline{j} + (\sin E \sin A \sin \epsilon + \cos E \cos \epsilon)\ \overline{k} \right]$$

$$V'_{\psi_{yz}} = (\Delta\psi \cos E)\ \overline{j}$$

CONVERSION TO X-Y RETICLE DISPLACEMENTS

The expressions for $\overline{V}'_{yz}$ describe the motion of the optical axis in the presence of oscillations. To convert these motions into the conventional X-Y directions for two dimensions, the Y'-axis becomes X, and the Z-axis becomes Y. To convert a motion of the axis to a motion of the reticle, merely change all signs. The result is:

$$\theta_x = -\sigma_2 \rho \Delta\theta \sin A \sin \nu$$

$$\theta_y = -\sigma_2 \rho \Delta\theta (\sin E \cos A \sin \nu + \cos E \cos \nu)$$

$$\phi_x = -\sigma_1 \delta \Delta\phi \cos A \sin \epsilon$$

$$\phi_y = \sigma_1 \delta \Delta\phi (\sin E \sin A \sin \epsilon + \cos E \cos \epsilon)$$

$$\psi_y = -\Delta\psi \cos E$$

where

$$\rho = \cos \left[\sin^{-1} (\sin A \cos E) \right]$$

$$\delta = \cos \left[\sin^{-1} (\cos E \cos A) \right]$$

$$\nu = \tan^{-1}\left(\frac{\sin E}{\cos E \cos A}\right)$$

$$\epsilon = \tan^{-1}\left(\frac{\sin E}{\cos E \sin A}\right)$$

Reticle displacements, then, are

$$\Delta x = \theta_x + \phi_y$$

$$\Delta y = \theta_y + \phi_y + \psi_y$$

APPENDIX B

DERIVATION OF OFFSET, KINEMATIC TARGETING EQUATIONS (DISCRETE VISUAL ACQUISITION METHOD)

1. DERIVATION OF OFFSET, THREE-AXIS EQUATIONS

a. Statement of the Problem

Due to the errors that accumulate in aircraft navigation systems, it is desirable to periodically update the position coordinates of the vehicle. This can be done by passing over a known position and inserting the known coordinate into the system at that instant. However, since it is not always convenient to pass directly over the known point, a need exists for updating the navigation system from a known position, which is viewable and offset from the ground track. The rotatable aimsight can be used to perform this memory-point update with a very simple cockpit procedure and straightforward computer operations.

Since geographical points are located in earth coordinates, it is necessary to convert all angle and distance information into earth axes, and then perform the geometrical calculations to determine the aircraft present position.

As a further extension of this application, it is possible to pinpoint the geographical position of any sighted object, using the same basic equations developed for own-aircraft position updating and assuming the own-aircraft position is known, by means of an on-board navigation system. If a self-contained navigation system is not available, such target orientation can still be achieved in terms of range and bearing quantities that are first calculated to yield geographic coordinates. In this latter case, some suitable flight velocity sensing and computation would be required to continuously update range and bearing to the target.

The functions noted above are termed own-aircraft orientation and target orientation, respectively. In both cases, vertical position is also derived either as aircraft altitude above target or target pressure altitude above standard sea level.

b. <u>Definitions and Conventions</u>

Aircraft and earth axes are shown in Figure B-1. In this figure, all rotations shown except the aimsight elevation (E) are positive. The symbols and conventions used are:

Symbol	Definition	Positive Direction
θ	Aircraft pitch (earth coordinate)	Nose up
ϕ	Aircraft roll (aircraft coordinate)	Right wing down
ψ	Aircraft azimuth (earth coordinate)	Clockwise
A	Azimuth of line of sight (aircraft coordinate)	Clockwise
E	Elevation of line of sight (aircraft coordinate)	Above aircraft horizontal
θ_O	Elevation of line of sight (earth coordinate)	Above earth horizontal
ψ_{OR}	Relative bearing of line of sight (earth coordinate)	Clockwise
t_1, t_2	Points in time	
λ_T, L_T	Latitude and longitude of target	Depends on the hemisphere
λ_2, L_2	Latitude and longitude of aircraft at t_2	Depends on the hemisphere

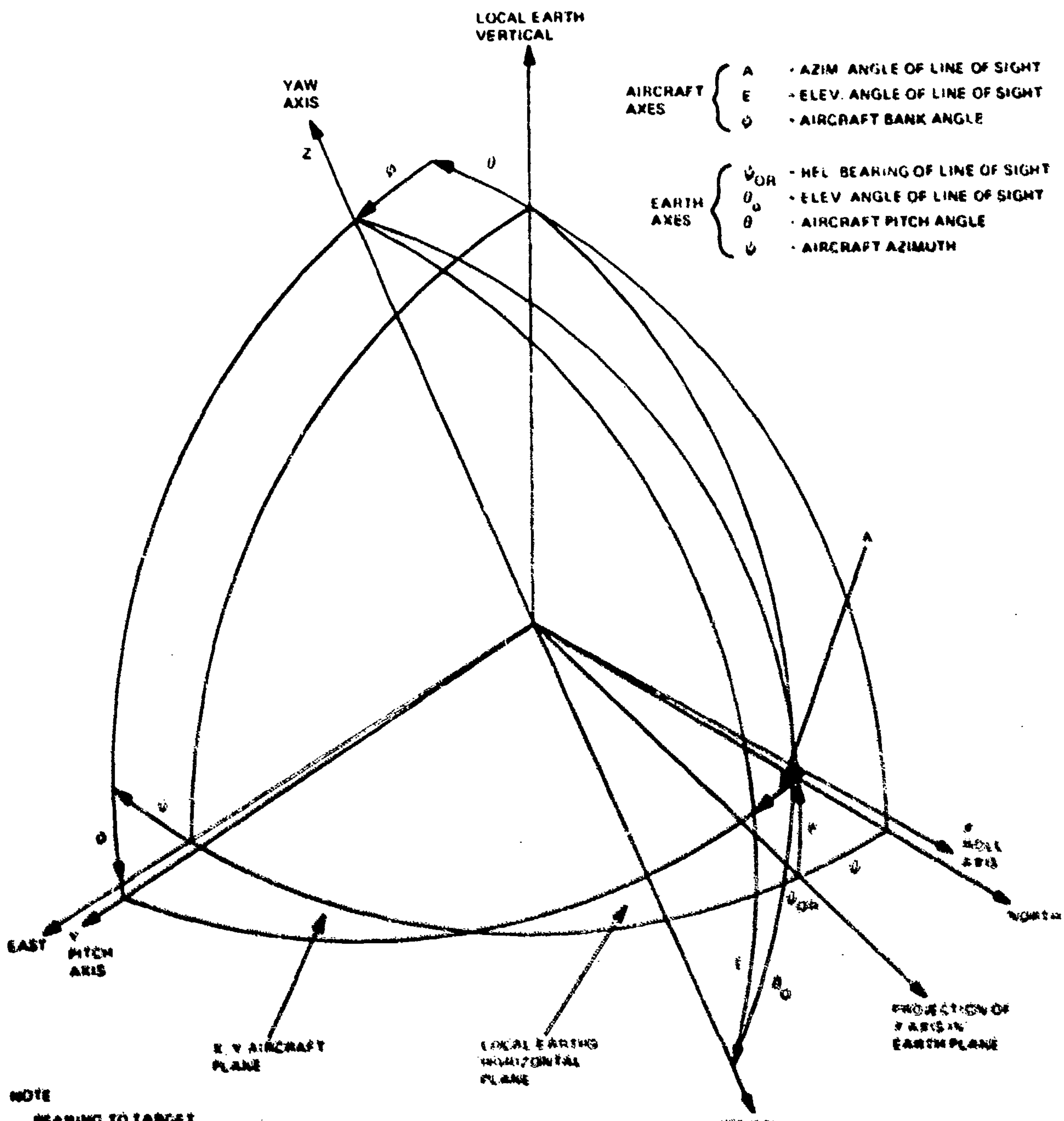

Figure B-1
Coordinate Transformation Geometry - Aircraft to Stable Earth Axes

Symbol	Definition	Positive Direction
R_2	Ground distance from (λ_2, L_2) to (λ_T, L_T)	Positive only
R_λ, R_L	Latitudinal and longitudinal components or R	See page B-9
ψ_{OR_1}, ψ_{OR_2}	Relative bearing of target (earth coordinate) at t_1, t_2	Clockwise
β_1, β_2	Aircraft drift angle at t_1, t_2	Nose right of track
ψ_1, ψ_2	Aircraft azimuth at t_1, t_2	Clockwise
D	Distance travelled from t_1 to t_2 (assumed straight line)	Positive only
ψ_{O_1}, ψ_{O_2}	Bearing to target at t_1, t_2	Clockwise
δ	Angle at target subtended by D (earth coordinate)	Positive only
S, T, U, V	Designations of points in Figure B-7	

c. Coordinate Transformation Equations

The equations for coordinate transformation of the azimuth and elevation aimsight angles from aircraft to stable earth axes are derived below. These equations are developed as follows:

- Define the line of sight as a unit vector described in aircraft coordinates by two angles (A and E)
- Calculate the x-y-z components (aircraft axes) of the unit vector
- Calculate the X-Y-Z components (earth axes) of (x, y, z)

• Sum the x-components of (x, y, z). Similarly the y- and z-components.

• Calculate the two angles (ψ_{OR}, θ_0) in earth coordinates that describe the unit vector.

(1) The unit vector described by A and E is shown in Figure B-2. A and E are positive.

(2) The coordinate components (aircraft axes) of the unit vector are:

$x = \cos A \cos E$

$y = \sin A \cos E$

$z = \sin E$

(3) The coordinate components (earth axes) of x, y and z are shown in Figures B-3, B-4 and B-5; the components are summarized in Table B-1.

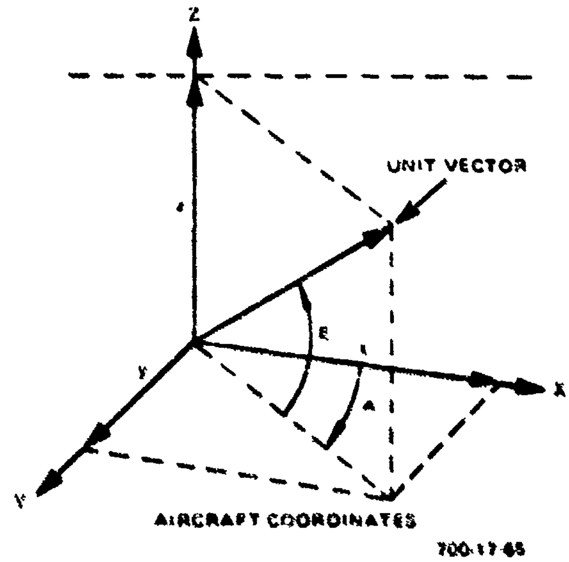

Figure B-2

TABLE B-1

PROJECTION OF x, y, z ONTO THE X-Y-Z AXES

Axis \ Projection of	x (Figure B-3)	y (Figure B-4)	z (Figure B-5)
X	$x \cos \theta$	$y \sin \phi \sin \theta$	$-z \cos \phi \sin \theta$
Y	0	$y \cos \phi$	$z \sin \phi$
Z	$x \sin \theta$	$-y \sin \phi \cos \theta$	$z \cos \phi \cos \theta$

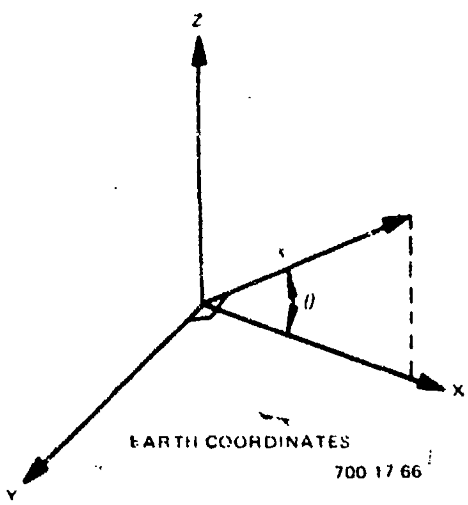

Figure B-3

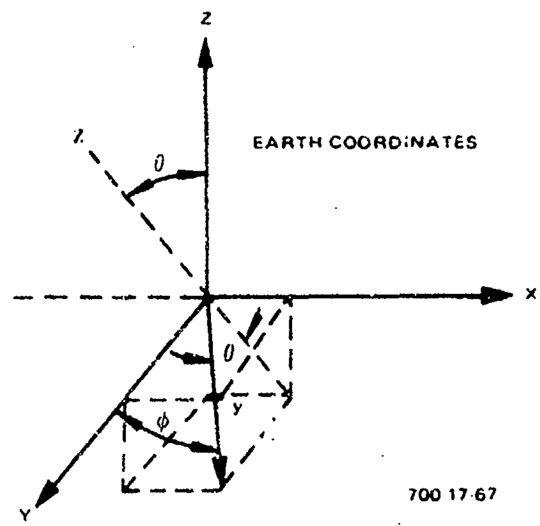

Figure B-4

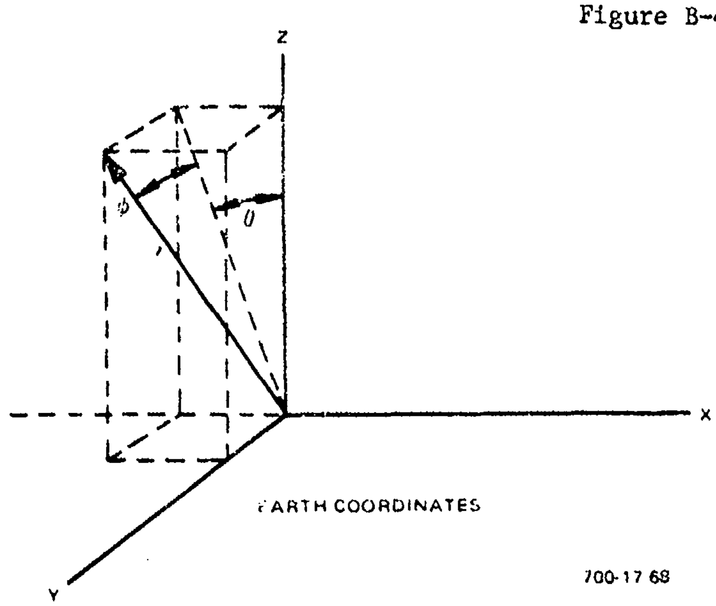

Figure B-5

(4) Therefore th: unit vector is resolved into the following components (earth coordinates).

$$X\text{-comp} = x \cos\theta + y \sin\phi \sin\theta - z \cos\phi \sin\theta$$

$$Y\text{-comp} = y \cos\phi + y \sin\phi$$

$$Z\text{-comp} = x \sin\theta - y \sin\phi \cos\theta + z \cos\phi \cos\theta$$

Substituting the values of x, y, z from (1)

$$X\text{-comp} = \cos A \cos E \cos\theta + \sin A \cos E \sin\phi \sin\theta - \sin E \cos\phi \sin\theta$$

$$Y\text{-comp} = \sin A \cos E \cos\phi + \sin E \sin\phi$$

$$Z\text{-comp} = \cos A \cos E \sin\theta - \sin A \cos E \sin\phi \cos\theta + \sin E \cos\phi \cos\theta$$

or in matrix form:

$$\begin{bmatrix} X\text{-comp} \\ Y\text{-comp} \\ Z\text{-comp} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\phi \sin\theta & -\cos\phi \sin\theta \\ 0 & \cos\phi & \sin\phi \\ \sin\theta & -\sin\phi \cos\theta & \cos\phi \cos\theta \end{bmatrix} \times \begin{bmatrix} \cos A \cos E \\ \sin A \cos E \\ \sin E \end{bmatrix}$$

(5) ψ_{OR} and θ_0 are shown in Figure B-6 (earth coordinate).

$$\theta_0 = \sin^{-1} (Z\text{-comp})$$

$$\psi_{OR} = \tan^{-1} \frac{Y\text{-comp}}{Z\text{-comp}}$$

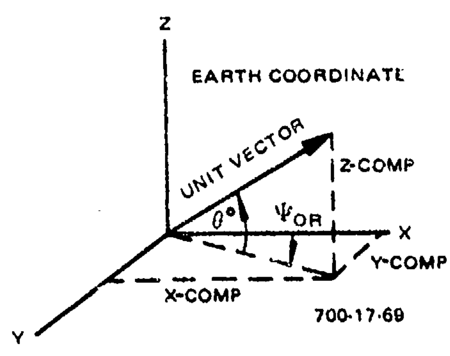

Figure B-6

Therefore

$$\theta_0 = \sin^{-1} (\cos A \cos E \sin \theta - \sin A \cos E \sin \phi \cos \theta + \sin E \cos \phi \cos \theta)$$

$$\psi_{OR} = \tan^{-1} \frac{\sin A \cos E \cos \phi + \sin E \sin \phi}{\cos A \cos E \cos \theta + \sin A \cos E \sin \phi \sin \theta - \sin E \cos \phi \sin \theta}$$

(6) If operating procedures are such that θ and ϕ are small (<10 degrees), the matrix is reduced by the approximations sine a $\approx$ a, cosine a $\approx$ 1 to:

$$\begin{bmatrix} \text{X-comp} \\ \text{Y-comp} \\ \text{Z-comp} \end{bmatrix} \approx \begin{bmatrix} 1 & \phi\theta & -\theta \\ 0 & 1 & \phi \\ \theta & -\phi & 1 \end{bmatrix} \times \begin{bmatrix} \cos A \cos E \\ \sin A \cos E \\ \sin E \end{bmatrix}$$

and

$$\theta_0 \approx \sin^{-1} (\theta \cos A \cos E - \phi \sin A \cos E + \sin E)$$

and

$$\psi_{OR} \approx \tan^{-1} \left(\frac{\sin A \cos E + \phi \sin E}{\cos A \cos E + \phi\theta \sin A \cos E - \theta \sin E} \right)$$

NOTE: θ_0 will probably be <90 degrees. ψ_{OR} need not be <90 degrees. If ψ_{OR} is expected to reach angles such that $|\psi_{OR}| > 90$ degrees, there must be some scheme to define the quadrant ψ_{OR} is in. The information is available in the numerator (Y-coordinate) and denominator (X-coordinate) of the tangent^{-1} expression.

These expressions can be used to transform a sighting taken with an aimsight (with the aircraft in any attitude) into angles measured in earth coordinates. This basic information can be applied to various flight requirements; some of these applications are discussed in the subsequent paragraphs.

d. Own-Aircraft Orientation (Includes Position Update)

One of the most obvious applications of a rotatable sight is for position updating when in sight of a known checkpoint. The geometry is shown in Figure B-7. All information is referenced in earth coordinates, as transformed by the previously derived equations. The geometry illustrated is a plan view of the ground plane as reflected by latitude (λ), longitude (L), and relative bearing (ψ_{OR}) which are all measured in the X-Y plane.

CALCULATION OF HORIZONTAL RANGE AND BEARING

Applying the law of sines to triangle STU of Figure B-7

$$\frac{D}{\sin\delta} = \frac{R_2}{\sin\left(\psi_{OR_1} + \beta_1\right)} \quad \text{or} \quad R_2 = \frac{D\sin\left(\psi_{OR_1} + \beta_1\right)}{\sin\delta}$$

Since

$$\delta = \pi - \left\{\left[\psi_{OR_1} + \beta_1\right] + \left[\pi - \left(\psi_{OR_2} + \beta_2\right)\right]\right\}$$

$$= \left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)$$

Then

$$\text{range } R_2 = \left|\frac{D\sin\left(\psi_{OR_1} + \beta_1\right)}{\sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]}\right|$$

and

$$\text{bearing } \psi_{OR} = \psi_2 + \psi_{OR_2}$$

(Typically D is obtained by time integrating sensed ground speed at a 2 per second rate.)

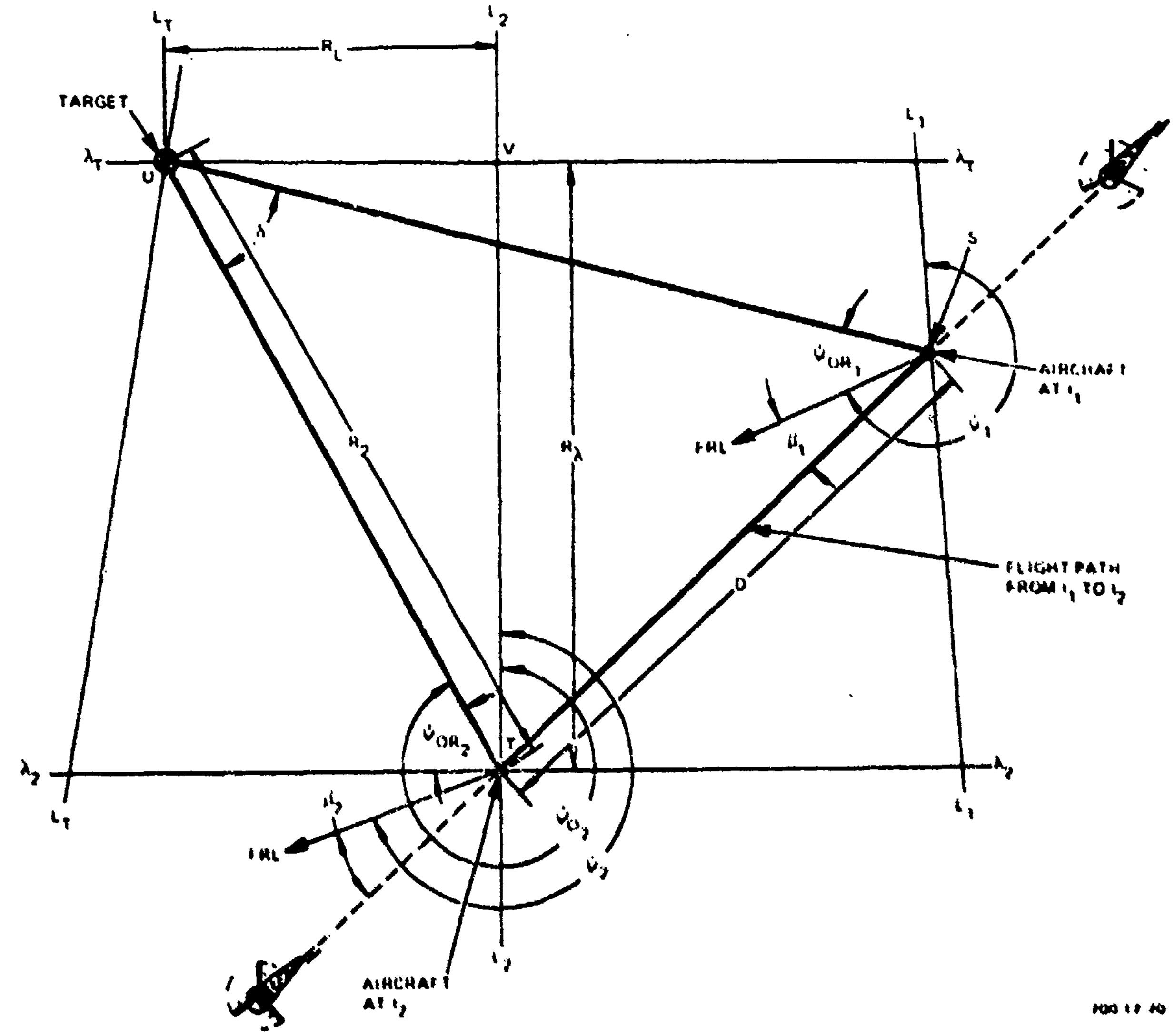

Figure B-7

CALCULATION OF ALTITUDE ABOVE TARGET

Aircraft altitude above the target at the instant of t_2 is derived from the simple trigonometric relationship of Figure B-8.

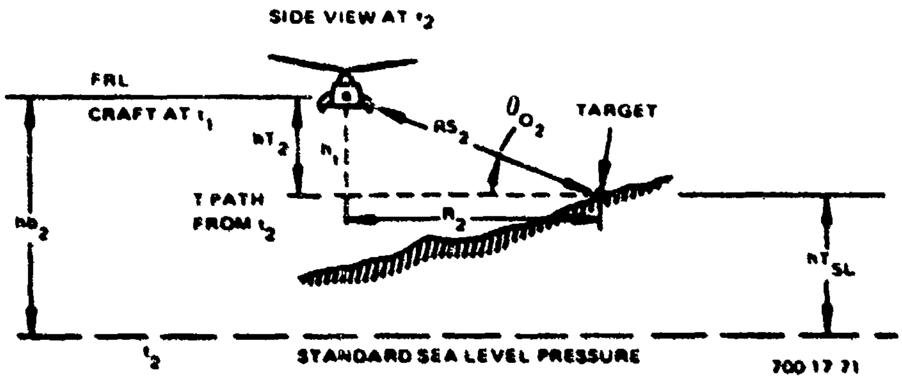

Figure B-8

The elevation angle θ_{O_2} and distance R_2 have previously been computed. Therefore,

$$hT_2 = R_2 \tan \theta_{O_2}$$

CALCULATION OF AIRCRAFT LATITUDE AND LONGITUDE

- Basic Latitude/Distance Relationship

$$1 \text{ nm lat} = 1 \text{ min of arc (lat)}$$

Therefore

$$(R_\lambda \text{ nm}) \frac{1 \text{ min of arc}}{1 \text{ nm lat}} = R_\lambda \text{ min of arc latitude}$$

North of the equator, latitude increases northward. South of the equator, latitude increases southward.

- <u>Basic Longitude/Distance Relationship</u>

$$1 \text{ nm long.} = \left(\frac{1}{\cos\lambda}\right) \text{min of arc (long.)}$$

Therefore

$$\left(R_L \text{ nm}\right)\left(\frac{1 \text{ min of arc}}{\cos\lambda \text{ nm long.}}\right) = \frac{R_L}{\cos\lambda} \text{ min of arc longitude}$$

East of 0-degree longitude, longitude increases eastward. West of 0-degree longitude, longitude increases westward.

- <u>Calculation of Distances Along Meridian and Parallel</u>

From triangle TUV in Figure B-7

$$R_\lambda = \pm R_2 \cos\psi_{O_2} \quad \begin{cases} + \text{ north lat} \\ - \text{ south lat} \end{cases}$$

and

$$R_L = \pm R_2 \sin\psi_{O_2} \quad \begin{cases} + \text{ east long.} \\ - \text{ west long.} \end{cases}$$

or

$$R_\lambda = \pm \frac{\left|D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \cos\left(\psi_2 + \psi_{OR_2}\right)}{\left|\sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]\right|} \quad \begin{cases} + \text{ north } \lambda\text{, east long.} \\ - \text{ south } \lambda\text{, west long.} \end{cases}$$

and

$$R_L = \pm \frac{\left|D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \sin\left(\psi_2 + \psi_{OR_2}\right)}{\left|\sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} - \beta_1\right)\right]\right|} \quad \begin{cases} + \text{ north } \lambda\text{, east long.} \\ - \text{ south } \lambda\text{, west long.} \end{cases}$$

- <u>Final Expression of Aircraft Latitude/Longitude</u>

The target latitude is λ_T. Applying R_λ and the latitude conversion:

$$\text{A/C lat } \lambda_2 = \lambda_T - R_\lambda = \lambda_T - \left[\frac{\left| \pm D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \cos\left(\psi_2 + \psi_{OR_2}\right)}{\left| \sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]\right|} \right] \begin{cases} + \text{ north latitude} \\ - \text{ south latitude} \end{cases}$$

The target longitude is L_T. Applying R_L and the longitude conversion:

$$\text{A/C long. } L_2 = L_T - \frac{R_L}{\cos \lambda_T} = L_T - \left[\pm \frac{\left| D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \sin\left(\psi_2 + \psi_{OR_1}\right)}{\cos \lambda_T \left| \sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]\right|} \right] \begin{cases} + \text{ east longitude} \\ - \text{ west longitude} \end{cases}$$

<u>NOTE</u>: These equations are based on the assumption that the horizontal flight path from t_1 to t_2 is approximately a straight line along a course $(\psi_1 - \beta_1)$. If the ground track is not a straight line, but the interconnecting straight line azimuth (ψ_T) and distance (D) from the aircraft position at t_1 to the aircraft position at t_2 can be determined (as is possible with doppler navigators), the solution is not appreciably more difficult. Expressions $(\psi_{OR} + \beta)$ are replaced by $(\psi - \psi_T + \psi_{OR})$ where $(\psi - \psi_T)$ is an equivalent drift angle replacing β. There is no restriction imposed by this solution on the vertical flight path, i.e., altitude at t_1 and t_2 may be different.

e. Target Orientation

The equations for geographic target location are the same as for aircraft position updating, except for a simple interchange of the known and unknown latitude and longitude quantities.

$$\text{target lat } \lambda_T = \lambda_2 + R_\lambda = \lambda_2 \pm \frac{\left|D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \cos\left(\psi_2 + \psi_{OR_2}\right)}{\left|\sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]\right|} \begin{cases} + \text{ north latitude} \\ - \text{ south latitude} \end{cases}$$

$$\text{target long. } L_T = L_2 + \frac{R_L}{\cos\lambda_2} = L_2 \pm \frac{\left|D \sin\left(\psi_{OR_1} + \beta_1\right)\right| \sin\left(\psi_2 + \psi_{OR_2}\right)}{\cos\lambda_2 \left|\sin\left[\left(\psi_{OR_2} + \beta_2\right) - \left(\psi_{OR_1} + \beta_1\right)\right]\right|} \begin{cases} + \text{ east longitude} \\ - \text{ west longitude} \end{cases}$$

Refer to Figure B-8 for the following discussion. The elevation angle (θ_{0_2}) and the distance (R_2) have been computed. Therefore, altitude of target above sea level reference is

$$hT_{SL} = hb_2 = hT_2$$

where

$$hT_2 = R_2 \tan\theta_{0_2}$$

and hb_2 is aircraft pressure altitude sampled at instant t_2. (Computed hT_{SL} is based on existing barometric pressure conditions at time of acquisition.)

f. Summary of Equations

COORDINATE TRANSFORMATION

$$\theta_0 = \sin^{-1} (\cos A \cos E \sin \theta - \sin A \cos E \sin \phi \cos \theta + \sin E \cos \phi \cos \theta)$$

$$\psi_{OR} = \tan^{-1} \left(\frac{\sin A \cos E \cos \phi + \sin E \sin \phi}{\cos A \cos E \cos \theta + \sin A \cos E \sin \phi \sin \theta - \sin E \cos \phi \sin \theta} \right)$$

With small angle approximations:

$$\theta_0 \approx \sin^{-1} (\theta \cos A \cos E - \phi \sin A \cos E + \sin E)$$

$$\psi_{OR} \approx \tan^{-1} \left(\frac{\sin A \cos E + \phi \sin E}{\cos A \cos E + \phi\theta \sin A \cos E - \theta \sin E} \right)$$

POSITION UPDATE (OWN-AIRCRAFT ORIENTATION)

$$\lambda_2 = \lambda_T - R_\lambda = \lambda_T - \left(\pm R_2 \cos \psi_{0_2} \right) \begin{cases} + & \text{north lat} \\ - & \text{south lat} \end{cases}$$

$$L_2 = L_T - \frac{R_L}{\cos \lambda_T} = L_T - \left(\pm R_2 \frac{\cos \psi_{0_2}}{\cos \lambda_T} \right) \begin{cases} + & \text{east long.} \\ - & \text{west long.} \end{cases}$$

where

$$\psi_{0_2} = \psi_2 + \psi_{OR_2}$$

and

$$R_2 = \left| \frac{D \sin \left(\psi_{OR_1} + \beta_1 \right)}{\sin \left[\left(\psi_{OR_2} + \beta_2 \right) - \left(\psi_{OR_1} + \beta_1 \right) \right]} \right|$$

TARGET LOCATION (TARGET ORIENTATION)

$$\lambda_T = \lambda_2 + R_\lambda = \lambda_2 \pm R_2 \cos \psi_{0_2} \quad \begin{cases} + \text{ north lat} \\ - \text{ south lat} \end{cases}$$

$$L_T = L_2 + \frac{R_L}{\cos \lambda_2} = L_2 \pm \frac{R_2 \cos \psi_{0_2}}{\cos \lambda_2} \quad \begin{cases} + \text{ east long.} \\ - \text{ west long.} \end{cases}$$

where ψ_{0_2} and R_2 are the same as above.

$$hT_{SL} = hb_2 - R_2 \tan \theta_{0_2}$$

g. Relative Aircraft and Target Orientation in Range, Bearing and Altitude

Situations may exist where relative orientation of an aircraft to a sighted target is desired, where neither the target nor the aircraft geographic position is known. An example would be a close support attack mission where a target of opportunity exists and the gunship is equipped with a Doppler radar for flight velocity sensing, but not a complete navigation system including the computer. What is required in this case is a continuous update of range, bearing and altitude to the target after the point of sensed acquisition. This data, of course, would be stored and typically used for such purposes as display designation, generation of steering guidance, and calculation of slant range to target for gun/rocket fire control.

Updated target range and bearing are derived in Figure B-9. The aircraft is not constrained to any flight path after the sensed acquisition at t_2. Sensing means (e.g., Doppler radar and AHRS), by which the distance traversed along north-south and east-west coordinates, are assumed.

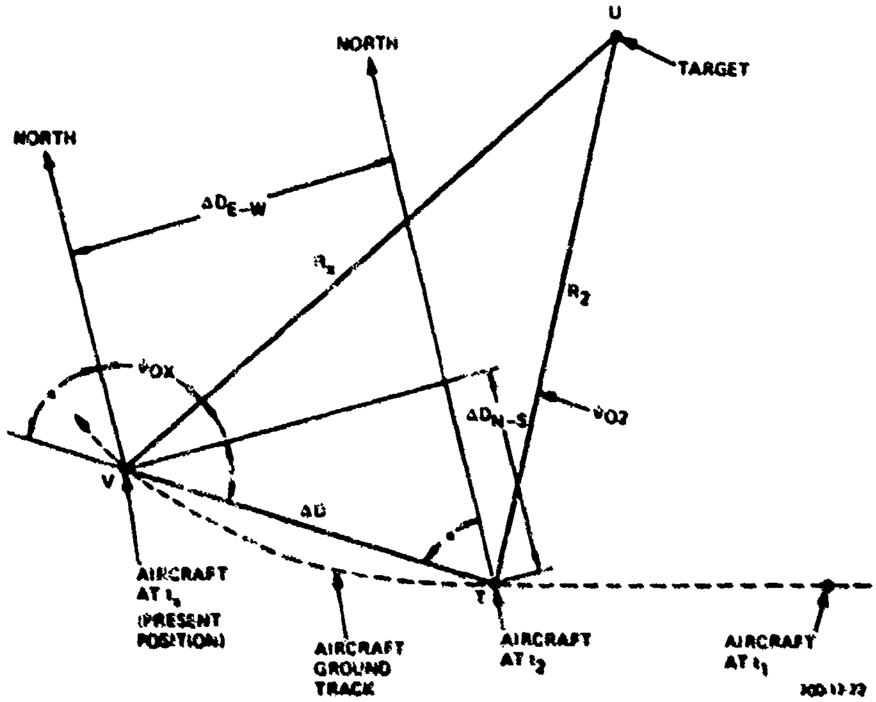

Figure B-9
Relative Aircraft and Target Orientation Geometry

$$\Delta D = \sqrt{(\Delta D_{E-W})^2 + (\Delta D_{N-S})^2}$$

$$\alpha = \tan^{-1} \frac{\Delta D_{E-W}}{\Delta D_{N-S}}$$

From solution of oblique triangle (UVT)

$$\text{range } R_x = \sqrt{(R_2)^2 + (\Delta D)^2 - 2(R_2)(\Delta D) \cos (\alpha + \psi_{0_2})}$$

where R_2 and ψ_{0_2} were computed previously.

$$\text{bearing } \psi_{0_x} = 180 \text{ deg} - \epsilon - \alpha$$

where

$$\epsilon = \sin^{-1} \frac{R_2 \sin\left(\alpha + \psi_{0_2}\right)}{R_x}$$

Updated altitude above the target is simply obtained from Figure B-8 as follows:

$$hT_x = hT_2 - (hb_2 - hb_x)$$

where hT_2 was previously computed and hb_2 and hb_x are aircraft pressure altitude sampled at time t_2 and t_x, respectively.

Slant range, if required, is obtained from:

$$Rs_x = \sqrt{(hT_x)^2 + (R_x)^2}$$

2. DERIVATION OF OFFSET, TWO-AXIS EQUATIONS

The derivation of equations representing a trigonometric solution of an oblique triangle located in a vertical plane perpendicular to the earth's local horizontal is presented in the following paragraphs. This triangle is kinematically established in flight by two abritrary line-of-sight acquisitions of a stationary target. The mathematical solution and order of execution described below is only one of several possible approaches. The optimum solution would depend upon the computer model selected (i.e., instruction repertoire, arithmetic hardware, etc) where memory and processor hardware minimization is usually of paramount importance.

The acquisition geometry is shown in Figure B-10. At the instant of visual acquisition at points 1 and 2, the following variables are sampled and stored:

- Barometric altitude - hb_1, hb_2
- Depression angle - θ_1, θ_2

  <u>NOTE</u>: These angles are obtained by subtracting aircraft pitch angle from the actually sensed angle subtending the aircraft X-axis and the line of sight.

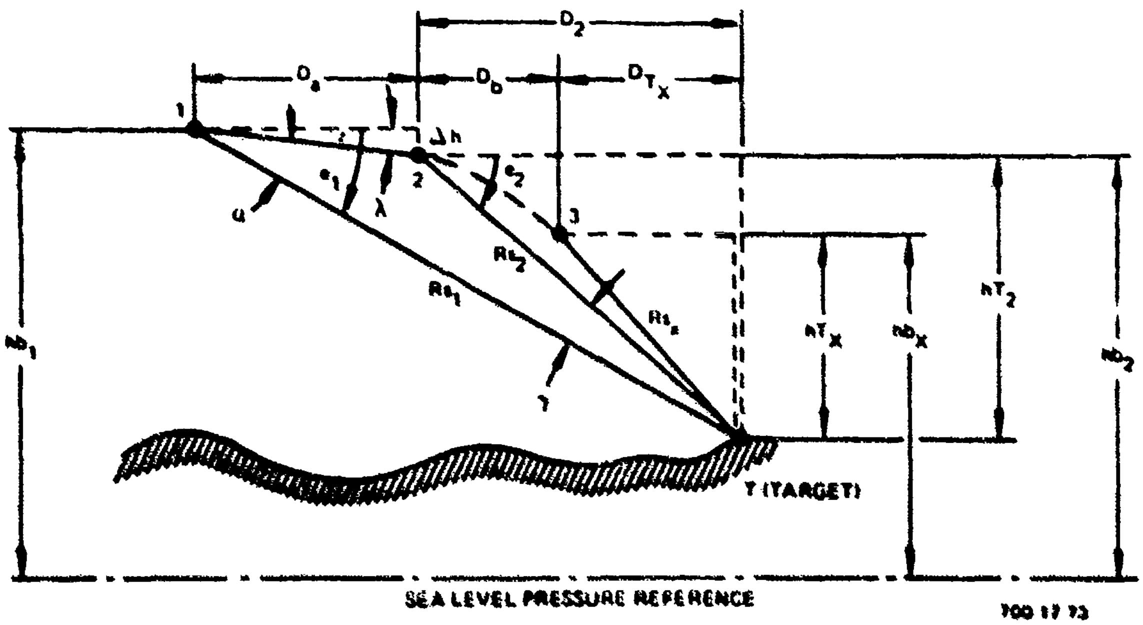

Figure B-10
Two-Axis Kinematic Targeting Geometry

Unless noted otherwise, the operations that follow are executed only once in the computer upon completion of the second acquisition. No time problem is anticipated in accommodating these one-shot processing functions within any current, high speed digital computer that may be incorporated into the helicopter avionic system. This is because of the relatively long time (typically 1.0 second) that can be allocated for this purpose.

(1) $D_a = \int_{t_1}^{t_2} Vg \, dt$

NOTE: This function to be executed as estimated 2 per second frequency between acquisitions at points 1 and 2 where Vg is also sampled at 2 per second rate.

(2) $\Delta h = hb_1 - hb_2$

(3) $Z = \sqrt{(\Delta h)^2 + (D_a)^2}$

(4) $\text{Tan } \lambda = \frac{\Delta h}{D_a}$

(5) $\lambda = \tan^{-1} \frac{\Delta h}{D_a}$

(6) $\gamma = e_2 - e_1$

(7) Derive $\sin \gamma$

(8) Derive $\sin e_2$, $\cos e_2$

(9) $\alpha = e_1 - \lambda$

(10) Derive $\sin \alpha$

(11) $Rs_2 = \frac{Z \sin \alpha}{\sin \gamma}$

(12) $hT_2 = Rs_2 \sin e_2$

(13) $D_2 = Rs_2 \cos e_2$

(14)* $hT_x = hT_2 - (hb_2 - hb_x)$

(15)* $D_b = \int_{t_2}^{t_x} Vg \, dt$

(16)* $DT_x = D_2 - D_b$

(17)* $Rs_x = \sqrt{(hT_x)^2 + (DT_x)^2}$

NOTE: In items (14) and (17), hT_x, Rs_x are the desired end variables.

In the above equations,

Vg = aircraft ground speed

hb_1, hb_2, hb_x = pressure altitudes

e_1, e_2 = target depression angles from local horizontal

D_a, D_b, D_2, DT_x = horizontal distances

Rs_1, Rs_2, Rs_x = slant ranges to target

hT_2, hT_x = altitudes above target

*Calculation is to be performed at 5 per second rate after acquisition at point 2.

APPENDIX C

OPTICAL PROJECTOR STUDIES FOR HUD SYSTEMS

HEADS UP DISPLAY SYSTEMS

TASK I

Prepared by: Farrand Optical Co., Inc.
Under Contract No. 418294-13
Project No. 403

For: The Sperry Rand Corp.
Great Neck, L. I., N. Y.

8-26-69
HUD Study
Task I
40301

TABLE OF CONTENTS

*Sperry note: Not included

HEADS UP DISPLAY SYSTEMS

1. DISCUSSION

Task Item I

Four optical concepts have been studied in the preliminary phase of the program. These were:

A) On-Axis Refractive System

B) On-Axis Reflective System

C) Off-Aperture Reflective System

D) Helmet Sight

All but the helmet sight concept are being studied in the quantification and trade-off investigation of Task Item II.

A general discussion of the optical principles involved in head up displays as well as comparisons and evaluations of the on axis refractive and off-aperture reflective approaches is included in the Farrand brochure which is attached for convenience.*

Concepts

A) On-Axis Refractive System

This approach is based on the gunsight collimator but with a significant extension of the field and aperture sizes. It is the most straight-forward approach and is very often the easiest to install. A very good compromise of many performance factors can be effected with this approach, e.g. 25° field, 6" aperture and 15 lb. weight for the 2 input RF4C unit. Very high optical accuracies are

*Sperry note: This brochure is not included in this appendix.

obtained with flat faceplate CRT tubes. The f/1.3 optics are a good reference compromise between geometric speed and good correction for parallax and mapping accuracies. A fast geometric speed is advantageous to obtain smaller image formats. For example, if an f/0.95 optical system could be used instead of f/1.3, a 3.6 inch dia. image format could be reduced to 2.63 inches. Although higher line brightnesses could be obtained this way, problems occur with optical correction for large fields and loss of field and aperture due to insufficient space for an internal folding mirror.

To gain a preliminary look at the problem of handling a 35° total field with the refractive system approach, the RF4C optical system was reevaluated for this field size. Whereas at the 12.5° semi field angle 2 mils of parallax occur, at 17.5°, 10 mils are present over about one inch of head motion. Some experience with similar designs at 16° semi field angle indicated that not much improvement could be expected. However, the redesign effort considering a concave CRT faceplate allows excellent performance levels over the entire 35° field with two less glass elements than the RF4C unit. This promising development will be used as the basis for the Task II refractive system approach and as part of the off-aperture reflective system approach. The performance will be discussed in detail in Task II but can be characterized as at least as good as the RF4C. This approach also offers the highest transmissivity.

B) On-Axis Reflective System

This concept has been explored in a previous proprietary program using catadioptric system designs developed by Farrand and optimizing for a HUD application by altering the configuration, pupil location, vignetting, correction, etc. Figure 1 shows this concept in an overhead configuration but it can also be mounted in an instrument panel similar to the RF4C.

The concept has significant advantages in weight, cost, simplicity and geometric speed compared to the on-axis refractive system although the vertical pupil would be limited to about f/1.0 because of the internal beamsplitter. A convex CRT faceplate is required for large field systems but this would present little difficulty.

One potential major drawback of the approach is the relatively poor transmission compared to the on-axis refractive approach. This is due to the inclusion of the internal beamsplitter which is used at 50% reflection and 50% transmission to give a total transmission of 25% (neglecting the combiner) of the refractive system.

This reduction is ameliorated somewhat by the fact that

1. No apparent brightness is lost because of color aberrations (es. 5%).
2. Fewer optical elements are used (est. 5%).
3. A shorter focal length optical system can be used, thereby requiring proportionately smaller line widths for the CRT. If we assume the gain to be inversely proportional to the focal length and that the focal length is reduced by the ratio of f nos. ($\frac{.8}{1.3}$), the gain can be estimated as 60%.

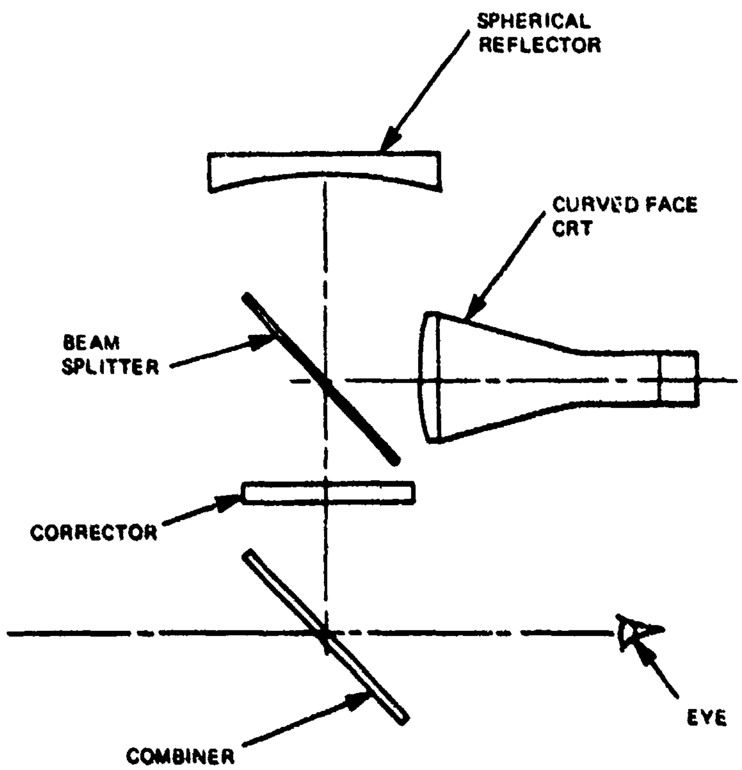
SPHERICAL
REFLECTOR
CURVED FACE
CRT
BEAM
SPLITTER
CORRECTOR
COMBINER
EYE

Figure 1

The effective system brightness will thus be about 44% of that of the reference refractive system.

One problem uncovered in the preliminary analysis is the mapping error levels referred to the given Sperry mapping function.* For fields up to 25°, the errors are reasonable but for 35° systems, the function would produce errors of 2 mils around 7.5° semi field angle up to 7 mils at the edge. The quantification and suggested corrections for this problem will be given in the Task II documentation.

C) Off-Aperture Reflective System

This arrangement is relatively complicated compared to the on axis systems and therefore is less desirable from a weight and cost standpoint. Some mild aspheric surfaces are also required which have significant effect on cost and perhaps manufacturing reproducibility. Although optical accuracies are quite good from a design standpoint, the finished item will probably not meet theoretical predictions by a factor of 1.5 to 2.0 in terms of parallax. These errors would result in approximately a 2 mil parallax error in the central field region over a 5 inch wide pupil. Mapping accuracies can be brought under excellent control with a 46° total deflection angle CRT (this will be further documented in Task II) and is less sensitive to manufacturing and assembly error than the parallax situation.

*Sperry note: This mapping function is supplied as a reference at the end of this Task I Report by Farrand.

Physically, the concept can present difficulties because of the folding mirror location.

With the previous commentary on the associated problems, one may wonder whether the concept has any real advantages and of course it does. It allows an enormous instantaneous field with reasonable weight and accuracies for its purpose. With its pupil designed to be imaged at the pilot alert eyepoint, the entire field is visible at one time. And since the combiner "eyepiece" is optically closer to the eye than with the normal on-axis system which requires a separate folding beamsplitter, the combiner is smaller than the aperture of the equivalent instantaneous field on-axis system. (See the attached technical brochure for further discussion on the concept.)*

Some work has been done previously on reducing the weight by reshaping the pupil, thinning elements and using less dense glasses. It has been estimated that a 35° system with a 3" x 5" pupil would weigh 30 pounds and this value will be used when comparing systems.

Preliminary analyses show the system very amenable to adaptation from the previous 25° design to 35°. The collimator portion would utilize the on-axis refractive design with a concave faceplate for best results.

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*Sperry note: This brochure is not included in this appendix.

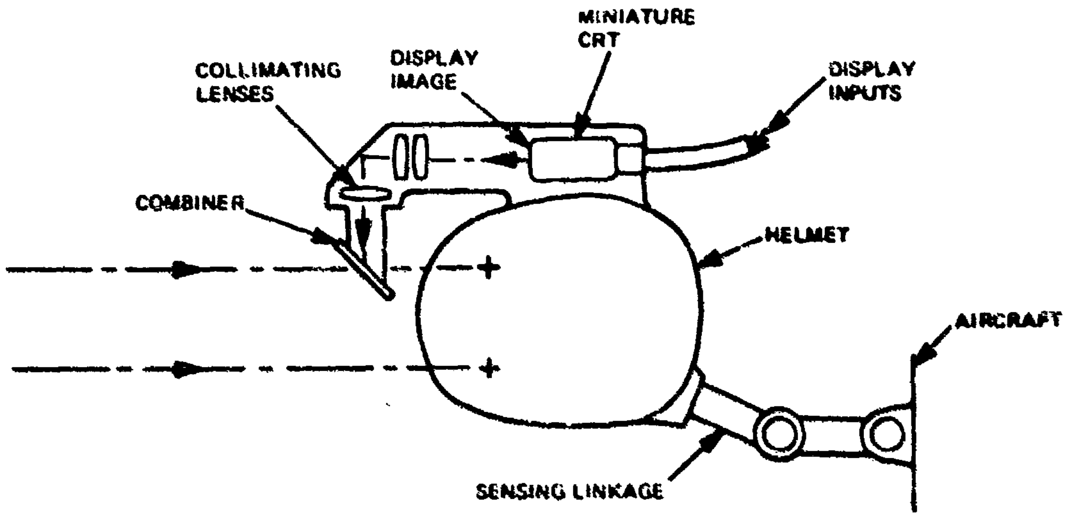
Summary of Optical System Concepts

	Major Advantages	Major Disadvantages
On Axis Refractive	Cost, accuracy, configuration for moderate apertures and eye relief distances. Obvious choice for small aperture systems.	Weight goes up drastically for large apertures.
On Axis Reflective	Cost and configuration size for moderate to large apertures. Weight approx. 2/3 of On axis refractive system. CRT size minimized due to f 1.0 or faster design. Color correction optimum.	Transmission effectively only 30% to 60% of On axis refractive system. Vertical field not as large as horizontal for systems f 1.0 or faster.
Off Aperture Reflective	Very large instantaneous fields with moderate weight. Most suitable for large fields and long eye relief. Transmission almost as high as On axis refractive system. 12" to 16" apertures quite practical.	Overall weight higher than other concepts (although much lighter than others with equivalent apertures). Cost approx. 3X on axis refractive system. Folding mirror hinders configuration.

In general, all of the systems studied have inherently relatively high optical accuracies for head up applications. They are based on proven designs and have already been through the optimum weight vs. accuracy trade-off so important in the initial concept. No significant weight savings can be applied without a drastic loss of accuracy.

D) Helmet Mounted Display Units

General Set Up



1. The basic advantages of the helmet mounted display units are as follows:

   a) Conserves prime instrument panel space.

   b) Wide instantaneous and total fields of view are possible.

   c) Head motion can be used to aim weapons.

2. The basic disadvantages are:

   a) The weight and inertia of head mounted gear is fatiguing.

   b) Adequate resolution is more difficult to obtain.

   c) High voltage insulation at high altitudes must be made safe.

   d) The sensing linkage loop to control the display inputs requires considerably more hardware.

   e) Helmet must be removed or disconnected before ejection.

   f) High "g's" cause additional neck strain unless some fairly complex counterbalancing linkage or servoing is used.

3. Variations of helmet mounted display units.

a) If the combiner is made opaque in order to obtain more display brightness, there is difficulty in properly fusing the images from both eyes in the horizontal direction.

b) If the fairly complex sensing linkage and loop is eliminated, there will be no visual correlation between the outer world and the display. The display then becomes merely an instrument panel display mounted on the head.

c) The mechanical sensing linkage could be converted to an optical sensing linkage by means of mirrors, photo diodes, and laser beams between the helmet and aircraft structure.

4. Conclusions

a) Extensive development work in many areas will be needed to produce a satisfactory helmet mounted sight unit.

b) Generally the purpose and environment of a sight unit will vary the significance of the advantages and disadvantages of various approaches. Under some conditions an advantage of one approach may heavily outweigh one or more of its disadvantages. There is in general no all-purpose sight unit. The purpose and environment should first be specified then a most satisfactory unit can be tailored to suit the conditions.

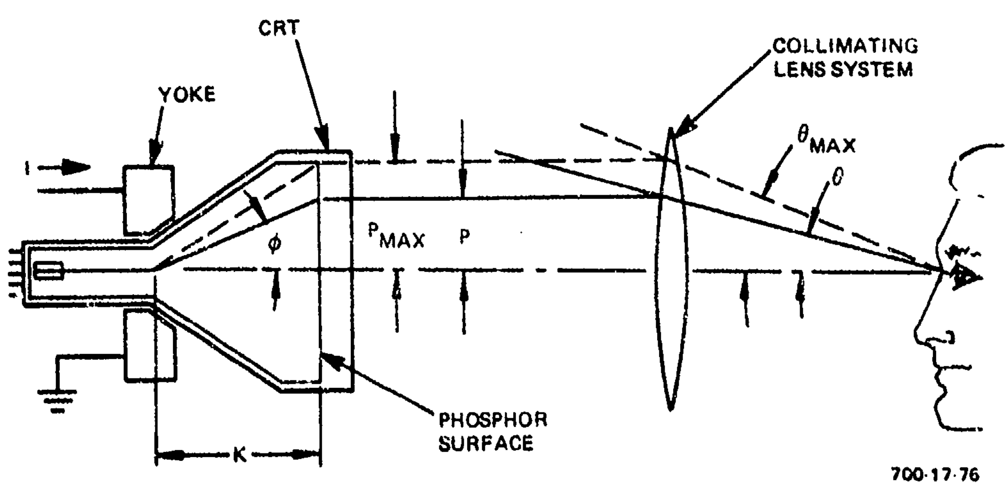
CRT MAPPING FUNCTION

The following information is not part of the report submitted by Farrand. It is supplied as a reference.

The basis for a typical CRT mapping function to be incorporated in the optics design is provided below. The following parameters should be taken into account as described:

- Images are developed on the interior phosphor surface of a CRT having a maximum useable circular area of P_{MAX} radius.
- The center of deflection of the yoke results in the electron beam having an apparent origin at a distance (K) from the phosphor screen.
- The sine of the electron beam deflection angle (sine ϕ) is proportional to the current passing through the yoke winding.
- At the maximum perceived field angle (θ max) the CRT image should be at the edge of the usable area (P_{MAX}).
- It is required to have the perceived field angle (θ), proportional to the current (I) in the yoke.

The parameters involved are shown in the following figure.



The following equation has been developed relating the various parameters:

$$\theta = \frac{\theta_{MAX}\sqrt{1 + \frac{K}{P_{MAX}}^{2}}}{\sqrt{1 + \frac{K}{P}^{2}}}$$

Substituting values for a typical CRT and field of view results in the following equation:

$$P_{MAX} = 1.8 \text{ in. for } \theta_{MAX} = 12.5 \text{ deg}$$

$$K = 5.1515 \text{ in.}$$

then

$$\theta = \frac{37.8953 \text{ deg}}{\sqrt{1 + \frac{5.1515}{P}^{2}}}$$

<u>NOTE:</u> The values selected for P_{MAX} and K yield a CRT total deflection angle (i.e., 2ϕ) of approximately 40 degrees.

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HEADS UP DISPLAY SYSTEMS

TASK II

Prepared by: Farrand Optical Co., Inc.
Under Contract No. 418294-13
Project No. 403

For: The Sperry Rand Corp.
Great Neck, L.I., N.Y.

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LIST OF ILLUSTRATIONS

NOTE: Field vs. Head Motion Drawings #137151 Sheets 1,2,3 and #137152 Sheets 1,2,3 are included in this task as separate drawings.

1. INTRODUCTION

The major purpose of Task II is to quantify an assortment of optical systems useful for installation in a helicopter. The number of systems being studied permits interpolation of most of the desirable parameters for a wide range of system goals. Trade-offs between weight, configuration, fields, apertures and CRT size characteristics can readily be made using the reference drawings and tables. The master matrix Figure No. 6 should prove most helpful in this regard.

2. COMPARISON OF OPTICAL SYSTEM TYPES

Each of the 3 classifications of optical systems studies has certain peculiarities that prevent clear cut comparisons in all categories. An example would be a comparison of eye relief. The off-aperture system uses a combiner that can be considered an aperture stop for the system, while the on-axis refractive system has a tilted combiner ahead of the aperture stop. In the first case, a folding mirror represents the nearest physical obstruction to the pilot while in the second, the tilted combiner is the nearest element. Each system might thus be more favorable for a particular installation configuration even with very similar specifications. For this reason, it is strongly recommended that use by made of the family drawings in preparing layouts to be used in conjunction with the pupil-field reference drawings supplied. Using the master matrix for trade-off analysis along with the layout study should lead to fairly clear trade-off decisions.

2.1 Family Drawings

A family drawing was made for each of the subsystem types to aid in making layouts for installation studies. Pertinent physical dimensions, weight and faceplate diameters are included. Optical characteristics are included in the master matrix summary drawing.

The general comments about each system type as discussed in the task I report still apply. In all cases, however, the data generated for the master matrix summary drawing will supercede or quality prior statements.

Each family drawing contains the following data:

1. System item no. for identification purposes.
2. Aperture refers to free (clear) aperture of outer lens element.
3. Total field is the maximum circular field available with head motion if necessary.
4. Usable CRT faceplate diameter is expressed as a chordal minimum dimension in inches for each system. Faceplates are flat except where an asterisk denotes the requirement of a curved faceplate important in maintaining good parallax correction over the entire field.
5. Alphabetic designations refer to physical dimensions including pupil dimensions in the off-aperture system case. Dimension "D" in the on-axis refractive system and "C" in the on-axis reflective system are given only approximately because of the dependence

on the variables of cockpit configuration, combiner tilt angle, pilot eyepoint and instantaneous field. All dimensions are in inches.

6. The approximate weights are given in pounds for systems with all glass optics, aluminum structures and a single CRT input only but do not include the weight of the CRT and associated electronics.

2.2 Optical Parameters

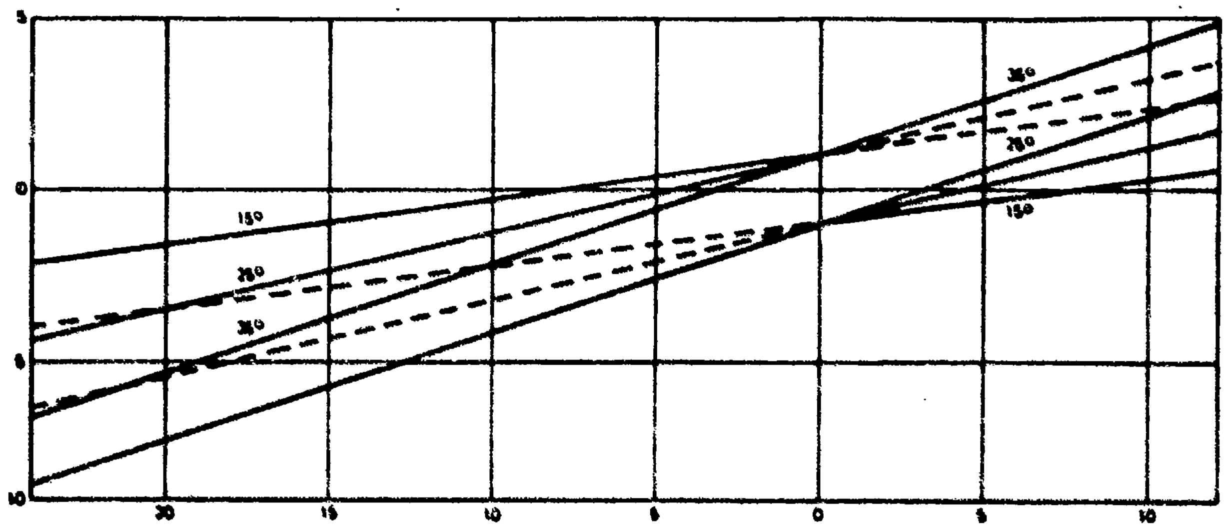
2.2.1 Instantaneous Monocular and Binocular Fields

The instantaneous monocular field refers to the field subtended by one eye placed at a given eye distance along the optical axis and is normally given by 2 arctan $(\frac{\text{aperture}}{2 \text{ eye dist.}})$. When viewing with both eyes, the horizontal instantaneous field is normally increased because of the interpupillary distance. This would increase the field to 2 arctan $(\frac{\text{aperture} +2.5}{2 \text{ sys dist.}})$.

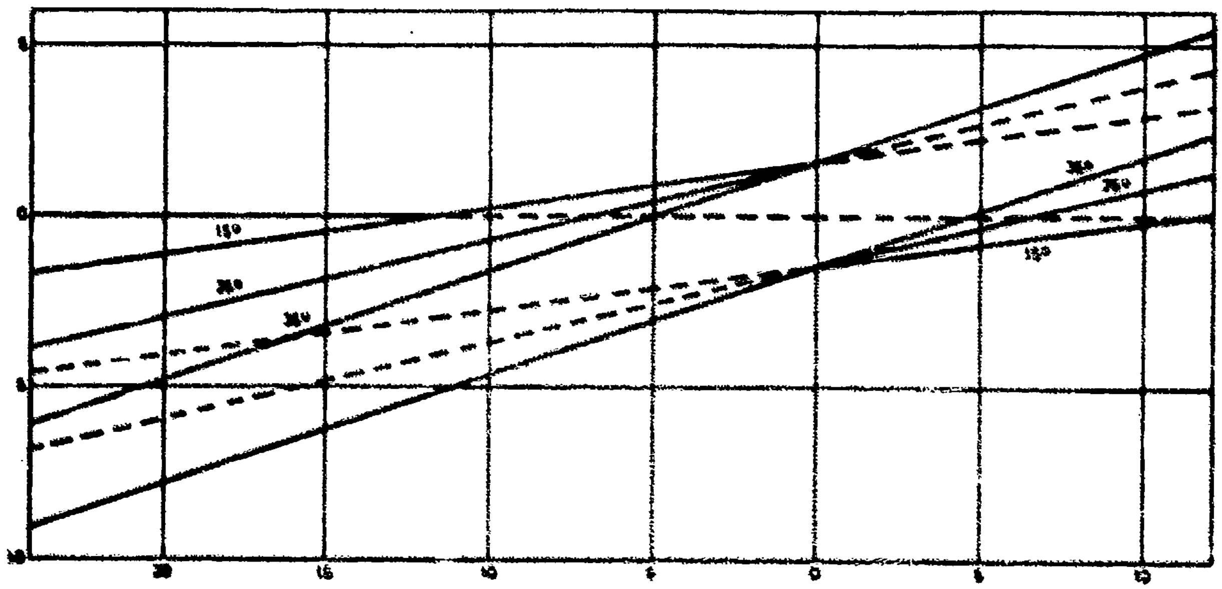
The above equations apply to the on-axis systems whose apertures act like "portholes", i.e. the closer you get, the more instantaneous field is available and if you move left you can see more field toward the right. Tabulations of the instantaneous fields for 18" and 24" eye to lens distances are included in the master matrix summary drawing.

In the off-aperture system case, the situation is not as simple. Here, the "porthole" is moved 18" or 24" from the combiner (aperture) so as to place it at the pilot eyepoint. The "porthole" size and shape is that of the pupil, 2"x4" or 3"x5". If the pilot moves both eyes out of this pupil, no field is seen while if both eyes are anywhere within the pupil, the entire field is visible binocularly. Unless the field is limited by the combiner width, the total horizontal field is available instantaneously. The vertical field is normally somewhat restricted by the combiner height and folding mirror vertical dimension. All of this data is tabulated in the master matrix summary drawing.

To aid in determining the actual monocular and binocular fields over a variety of head positions and eye distances for layout studies, a series of full scale field of view versus pupil drawings were prepared and are included in this study as separate drawings (137151, 3 sheets and 137152, 3 sheets). By placing a full size layout combiner over these reference drawings, actual physical clearances can be established as well as head motion vs. field trade off data. For drawing 137151 the off-aperture combiner should be placed either 18" or 24" to the left of the pupil (the combiner radius can be assumed to also be 18" or 24"). For drawings 137152, the outside lens aperture should be placed at the pupil near the left edge of the drawing.

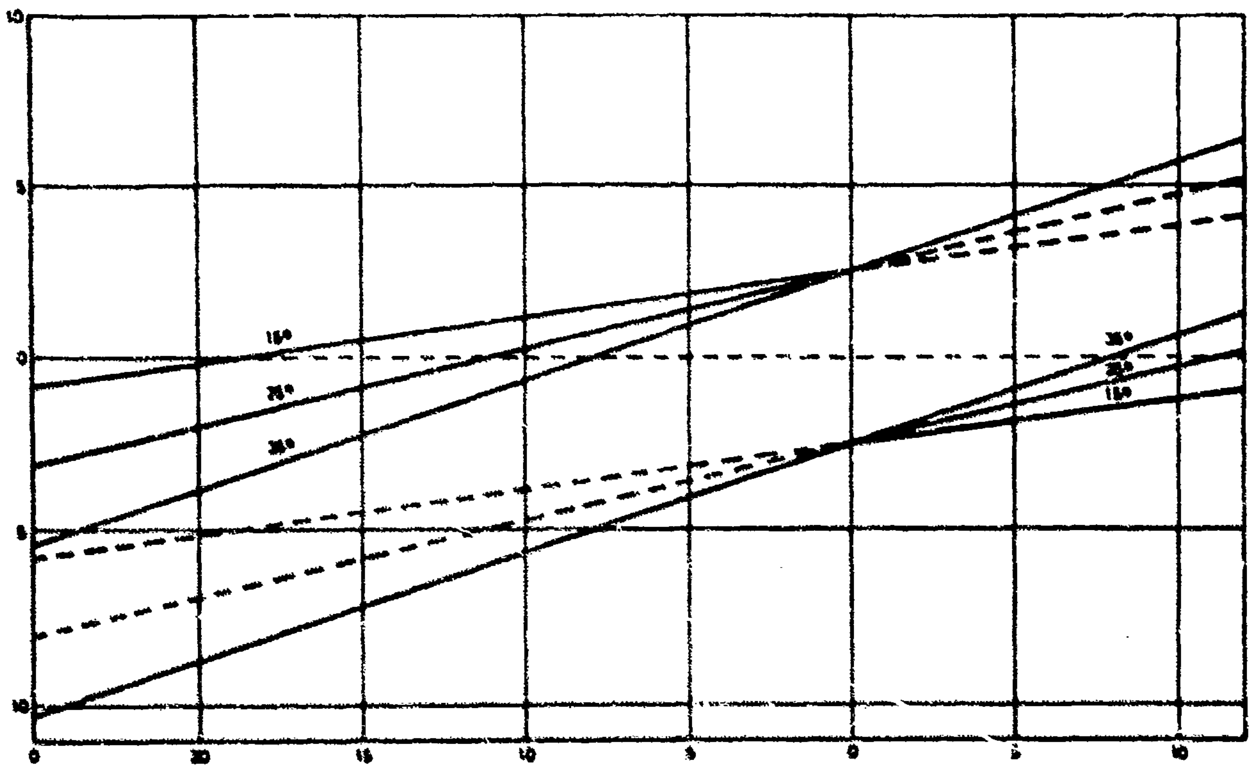


Drawing No. 137151 (Sheet 1 of 3)
Off-Aperture Reflective Field
vs Head Motion for 2-Inch Pupil

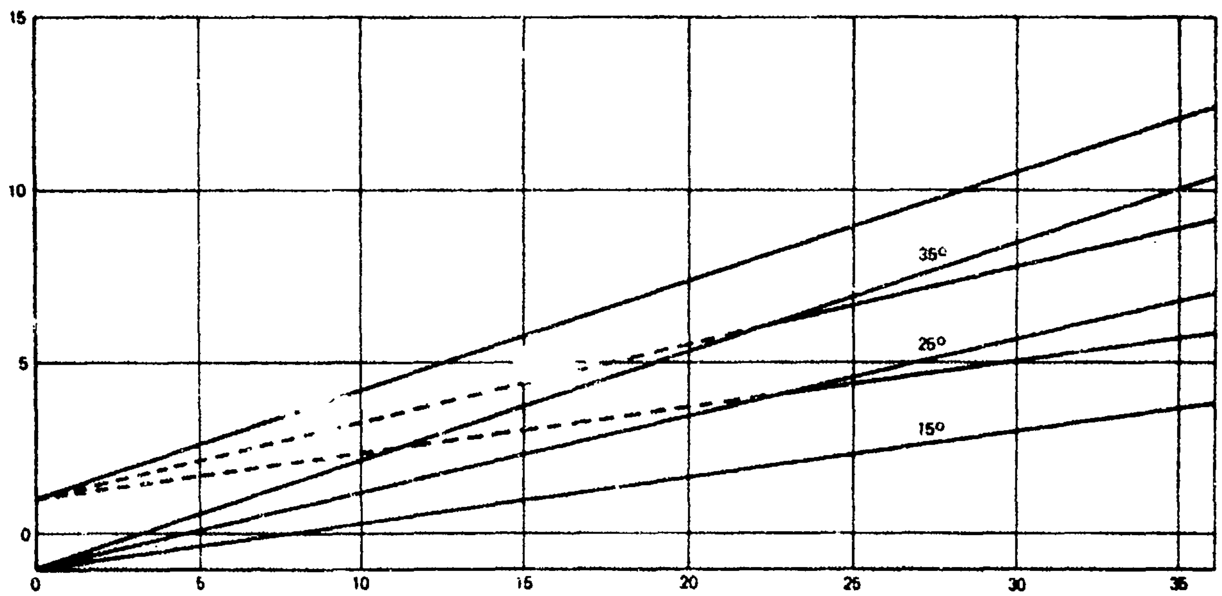


Drawing No. 137151 (Sheet 2 of 3)
Off-Aperture Reflective Field
vs Head Motion for 3-Inch Pupil

C.2-6-C

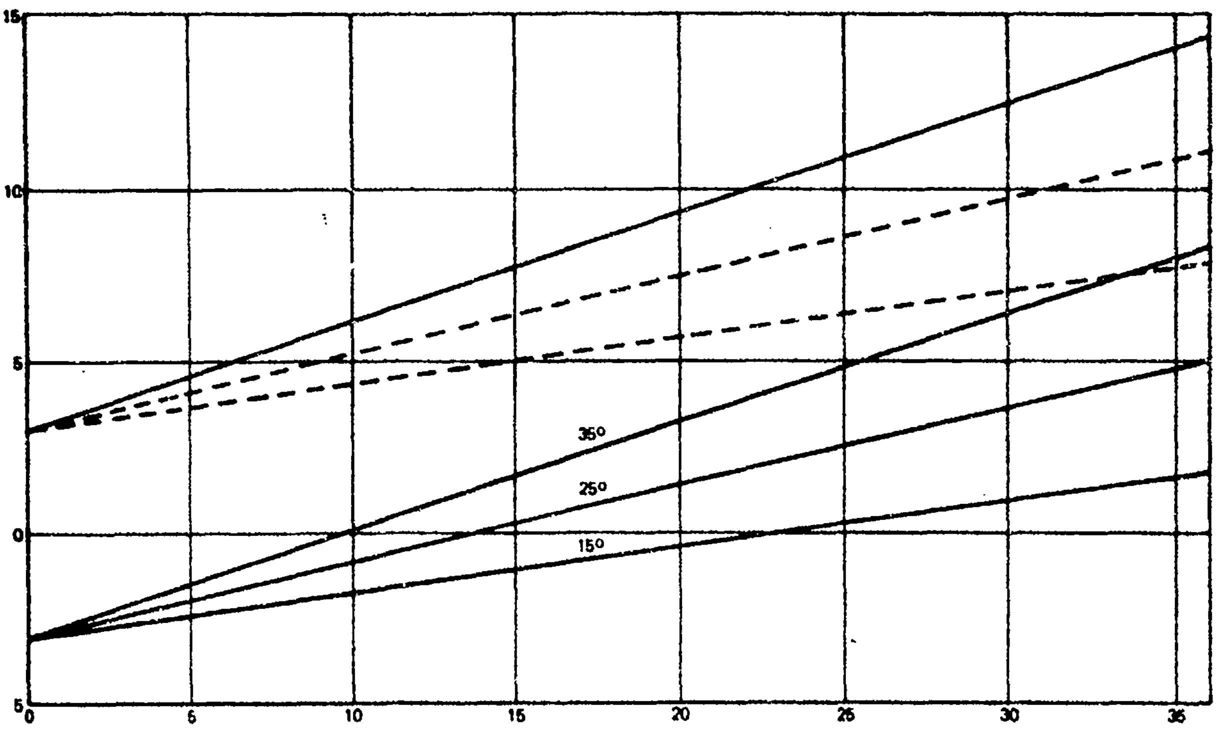


Drawing No. 137151 (Sheet 3 of 3)
Off-Aperture Reflective Field
vs Head Motion for 5-Inch Pupil



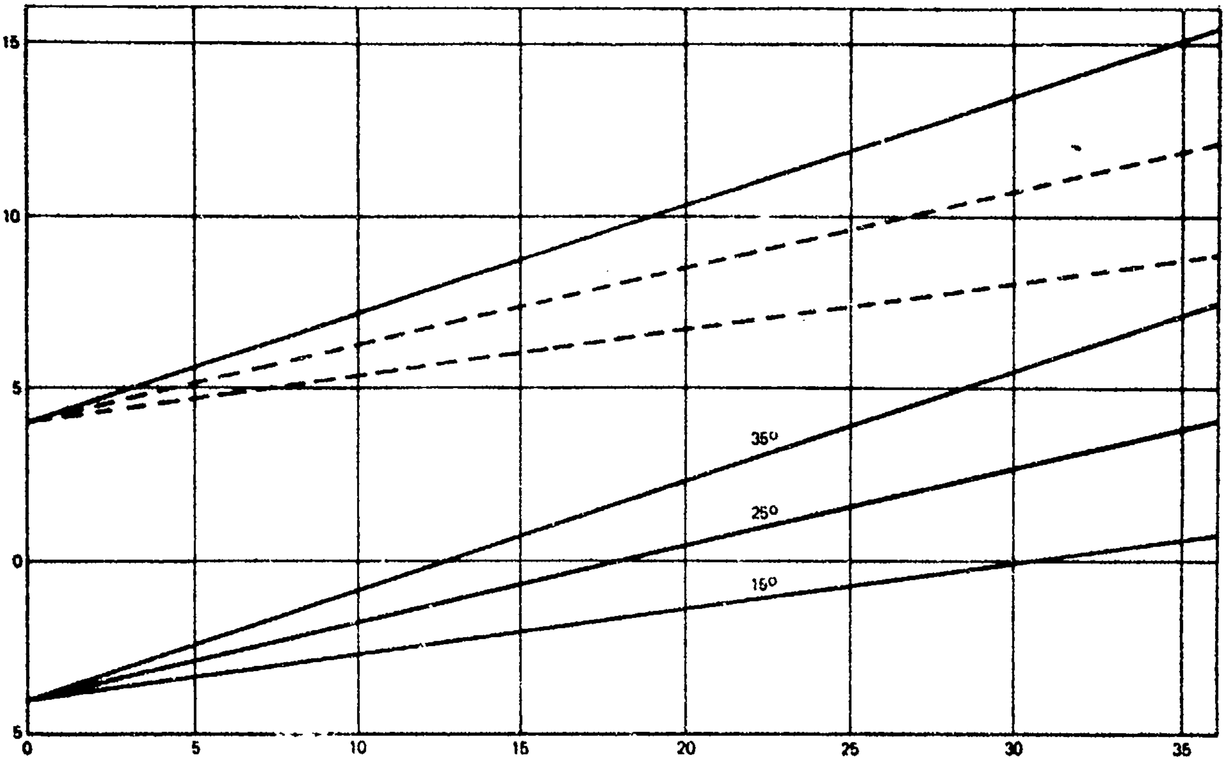
Drawing No. 137152 (Sheet 1 of 3)
On-Axis Refractive or Reflective
HUD-Field vs Head Motion for 2-Inch
Aperture

C.2-6-e



Drawing No. 137152 (Sheet 2 of 3)
On-Axis Refractive or Reflective
HUD-Field vs Head Motion for 6-Inch
Aperture

C.2-6-f



Drawing No. 137152 (Sheet 3 of 3)
On-Axis Refractive or Reflective
HUD-Field vs Head Motion for 8-Inch
Aperture

2.2.2 Optical Accuracy

Each design form was developed to a point where assurance of a high accuracy system was obtained. Designs were optimized for minimum parallax over a 6" wide head motion envelope and for an 18" to 24" eye relief distance. If a specific head motion envelope, eye relief and total field were to be specified, the optical accuracy could be slightly improved during the final design stage.

The optical accuracy is best analyzed by considering separately the two major parameters:

1. Distortion (or system mapping including CRT)
2. Parallax (swimming of image with head motion)

1. Distortion

Each system type was compared for distortion "match" with the CRT equation supplied by Sperry. The following analysis was made of the relation between the deflection angle of the CRT and the optical system mapping function.

Optimizing the mapping match between CRT and optics

It is important to minimize the mapping errors resulting from the mismatch of CRT mapping functions and optical system mapping functions.

These errors should not be confused with the parallax errors resulting from aberrations in the optics which cause images to "swim" with head motion.

The uncorrected mapping errors would result in image position errors only. One method of correction is to include electronic compensation by alteration of position signals. A second method involves changing the maximum beam deflection angle in order to alter the mapping function. While this approach may add some difficulty in beam focussing and power requirements in the case of larger deflection angles and greater tube length in the case of smaller deflection angles, the approach is relatively simple and powerful in obtaining good accuracy.

An analysis was made of mapping function errors of the reference optical systems and how the CRT beam deflection angle affects these errors.

A method has been worked out so that the optimum maximum deflection can be selected for each optical system.

The results appear in Figure 4.

The symbols K, C, and θ are given in the following reference relationships:

P is the cathode ray tube chordal height on the phosphor

ϕ is the semi deflection angle of the CRT

θ is the real world semi field angle at the pilot eyepoint

$$K = \frac{P}{\tan \phi}$$

$$C = \frac{\theta}{\sin \phi}$$

$$\theta = \frac{C}{\sqrt{1 + \left(\frac{K}{P}\right)^2}}$$

Mapping error (mils) vs. maximum CRT beam

Deflection angle for systems of focal length F - 7.83

			Refractive (design 6)			Reflective			Off-Aperture		
K	C	θ*	7.5°	12.5°	17.5°	7.5°	12.5°	17.5°	7.5°	12.5°	17.5°
6.898	53.09	19°16'	+2.0	0	-4.0	+2.2	0	-7.0	-1.4	-2.2	+12.0
9.634	71.405	14°11'	+.4	-.4	+2.2						
5.836	43.41	23°46'							+.1	0	+.3
13.5508	100.78	10°				+1.3	0	-3.8			

*Sperry note: $\theta = \phi_{MAX}$

FIGURE 4

Each system was first evaluated for the original max-deflection angle of 19°16'. The off-aperture system was modified from the original Farrand design to accommodate a larger field and concave CRT face. The reflecting system design is a scaled version of a previous Farrand design and requires a convex tube face.

Conclusions

1. Refractive design "6"

   Considerable improvement is evident by reducing the deflection angle to 14°11' where the mapping error is less than .5 mils over the central 25° and approx 2 mils at the edge of the 35° total field.

2. Reflective design

   This system with the original 19°16' deflection angle has only moderate mapping accuracy when used as a 35° total field although when used for 25° systems it is amenable to excellent compensation. Reducing the deflection angle to 10° improves the mapping by almost a factor of 2, but this requires a long tube. The tube size may be acceptable however, because this system is capable of much greater horizontal pupil sizes for the same parallax correction and focal length compared to the refractive system.

3. Off-Aperture design

   This system has quite poor mapping for the original 19°16' deflection angle but when 23°46' is used, a spectacular improvement is obtained, resulting in less than 0.5 mils error over the entire field. Since the parallax errors are also well controlled for the components of this system, it appears that this system can provide even greater field than heretofore studied.

It appears that altering the max deflection angle of the CRT beam is a useful tool in obtaining high mapping accuracy from any of the system approaches being studied with the exception of off-aperture system #4 which has 6 mils error at the field edge as noted in the master matrix summary drawing.

2. Parallax

In considering parallax errors, as noted earlier, we should establish firm ground rules on how a given system is used, e.g. head motion, eye relief so that the best design for the purpose can be obtained. We can however, assume that the highest accuracy is necessary at the field center and that the field edges of the larger field systems are used primarily for symbology not requiring as high a positional accuracy. All of the system types studies meet this criteria and some appear to offer almost as high accuracy over the entire field as at the center.

The high correction generally exhibited does not represent a significant "variable" that can easily be traded off for example to obtain a faster system (smaller CRT) or more compact physical arrangement. Each system type has previously gone through an optimizing process for weight vs. optical performance so that the results of this study can be considered very realistic and representative of final designs.

A tabulated estimate of parallax errors is given in the master matrix summary table.

3.0 SECONDARY RETICLE INPUT

A second input of large field could be incorporated as a simultaneous or independent alternate by using the internal folding mirror in the On-axis refractive system or Off-aperture reflective system. The mirror could rotate (as in the RF4C 6" aperture unit) to bring in the second input, or could be made a beamsplitter for simultaneous viewing (as in the prototype off-aperture system). The optical arrangement of the on-axis reflective system precludes the use of the internal beamsplitter in this manner.

In the case of a small 2° second input used independently, a different approach is probably desirable from a weight, configuration and efficiency standpoint. A fixed reticle package containing the reticle, fiber optics light pipe and lens assembly could be brought in as shown in figure 5. The small field lens acts to project the reticle to a virtual image optically coincident with the CRT phosphor surface. Of course this assembly must be rotated or slid into position only as an alternate input. The mechanical structural supports can also provide the motion corresponding to depression angle inputs. One complication in this regard should be noted: In order to maintain collimation as the reticle is depressed, it must be moved in an arc, curving away from the CRT (concave) for the on-axis refractive and off-aperture reflective system, and curving toward the CRT (convex) for the on-axis reflective system.

The curved depression motion might be avoided if the device can be located between the CRT and the negative field lens. Some degradation of CRT system accuracy at the field edges would result from the necessary increase in the air gap, while the reticle accuracy would be maximized because the small field lens could probably be eliminated.

In any case, this general approach to the problem is advantageous from a weight, configuration and transmission consideration and is applicable to all of the systems under study.

The additional weight should be approximately 1 pound for any of the 6 or 8 inch aperture on-scale systems or all of the off-aperture systems.

4.0 PLASTIC OPTICS AND WEIGHT ANALYSIS

Plastic optical elements offer the potential of significant weight savings compared to glass optical elements. In some cases, particularly where aspherics are concerned, manufacturing costs can be significantly lowered and reproducibility enhanced.

Serious potential problems exist with respect to temperature versus lens stability and environmental exposure so that it is felt that inclusion of plastic elements should be considered in a weight reducing experimental program after a prototype design is fully proved with glass optics.

Other problems involving surface uniformity, manufacturing methods, necessary edge thicknesses, steep curves and coating methods suggest that abandonment of the straightforward development of glass systems is risky.

The most effective place to use a plastic would be for the combiner element in the off-aperture systems. However, since this element is used in a reflecting mode where surface shape is very sensitive and is also vulnerably located, its use here does not appear practical.

Plastic elements can be used to replace both crown and flint elements in a given optical design but the plastic "flint" imposes more of an optical design constraint because of its low index of refraction. When an equipment installation envelope is tight, the plastic "crowns" also represent physical limitations relative to using high index glass elements in a more compact design. Plastic systems must be larger than glass systems. Internal "folding" problems will also be more difficult. The approximate weight of the systems studied using plastic elements for all internal glass refracting elements is as follows:

On Axis Refractive Systems

Item No.	Aperture	Total Field	Weight (pounds) Glass Optics	Plastic Optics
1	2"	15°	1.7	1.4
2	2"	25°	1.7	1.4
3	2"	35°	1.7	1.4
4	6"	15°	13	10.4
5	6"	25°	14	11.2
6	6"	35°	14.5	11.6
7	8"	25°	29	23.2
8	8"	35°	29.5	23.6

On Axis Reflecting Systems

Item No.	Aperture	Total Field	Weight (pounds) Glass Optics	Plastic Optics
1	2"	15°	1.5	1.3
2	2"	25°	1.5	1.3
3	2"	35°	1.5	1.3
4	6"	15°	11	10
5	6"	25°	11	10
6	6"	35°	11	10
7	8"	25°	20	18
8	8"	35°	20	18

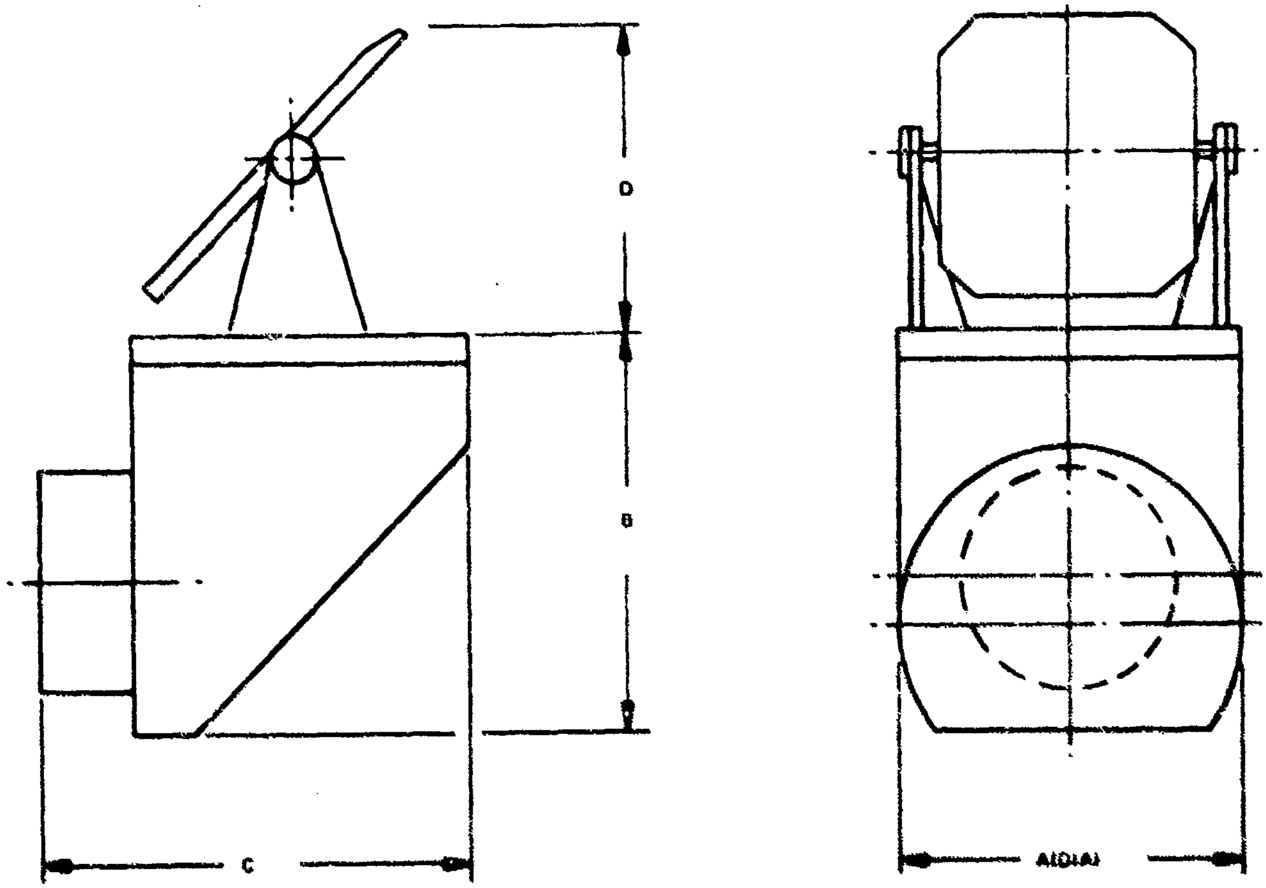
Off Aperture Reflective Systems

Item No.	Combiner Width	Total Field	Weight (pounds) Glass Optics	Plastic Optics
1	13	25°	31	26.6
2	16	35°	33	28.6
3	13	25°	21	18.6
4	13	25°	13.5	12.3
5	16	25°	38	33
6	20	35°	40	35

If the outside lens element of each system were also made of plastic, the following additional savings could be made:

On axis refractive system 6" aperture	1 pound
On axis reflective system 6" aperture	.5 pound
Off aperture reflective system #1	.6 pound

All of the above weight studies were based on using aluminum structures and no reticle input, CRT or electronics.

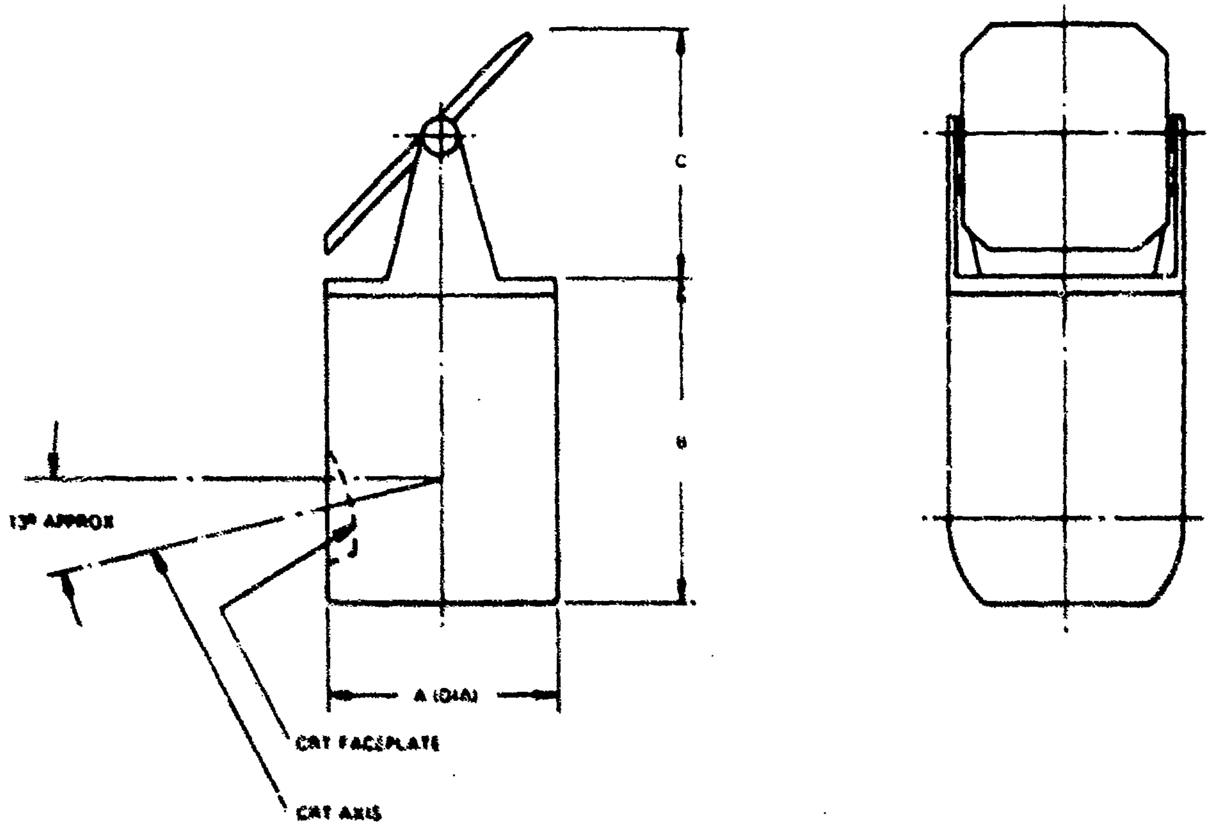


SYSTEM ITEM NO	APERTURE	TOTAL FIELD	USABLE CRT FACEPLATE DIA	A	B	C	APPROX WEIGHT (POUNDS)
1		15°	0.8"	2.5	3	3	1.7
2	2"	25°	1.3"	2.5	3	3	1.7
3		35°	1.9"*	2.5	3	2	1.7
4		15°	2.1"	7	8	8	12.0
5	6"	25°	3.6"	7	8	8	14.0
6		35°	5.1"*	7	8	8	14.5
7	8"	25°	4.8"	9	10.2	10.2	29.0
8		35°	6.6"*	9	10.2	10.2	29.5

*CONCAVE CRT FACEPLATE REQUIRED

NOTE 1 ALL DIMENSIONS IN INCHES
2 D DIMENSION APPROX EQUAL TO APERTURE

Fig. 1 – On Axis Refractive Systems

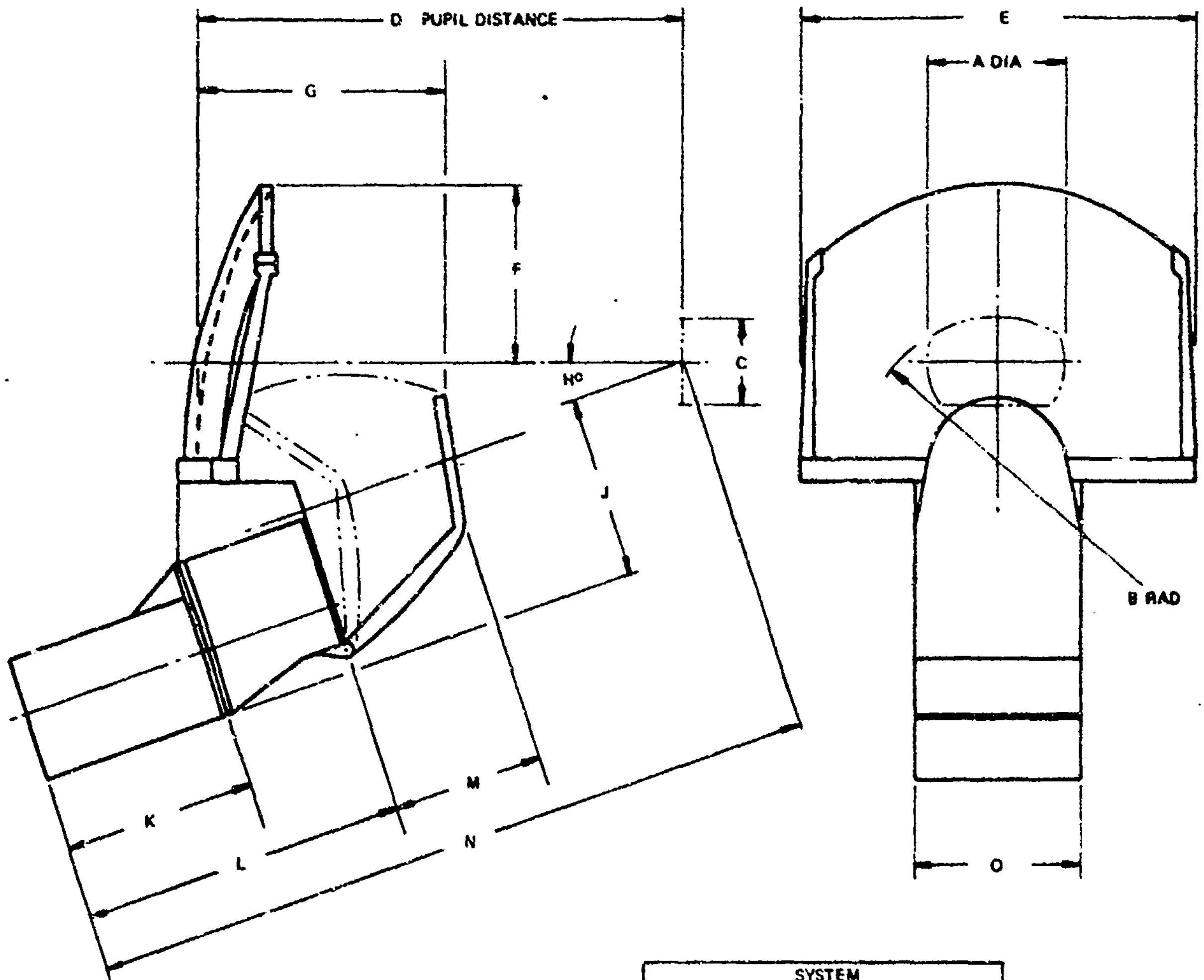


SYSTEM ITEM NO	APERTURE	TOTAL FIELD	USABLE CRT FACEPLATE DIA	A	B	APPROX WEIGHT (POUNDS)
1		15°	0.6"	2.5	7.8	1.5
2	3"	25°	1.0"	2.5	7.8	1.5
3		25°	1.3"	2.5	7.8	1.5
4		15°	[illegible]	6.8	7.7	11.0
5	6"	25°	2.0"	6.8	7.7	11.0
6		35°	2.8"	6.8	7.7	11.0
7	8"	25°	[illegible]	9.0	10.3	30.0
8		35°	5.1"	9.0	10.3	25.0

NOTE 1 CONVEX FIELD [illegible] PLATE REQD
2 ALL DIMENSIONS IN INCHES
3 C DIMENSION APPROX EQUAL TO APERTURE

Fig. 2 - On Axis Reflective Systems

C. 2-15-C

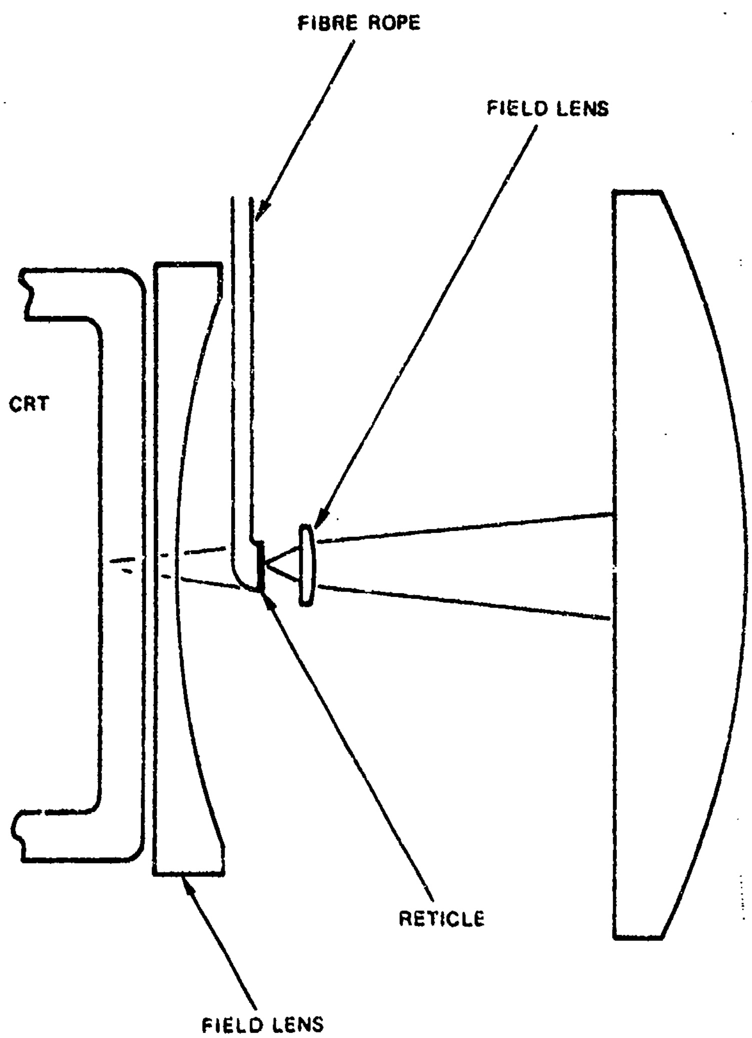


		SYSTEM					
		1	2	3	4	5	6
APPROXIMATE WEIGHT		31	33	21	13 5	38	40
USABLE CRT FACEPLATE DIA		3.0	*4.9	2.4	*2.9	3.0	*4.9
TOTAL FIELD		25°	36°	25°	26°	26°	35°
PUPIL DIMENSIONS	A	5	6	4	4	6	6
	B	5	5	4	4	6 7	6.7
	C	3	3	2	2	3	3
	D	18	16	18	18	24	24
	E	14	17	14	14	17	21
	F	6	5	4	4	7	7
	G	9.4	9 4	9.4	8 3	12 4	12.4
	H	18°+	18°+	14°+	12°+	18°+	18°+
	J	6	6	5	3 9	7 7	7.7
	K	7	7	6 8	5.7	7	7
	L	12	12	10.7	9.6	13.7	13 7
	M	5.6	5.6	6.2	2.6	8.6	8.6
	N	26	26	26	22.7	34.7	34 7
	O	6	6	4.6	3.8	6	6

*USES SPECIAL CONCAVE CRT FACE. OTHERS ARE FLAT.

Fig. 3 Off-Aperture Reflective Systems

C.2-15-d



2° Reticle Input Method (Typical) Fig. 5

MASTER MATRIX SUMMARY OF HUD SYSTEM PARAMETERS

FIGURE NO. 6

System Type	Item #	Aperture	Pupil Size	Relative Trans-mission	Total Field	Instantaneous Monocular Field				Instantaneous Horizontal Binocular Field		Useable CRT Faceplate Dia.	CRT Faceplate Shape	Accuracy (mr)					Tot. Weight with Aluminum Mount Internal Optics	
						18" Eyepoint		24" Eyepoint						Mapping		VG Parallax Over Aperture				
						Hor.	Vert.	Hor.	Vert.	18" Eyepoint	24" Eyepoint			1/2 Field	Full Field	Center	1/2 Field	Full Field	Glass	Plastic
On Axis Refractive	1	2"	2"	1	15°	6.4°	6.4°	4.8°	4.8°	14.4°	10.8°	0.8"	Flat	.1	.2	.5	.5	.5	1.7	1.4
	2	2"	2"	1	25°	6.4°	6.4°	4.8°	4.8°	14.4°	10.8°	1.3"	Flat	.2	.5	.5	.8	1.0	1.7	1.4
	3	2"	2"	1	35°	6.4°	6.4°	4.8°	4.8°	14.4°	10.8°	1.9"	Concave	.5	2.2	.5	1.0	1.5	1.7	1.4
	4	6"	6"	1	15°	15°	15°	14.3°	14.3°	15°	15°	2.1"	Flat	.1	.2	.5	.5	.5	13	10.4
	5	6"	6"	1	25°	18.9°	18.9°	14.3°	14.3°	25°	20.3°	3.6"	Flat	.2	.5	.5	.8	1.0	14	11.2
	6	6"	6"	1	35°	18.9°	18.9°	14.3°	14.3°	26.9°	20.3°	5.1"	Concave	.5	2.2	.5	1.0	1.5	14.5	11.6
	7	8"	8"	1	25°	25°	25°	18.9°	18.9°	25°	24.9°	4.8"	Flat	.2	.5	.5	.8	1.0	29	23.2
	8	8"	8"	1	35°	25°	25°	18.9°	18.9°	33°	24.9°	6.8"	Concave	.5	2.2	.5	1.0	1.5	29.5	23.6
On Axis Reflective	1	2"	2"	.3	15°	6.4°	4.3°	4.8°	3.2°	14.4°	10.8°	0.6"	Convex	.3	.6	.5	1.0	2.0	1.5	1.3
	2	2"	2"	.3	25°	6.4°	4.3°	4.8°	3.2°	14.4°	10.8°	1.0"	Convex	.5	1.0	.8	1.5	3.0	1.5	1.3
	3	2"	2"	.3	35°	6.4°	4.3°	4.8°	3.2°	14.4°	10.8°	1.3"	Convex	1.5	4.0	1.0	2.0	4.0	1.5	1.3
	4	6"	6"	.3	15°	15°	12.6°	14.3°	9.5°	15°	15°	1.7"	Convex	.3	.6	.5	1.0	2.0	11	10
	5	6"	6"	.3	25°	18.9°	12.6°	14.3°	9.5°	25°	20.3°	2.8"	Convex	.5	1.0	.8	1.5	3.0	11	10
	6	6"	6"	.3	35°	18.9°	12.6°	14.3°	9.5°	26.9°	20.3°	3.8"	Convex	1.5	4.0	1.0	2.0	4.0	11	10
	7	8"	8"	.3	25°	25°	17°	18.9°	12.6°	25°	24.9°	3.7"	Convex	.5	1.0	.8	1.5	3.0	20	18
	8	8"	8"	.3	35°	25°	17°	18.9°	12.6°	33°	24.9°	5.1"	Convex	1.5	4.0	1.0	2.0	4.0	20	18
Off-Aperture Reflective	1	14" wide	3"x5"	.9	25°	25°	22°	25°	22°	25°	25°	3.0"	Flat Concave	.4 .1	1.0 .2	1.0	2.0	3.0	31	26.6
	2	17" wide	3"x5"	.9	35° Hor. 25° Vert.	35°	22°	25°	22°	35°	35°	4.9"	Concave	.2	.5	1.0	2.0	3.0	33	28.6
	3	14" wide	2"x4"	.9	25°	25°	22°	25°	20°	25°	25°	2.4"	Flat Concave	.4 .1	1.0 .2	.8	1.2	2.5	21	18.6
	4	14" wide	2"x4"	.9	25°	25°	20°	25°	18°	25°	25°	2.9"	Concave	2.0	6.0	.8	1.5	3.0	13.5	12.3
	5	17" wide	3"x5"	.9	25°	25°	22°	25°	22°	25°	25°	3.0"	Flat Concave	.4 .1	1.0 .2	1.0	2.0	3.0	38	33
	6	21" wide	3"x5"	.9	35° Hor. 25° Vert.	35°	22°	35°	22°	35°	35°	4.9"	Concave	.2	.5	1.0	2.0	3.0	40	35

C.2-15-F

APPENDIX D

COMPUTER PROGRAMMING ANALYSIS

The results of preliminary programming analysis associated with the computer solution of various kinematic targeting and aimsight reticle stabilization equations are presented in this appendix. Five real-time, avionic computers were selected as representative models in this analysis. These machines reflect various memory types (magnetic core, plated wire, solid state) and encompass a broad spectrum of processing speeds. For purposes of this analysis, fixed-point arithmetic operation was assumed; actually, very little advantage, if any, is gained with a floating-point, arithmetic unit because the equations are comprised almost exclusively of trigonometic functions requiring very little scaling.

The essential output of the analysis consists of estimated time and memory space requirements, applicably expressed for any real-time avionic computer, including the five machines considered herein. This data is separately presented for each of the principal targeting and aimsight stabilization functions analyzed. Thus, by appropriately adding time and memory values for any selected combination of functions, the feasibility of employing any candidate computer model can be established. This applies to new, independent computers such as may conceivably be provided in a HUD system, as well as any existing computer with spare capacity, such as the AN/APN-77, -78 units provided as part of the CH-46F, CH-53D SCNS.

To simplify the analysis, a basic instruction repetoire commonly incorporated in aircraft digited computers was assumed. The principal distinction made in the programming analyses among the five representative computers relates to the divide operation, where divide hardware is contained in two of the machines, and a programmed, divide subroutine is required by the other three. The five representative computers considered in this study are:

Manufacturer	Computer
• Sperry Gyroscope	Core Stack Model No. 1
• Sperry Gyroscope	Core Stack Model No. 2
• Sperry Gyroscope	Solid State Memory Display Computer
• Teledyne	AN/APN-77, -78
• Univac	UNIVAC® 1819 Computer

The results of this programming analysis are summarized in Paragraph D.6 below; in addition, appropriate conclusions concerning the practical implementation of the functions considered are presented.

1. SUBROUTINE ESTIMATING FACTORS

- Grey-to-Binary Conversion (10 bits)

    40 add times
    55 storage locations

- Sine, Cosine Derivations

    112 add times
    41 storage locations

- Arc Target

    265 add times
    65 storage locations

- Arc Sine

  201 add times

  30 storage locations

- Divide

  200 add times

  62 storage locations

- Square Root

  165 add times

  90 storage locations

2. AIMSIGHT STABILIZATION EQUATIONS TO COMPENSATE FOR ATTITUDE MOTION EFFECTS

   NOTE: Refer to Appendix A for equations to be solved. Digited compensation functions, if required for loop stability, are not included in this programming analysis.

- End Variables Calculated

  ΔX, ΔY

- Processing Rate

  10 per second

- Total Operations Required per Cycle (Including I/O)

  With divide subroutine

  Fixed storage (program/constants) - 495 words

  Operand storage - 28 words

  With divide hardware

  Fixed storage - 433 words

  Operand storage - 28 words

3. OFFSET, THREE-AXIS, KINEMATIC TARGETING EQUATIONS (DISCRETE VISUAL ACQUISITION METHOD)

The information contained in this paragraph is related to the processing of the equations derived in Appendix B, Paragraph 1. Since a more extensive set of processing requirements is presented by target orientation than by own-aircraft orientation, the equations associated with this function were selected for analysis.

CALCULATION OF DISTANCE TRAVERSED

- Variable Calculated

  D

- Processing Rate

  2 per second

- Total Operations Required per Cycle

  22 add times

  1 multiply time

- Memory Required

  Fixed storage - 23 words

  Operational storage - 2 words

CALCULATION OF ABSOLUTE TARGET POSITION

- End Variables Calculated

  λT, L_T, hT_{SL}

- Processing Rate

  Once only

- Total Operation Required per Cycle (Including I/O)

  With divide subroutine

    3752 add times
    28 multiply times

  With divide hardware

    2752 add times
    28 multiply times
    5 divide times

- Memory Required

  Fixed storage - 164 words

  Operand storage - 28 words

<u>NOTE</u>: This memory estimate assumes that the equations of Paragraph 2 above are also implemented.

<u>SUBSEQUENT RELATIVE POSITION UPDATE</u>

- End Variables Calculated

  [illegible], $[illegible]_x$, hT_x

- Processing Rate

  5 per second

- Total Operations Required per Cycle (Including I/O)

  With divide subroutine

    776 add times
    3 multiply times

With divide hardware

576 add times

3 multiply times

1 divide time

- Memory Required

Fixed storage - 108 words

Operand storage - 18 words

NOTES: 1. This memory estimate assumes that the equations of Paragraph 2 above are also implemented.

2. The equations for deriving R_x, ψo_x, hT_x used in this analysis are not those contained in Appendix B, Paragraph 1.g. Rather a much simpler set of equations were assumed reflecting well known conformal mapping geometric relationships between Δ latitude/longitude and linear distances.

4. OFFSET, TWO-AXIS, KINEMATIC TARGETING EQUATIONS (DISCRETE VISUAL ACQUISITION METHOD)

NOTE: Refer to Appendix B, Paragraph 2 for equations to be solved.

CALCULATION OF DISTANCE TRAVERSED

- Variable Calculated

D_a

- Processing Rate

2 per second

- Total Operations Required per Cycle (Including I/O)

  22 add times

  1 multiply time

- Memory Required

  Fixed storage - 23 words

  Operand storage - 2 words

<u>NOTE</u>: This storage is not required is equation of Paragraph 3 (Calculation of Distance Traversed) is also programmed.

INITIAL CALCULATION OF RELATIVE TARGET POSITION

- End Variables Calculated

  Rs_2, hT_2, D_2

- Processing Rate

  Once only

- Total Operations Required per Cycle (Including I/O)

  With divide subroutine

  1330 add times

  5 multiply times

  With divide hardware

  928 add times

  5 multiply times

  2 divide times

- Memory Required

  Fixed storage - 59 words

  Operand storage - 15 words

<u>NOTE</u>: This memory estimate assumes equations of Paragraph 2 are also implemented.

<u>SUBSEQUENT RELATIVE ORIENTATION UPDATE</u>

- End Variables Calculated

  hT_x, Rs_x, DT_x

- Processing Rate

  5 per second

- Total Operation Required per Cycle (Including I/O)

  220 add times

  3 multiply times

- Memory Required

  Fixed storage - 39 words

  Operand storage - 6 words

<u>NOTE</u>: This memory estimate assumes equations of Paragraph 2 are also implemented.

5. OFFSET, THREE-AXIS, KINEMATIC TARGETING EQUATIONS (CONTINUOUS TRACKING, ANGULAR RATE SENSING METHOD)

   <u>NOTE</u>: Refer to Figure 3-10 for equations to be solved.

   - End Variables Calculated

     Rs, ψ_{OR}, θ_o

- Processing Rate

  5 per second

- Total Operations Required per Cycle (Including I/O)

  With divide subroutine

  2094 add times

  17 multiply times

  With divide hardware

  1494 add times

  17 multiply times

  3 divide times

- Memory Required

  Fixed storage - 35 words

  Operand storage - 6 words

<u>NOTE</u>: This memory estimate assumes equations of Paragraph 2, and the equations for ψ_{OR}, θ_o, cosine θ_o of Paragraph 3 (Calculation of Absolute Target Position) are also implemented.

6. SUMMARY OF RESULTS

The processing speeds of five avionic computers encompassing a broad range of complexity and speed are presented in Table D-1. These models are representative of many such machines available in industry. Except for the Sperry Core Stack Model No. 1, which is an obsolete, early production unit, all the computers are relatively recent developments and were selected, in part, because their characteristics were readily available to Sperry. The Teledyne ASN-77, -78 computers provided for the Navy SCMS were selected to ascertain the feasibility of accommodating the functions considered in this study in these computers.

TABLE D-1

PROCESSING SPEEDS OF REPRESENTATIVE COMPUTERS

Function	Speed in Microseconds				
	Sperry Gyroscope Core Stack Model No. 1	Teledyne ASN-77, -78	Sperry Gyroscope Core Stack Model No. 2	Sperry Solid-State Display Computer	Univac 1819
Add (Short Order)	18.5	12	9	6	4
Multiply	61.7	49.5	24	16.5	26
Divide	-	67	-	-	26

The time requirements developed in Paragraphs 2, 3, 4 and 5 of this appendix are summarized in Table D-2. Absolute times are obtained by simply multiplying the number of short-order, multiply and divide operations indicated by the associated processing times listed in Table D-1 for each computer. The total time for each principal function is then translated into a duty cycle based on the selected processing frequency or rate. The times associated with the calculation of distances (Paragraphs 3 and 4 - Calculation of Distance Traversed) are excluded because their execution is not coincident with the other more extensive functions.

In making use of the data of Table D-2, the targeting functions B, C, and D listed in the left-hand column, although they conceivably could all be programmed into a computer, would never be executed simultaneously in any combination. Hence, the associated duty cycles are to be individually considered and not summed. Any one of these three functions, however, is processed simultaneously with the stabilization function (A). Thus, it is clear that the combination of aimsight stabilization (A) and the offset, three-axis targeting using the continuous tracking method (D) represents the worst case in computer time demand. The estimated total duty cycle ranges from 68.4 percent for the Sperry Core Stack Model No. 1 to 12.4

percent to the faster, more powerful Univac 1819. However, preliminary programming analyses of the type conducted in this study all too often are proven to be optimistic where the actual time established after final, detailed programming exceeds the initial estimates. For the analyses conducted in this study, it is recommended that all estimates be increased by 50 percent, which is deemed to represent a reasonable safety margin.

Based on this assumption, the following conclusions can be drawn. First, a slow machine of the Sperry Core Stack Model No. 1 type is marginally limited in time and should be excluded from consideration. Secondly, extending the SCNS APN-77, -78 beyond its current navigation functions requires (26.0 + 9.5) x 1.5 = 55 percent in time availability. This can probably be accommodated since considerable spare time is known to exist in the SCNS computer because of the deletion of many functions such as terrain following, stationkeeping, etc from the original developmental Integrated Helicopter Avionics System (IHAS). Finally, the other three computers considered have more than adequate capacity to accommodate the targeting functions. However, the additional augmenting functions of HUD symbol generation, gun/rocket fire control, and steering guidance likely to be incorporated must be considered in retrofitting a helicopter system for kinematic targeting. Based on recent Sperry development efforts in digital-computer-centered, synthetic symbol displays and airborne fire control systems, it can be reasonably concluded that a single computer in the current state of the art (e.g., short-order cycle time of 3 to 4 microseconds) will accommodate the time requirements of this integrated set of functions.

The memory requirements for each function are summarized in Table D-3. In this case, the storage requirements are virtually the same for all computers. The slight difference noted reflects the use of programmed subroutines versus hardware for the divide operation. If all four functions listed in Table D-3 were to be implemented, about 1000 words of program memory and 100 words of operand/scratch pad memory would be required.

If these estimates are again factored by 50 percent to account for oversights likely to be uncovered in the final programming design, the final estimate would be 1500 words of program and 150 words of variable memory.

TABLE D-2

SUMMARY OF COMPUTER TIME ANALYSIS

Targeting Functions	Sperry Gyroscope Core Stack Model No. 1			Teledyne AN/ASN-77, -78			Sperry Gyroscope Core Stack Model No. 2			Sperry Gyroscope Solid-State Display Computer			Univac 1819		
	Number of Operations	Time/Cycle (msec)	Duty Cycle (%)	Number of Operations	Time/Cycle (msec)	Duty Cycle (%)	Number of Operations	Time/Cycle (msec)	Duty Cycle (%)	Number of Operations	Time/Cycle (msec)	Duty Cycle (%)	Number of Operations	Time/Cycle (msec)	Duty Cycle (%)
A. Aimsight Stabilization (10/sec rate)															
Add	2555	47.30	-	2155	25.85	-	2555	23.20	-	2555	15.35	-	2155	8.62	-
Multiply	19	1.17	-	19	0.94	-	19	0.46	-	19	0.31	-	19	0.49	-
Divide	-	-	-	2	0.13	-	-	-	-	-	-	-	2	0.05	-
Total	-	43.47	48.5	-	26.92	26.9	-	23.66	23.7	-	15.66	15.7	-	9.16	9.2
B. Offset, 3-Axis Targeting (Discrete Acquisition)															
• Absolute Target Position (once only in 1 second)															
Add	3752	69.41	-	2752	33.02	-	3752	33.77	-	3752	22.51	-	2752	11.01	-
Multiply	28	1.72	-	28	1.38	-	28	0.67	-	28	0.46	-	28	0.73	-
Divide	-	-	-	5	0.34	-	-	-	-	-	-	-	5	0.13	-
Total	-	71.13	7.1	-	34.74	3.5	-	34.44	3.4	-	22.97	2.3	-	11.87	1.2
• Relative Position Update (5/sec rate)															
Add	776	14.36	-	576	6.91	-	776	6.98	-	776	4.66	-	576	2.30	-
Multiply	3	0.19	-	3	0.15	-	3	0.07	-	3	0.05	-	3	0.08	-
Divide	-	-	-	1	0.07	-	-	-	-	-	-	-	1	0.03	-
Total	-	14.55	7.3	-	7.13	3.6	-	7.05	3.6	-	4.71	2.4	-	2.41	1.2
C. Offset, 2-Axis Targeting (Discrete Acquisition)															
• Initial Relative Position (once only in 1 second)															
Add	1330	24.60	-	928	11.12	-	1330	11.96	-	1330	7.98	-	928	3.71	-
Multiply	5	0.31	-	5	0.25	-	5	0.12	-	5	0.08	-	5	0.13	-
Divide	-	-	-	2	0.13	-	-	-	-	-	-	-	2	0.05	-
Total	-	24.91	2.5	-	11.50	1.2	-	12.08	1.2	-	8.06	0.8	-	3.89	0.4
• Relative Position Update (5/sec rate)															
Add	220	4.07	-	220	2.64	-	220	1.98	-	220	1.32	-	220	0.88	-
Multiply	3	0.19	-	3	0.15	-	3	0.07	-	3	0.05	-	3	0.08	-
Divider	-	-	-	0	0	-	-	-	-	-	-	-	0	0	-
Total	-	4.26	2.1	-	2.79	1.4	-	2.05	1.0	-	1.37	0.7	-	0.96	0.5
D. Offset, 3-Axis Targeting (Continuous Tracking) (5/sec rate)															
Add	2094	38.74	-	1494	17.93	-	2094	18.85	-	2094	12.57	-	1494	5.98	-
Multiply	17	1.05	-	17	0.85	-	17	0.41	-	17	0.28	-	17	0.44	-
Divide	-	-	-	3	0.20	-	-	-	-	-	-	-	3	0.07	-
Total	-	39.79	19.9	-	18.98	9.5	-	19.26	9.6	-	12.85	6.4	-	6.49	3.2

TABLE D-3

SUMMARY OF COMPUTER MEMORY REQUIREMENTS

Targeting Functions	Sperry Core Stack Model No. 1 Computer		Teledyne AN/ASN-77, -78 Computer		Sperry Core Stack Model No. 2 Computer		Sperry Solid-State Display Computer		Univac 1819 Computer	
	Fixed Storage (Program/ Constants)	Variable Storage (Operand)	Fixed Storage (Program/ Constants)	Variable Storage (Operand)	Fixed Storage (Program/ Constants)	Variable Storage (Operand)	Fixed Storage (Program/ Constants)	Variable Storage (Operand)	Fixed Storage (Program/ Constants)	Variable Storage (Operand)
Aimsight Stabilization	495	28	433	28	495	28	495	28	433	28
Offset, 3-Axis Targeting (Discrete Acquisition)										
Distance Traversed	23	2	23	2	23	2	23	2	23	2
Absolute Target Position	164	28	164	28	164	28	164	28	164	28
Relative Position Update	108	18	108	18	108	18	108	18	108	18
Subtotal	295	48	295	48	295	48	295	48	295	48
Offset, 2-Axis Targeting (Discrete Acquisition)										
Initial Relative Position	59	15	59	15	59	15	59	15	59	15
Relative Position Update	39	6	39	6	39	6	39	6	39	6
Subtotal	98	21	98	21	98	21	98	21	98	21
Offset, 3-Axis Targeting (Continuous Tracking)	35	6	35	6	35	6	35	6	35	6
TOTAL*	923	103	861	103	923	103	923	103	861	103

*If all functions are implemented.

APPENDIX E

OTHER POTENTIAL HELICOPTER OPERATIONS FOR HEAD-UP DISPLAY APPLICATION

The potential applications outlined in this appendix are not covered in the main body of the report. These applications reflect both unique missions and certain operational flight modes common to several missions. All the applications discussed are conceptual in nature and require further study to assess their practicality and value.

1. ARTILLERY FIRE SUPPORT

A concept for a new helicopter combat role was disclosed by Sikorsky to Sperry. This application involves the use of recoilless cannon aboard helicopters for distance fire support of ground forces. As conceived, the armed helicopters would provide such artillery support in forward combat areas more rapidly than that possible with conventional ground-based or vehicle-carried cannon. Firing would be executed with the helicopter in a low altitude hover against both visible and hidden targets. Since the recoilless armaments would be boresighted to the vehicle longitudinal axis, some form of three-axis attitude orientation guidance is required to control weapon firing. For visual targets such as on the front side of a hill, the necessary fire control data can be supplied by a simple, head-up optical sight. Aim control in two-axes is required; namely, elevation and azimuth, with vehicle roll angle maintained at zero. This can be achieved with just three symbols: a boresight image, an aim circle slewable in two-axes, and a set of roll indexes for wings level alignment. Prior to firing of the first shell, the aim circle is locked onto the vehicle boresight image. Initially, the pilot mentally computes the ballistic drop from estimated range, aligns the boresight at some point relative to the sighted target, and fires once for effect. At the instant of firing, pitch and heading angles are sampled. The aim circle is then manually depressed and also moved laterally, if a cross-wind exists, to the observed point of impact. The elevation and azimuth angles at this point of overlay are also sampled. Thus, through appropriate subtraction, the trajectory displacement in both elevation and azimuth are obtained, and the aim circle is automatically repositioned relative to the boresight to account for attitude changes during the process of firing and subsequent acquisition. With the display now set for accurate firing, the pilot adjusts attitude to overlay the aim circle onto the actual target. The process can be repeated for finer correction or if wind shifts occur. This process is an essentially visually controlled delivery system, and a ballistics computer is not required. Additionally, the simplicity of the display enables the use of inexpensive illuminated reticles as the image source rather than a CRT.

Attacks against targets obstructed from view by terrain (e.g., lobbing of shells on the backside of a hill), would likely be assisted through voice communication by forward ground or airborne observers. Whether spotter assistance is provided to zero in on the target, or whether a fire control solution is computed on board from designated coordinates, an optical HUD provides a logical means of orienting the angle of fire. In this attack situation, however, the aim circle provided for the direct visual attack mode would be earth stabilized for the effects of attitude motion. The aim circle would be manually or automatically positioned in elevation and azimuth (and readjusted as required if forward spotters are employed), and the vehicle boresight would be aligned to this circle prior to firing. The aim circle could be supplemented or replaced by stabilized elevation and azimuth scales, if this is deemed necessary for the zeroing-in adjustment process.

2. SPECIAL STORES DROP

Operations, in which electronic personnel detectors are dropped from helicopters moving at high speed, are being conducted in Southeast Asia. A need to achieve a more precise delivery of these devices than is presently possible has been expressed. The nature of these devices and the required accuracy of drop are classified. However, since the delivery is a visual operation, it is presumed that a head-up optical display would be a necessary element of any system designed to improve the CEP performance of this mission.

3. AIR-TO-GROUND BOMB DELIVERY

Marine Corps personnel at NATC, Patuxent River, Maryland, have indicated that they are studying the possibility of conducting flight test demonstrations of bomb delivery from attack helicopters. Specifically, the armaments under consideration include Fuel Air Explosives (FAE), Mk 115 Mod 0 Helicopter Trap Weapon (HTW), Mk 77 napalm, Mk 76 and Mk 106 Practice Multiple Bomb Rack (PMBR), and the Rockeye II antipersonnel weapons. The indicated objective at this time is to test feasibility of installation, drop effects, and vehicle stability effects. The advent of such bomb delivery in close support helicopter operations would require a HUD, perhaps of a design reflecting a continuous explicit solution system of the type provided in advanced, fixed-wing attack aircraft.

A capability exists in Navy APW helicopters, such as the SH-3 A, D, for a depth bomb attack against submarines. Although such an attack can theoretically be made against unseen submarines from information supplied by other helicopters and fixed-wing aircraft engaged in a tactical APW operation, the accuracy in position determination limits its effectiveness. Homing torpedoes, therefore, are the primary attack weapon. However, situations occasionally arise in tactical exercises where enemy submarines are visually detected (at sufficiently high altitudes) in shallow coral waters or where the submarine is otherwise close to the water surface. In view of the relatively small lethal radius (15 to 17 feet) of conventional depth bombs, a visual display means of delivery to improve kill probability may be warranted if cost can be sufficiently minimized (e.g., if an optical display is already provided for other purposes). In addition to the usual acquisition, ranging and atmospheric trajectory solution functions involved in air-to-ground bomb delivery, two additional elements are involved in submarine bomb attack problem. The first concerns the bomb hydrodynamics during its descent in water, which must be accounted for in the total solution. The second is related to the target tracking function and the need to sense submarine velocity and estimate target depth. Well-known methods of sensing absolute target velocity or relative velocity are available, including the use of angular LOS rate from an optical aimsight. In addition, since a submarine does not ordinarily change course frequently and is unlikely to be aware of the attacking helicopter, its velocity could also be sensed by a simple stationkeeping procedure for a short interval of time. A simple deviation cue on the HUD can assist in this function.

A relatively simple system appears to be possible for a vehicle such as the SH-3A, D. This vehicle already contains Doppler radar, providing flight velocity data. In addition, continuous derivation of slant range via the optical sighting techniques described in Subsection III.H.7 is enabled by the altimeter radar. The only new equipment required is a computer-driven HUD and an AHRS to replace the existing VG/DG.

4. TROOP/CARGO PARADROP

A number of proposals have been made to provide the services with a light V/STOL transport (e.g., Air Force LTT) with troop and cargo paradrop capability. Certain helicopters, such as the H-53, have been considered as possible candidates to meet this requirement if established.

Doctrine requires that most, if not all, paradrop operations be conducted under day or night VFR conditions. In advanced high performance paradrop systems, some form of visual or radar acquisition of the drop zone or nearby checkpoint is required to derive offset or update present position. Accordingly, a fixed or moveable optical projector may be specified in a paradrop system to either point a ranger or assist in kinematically orienting the drop zone.

5. AIRBORNE INTRUDER INTERCEPT

Preliminary conceptual studies are known to have been conducted by at least one helicopter manufacturer for a high speed, heavily armed helicopter designed to detect and attack low flying helicopter intruders. In this concept, such a helicopter loitering on an assigned orbit or hover station and employing an advanced 360-degree MTI search radar for detection is envisioned. Several weapons, including missiles, are contemplated, involving various air-to-air combat tactics. A HUD is a candidate system element being considered, to be used primarily for visual fire control and during low altitude flight under night VFR/IFR conditions.

6. FULL NIGHT, AIDED-VISUAL OPERATIONS

All three services are currently engaged in extensive planning and developments to incorporate LLLTV and IR forward-looking sensors in attack gunship and SAR helicopters for night combat operations. These sensors are primarily intended to aid in the detection of enemy targets, downed airmen, and remote landing areas, and, in certain cases, to provide an aided-visual view of the forward field for landing approach flight control purposes. Additionally, various proposals have been made and studies conducted on the use of wide-field IR systems during enroute formation flight at night. As far as can be determined, this latter application has not been accepted by any service for helicopter use.

With regard to night detection operations, it is recommended that serious consideration be given to presented collimated IR or LLLTV pictorial scan data on a moveable, hand-gripped aimsight of the type described in Section V of this report. In such an arrangement, the two-servo-driven aim reticle incorporated for day/VFR operations would be replaced by a miniature CRT of about 1 to 2 inches in diameter. This size tube, when used in conjunction with low cost, low transmission efficiency-reflective optics, provides the high brightness necessary to view a projected aim circle during high ambient day conditions. The 11-degree mapped field recommended for the servoed aimsight, however, may have to be increased to accommodate the video scan field to be displayed at night.

This scheme offers a number of important advantages. First, with respect to the copilot/gunner's station, it provides a low-cost alternative to providing a CRT display on an already crowded instrument panel. This of course presupposes the provision of an aimsight for day operations. Second, it eases the task in the slewing. Third, it provides the operator with a more rapid, effective means of remotely positioning the electro-optical sensor to the desired point angle, in that his direction of view is coincident with that of the sensor onto the real world. Provision of a panel-mounted CRT display eliminates the need for the operator to occasionally scan through his windshield for possible cues. This can be quite significant, especially in operations where some limited visibility exists, resulting in distinguishable terrain contours and other features, or where light signals are anticipated from friendly forces. Finally, with a highly accurate positioning system, the operator may, under certain conditions, be able to correlate real world objects with the sensed image, which could aid the identification task.

To effect acquisition, a simple aim circle pointed during raster scan deadline is provided. This symbol would be fixed at the center of the video field since this sensor would presumably be attitude stabilized in earth coordinates. Target orientation can, if desired, be implemented by the kinematic targeting technique described in Subsection III.H.4. Upon completion of the acquisition, it is conceived that the target, in addition to being designated on the pilot's primary display (e.g., HUD or VSD), would also be displayed on the copilot's aimsight as a synthetic symbol (e.g., square) to assist in any subsequent re-acquisition update that may be necessitated by error accumulation in the avionics during maneuver or intentional change in the target position. The display of a designated target symbol is not possible without considerable added complexity in the servoed aimsight design discussed in Section V.

The display of LLLTV or IR pictorial video on the controlling pilot's fixed HUD projector is a projection that has been widely considered and studied. There are many ramifications and uncertainties concerning the effectiveness of this display approach to flight control; hence, no firm recommendations are presented in this report. However, the general inclination throughout the services and industry appears to be negative primarily because of objections to the resulting total occlusion of the forward field of view.

A number of other missions and operations were investigated for which the applications of a HUD could not be reasonably substantiated in terms of its effectiveness value. These include:

- Reconnaissance (visual/photographic)
- Reconnaissance (personnel deployment)
- Mine detection
- Mine laying
- Light Airborne Multi-Purpose System (LAMPS)
- Formation flight (stationkeeping)

- Letdown to small, moving ships
- Moving ship-to-air refuel or hoist (stationkeeping)
- Target acquisition by hunter, observation aircraft (except for aimsight to point laser (ranger)

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1. Farrand Optical Company, Bronx, N.Y.

   Mr. A. Nagler

2. Sikorsky Aircraft, Stratford, Conn.

   Messrs. T. Krok, J. Dupnik, P. Guinn, M. Nabor, R. Wragg, C. Brown, J. Parker

3. Vertol Division, Boeing Company, Philadelphia, Pa.

   H-46 Project Personnel

   Messrs. D. Tutt[illegible], R. Bradbury, J. Macrino

   Avionic, Cockpit, and Human Factors Staffs

   Messrs. Zeller, E. Piper, R. Longhead, A. Saerbet, B. Croft

4. U.S. Marine Corps Development Center, Quantico, Va.

   Lieutenant Colonel Parish
   Major's Crone and Machado
   Mr. George Brigham

5. NASA, Langley Field, Va.

   Messrs. J. Reeder, R. Sommer, R. Tapscott, J. Garren, E. Dunham

6. Kaman Aircraft, Bloomfield, Conn.

   Messrs. Silverio, W. Batesole (Telcon)

7. North American Rockwell, Columbus, Ohio

   Mr. E. W. Smith (OV-10 Project Engineer) (Telcon)

8. Naval Air Systems Command, Washington, D.C.

   Major D. Carr (OV-10 Claps Desk Officer) (Telcon)

LIST OF ORGANIZATIONS/PERSONNEL CONSULTED OR INTERVIEWED (cont)

9. Sperry Systems Management Division, Great Neck, N.Y.

Mr. R. Strazulla (Manager, Avionics)

10. NATC, Patuxent River, Md.

Messers. S. Cameron, D. French, R. Buffum
Lieutenant Commander B. Fleming
Major's B. Krages, W. J. Scheuren
Lieutenant Nelson

11. Quonset Point Naval Air Station, Quonset, R.I.

Lieutenant Commanders Saurey and Kuhnman.

12. Teledyne Systems Company, Hawthorne, California

Dr. L. Unger

13. U.S. Army Aviation School, Fort Bucker, Alabama

Major J. Morel
Chief Warrant Officer N. Lukshin

(These officers were interviewed at Sperry.)

14. Naval Air Test Center, Patuxent River, Md.

Major M. Ripley (USMC)

(This officer was interviewed at Sperry.)