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AIRBORNE ELECTRONIC TERRAIN MAP SYSTEM
A Literature Review

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FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
Air Force Aerospace Medical Research Laboratory

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Currently, the United States Air Force is placing significant emphasis on low-altitude high-speed profiles for tactical aircraft survivability. In order to execute these terrain avoidance profiles, pilots require an efficient and credible source of terrain relief information for both accurate and safe navigation and to alleviate the high workload associated with the primary pilotage function. This report highlights many of the limitations of current airborne sources of cartographic information and describes a viable alternative

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--the Airborne Electronic Terrain Map System (AETMS). The AETMS consists of an in-the-cockpit, computer-generated, wide-area terrain map display, capable of providing forward-looking perspective and/or planimetric information. Because of the large integrated data base, real-time information source for many mission segments. The system is totally self-contained and passive, which precludes the possibility of jamming and reduces detection probability.

SUMMARY

Currently, the United States Air Force is placing significant emphasis on low-altitude high-speed profiles for tactical aircraft survivability. In order to execute these terrain avoidance profiles, pilots require an efficient and credible source of terrain relief information for both accurate and safe navigation and to alleviate the high workload associated with the primary pilotage function. This report highlights many of the limitations of current airborne sources of cartographic information and describes a viable alternative--the Airborne Electronic Terrain Map System (AETMS). The AETMS consists of an in-the-cockpit, computer-generated, wide-area terrain map display, capable of providing forward-looking perspective and/or planimetric information. Because of the large integrated data base, the AETMS is amenable to multiformatting to provide an optimized, real-time information source for many mission segments. The system is totally self-contained and passive, which precludes the possibility of jamming and reduces detection probability.

PREFACE

This report documents a literature review conducted by the Visual Display Systems Branch, Human Engineering Division of the Air Force Aerospace Medical Research Laboratory, under Work Unit 71841130, "Terrain Map System Simulation Support." This work was requested by the Information Presentation Control Group of the Systems Avionics Division, Air Force Avionics Laboratory, in support of USAF Project 2003, "Avionics System Design Technology, 'Task 06,' Information Processing Systems." The effort was supported, in part, by Systems Research Laboratories, Inc., Dayton, Ohio, under Air Force Contract No. F33615-79-C-0503. Dr. John F. Courtright was the Air Force Contract Monitor.

The authors express their appreciation to Mr. William N. Kama, Dr. John O. Mysing, Dr. Louis A. Tamburino, Capt. Frederick Barney, and Lt. Donald Sander for their support and encouragement. The study is considered very important to, and timely for, the development of a pilot-oriented terrain information display system required for performing terrain avoidance flight at reduced workload.

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LIST OF ABBREVIATIONS

A/C	Aircraft
AETMS	Airborne Electronic Terrain Map System
AFAL	Air Force Avionics Laboratory
AGL	Above Ground Level
AGARD	Advisory Group for Aerospace Research and Development
AMRL	Aerospace Medical Research Laboratory
AWACS	Advanced Airborne Warning and Control System
C^3	Command, Control, and Communication
CRT	Cathode Ray Tube
ECM	Electronic Countermeasure
FEBA	Forward Edge of Battle Area
FLIR	Forward Looking Infrared
FOV	Field of View
GPS	Global Positioning System
HSD	Horizontal Situation Display
HUD	Head-Up Display
IFR	Instrument Flight Rules
JTIDS	Joint Tactical Information Distribution System
LAHS	Low-Altitude High-Speed
TA	Terrain Avoidance
VFR	Visual Flight Rules
VSD	Vertical Situation Display

INTRODUCTION

GENERAL

Toward the end of the war in Southeast Asia, U.S. tactical aircraft (A/C) could penetrate the heavily defended airspace of North Vietnam at medium altitudes because of the limited diversity of surface-to-air defenses and the effectiveness of electronic countermeasure (ECM) pods (Crawford, 1977). These tactics, however, were unsuccessful (as evidenced by high attrition rates) when employed by the Israeli Air Force in the 1973 Middle East War. The reduction in effectiveness appears to be due to diversity and redundancy of Arab surface-to-air defense systems. "Analysis of the 1973 Middle East War and the surface-to-air defenses present there, which are representative of those available to Warsaw Pact countries, leads to the conclusion that it may be extremely costly for present generation fighter aircraft to again penetrate highly defended air space at medium altitudes with a family of ECM pods (not yet available) and defense suppression techniques" (Crawford, 1977). In light of these facts, there is an emphasis on low-altitude, high-speed penetration profiles (e.g., terrain avoidance and following).

The problems to be expected by implementing this profile are substantial. Low-altitude high-speed flight over heavily defended, unfamiliar territory places a heavy burden on the aircrew (especially for single-seat tactical A/C). The pilot must navigate, avoid ground fire, acquire the target, and deliver munitions while trying to maintain the lowest possible profile (Crawford, 1977). The pilotage and navigation problems expected in this regime are compounded by the concurrent emphasis on all-weather, night operations. For example, the draft Statement of Work for the Enhanced Tactical Fighter states the role of this weapon system is "to detect, attack, and destroy hard mobile targets" . . . with particular emphasis . . . "on second echelon forces during night and all-weather conditions."

Low-altitude, all-weather requirements are particularly difficult to meet in Central Europe where ceiling and visibility restrictions are severe. Table 1 presents typical ceiling limitations. Army field forces are told (AFM 100-5, Operations) that "due to the incidence of ceilings that are 1,000 feet or less, Commanders can expect a one-third degradation in close air support missions during the December-February time frame." Similar decrements to Air Force capabilities are expected as a result of reduced visibility ranges.

Any pilotage/navigation aid that can reduce workload or otherwise enhance mission success must be considered a significant technological goal. Terrain avoidance and following radar systems substantially reduce pilotage problems. These systems, however, are extremely costly and subject to jamming. Since the systems are "active," detection probability may increase dramatically. At best, only a single, narrow trace is imaged. The airborne electronic terrain map system (AETMS), currently being developed by the Air Force Avionics Laboratory (AFSC) at Wright-Patterson AFB,

TABLE 1. AVERAGE CEILINGS OVER WESTERN EUROPE

(More than 50 percent Cloud Cover)
Expressed as a Percentage for Three-Month
Periods [from FM 100-5]

	Mar-May	June-Aug	Sep-Nov	Dec-Feb
No Ceiling	29.7%	33.9%	25.1%	15.7%
2000 Plus	49.2	50.2	42.3	41.2
1500-2000	3.9	2.4	4.0	5.6
1000-1500	5.4	3.9	6.2	9.8
500-1000	6.5	5.0	8.0	14.1
Under 500	5.3	4.6	14.4	13.6
Average*	6.2%	6.7%	18.5%	17.1%

*The incidence of ceilings less than 500 feet is markedly increased when coupled with fog as in this chart.

addresses both pilotage and navigation problem areas for low-level flight. The AETMS consists of an in-the-cockpit, computer-generated, wide-area terrain map display, capable of providing forward-looking perspective and/or planimetric information. Because of the large integrated data base, the AETMS is amenable to multiformatting to provide an optimized, real-time information source for many mission segments. The system is totally self-contained and passive, which precludes the possibility of jamming and reduces detection probability.

OVERVIEW OF THE AETMS

The AETMS is extremely versatile. It can be used with other sensors and systems. Used in conjunction with TA radar, it may provide a high degree of accuracy with a significantly lower duty cycle--which would reduce detection probability. By combining FLIR or low-light television with an AETMS display, two distinct sources of information can be cross validated. If the distinct sources of information are in relatively close registration, pilot confidence in both systems will be increased.

The AETMS is more than just a horizontal or vertical situation map system. It is an integrated information system which will supplement current aircraft systems, giving the pilot the capability to negotiate low-level high-speed profiles.

The digital recordings of the Defense Mapping Agency (DMA) world-wide data base are preprocessed, as depicted in Figure 1, to obtain polynomial fits for the terrain elevations. These polynomials are stored as sequences of coefficients (i.e., compressed form). The on-board mass memory of the AETMS would be loaded from the world-wide base. The A/C navigation system would provide present position inputs to the on-board computer which uses them to access memory. The retrieved coefficients would be used to generate a terrain relief display for the pilot/navigator. (See Figure 2.)

The above explanation is highly simplistic in nature. See Tamburino, 1977, for a detailed overview of the AETMS.

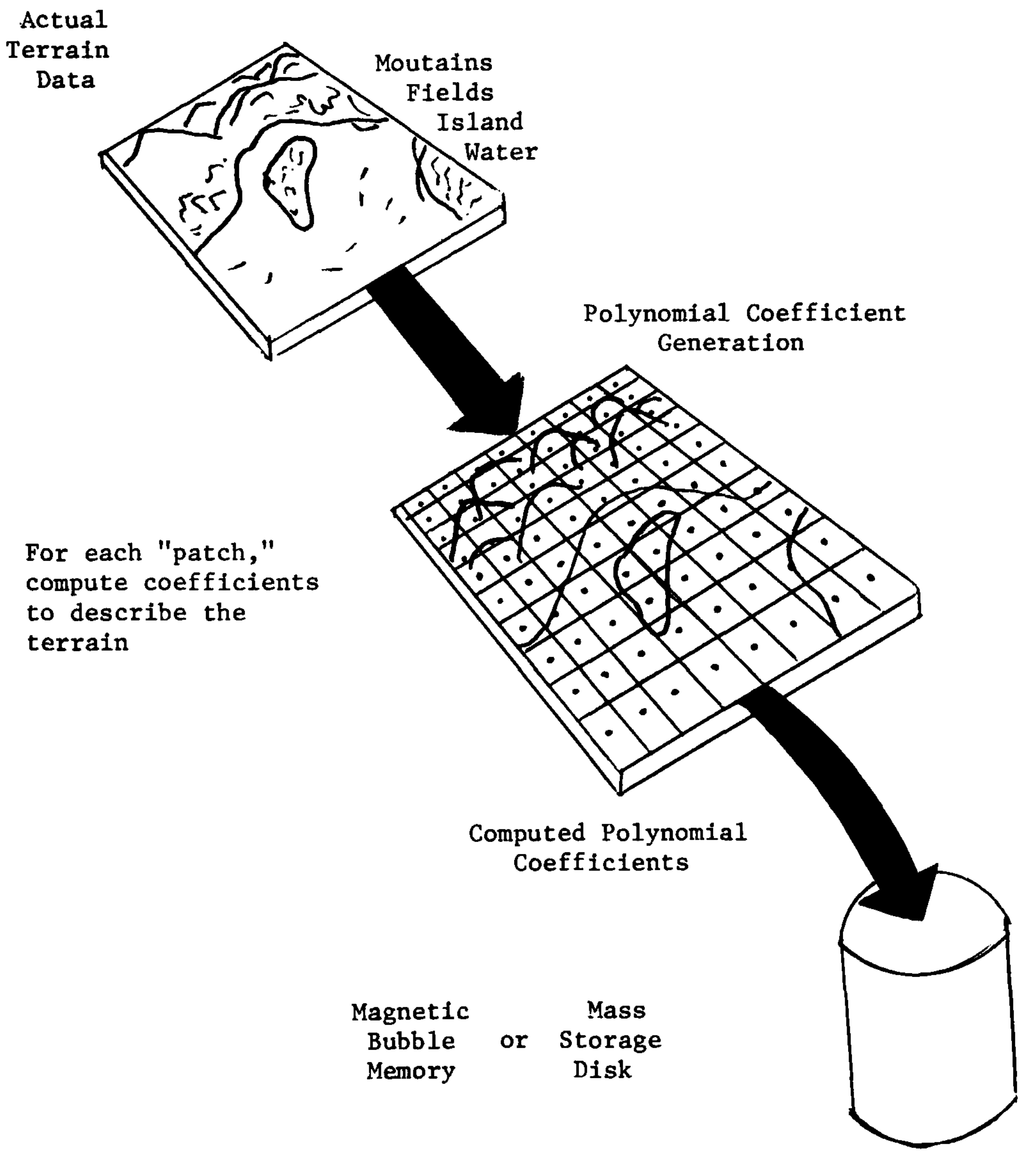


Figure 1. AFAL Data Base Modeling (Surface Averaging) Technique

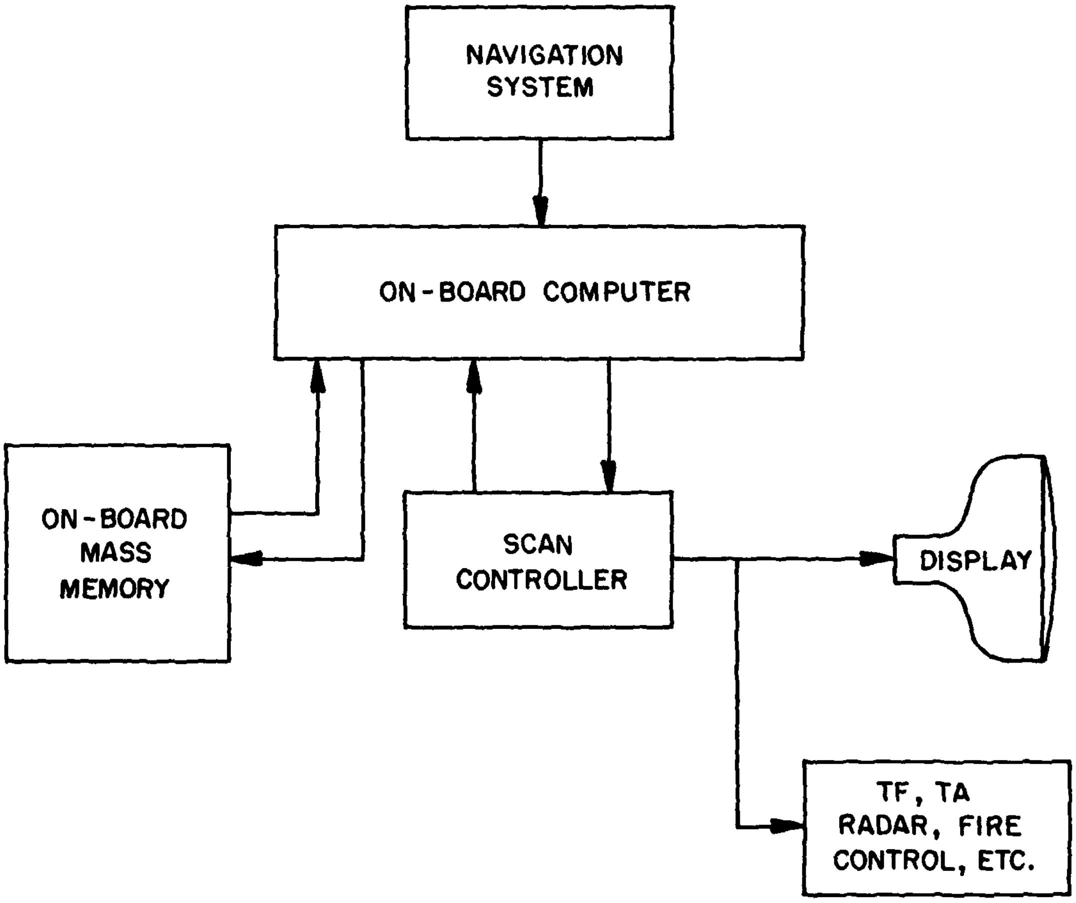


Figure 2. Simplified Block Diagram of the AETMS

CARTOGRAPHIC INFORMATION DISPLAYS

TASKS REQUIRING CARTOGRAPHIC INFORMATION

In order to maintain a low-level high-speed profile, the pilot will need a substantial amount of cartographic information. A list of candidate pilot tasks that require cartographic information was compiled by Carel et al., 1974, and includes:

- Reading out position
- Matching the outside visual world with cartography
- Matching ground mapping sensor data with cartography
- Correlating cartography with preflight planning information
- Updating navigation system
- Updating flight plan
- Evaluating stored threat data
- Evaluating real-time sensed threat data
- Following computed guidance paths

OTHER TASKS FACILITATED BY CARTOGRAPHIC INFORMATION

Aircraft with radar homing and warning systems currently include a display to present sensed threat data and steering information in bearing coordinates. Both stored and sensed threat data can be incorporated in a map display so that they can be easily related to ground coordinates and aircraft position (also see section on Command, Control and Communication [C^3] Considerations). This makes it easier to interpret the threat and perform necessary actions.

Carel, 1974, proclaims the benefits of integrating steering commands with cartographic information.

"Steering commands or computed guidance paths could also be presented on a map display. Electronic map display system developments have been working toward this end. Both horizontal and vertical steering commands can be electronically generated and displayed. This requires a sophisticated map display system beyond the 'simple' roller map or projected map display system. In fact, the map display becomes much more than a display to replace hand-held charts. A capability for displaying guidance information is technically within the state of the art and should be given serious consideration when aircraft cockpits are in the design stage. However, it may well result in a display system that significantly improves pilot performance and reduces pilot workload by the integration of cartographic information with other sources of information."

LIMITATIONS OF HAND-HELD CHARTS

The pilot must integrate the chart information with performance indices to determine necessary control actions to reach his destination. Integration of the two sources of information is not facilitated by their differential formatting and locations.

The pilot must divide his attention between performance displays and the chart (in addition to the outside world) in an attempt to determine his exact location and the appropriate flight control actions to get where he should be. The two sources of information are physically separated in space, and therefore the time necessary to scan (scan time) is considerably increased. An increase in scan time undoubtedly increases head-down time, which is critical when flying "on the deck." Additionally, there is differential eye accommodation and covergence for the hand-held map and the panel performance displays so that more head-down time is necessary to scan between the two sources of information. This compounds the accommodation transitions from panel to outside world.

Transition from integration of the two sources to necessary control actions is difficult. The pilot may correlate a feature on the map with a terrain feature and look at the longitude/latitude on the panel display so that he knows exactly where he is. Steering information which would aid him in determining appropriate control actions is lacking, however. By using the hand-held chart, the pilot must mentally "compute" the appropriate steering action, which increases workload.

Another major drawback of hand-held charts is that they do not necessarily supply the appropriate information. At certain times excessive clutter increases the amount of time necessary to extract critical information. Under other conditions, insufficient information is presented. In short, the amount and type of information present when the hand-held maps "go to press" is fixed at that event.

Perhaps an obvious but significant limitation of hand-held charts is the reduced availability of one hand because it is being used to refold the map or trace along the flight path. There is also an increase in head-down time while the pilot rearranges the map. The pilot could try to circumvent this problem by exposing a larger portion of the map, which would decrease the number of times it would have to be refolded. Exposing a larger area of the map, however, may not effectively reduce time, since additional search time is necessary as the area of regard increases, and the larger sheet may also prove cumbersome.

MAP DISPLAYS (GENERAL)

In an attempt to circumvent the limitations of the hand-held chart and facilitate information integration (thereby reducing workload), there has been a concerted effort to develop "automated" map displays. Since the map display is automated and can be used in conjunction with a "window," the pilot will be relieved of the burden of handling the map and scanning large areas of the map to determine position. Proper positioning of the display can decrease the physical distance between it and the performance displays, reducing scan time. Better yet, critical performance information can be incorporated in the map display.

Many of the other benefits of map displays were highlighted by Dr. J. McGrath in an address given at the 1971 AGARD meeting in Paris.

> "The benefits of the pictorial presentation of navigation information have been predicted and proclaimed for many years. Foremost, an automatic map display will provide the aircrew with immediate and continuous geographic orientation--something that cannot be provided by any other form of cockpit display. Map displays unload the major burden of navigation tasks from the aircrew and have been shown to improve the pilot's control of the aircraft. Navigation information is presented on a map display in a form that is immediately appreciated and ready for action, so the likelihood of a catastrophic blunder in navigation is reduced or eliminated. Map displays can provide a convenient medium for cross-checking the outputs of two or more navigation systems. They can provide a useful communication link between the aircrew and the onboard computer, so that the pilot can address navigational problems to the computer in a convenient manner. Most of these systems also can provide storage and display of a variety of aeronautical information other than that contained on the charts. A map display can improve the pilot's ability to anticipate and recognize checkpoints seen in the real world or on radar and thereby provide timely updating of the navigation system. With appropriate data-link developments, automatic position-reporting and air traffic control can be mediated through map-display systems. A variety of other potential benefits can accrue from properly designed map displays, such as a graphic display of fuel-management information, a means for reducing preflight planning time, and a possible source of mission history records. In short, airborne map-display systems provide the best available solution to the problem of pilot orientation and workload reduction." (Carel et al., 1974)

CONTEMPORARY MAP DISPLAYS

Presently there are four basic types of map displays: direct-view, projected, combined map/CRT, and electronically generated. The advantages and limitations of each type will be reviewed, followed by a discussion of a variety of operational problems affecting map displays in general. (See Table 2 for a summary of the advantages and limitations of each display type.)

Direct-View Map Displays

We begin our discussion of display types with the earliest developed, easiest to implement, and least costly map display. Unfortunately, it is also the one with the fewest capabilities. Direct-view map displays use paper charts mounted on rollers. The chart is transferred from one roller to another to depict aircraft movement along one axis while the aircraft symbol moves across the chart to correspond with movement in the other axis. Both movements are automatically produced through doppler or digital computation inputs.

"The principal advantages of direct-view displays are that they can be used with standard paper charts, so that cartographic support is readily available, and the pilot has direct access to the chart, so that he can mark

TABLE 2. ADVANTAGES AND DISADVANTAGES OF CONTEMPORARY MAP DISPLAYS

MAP DISPLAY	ADVANTAGES	DISADVANTAGES
Direct-View	Uses standard paper charts (existing cartography is readily available) Pilot can mark flight plan, chart amendments and mission intelligence data Actual track flown can be recorded on map Lightweight Portable Relatively inexpensive Passive (nonemitting)	Storage capacity (hence cartographic coverage relatively small) Cumbersome to implement in-flight chart changes Chart orientation fixed (usually north-up) Heading and steering information cannot be readily displayed No look-ahead options No chart magnification options No clutter/declutter option
Projected	Large cartographic coverage Magnification options are available (which aids in legibility) Variety of scales available	Pilot cannot annotate chart with flight plan, chart amendments and mission intelligence data No clutter/declutter options Specialized microcharts are necessary

TABLE 2. ADVANTAGES AND DISADVANTAGES OF CONTEMPORARY MAP DISPLAYS (continued)

MAP DISPLAY	ADVANTAGES	DISADVANTAGES
Projected (continued)	Variable chart orientation (e.g., track-up, north-up) Integration of steering information possible Can be used to update navigation system Passive (nonemitting)	
Combined MAP/CRT	*Multipurpose display* Limited form of chart annotation is possible by using CRT *for generating* course lines, checkpoint symbols Information can be real-time *or predictive* (Plus all advantages in PROJECTED MAP - above)	Complex and expensive Legibility problems because of the need for compatible brightness of map image with CRT imagery Five methods of combining MAP/CRT--ALL BULKY Specialized microcharts are necessary No clutter/declutter options
Electronic	More accurate than optical/mechanical (i.e., direct-view, projected and MAP/CRT) because it follows digital commands and has no moving parts	Extensive topical detail lacking at present time

TABLE 2. ADVANTAGES AND DISADVANTAGES OF CONTEMPORARY MAP DISPLAYS (continued)

MAP DISPLAY	ADVANTAGES	DISADVANTAGES
Electronic (continued)	Readily adapted to changing requirements (growth and refinements are primarily tied to software as opposed to hardware) Multipurpose display Information can be real time or predictive Chart changes are easily performed Magnification options available Chart graphics can be rotated without rotating alphanumerics Chart amendments and mission intelligence data can be incorporated Variable chart orientation Can be used to update navigation system Variable chart orientation can be used to update navigation system Only information necessary for each mission phase need be presented	Considerable computer capabilities necessary

TABLE 2. ADVANTAGES AND DISADVANTAGES OF CONTEMPORARY MAP DISPLAYS (continued)

MAP DISPLAY	ADVANTAGES	DISADVANTAGES
Electronic (continued)	Data base (DMA) available Passive (nonemitting) Integrated heading and steering information possible	
AETMS	Has all the advantages of the "electronic" (above) PLUS addresses the vertical as well as the horizontal situation	Technology dependent tradeoff exists between area coverage and resolution of relief detail. (This will be alleviated with the implementation of bubble memory)

it with flight plan, chart amendments, and mission intelligence data" (Abraham and Campbell, 1966). The displays are lightweight, portable and relatively inexpensive. Additionally, a pen can be inserted to trace the track actually flown which will aid in debriefing and localizing (previously) unknown enemy threats for subsequent missions.

The principal disadvantage of the direct-view map display is that heading and steering information cannot be readily incorporated on the display. Hence, the problem of scanning and integrating information from several physically separated displays still exists. The effective operating range of the display is limited because the chart storage capacity is relatively small. Other limitations include the lack of: look-ahead options, chart magnification options (which are useful if legibility is poor), and clutter/declutter options (which will add or delete detail as a function of information needs). Finally, chart orientation is fixed (usually north-up). Results of a survey (of A-7E pilots) by Carel et al., 1974, indicate that 96 percent of the pilots prefer track-up when flying low-altitude missions. The north-up mode provided by the direct-view display, therefore, does not supply the pilot with the preferred map orientation.

Projected Map Displays

Projected map displays rear-project microfilmed transparencies of the original chart on a display screen. Typically, an aircraft symbol is transcribed on the display surface and the chart moves under the symbol to corrrespond to current aircraft position.

Projected map displays address many of the limitations of the direct-view displays. Microfilmed transparencies are more compact than the original chart they were produced from and, therefore, cartographic coverage is increased. Since the image is projected, both north-up and track-up modes are available. Heading and steering information can be incorporated on the map display itself (see Table 3). Look-ahead, magnification, and variable scale options are also available.

TABLE 3. OPTIONS AVAILABLE WITH PROJECTED MAP DISPLAYS

- Magnification
- Variety of Track Modes
- Update Computed Position
- Automatic Chart Changing
- Centered/Decentered Mode
- Communication with the Computer
- Variety of Scales
- Integrated Steering
- Waypoint Programming
- Built-In Test and Failure Warning
- Display of Digital Information

The projected chart, however, does have some limitations. The microfilm is produced from a standard paper chart; therefore, clutter/declutter options are not available and it is time-consuming and costly to produce the film.

The principal limitation of projected map displays is that the pilot cannot readily annotate the chart with flight plan information. In other words, the display will tell the pilot where he is and what course to fly to reach a programmed destination, but typically will not tell him where he should be with regard to his planned route and arrival times (Carel et al., 1974).

Combined Map/CRT

In a combined map/CRT display, cartographic information is presented on a cathode ray tube (CRT) in register with alphanumeric or symbolic information. "The advantages to be gained from combined map/CRT displays (as opposed to the projected map displays) derive mainly from the versatility of the CRT as a display medium. The CRT information can easily be selected, amended, or updated; dynamic movement, intensification, or blinking of symbology is readily accomplished, and the display can be used for a variety of purposes in order to conserve panel space in the cockpit" (Carel et al., 1974). Additionally, ground-mapping radar information can be superimposed on the map to aid in navigation and target identification. According to Carel, 1974, one significant limitation is that "every map/CRT system that has been developed to date has encountered serious legibility problems because of the need for compatible brightness of the map image with CRT imagery."

Electronic Map Displays

In the electronic map display all information, including cartography, is generated electronically. Both alphanumeric and cartographic data are presented on a CRT using raster or preferably calligraphic (stroke-written) symbol generation techniques. Horizontal and vertical deflection signals are produced from computer-stored digital information which defines X, Y, and Z coordinates of the information elements. Updating is accomplished from navigation system (INS) inputs and is refreshed at a fairly rapid rate.

> "The chief advantages of the all-electronic approach to map-display design is that maximum exploitation is made of the versatility for time-shared or combined-image displays that is inherent in a CRT linked to a digital computer. The aim is to produce a multi-mode display that can present to the pilot the exact information he needs at each phase of flight through selective data presentation and display time sharing. All-electronic systems are expected to be more accurate and reliable than optical/mechanical systems because they directly follow digital commands and have no significant moving parts." (Carel, 1974).

Additionally, Carel, 1974, notes that changes in chart frames are made automatically and consistently, chart graphics can be rotated without affecting the alphanumerics, and any cartographic orientation (north-up, track-up, etc.) can be programmed and selected.

The principal limitations of electronic map systems are that, at the present time, they do not have airborne capabilities for storing, accessing, and processing the extensive amounts of data required for presenting full-color, chart-like displays.

AIRBORNE ELECTRONIC TERRAIN MAP SYSTEM

General

The Airborne Electronic Terrain Map System (AETMS) uses an electronic, computer-mediated approach to real-time map generation. It has the potential for all capabilities described in the Electronic Map Displays section. In addition to presenting the horizontal situation, the AETMS also provides a perspective terrain map of the vertical situation. This is expected to be a significant technological advancement in light of current Air Force emphasis of low-altitude, high-speed (LAHS) profiles mandated for tactical aircraft survivability.

The majority of contemporary map displays were developed before the LAHS profile became a requirement. These profiles, as they are understood for the 1980s (Crawford, 1976), stress:

- Altitudes significantly below 500 ft/AGL
- Speeds commensurate with A/C and pilot capabilities
- Emphasis on terrain masking and passive sensor operation to decrease detectability
- Use of standoff weapons (especially missiles) which require greater accuracy in navigation to target areas
- Minimization of "pop-up" to facilitate target acquisition and weapons delivery

For the first time, the tactical Air Force is confronted with operating high performance A/C under true TA flight profiles. The difficulty associated with TA flight is intensified since these profiles must be executed under night and adverse weather conditions as well as VFR. The difficulty of this task is further increased by the presence of ground-to-air defenses and air-to-air threats.

The real problem posed by TA flight is survivability, including mission accomplishment, under high-stress, high-workload conditions. All of the pilotage/navigation tasks described by Carel (above) become more critical when attempted under these conditions. Therefore, the multifaceted capabilities of the AETMS, which combines HSD and VSD information elements in an integrated display format, offer an opportunity for both exploiting technology beyond that of conventional electronic map displays and providing a significant systems effectiveness increment, especially in the context of the 1980s scenario.

WORKLOAD REDUCTION

The AETMS offers one of the few viable opportunities to effect a major decrease in workload in TA flight conditions because of the "natural" perspective of the display terrain. The availability of forward-looking computer-generated imagery reduces pilot/navigator uncertainty and greatly facilitates transition from the cockpit to the real world by providing a compatible information source. The possible presentation of a minimum amount (i.e., ridge line only) of AETMS data on the HUD offers an extremely appealing option to eliminate head-down time during the most critical tasks (e.g., target acquisition and weapons delivery). This would represent one possible mode of "decluttered" operation allowing the pilot to concentrate on HUD symbology while monitoring his A/C's relationship to the terrain. This would extend weapon systems effectiveness from VFR to night/adverse weather. Inclusion of man-made (cultural) obstacles in the AETMS data base would further reduce pilot uncertainty and support both mission planning and enroute decision making. A similar performance improvement is associated with the inclusion of threat envelope data for AETMS presentation.

Long standoff target acquisition through the use of narrow FOV sensors (e.g., second generation and advanced FLIR) requires both accurate navigation and 3-D positioning of the A/C with respect to the target. This can be even more difficult to achieve if target reacquisition must follow an intervening use of terrain masking. The AETMS facilitates these significantly.

The emphasis on precise navigation can be positively responded to because of the inherent AETMS capability for establishing the location of off-track (but within the AETMS FOV) way points, thus obviating any need for direct overflight. Because the AETMS can function as a dedicated HSD, the pilot/navigator can select an optional HSD-like format when his workload permits exploitation of head-down displays.

PILOTAGE/NAVIGATION INFORMATION REQUIREMENTS

GENERAL

Establishing information requirements is a fundamental step in display systems design. It provides a systematic method for guiding the selection of formatting, display modes and symbology, which must be taken into consideration by the systems designers. Since information required by the pilot may be different for each mission phase, our discussion will examine information requirements for each phase. By taking a microapproach to the problem (i.e., breaking the mission into segments), essential information necessary for each segment can be more readily determined. A general mission scenario includes: low-level penetration/terrain and (known) ground threat avoidance, navigation to target, target acquisition, weapons delivery, damage assessment, and egress. We assume that the pilot will take off, ascend to cruise altitude, descend to penetration altitude before crossing the FEBA (forward edge of battle area) and, at the end of the mission, land. These segments do not rely on terrain information. Further, since weapons delivery tactics are dictated primarily by the specific ordnance, the following review focuses on navigation and pilotage under terrain avoidance profiles.

NAVIGATION

Typically, horizontal situation displays (HSD) are the primary source of navigation information. With the development of moving map displays over the past two decades, there is a considerable amount of data concerning information requirements for HSDs (see Ketchel and Jenney, 1968; Soliday and Milligan, 1967; and Carel et al., 1974).

Table 4 summarizes HSD information requirements based on current display design in the F-111B and A-7E, and human factors studies (Soliday and Milligan, 1967; Ketchel & Jenney, 1968; and Carel et al., 1974). The ratings of desirable or mandatory are based upon agreement or consensus in the literature. Mandatory ratings indicate nearly unanimous agreement among designers and/or researchers as to the necessity of the information. A rating of desirable does not necessarily indicate that the information is not as important, just that currently there is insufficient literature to support its merit or the information could not be readily incorporated in "nonelectronic" terrain map svstems.

TABLE 4. COMPOSITE TABLE OF HSD INFORMATION REQUIREMENTS

INFO REQUIREMENT	RATING
A/C POSITION	Mandatory
COMPASS ROSE	Mandatory
HEADING	Mandatory
COURSE	Mandatory
GROUND TRACK	Mandatory
FUEL QUANTITY OR RANGE	Desirable
TIME TO CHECKPOINT	Desirable
TIME TO TARGET	Desirable
GROUNDSPEED	Desirable
MISSION BRIEFING DATA	Desirable
TARGET LOCATION	Desirable
CHECKPOINT LOCATION	Desirable
KNOWN GROUND THREATS	Desirable
COURSE DEVIATION	Desirable

AIRCRAFT POSITION (MANDATORY): Display of a symbol representing the aircraft in relation to the chart. The aircraft symbol should be displayable in both a centered and decentered mode at the pilot's option.

COMPASS ROSE (MANDATORY): A compass around the periphery of the display. The compass either remains stationary (i.e., north-up mode) or rotates (track-up mode) in correspondence to aircraft heading.

HEADING (MANDATORY): Display of a pointer adjacent to the compass rose or a line passing through the aircraft symbol and compass rose which indicates current aircraft heading.

COURSE (MANDATORY): Desired path of the aircraft over the ground. The course is typically displayed as a line transecting the display and compass rose or a hash mark adjacent to the compass rose. The course marker is essentially command information.

COURSE DEVIATION (DESIRABLE): A readout of lateral deviation, in distance, from the planned course. This information may be extremely useful when the pilot is attempting to locate targets and checkpoints.

GROUND TRACK (MANDATORY): The actual track the aircraft makes over the ground. "The interplay of ground track with course and heading provides the pilot with an index of aircraft performance in the horizontal situation and with derivative information such as drift. These three elements and aircraft position thus constitute the basic elements of the horizontal situation display." (Ketchel and Jenney, 1968.)

FUEL QUANTITY OR RANGE (Desirable): Fuel quantity refers to the amount of fuel remaining. Fuel range, however, may be a more useful index for navigation since it integrates fuel quantity, flow rate, and ground speed into a form more readily interpretable in the context of the horizontal situation.

TIME TO CHECKPOINT AND TARGET (Desirable): Digital readout of time to next checkpoint and/or target.

GROUND SPEED (Questionable): Primarily, ground speed is used to calculate fuel range and time to a target or checkpoint. It may not be necessary if fuel range and time to checkpoint and target are displayed.

TARGET AND CHECKPOINT LOCATION (Desirable): Symbols representing primary and secondary targets, and checkpoints.

KNOWN GROUND THREATS (Desirable): Symbols representing the location of a priori known ground threats.

MISSION BRIEFING DATA (Desirable): Additional a priori information such as weather, ground threats and their effective envelopes, rendezvous points, as well as target and checkpoint locations. (These additional data are currently entered manually as part of the mission briefing on the hand-held chart or data card.)

TERRAIN AVOIDANCE

Empirical evidence from flight testing of the A-6A display and from flight simulation studies of other displays (McGrath et al., 1964; Soliday and Milligan, 1967) demonstrates that display formats which combine pictorial status information (about the vertical situation) and symbolic command information are effective in low-altitude, high-speed flight. (Ketchel and Jenney, 1968.) Table 5 is a summary of terrain avoidance (TA) information requirements specified by Ketchel and Jenney, 1968, which are defined below.

TABLE 5. TERRAIN AVOIDANCE INFORMATION REQUIREMENTS

PRIMARY	
TERRAIN ANGLE/ALTITUDE (referenced to flight path)*	Mandatory
TERRAIN RANGES*	Mandatory
VERTICAL DISTANCE/CLEARANCE TO TERRAIN*	Mandatory
AZIMUTH OR HORIZONTAL DISPLACEMENT OF TERRAIN (referenced to flight path)**	Mandatory
FLIGHT PATH	Mandatory
AIRSPEED	Mandatory
PITCH (climb) COMMAND	Mandatory
NAVIGATION STEERING COMMANDS	Mandatory
ATTACK COMMAND	Mandatory

TABLE 5. TERRAIN AVOIDANCE INFORMATION REQUIREMENTS (continued)

SECONDARY	
CLIMB ANGLE	Mandatory
ROLL ANGLE	Mandatory
HEADING AND TURN RATE	Mandatory
ALTITUDE (sea level)	

*Incorporated in pitch command
**Incorporated in terrain perspective

TERRAIN ANGLE/ALTITUDE (Mandatory-TA Only): Indicates the relationship between current A/C position and the elevation of the terrain dead ahead.

TERRAIN RANGE (Mandatory-TA Only): The distance between the A/C and the terrain dead ahead.

VERTICAL DISTANCE/CLEARANCE TO TERRAIN (Mandatory-TA Only): Predicted clearance distance between A/C and terrain if current heading, pitch, and airspeed are maintained.

PITCH (climb) COMMAND (Mandatory-TA Only): Essentially indicates stick movement necessary to negotiate terrain based on the above parameters.

TERRAIN AZIMUTH OR HORIZONTAL DISPLACEMENT (Mandatory-TA Only): Information about the terrain located on either side of the A/C flight path. (Indicates cross-over profile.)

FLIGHT PATH (Mandatory-TA and TF): Predictive vector or symbol denoting impact point if current heading, pitch, and airspeed are maintained.

AIRSPEED (Mandatory-All Phases): A/C airspeed.

NAVIGATION COMMAND (Mandatory-All Phases): Specifies heading angle for desired course and/or targets and checkpoints.

ATTACK COMMAND (Mandatory-Attack Only): Presents target location cue.

CLIMB ANGLE; ROLL ANGLE; HEADING AND TURN RATE (Mandatory-All Phases): In the TA mode they are used to compute A/C current status which will be integrated with terrain parameters to determine appropriate climb command. Ketchel and Jenney, 1968, also specify climb and roll angle as general VSD information requirements.

ALTITUDE (sea level): Indicates A/C and terrain altitude above sea level. Used in the computation of climb command.

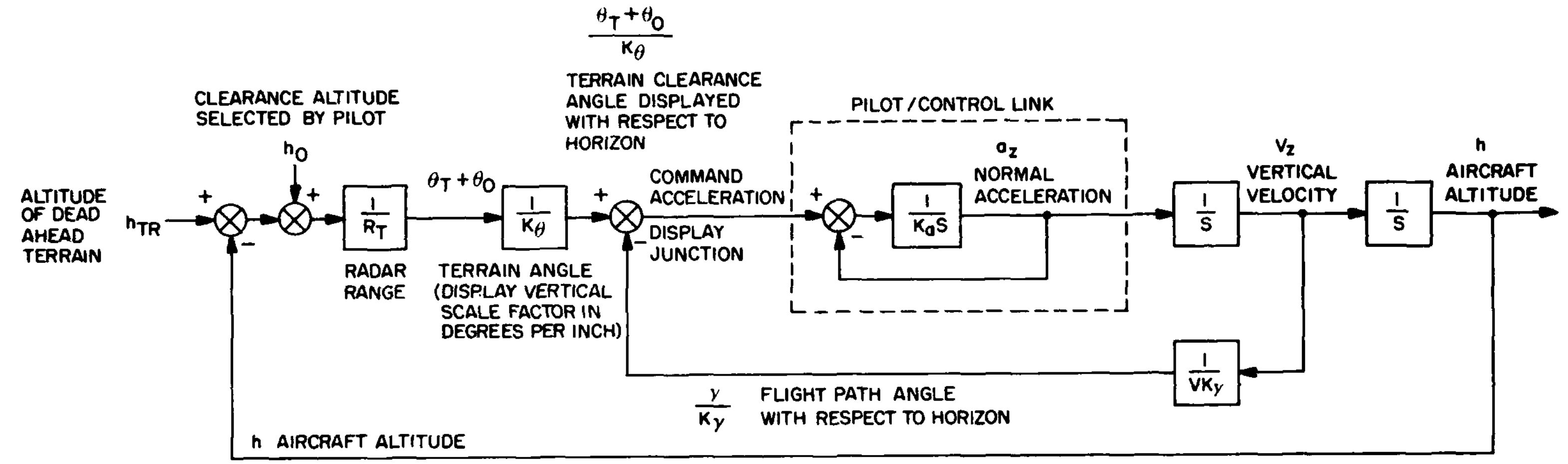
The vertical dimension of a terrain avoidance display should indicate the relationship between flight path and terrain elevation angle. Ketchel and Jenney, 1968, make a strong case for this viewpoint by considering altitude management as a function of the longitudinal control system. "Theoretically, thrust variation provides the ability to change altitude at a constant airspeed, while longitudinal control enables the exchange of kinetic and potential energy." For example, at normal cruise speed for the A-6A, the potential-kinetic energy transfer results in an exchange of 25 feet per knot through a range of approximately 100 knots. In other words, fixed throttle at cruise speeds can result in altitude variations of up to ±2500 feet, which would permit exclusive use of longitudinal control for altitude management in all but extremely rough terrain.

To use the longitudinal control system effectively for altitude control, the pilot's stick movements should relate to his view of altitude status provided by the display. "In other words, the display of terrain elevation with respect to flight path should be vertically oriented in cockpit coordinates, and the rate at which the angle changes should be proportional to control force."

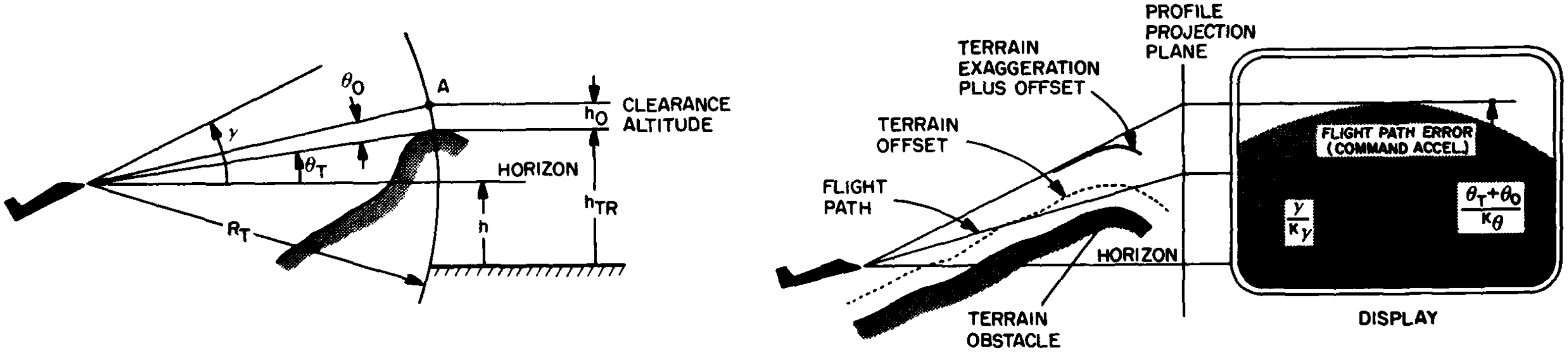
Because control/display relationships for terrain avoidance are inherently complex, Ketchel and Jenney, 1968, derive a closed-loop "servo model" for determining information requirements. Although simplified in nature, their model highlights basic information, symbol scaling, and display format requirements. (See Table 6 and Figure 3.) To this point, we have emphasized the vertical situation in terrain avoidance flight. McGrath et al., (1963, 1964, 1969), however, also stress the importance of continuous geographic orientation. Since terrain avoidance requires frequent heading changes and constant display monitoring (because of the severe penalty for error), it appears necessary to include some navigation information (e.g., course) on the VSD. This additional information will reduce the pilot's need to divide his attention between the TA display (VSD) and navigation display (HSD) to maintain geographical orientation.

TABLE 6. SYMBOL KEY FOR FIGURE 3

hTR	altitude (sea level)
R_T	terrain range "dead ahead"
h_o	offset altitude
h	aircraft altitude
K	display scale factor
γ	climb angle
K_γ	horizon scaling factor
a_z	acceleration
V_z	vertical velocity
V	aircraft velocity



BLOCK DIAGRAM FOR SINGLE RANGE TERRAIN FOLLOWING MODEL



PROFILE FOR TERRAIN FOLLOWING

FLIGHT PATH ORIENTED CONTACT ANALOG TERRAIN DISPLAY

Figure 3. Terrain Following Model and Display
(From Ketchel and Jenney, 1968)

DISPLAY FIELD OF VIEW AND SCALING FOR TERRAIN AVOIDANCE

Vertical

Determination of the field of view (FOV) for terrain avoidance is based upon "down-look" and "up-look" angle. The down-look angle limit and maximum range of the display system should provide coverage sufficient to avoid loss of contact with terrain during pull-up. The vertical FOV is defined by the maximum climb angle and terrain upslope angle. Ketchel and Jenney maintain that instantaneous climb angle and sustained terrain upslope seldom exceed +25 degrees. A maximum down-look angle of -25 degrees would, therefore, be required to maintain visual contact with the terrain during pull-up.

The up-look angle of a terrain avoidance display should provide coverage which identifies dangerous obstacles in relation to aircraft climb performance and g-envelope. For the A-6A, Ketchel and Jenney estimate the angle to be approximately +10 degrees.

A scale factor of 6 degrees per inch on a display with a 6-inch vertical dimension would satisfy the +10 to -25 degree field-of-view requirement derived above.

The total vertical FOV may not necessarily need to be fixed at a depression angle of 10 degrees as the above argument suggests. Since the display is computer-generated, it may normally depict a wings level or aircraft boresighted view and employ depression of the FOV only to null out aircraft climb angle. This would result in a slight improvement in pilot "look ahead" range for level flight and assure that contact was never broken with the ground during short duration climbs. It must be emphasized that this is for short duration climbs ONLY, because it does not represent a TRUE out-of-the cockpit view and might result in disorientation if sustained for more than a few seconds.

Horizontal

When maneuvering around obstacles, the pilot needs as wide a horizontal field of view as possible. The 35-degree FOV, which may be adequate for the vertical situation, would not provide the pilot with many alternatives if applied to the horizontal situation. Ketchel and Jenney, 1968, was the only study that addressed specifications for horizontal FOV and their estimate of 80 degrees is only an educated conjecture (not empirically determined). Updating the terrain map for an FOV of this magnitude may pose formidable problems for the display designers. A 35-degree horizontal FOV may be sufficient, however, if a course indication is provided to the pilot which would direct him to the approximate vicinity (±1/2 mile) of the optimal crossover point. A further aid might be a manual control which would permit the pilot to "step" one-half to one full horizontal FOV to the left or right to gain a "preview" opportunity. Neutral on this control would be boresighted in azimuth to the A/C longitudinal axis.

STATE-OF-THE-ART COMMAND,
CONTROL, AND POSITIONING SYSTEMS

There is a concerted effort in the military today to develop global command, control, and positioning systems. Because of its software orientation, the AETMS may be readily integrated with these systems.

JTIDS

In 1975, a major effort was initiated to develop a digital, secure, jam-resistant communications sytem for real-time update, command, and coordination of combat operations. The Joint Tactical Information Distribution System (JTIDS) will link tactical and air defense systems of all military services. It will provide:

Supplementary threat warning
Jam-resistant communications
Target intercept enhancement
Relative navigation capabilities
Blind NAV bombing capabilities
Current changes in adverse weather conditions

JTIDS is slated to be fully operational by 1984.

AWACS

The Advanced Airborne Warning and Control System (AWACS) is another surveillance, command, control, and communication system. It has the capabilities to detect and track airborne aircraft at any altitude. Several exercises were performed in 1976 to evaluate AWACS' ability to perform surveillance, provide command and control communications, and to operate with extensive airborne and ground ECM. The AWACS reportedly equalled or exceeded all expectations.

GLOBAL POSITIONING SYSTEM (GPS)

Precise, three-dimensional position and velocity information is the goal of the NAVSTAR Global Positioning System (GPS). Currently in the validation phase, the GPS can apparently yield the desired accuracy.

The GPS functions by transmitting a signal to several satellites and calculating the time it takes to return. The user's position can be accurately determined from transmission time and the satellites' positions. If full-scale development is approved in 1978-79, twenty-four satellites should be orbited by 1984 for global coverage.

CONCLUSIONS

Currently documented operational concepts, emphasizing terrain avoidance flight under all-weather, night conditions, contain critical mission segments which appear to significantly tax the capabilities of contemporary cartographic information displays. The possibly severe limitations of these information sources may result in unacceptable levels of pilot/navigator workload, loss of mission effectiveness, and inability to carry out the required profiles at an acceptable risk. This problem will be compounded by the interfacing of global C^3 systems, and multiple information sources which must be integrated both physically in the cockpit and cognitively by the pilot. The Airborne Electronic Terrain Map System offers the Air Force a beneficial solution to these deficiencies in operational capability.

The AETMS, because of its programmable format selection, affords the aircrew member either forward-looking or downward-looking perspective displays of terrain relief information. This permits optimizing the transfer of cartographic data in terms of both perspective and area displayed, based on the requirements of the specific mission segment being accomplished. As a computer-generated display, the AETMS offers a simple and direct approach to integrating JTIDS or other external information sources. Further, because of the realistic, perspective display capability, correlation of terrain relief information and on-board passive sensor (e.g., FLIR) information is greatly facilitated. A novel application of the AETMS, that may prove to be of immense benefit to the tactical pilot, is the capability to perform inflight route preview or "look-ahead"; this may be of particular importance in selecting weapon delivery tactics, responding to inflight mission diversions, transitioning from loiter to penetration segments, or choosing egress routes. The continued development of the AETMS by the Air Force Avionics Laboratory will enhance the technology base applicable to terrain avoidance flight and provide a strong increase in weapon systems capabilities to perform such missions.

APPENDIX

This Appendix contains author abstracts for 37 documents considered to be relevant to further development and refinement of the Airborne Electronic Terrain Map System or which reflect the state of the art for airborne map displays.

All references relating to display specifications that are cited in the main body of the report are included.

Bate, A. J., April 1967, A Comparison of Cockpit Warning Systems, AMRL-TR-66-180, Aerospace Medical Research Laboratory, Aerospace Medical Division, Wright-Patterson AFB, OH.

This experiment was designed to compare three types of aircraft cockpit warning systems: (1) Visual: malfunctions simultaneously activated a master warning light and a specific malfunction indicator light. (2) Visual and Tone: malfunctions simultaneously activated an intermittent sweeping tone (through earphones), a master warning light, and a specific malfunction indicator light. (3) Visual and Voice: malfunctions simultaneously activated a master warning light, a specific malfunction indicator light, and a voice recording which informed the operator through his earphones of the specific malfunction needing attention. Three groups of 11 university students served as subjects. While responding to a visual, visual-tone, or visual-voice warning system, each subject was also required to find and position, under cross hairs, a series of strategic targets on a strip of rear-projected aerial photographic imagery. No statistically significant differences among the three warning systems were found in the speed of reaction to the master warning light, reaction to the specific-indicator panel, total reaction time, or number of strategic targets found or missed. The results of this study suggest that the addition of either a tone or a voice warning to a visual, master plus specific, malfunction warning system is of questionable value in a "head-in" cockpit situation where the visual system can be seen. In situations where a more complex response is required, or where the pilot's attention is required outside the cockpit, the addition of an aural signal to the visual system may be an advantage or in some instances mandatory. The data from this experiement do not suggest that a voice warning system has any advantage over a simple aural signal for augmenting a visual system.

Birt, J. A., and H. L. Task, September 1973, Proceedings of a Symposium on Visually Coupled Systems: Development and Applications, AMD-TR-73-1, Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH.

This first VCS symposium was sponsored by the Air Force Systems Command's Aerospace Medical Division (AMD) at Brooks AFB, Texas, and by AMD's laboratory which has promoted Air Force VCS development and application work, the Aerospace Medical Research Laboratory from Wright-Patterson AFB, Ohio. Participants and papers from DOD agencies and industry brought together the major VCS ideas as of November 1972,

Burton, G. T., and B. R. Clay, December 1977, HHSD Demonstration Model Development, RCA, Government Systems Division, Automated Systems, Burlington, MA.

This final report summarizes the status of the Holographic Horizontal Situation Display effort. This program's objective was the development and optimization of the techniques and hardware required to demonstrate a bright, high-contrast, annotatable, multicolor display. Display hardware with a CRT, tape transport, and source tapes was developed that demonstrates the characteristics of the focused image holographic storage technique as applied to the annotated moving map display requirement of the HHSD application of the AIDS program.

Carel, W. L., M. L. Hershberger, J. A. Herman, and J. J. McGrath, March 1974, Design Criteria for Airborne Map Displays, Vol. I: Methodology and Research Results; Vol. II: Design Criteria, 731101, Hughes Aircraft Co., Culver City, CA.

This is the final report of research conducted under ONR Contract N00014-71-C-0070, NR 213-075, entitled "Development of Design Criteria for Projected Map Displays." The work accomplished is reported in two volumes. Volume I describes the methods used to develop the design criteria and the results of the surveys, analyses, and experimental research conducted in the course of the program. Volume II consists of the statement of the design criteria.

Casella, J. R., H. Waruszewski, J. Reising, F. Kniess, J. Churchwell, and W. Pearson, June 1977, Joint Tactical Information Distribution System (JTIDS), Standard Symbology Phase I, Cockpit Display Presentation Formats and Flight Test Symbol Set, ASD/AES.

The proliferation of symbology for Electro-Optical (E-O) displays used in aircraft is a continuing problem. The Symbology Standardization Committee was established to derive a single set of standard symbols for Air Force aircraft JTIDS displays. This report documents the Phase I effort, "Paper Study and Analysis," of the committee and contains the symbol set recommendations and associated hardware requirements necessary for the JTIDS flight test. The Phase II effort, "Simulation and Flight Test," will involve extensive investigation of proposed symbols in order to establish a military stand for JTIDS.

Chiles, W. D., G. A. Ellis, and A. H. Roscoe, February 1978, Assessing Pilot Workload, AGARDograph No. 233, A051587, North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development.

The assessment of levels of pilot workload associated with the various phases and subphases of flight is important in the design, development and evaluation of aircraft handling qualities and of display and guidance systems. This AGARDograph, written primarily for flight test engineers and pilots, is intended as a guide to the different methods available for estimating workload and, in particular, to those techniques suitable for use in aircraft. An introductory chapter briefly reviews the various concepts and classifications of workload; the former tend to fall into two main areas: those related to workload as task-demands and those related to workload as pilot-effort. In Chapter 2, subjective assessment, at present the most used method, is discussed from the viewpoint of the test pilot. Physiological methods in general are reviewed in Chapter 3, with those techniques available for use in flight being discussed in more detail. Chapter 4 describes various objective methods and presents examples of their practical application. Whereas the methods in Chapter 2 and 3 are appropriate only to workload as effort, objective methods contain techniques appropriate to workload as task-demands as well as to effort. The former techniques are particularly valuable for providing data which can be used to construct models and to predict levels of workload. Different modeling techniques will be discussed in a proposed supplement entitled Engineering Methods.

Colgan, A. R., M. Jasper, P. A. DuPuis, G. W. Scott, and W. K. Pratt, January 1973, Integrated Cockpit Display System, AFAL-TR-73-50, Air Force Avionics Laboratory, Wright-Patterson AFB, OH.

This report contains the design analysis to determine the feasibility of an integrated cockpit display system, tailored to the 1975-1980 time period. Emphasis has been placed on the emerging requirements for new technology and subsystems beyond 1980. A series of sequential analyses for combat mission definition, aircraft performance, information requirements and cockpit configuration provides the baseline for dynamics, contents, and format. A basic system consisting of a dot matrix display functioning as a vertical situation display and a complete set of digital drive and processing hardware and software was used along with typical sensor output characteristics to develop a Part I Functional Specification. The results of this study will help to promote the advancement of technology in the evaluations of a digital avionics system for future aircraft.

Crawford, N. W., August 1977, Low Level Attack of Armored Targets, AD A054186, P-5982, The Rand Corp.

The proliferation, redundancy, and diversity of Soviet surface-to-air defenses, especially in defense of the battle area, severely limit the air space in which tactical aircraft can operate effectively and survive. Further complications arise when the scenario is Central Europe where weather and terrain play an important role.

Improvements in survivability may be gained through aircraft performance, ECM, penetration aids, and tactics. In the context of Central Europe, the latter method of improvement is explored. Low-altitude penetration and weapon delivery, with the requirements it places on defense penetration, navigation, target acquisition, munitions and training, is discussed.

Dunlap, D. F., C. B. Jeffrey, W. L. Polhemus, L. V. Ursel, E. H. Bolz, R. G. Schmidt, and E. Krug, October 1968, Computer-Display Feasibility Study for Flight Performance Optimization, AFFDL-TR-68-125, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, OH.

An airborne computer-display system is developed for the purpose of flying vertical plane optimum flight paths. System requirements are specified by first examining mission requirements, then operational requirements, and finally state-of-the-art constraints. The system is designed to provide command information for flying minimum time and fuel transition maneuvers, and maximum range and endurance cruise maneuvers. Optimal command data are derived, in the computer, from a series of stored profiles which reflect both the aircraft drag configuration and ambient weather conditions. System feasibility is demonstrated through a system description which consists of state-of-the-art computer and display equipments. A digital computer is shown to be more accurate, compact, and flexible than a comparable analog system. Displays consisting of an attitude director indicator, a flight profile indicator, and Mach number and altitude indicators are suggested for presenting command information. Final system size and weight are less than one cubic foot and fifty pounds, respectively. The system is tentatively developed for the F-104C, a contemporary aircraft for which a reasonable amount of optimum performance data is available. The system seems more applicable to developmental aircraft of the present era, however.

Egan, D. E., and J. E. Goodson, April, 1978, Human Factors Engineering for Head-Up Displays: A Review of Military Specifications and Recommendations for Research. Naval Aerospace Medical Research Laboratory, Naval Air Station, Pensacola, FL.

This report is a review of Human Factors literature and military specifications concerning Head-Up Displays (HUDs). The objective is to identify important categories of Human Factors research concerning virtual-image displays. These research categories are questions that must be answered before specifications can be written for the optimal design of HUDs.

The review encompassed an exhaustive list of references available through the Defense Documentation Center (DDC) as well as other pertinent sources not given in the DDC listing. Each requirement in the General Specification for Head-Up Displays, MIL-D-81641(AS), was compared with the available data. The data base for requirements and the importance of further research concerning each requirement were qualitatively rated. Categories of necessary research were established.

Human Factors knowledge has not kept pace with the proliferating uses of HUDs and the expansion of HUD technology. Consequently, the majority of existing Human Factors specifications for HUDs are based on expert opinion rather than empirical data. Several categories of research are required to provide an adequate data base for future specifications, and to understand how specific issues in the design of HUDs affect performance.

Flight Dynamics Control Research, December, 1963, Technology for Information Presentation, Part IV, Color Coding, ASD-TDR-63-000, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson AFB, OH.

This report describes efforts on use of color coding and distinctive markings in display design completed by Ritchie, Inc., under United States Air Force Contract AF 33(657)-10225. Major emphasis was placed on the color coding technique. In order to accomplish the objective of the Contract, which was to develop basic criteria to govern the use of color coding and distinctive markings on displays, four study programs were completed. These were (1) review of the use of color on present and proposed displays, (2) review of experimental and design literature, (3) development of the basic criteria for code selection and use of color coding, and (4) development of uses of color coding on displays and display panels.

Frajola, W. J., and S. M. Soliday, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. I, Part VI, Biochemical and Psychophysiological Analyses of Pilots' Responses to Stresses of Simulated Low Altitude, High Speed Flight. SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

Sixteen Air Force jet pilots were subjects in simulator tests of an E^2-type* terrain-following display, an Autonetics head-up display (HUD) and a Sperry Gyroscope Company HUD. Four pilots were tested with the E^2 display and six each with the Autonetics and Sperry displays. Biochemical parameters were measured before and after flights made at relatively high and relatively low acceleration intensity levels, and psychophysiological parameters were measured during these flights to determine the effects of the acceleration stresses on these parameters. Overall results showed that VMA (vanilmandelic acid) excretion increased from beginning to end of the

*The E^2 display provided altitude versus range and/or altitude versus airspeed graphic information.

flights made at the high acceleration intensity level. Respiratory rate increased from beginning to end of the flights, with greater increases occurring in the flights at the high acceleration intensity level.

Hanson, T. G., D. Jones, A. J. Macek, G. L. Peters, and J. H. Sanvig, July 1978, Research on Visual Display Integration for Advanced Fighter Aircraft, AMRL-TR-78-118, Aerospace Medical Research Laboratory, Aerospace Medical Division, Wright-Patterson AFB, OH.

The objective of this study is to develop and demonstrate a method for integrating displayed information in an advanced fighter aircraft. The study is limited to air-surface missions against an attacking mobile force in central Europe in the post-1985 time period. This report:

- Describes the method
- Illustrates, by example, the method
- Suggests a procedure for carrying the paper-and-pencil analysis results into simulation and modeling for further refinement of the integrated displays.

The basic idea of the paper-and-pencil method is to perform a detailed sequential analysis of the steps an aircraft crew performs during specific missions. Three missions were examined:

- Deep strike
- Battlefield interdiction
- Close-air support

Mission definitions, information on a baseline cockpit (F-16), and flying procedures are described in the report.

The sequential analysis of F-16 pilot mission procedures led to the discovery of aspects of F-16 cockpit design that made mission procedures difficult or awkward. These discoveries led to ideas for design improvement, generally by integrating displays. These design improvements were combined into a second cockpit. This advanced cockpit was analytically compared with the F-16 to determine relative strengths and weaknesses.

At this stage of the design process, additional simulation and modeling activities are recommended. A computer model of the aircraft performance can be used to design a simulation to determine the best combination of cockpit features. The simulation results will give a clearer definition of important design parameters and suggest further improvements. Simulation is part of a larger technique that assesses the importance of recent design improvements and indicates the benefits of further improvements.

Hitt, W. D., H. G. Schutz, C. A. Christner, H. W. Ray, and J. L. Coffey, September, 1960, Development of Design Criteria for Intelligence Display Formats, RADC-TR-60-201, Rome Air Development Center, Air Research and Development Command, Griffiss Air Force Base, NY.

The objective of the research program was to develop design criteria for intelligence display formats to be used in the Samos system. To meet this objective, the following five experiments were conducted:

1. A comparison of vertical and horizontal arrangements of alphanumeric material
2. An evaluation of formats for trend displays
3. An evaluation of methods for presentation of graphic multiple trends
4. An evaluation of five different abstract coding methods
5. An evaluation of the effect of selected combinations of target and background coding on map-reading performance

Huizar, N. R., and C. H. Ulrich, June 1976, Tactical and Night Operations Flight Maps, FM 231B, Headquarters, TCATA (TCATA-CSS-SE), Fort Hood, TX.

FM 231B was an evaluation of the utility of four experimental maps and two standard maps for tactical and night flight operations. Relative preferences of Army aviators regarding format and symbology of maps were also evaluated. The maps were used to plan and execute day and night low-level (LL), nap-of-the-earth (NOE), and cross-country operations. During night use, the maps were viewed under red light and with night vision goggles (AN/PVS-5). Aviators found the 1:50,000-scale air movement data map to be the best overall map for planning and flying tactical operations. For day and night cross-country flying, all tested maps were suitable. For night LL and NOE flying, none of the maps were found to be suitable. None of the 1:50,000-scale maps could be effectively read when using the night vision goggles. The aviators preferred the maps printed on white paper to those printed on black paper. More writing and legibility problems were experienced with the black maps than with the white. It was found that none of the maps could be used for night terrain flying if ground features were not adequately illuminated. Continued product improvement for the 1:50,000-scale air movement data map was recommended.

Ketchel, J. M., and L. L. Jenney, May 1968, Electronic and Optically Generated Aircraft Displays: A Study of Standardization Requirements, Janair Report No. 680505, U.S. Navy, Office of Naval Research, Washington, D.C.

This study reviewed and analyzed the research literature relating to electronically and optically generated aircraft displays. The purpose was to provide background information to support standardization of such displays for military aircraft. The scope of the inquiry was limited to vertical and horizontal situation displays, either of the direct-view or projected (head-up) type, used by the pilot for aircraft and mission control. The results have been set forth under three major headings:

1. Information Requirements--a synthesis of 16 system studies and 11 current display designs to determine the basic information content necessary for general flight and certain special missions
2. Symbology--an evaluation of research findings dealing with static and dynamic symbol characteristics and display format
3. Display Characteristics--a delineation of optimum visual characteristics of displays in relation to the use and the techniques of image generation

The report also contains an extensive bibliography and specific recommendations for additional research.

King, R. C., R. W. Wollentin, G. Gottelman, and C. A. Semple, August 1970, Electroluminescent Display Legibility Research and Development, AFFDL-TR-70-89, Air Force Flight Dynamics Laboratory, Research and Technology Division, Wright-Patterson AFB, OH.

Human factors and engineering design data have been developed which permit evaluation of electroluminescent (EL) displays for use in the aircraft cockpit. Display techniques have attempted to allow comfortable readability and useful operating lifetimes under ambient illumination conditions from darkness to 10,000 foot-candles. This was accomplished by a simulator study of state-of-the-art EL displays, followed by design and construction of improved displays in keeping with legibility requirements.

Mazza, J. D., September 1977, A Comparison of Integrated and Conventional Cockpit Warning Systems, Master's Thesis, Naval Postgraduate School, Monterey, CA.

An experiment was performed in which seventeen subjects responded to warning signals presented on displays simulating integrated and conventional aircraft cockpit warning systems. Performance using the conventional system was superior in terms of both mean reaction time and number of errors committed.

McGrath, J. J., and G. J. Borden, November 1963, Geographic Orientation in Aircraft Pilots: A Problem Analysis, Technical Report 751-1, Human Factors Research, Inc., Los Angeles, CA.

The research reported in this document represents the initial phase of a research program whose ultimate goal is to identify the factors that produce geographic disorientation in aircraft pilots, and to develop a body of empirical data relevant to the design of navigation displays and aeronautical charts.

McGrath, J. J. (Ed.), Geographic Orientation in Air Operations, 101-1, Proceedings of Symposium, Nov. 18-20, 1969, Joint Army-Navy Aircraft Instrumentation Research Program.

This document records the proceedings of a symposium on geographic orientation of aircraft pilots during various phases of air operations. The meeting was attended by over 200 experts in fields of technology related to the development and use of aeronautical charts and map-display systems for manned aircraft. The principal topics of the symposium were user requirements, cartographic developments, map-display design, CRT/map displays, human factors and systems analysis studies, cartographic support of map displays, and field evaluations of map displays.

The recorded proceedings include the manuscripts of a keynote address and 30 technical papers, edited transcripts of the discussions that followed the papers, summary reports of five special discussion groups, a special report of JANAIR research in this field, an overview of the symposium proceedings, and a directory of the participants.

Milligan, J. R., and S. M. Soliday, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. I, Part V, Prediction, SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

Sixteen Air Force pilots served as subjects in simulator evaluations of terrain-following displays. In making the evaluations, each subject took part in two experiments which presented different test conditions. Before beginning their tests, the pilots flew several training flights. One of these flights included a series of basic instrument maneuvers called a "Pattern B" which was used to establish performance baselines. Each pilot's absolute altitude error scores made during the terrain-following flights of the first experiment were averaged to give his terrain-following altitude error score for that experiment, and a similar average was calculated for the second experiment. Absolute altitude errors were also calculated for each pilot's Pattern B flights. The Pattern B scores for each pilot were then correlated with his average terrain-following error scores for the first and second experiments. The correlation of the Pattern B scores with the scores of the first experiment was +.735 ($p < .001$), and the correlation of the Pattern B scores with those of the second experiment was +.704 ($p < .001$). Comparisons of actual and predicted terrain-following error scores revealed an average prediction error of 8.4 percent for the first experiment and 9.2 percent for the second. The correlations indicate that a pilot's ability to maneuver while cross-checking basic instruments can be used to predict his ability to track a terrain-following command signal with a fairly high degree of accuracy.

Mills, G. S., M. A. Grayson, R. A. Jauer, and S. L. Loy, 1978, *Research on Visual Display Integration For Advanced Fighter Aircraft*, AMRL-TR-78-97, Aerospace Medical Research Laboratory, Aerospace Medical Division, Wright-Patterson AFB, OH.

This "Visual Display Integration" study was conducted to determine the display integration options projected as available for inclusion in an attack/fighter aircraft crew station design in the 1985-1990 time period. A second objective was the definition of an evaluation framework that would permit evaluation of the selected display options during future related studies.

Summarizing the results, it is clearly evident that the CRT, as Option 1, will retain its preeminence as the multifunction display unit for 1985-1990. Option 2 is the flat-panel plasma display, Option 3 is the flat-panel liquid crystal display, and Option 4 is the electroluminescent thin film-transistor display. It was concluded that man-in-the-loop simulations provide the best opportunity for evaluating these display options in future related work.

The rapid development of on-board computational capability has provided the aircraft crew station designer with the opportunity to present pilot information in varied quantities and formats. Increased complexity of the projected missions, weapons delivery, and aircraft systems has prompted a strong effort to provide better information and control to the weapons systems managers (the flight crews) via a fully integrated cockpit. The selection and implementation of the display system are fundamental to the realization of this important goal: a fully integrated crew station that provides low-workload, efficient control of the weapons system, thereby enhancing the probability of mission success and survival.

Potash, L. M., and T. E. Jeffrey, January 1978, *Factors in Design of Hardcopy Topographic Maps*, Technical Paper 284, Army Research Institute for The Behavioral and Social Sciences, Alexandria, VA.

A literature survey of factors in map design, including visual coding techniques and assessment techniques, is summarized in this report, as the first step in improving legibility and usefulness of hardcopy (printed) topographic maps.

Map design determinants are scale, interrelatedness of symbols, and a body of standardized symbols and modes of coding. Map scale influences fidelity, as small scale requires selection, simplification, and magnification of features. Clutter can be reduced by coding to differentiate information: color coding aids in identification and reduces location time; iconic and alphanumeric shape coding can be learned easily and are flexible; size coding requires considerable space and increases location time.

Among map assessment techniques, opinion sampling is relatively inexpensive but does not measure actual performance, and theoretical analysis is a limited first step only. Empirical analysis measures performance with the map product, either by assessing performance directly or by measuring the map-reading skills which underlie performance.

In comparisons of different types of hardcopy topographic maps, the best photo-based maps produce performance comparable to that with conventional line maps. Some Army users preferred to augment contour lines on conventional maps with layer tints for interpreting topographic relief. Future airborne map displays should consider the information requirements of pilots, effects of vehicle movement, and map legibility in poor light.

Semple, C. A., Jr., R. J. Heapy, E. J. Conway, Jr., and K. T. Burnette, January 1971, Analysis of Human Factors Data for Electronic Flight Display Systems, AFFDL-TR-70-174, Flight Dynamics Laboratory, Wright-Patterson AFB, OH.

This report presents the results of a review of 1,178 technical documents dealing with human factors considerations in electronic flight display systems. Design-oriented human factors data are presented for the following families of design considerations: display size, information coding, alphanumerics, scale legibility, visual acuity, display system resolution, flicker, contrast ratio requirements, and environmental variables including ambient illumination, vibration, and acceleration. Quantitative, design-oriented functional relationships are emphasized. Research recommendations are made where existing data were found inadequate for design use. A model is presented for organizing the variables impacting upon human performance as a function of electronic flight display system design.

Smith, H. A., and C. Goddard, May 1967, Effects of Cockpit Lighting Color on Dark Adaptation, AFFDL-TR-67-56, Air Force Flight Dynamics Lab, Air Force Systems Command, Wright-Patterson AFB, OH.

The report is addressed to the general problem area of the effects of color of illumination on early dark adaptation. An analysis of the relevant published literature is presented as it relates to the relative benefits of red cockpit lighting as opposed to white or other colors for night flying. A report of a demonstration which compared the effects of green and white lighting to red lighting on subsequent early dark adaptation is included. An annotated bibliography of the literature reviewed for the report is also presented. A systems approach to cockpit illumination is stressed.

Soliday, S. M., and J. R. Milligan, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. I, Part I, Evaluation of an E^2 Terrain-Following Display, SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

An E^2-type terrain profile display was evaluated as an aid to the pilot in simulated low-altitude high-speed terrain-following flight. The NAA-Columbus four-degree-of-freedom flight simulator was used. An aircraft representative of the RF-4C was programmed as the test vehicle by analog computers associated with the simulator. Four Air Force pilots made a total of 120 half-hour flights under various terrain, airspeed, turbulence, clearance altitude, and visibility conditions. The pilots' tasks during the flights were to maintain a given clearance altitude and heading at all times. The results revealed that terrain-following performance was as efficient without the E^2-type display as with it. Pilot opinion supported this finding, although some of the pilots felt that it could be useful as a secondary display if certain changes were made. General findings were that terrain-following efficiency varied with type of terrain, airspeed, visibility, and turbulence, but not with clearance altitude. Navigation was unaffected by any of the experimental conditions. Heart and respiration rates were within normal ranges for the types of tasks involved. Recommendations for alternate designs of E^2 displays are given in this report.

Soliday, S. M., and J. R. Milligan, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. I, Part III, Evaluation of a Sperry Head-Up Display, SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

A prototype Sperry Gyroscope Company Head-Up Display (HUD) was evaluated in simulated low-altitude high-speed terrain-following flight. The NAA-Columbus four-degree-of-freedom flight simulator was used. An aircraft representative of the RF-4C was programmed as the test vehicle through analog computers associated with the simulator. Six Air Force pilots made a total of 186 half-hour flights under various terrain, airspeed, turbulence, clearance altitude, and visibility conditions. The pilot's tasks during the flights were to maintain a given clearance altitude and heading at all times. The results showed that the pilots flew slightly better with the HUD than they did with conventional in-cockpit instruments, and that they maintained heading better with the HUD than without it. The pilots preferred the HUD to the in-cockpit instruments although they felt that numerous improvements could be made to the HUD. Heart rates were generally lower with the HUD. General findings were that terrain-following efficiency varied with type of terrain, airspeed, visibility condition, and clearance altitude, but not with turbulence. Navigation efficiency was affected only by the type of terrain-following display used. Heart rates varied slightly with airspeed and respiratory rates slightly with turbulence. However, all heart and respiratory rates were within the normal range for the tasks that were performed.

Soliday, S. M., J. R. Milligan, and R. R. Mourant, February 1967, Simulation of Low-Altitude High Speed Mission Performance, Vol. I, Part IV, Comparison of Three Terrain-Following Displays. Systems Engineering Group, Wright-Patterson AFB, OH.

Three terrain-following displays were evaluated in simulated low-altitude high-speed terrain-following flight. The three displays were (1) an E^2-type terrain-following display used in combination with an ADI command bar, (2) an Autonetics head-up display (HUD), and (3) a Sperry Gyroscope Company HUD. Sixteen Air Force pilots flew a total of 492 half-hour "missions" in a moving-base simulator which had four degrees of motion freedom. Four pilots were tested with the E^2 display and six each with the HUDs. Their primary task during all of the missions was to follow terrain contours at a given altitude, and their secondary task was to maintain a constant heading. Each subject served in two experiments. In the first, simulated flights were made under varied terrain, airspeed, and visibility conditions. In the second experiment, the simulated flights were made under varied conditions of air turbulence, clearance altitude, and visibility. Results of the first experiment showed that standard deviation of altitude error was significantly less for both HUDs than for the E^2 display. There were no major differences in altitude holding capability between the two HUDs. Results of both experiments showed that navigation was significantly better with the Sperry HUD than with the other two displays, and that the Sperry HUD received higher pilot ratings than either of the other two displays. Suggestions for the design of head-up displays based on the performance and comments of the pilots are given in this part of the report.

Soliday, S. M., and J. R. Milligan, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. II, Effectiveness of a Head-Up Display for Takeoff and Landing in a Fighter Aircraft, SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

A head-up display (HUD) was evaluated in simulated takeoff and landing using the NAA-Columbus four-degree-of-freedom moving-base flight simulator. An aircraft representative of the RF-4C was programmed as the test vehicle on analog computers associated with the simulator. In making a test flight, a pilot "took off" from one airfield in VFR conditions, encountered IFR conditions a short time after taking off, and flew to a second airfield in IFR conditions. He made an instrument approach and "landed" at the second airfield under various amounts of visibility restriction. Test flights were made with either the HUD or with conventional in-cockpit instruments, including the widely used instrument landing system (ILS) glide slope and course deviation indicators which were on the attitude direction indicator (ADI). The HUD was also tested under different turbulence conditions. Six Air Force pilots flew a total of 144 test flights. The results showed that the pilots approached and landed as well with the HUD as with the ILS, and that they approached and landed equally well with the HUD under the different visibility and turbulence conditions despite a lack of previous experience with the HUD. In fact, half the pilots preferred the HUD to the ILS. However, all of them made many suggestions for improvement of the configuration that was tested. Recommended design changes based on these suggestions are included in the report.

Soliday, S. M., and J. R. Milligan, February 1967, Simulation of Low Altitude High Speed Mission Performance, Vol. III, Evaluation of Navigational Displays in Terrain-Following Penetration Missions, SEG-TR-66-67, Systems Engineering Group, Wright-Patterson AFB, OH.

Realistic low-altitude high-speed tactical missions were simulated to provide a context for testing prototype terrain-following and navigation displays. The NAA-Columbus four-degree-of-freedom moving-base flight simulator was used. Aircraft representative of the RF-4C and the F-111 were programmed as test vehicles by analog computers associated with the simulator. Twelve Air Force pilots flew a total of 108 one and one-half hour missions. The pilots' tasks in the missions consisted of terrain-following; navigation, including checkpoint and target identification; correction of equipment malfunctions; and weapon delivery. Missions in which terrain-following was controlled by an autopilot were also simulated. Results showed that a head-up display of terrain-following information was generally superior to an in-cockpit display of the same information, and that a navigation display based on inputs from an inertial guidance system was superior to the conventional manner of displaying dead reckoning navigation information. The missions were flown sucessfully in both aircraft, but the representative RF-4C was superior to the representative F-111 in the most difficult flight conditions. Efficiency of pilot response to autopilot failure varied with environmental conditions such as terrain, airspeed, and visibility. Fatigue was not a great problem during the mission, although it did occur. The pilots generally had a high regard for the prototype displays, although they felt that many improvements could be made. Suggested improvements to the displays based on the pilots' comments are made, and future research is suggested.

Somers, P., and R. G. Pachella, February 1977, Interference Among Sources of Information in Complex Integrated Displays, 014523-1-T, The University of Michigan, College of Literature, Science and the Arts, Ann Arbor, MI.

The successful representation of complex information in a multidimensional display depends on the knowledge and exploitation of naturally occurring interdimensional relationships. Sets of dimensions vary in separability, the extent to which the perception of each dimension is independent of co-occurring dimensions. Nonseparability due to integrality among dimensions is distinguished from nonseparability due to masking and distraction. Intregrality may result from two separate types of dimensional relationships: combination and interaction. Combination can be isolated from interaction using filtering tasks with no speed stress. A method for measuring combination by requiring filtering in a similarity judgment task is developed and a demonstration experiment is presented.

Tamburino, L. A., December 1977, Airborne Electronic Terrain Map Display System, AFAL-TR-77-232, Air Force Avionics Laboratory, Wright-Patterson AFB, OH.

This report presents a new type of airborne terrain map and terrain avoidance system being developed at the USAF Avionics Laboratory. The system is completely adaptable to an aircraft's state vector and can be used without any externally radiating components such as radar. The system is based on polynomial surface modeling and uses low-cost, high-density mass memories for storing the polynomials. This report covers the mathematical fundamentals, hardware implementation, and real-time application of the system. A detailed description is given of two terrain displays being studied at AFAL: contour displays and true perspective graphic displays. Other terrain map applications include terrain following and navigation, flight simulators, RPV control and guidance displays, and enhanced radar displays.

Walchli, R. M., July 1967, Head-Up Display Review, Doc. No. F044-7U1. Bunker-Ramo Corporation, Defense Systems Division, Canoga Park, CA.

This report summarizes the work accomplished under Contract Task No. 2.1, Head-Up Display Search and Analysis. Reference sources searched consisted of the Flight Dynamics Laboratory Control Display Information Center (CDIC) and the facilities of the Defense Documentation Center. Task 2.1 was accomplished to provide background information preparatory to the initiation of a planned head-up display development effort. The report contains a brief historical review of the development of head-up displays, identifies areas requiring further research, and presents, as an Appendix, an annotated bibliography of the literature reviewed.

Wasicko, R. J., D. T. McRuer, and R. E. Magdeleno, December 1966, Human Pilot Dynamic Response in Single-Loop with Compensatory and Pursuit Displays, AFFDL-TR-66-137, Air Force Flight Dynamics Lab, Wright-Patterson AFB, OH.

The primary purpose of the experimental series reported here is to investigate, on a preliminary and exploratory basis, human operator performance differences between pursuit and compensatory displays. For each display type, a wide range of forcing function bandwidths and controlled element dynamics was used. The effect of the additional information provided by separately displaying both forcing function and controlled element output (pursuit), rather than their difference (compensatory), was evaluated using the mean-squared error and a quantity called the "effective open-loop describing function" ($Y\beta$).

As a prelude to the new data, past pursuit/compensatory tracking results are reviewed, and then a tie-in is made between these and the current series.

Williams, A. C. Jr., M. Adelson, and M. L. Ritchie, A Program of Human Engineering Research on the Design of Aircraft Instrument Displays and Controls, WADC Technical Report 56-526, AD 110424, Wright Air Development Center, Wright-Patterson AFB, OH.

This report outlines a program for research on the human factors in the design of aircraft instrument displays and controls. The effort is intended as a source for the Air Force Integrated Display-Integrated Control Program. It consists of three major approaches. One of these concerns the development of a cockpit for a particular airplane or type of airplane. Another consists in the development of principles of man-machine relations applicable to many types of aircraft. The third approach is that of working with formal conceptual systems which may have some promise of general applicability to the cockpit problems.

Yonemure, G. T., W. N. Benson, and R. L. Tibbott, November 1977, Levels of Illumination and Legibility, NBSIR 77-1306, National Bureau of Standards, Dept. of Commerce, Washington, D.C.

The visibility of tasks encountered in the working world ranges from easy to difficult-to-see objects. The assumption that experiments performed for threshold targets (difficult-to-see) can be extrapolated to higher contrast tasks (easy) was tested. The experiments indicate that threshold level studies should not be extrapolated to suprathreshold levels. The performance of the eye is not the same at the two levels. The threshold function is monotonic; that is, contrast required for detection decreases monotonically as luminance is increased, whereas the suprathreshold experiments result in a function with a minimum or optimum luminance level. Recommendations are made to expand the empirical base from which lighting level recommendations are derived to include the more commonly occurring situation involving visual task performance for suprathreshold tasks.

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