# FIFTH ADVANCED

# AIRCREW DISPLAY
# SYMPOSIUM
# PROCEEDINGS

## 15 AND 16 SEPTEMBER 1981

AT

## THE NAVAL AIR TEST CENTER
## PATUXENT RIVER, MARYLAND

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| P000 672 | Advanced Fighter Technology Integrator (AFTI) F-16 Display Mechanization. |
| P000 673 | Airborne Electronics Colour Displays. |
| P000 674 | Helmet Mounted Display Symbology for Helicopter Landing on Small Ships. |
| P000 675 | Head Up Display Operational Problems. |
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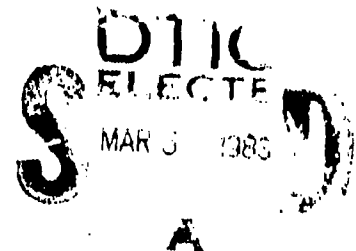
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| 0915 | NAVY POSTURE | Mr. Hal Andrews<br>NAVAIRSYSCOM |

### STATE-OF-THE-ART

Mr. F. C. Hoerner
NAVAIRTESTCEN

| | | |
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LTCOL D. Eliason, USAF

| | | |
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# HUMAN ENGINEERING
## IN
# AIRCRAFT & SYSTEM DESIGN

### PRESENTED TO
### THE US NAVY
### ANNUAL ADVANCED DISPLAY SYMPOSIUM

## by MR. G. ROE
## FUTURE PROJECTS DEPARTMENT

# HUMAN ENGINEERING IN AIRCRAFT AND SYSTEM DESIGN

## 1. Introduction

The last decade has seen a number of aircraft types developed which have implemented developments in engine, aerodynamic, material and avionic technologies to achieve improvements in operational effectiveness. To achieve significant benefits in these areas, the cost in terms of research - design-development has increased at an exponential rate, and this has been reflected in a general decline in the number of operational front-line aircraft. This phenomenon is not unique to the United Kingdom; as Fig.1 shown, the trend is very similar in the United States. This trend has led to the development of the multi-role aircraft concept in which an aircraft is expected to perform both air-air combat and air-ground attack roles in some instances during one mission; this naturally requires all the relevant cockpit display controls for both roles to be installed within the cockpit.

The aircraft which have ultimately achieved service status have also been faced with a daunting array of highly sophisticated ground defences, through which to pass to a target. As an example, Fig.2 shows the capabilities of just three current systems and shows that the only real hope of arriving at the target is to fly at high speed at very low level, thus reducing exposure time.

The cockpit designs which have developed during this period have been based largely on expediency, nearly always with a lack of design lead time, and the increasingly less warrantable assumption that the pilot is adaptive enough to learn how to deal with these even more complex systems.

To make matters worse there has been a parallel trend towards single seat aircraft. The increasing complexity, together with inadequate thought, or time for thought, as to the limits of human ability has led towards the pilot's being literally "saturated" with displays and controls.

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This paper will review historical cockpit development in response to the expanding flight envelope and the need to improve operational effectiveness and will show the impact of this on the number and type of cockpit displays and controls. The paper will then discuss the currently proposed extensions in capability for the next generation aircraft. Discussion will then be directed towards the difficulties these extensions will cause and possible means, such as reclined seats, electro optical displays, digital data transmission etc. which can be used to resolve them. Finally, the paper will take a short look into the future of cockpit display techniques and their possible impacts on cockpit design.

## 2. Historical Cockpit Development

The first identifiable aircraft was the Wright Flyer. The "cockpit" contained only two levers, one for rudder/wing warp, the other for elevator. This simple layout was acceptable as the pilot's task was simple - "Stay aloft as long as possible". This degree of simplicity did not remain; as the quest for increased performance grew, monit- oring/control of the very fickle engine became as important as con- trol of the flying surfaces and this led to the introduction of mixture controls, igniter, pressure, rpm and fuel flow displays - the "rot" had started.

By the start of the First World War, the now commonplace layout of the cockpit had developed - the pilot seated upright, a central joy-stick, the throttle mounted on the left, and prime displays reflecting the aircraft's systems. An example of the First World War cockpit is that of the SE5A, and this is shown in Fig. 3. The SE5A's major role was that of air defence/air combat. The pilot's data assimilation task was relatively simple, with indications of speed, height, heading and rpm being presented in the cockpit, but the increasing speed and altitude had dictated the need for special clothing, helmets, padded jackets, goggles and scarf ! As the aircraft of the 1920/30's developed and expanded, the flight envel- ope physiological problems began to appear. One such problem was disorientation caused by conflicting sensory information.

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During the early 1940's this prompted the development by two RAF
Officers, Reid and Johnson at RAE Farnborough, of the blind flying
panel (Fig. 4). This panel is located directly in front of the
pilot, below the coaming, to allow the pilot to move his attention
rapidly between the vital displays and outside world and this led
to the moving of other displays into the pilot's peripheral field
of view. The Spitfire cockpit (Fig. 5) is typical, with the blind
flying panel in the centre and gyro etc., to the left. During
World War II more sophisticated operational equipment also came
into service, such as gyro gun-sights, air-to-ground/air-to-air
communication. All of these required their own displays and
controls; the cockpit was quickly becoming overcrowded.

One would, I think, have expected, with the introduction of the jet
engine at the end of the Second World War, that the fighter cockpit
would simplify quite dramatically, some were convinced that it would.
In fact it did not and the Hunter's cockpit (Fig. 6) illustrates
this point. A most significant innovation was the ruling by the Air
Ministry in June 1947 that all new jet aircraft would have an emergency
ejection seat fitted. Pilots during the early jet age began to
experience regularly the problems of high sustained accelerations,
although the introduction to these problems dated back to the dive
bombers of the Second World War. To combat these problems the
Institute of Aviation Medicine developed the anti 'g' suit, a pair of
trousers which inflate in response to increased 'g' forces thus
restricting the engorgement of the lower body/legs with blood.

Over the next 2½ decades, significant developments in weapon system
complexity took place, together with further extension of the usable
flight envelope. Interceptor aircraft began to make use of radar.
Fig. 7 shows the Lightning's cockpit in which the radar display can be
seen high on the instrument panel, allowing the pilot to transfer his
attention very rapidly between display and the outside world.
Developing electronic technology provided the pilot with the Head-Up
Display; these allowed the pilot for the first time to view the
flight data superimposed on the outside world. Operational effective-
ness was increased by the introduction of laser marked target-seekers,
inertial navigation, electronic counter-measures etc. Each of these

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... required displays and controls, which jostled for position in the cockpit. A ... system offered a significant operational advantage ... at great pressure to install them, despite the ... economic problems.

As an example of a typical aircraft cockpit design of this period, ... the Sepecat Jaguar (Fig. 8). This shows the head-up display ... centre-pointing general flight functions, a digitally-driven moving map display below, flight system displays on the left, and a significant collection of engine and fuel displays. It is clear that cockpits have become very crowded. Also during this period the first operational V/STOL aircraft, the Harrier, entered service. In view of the transitional flight capability of this aircraft, it might be thought that the cockpit would contain many unusual features. As Fig. 9 shows it does not, the only unusual feature being the additional lever on the throttle box. This, when pushed forward, rotates the nozzles aft to accelerate the aircraft forward.

The pilot's attire caused further difficulties during this period. In the U.K. the I.A.M. developed in response to the changing operational situation, various liquid-cooling suits, air-ventilated suits and more up-to-date chemical defence-suits, most of which were introduced into service with various degrees of success, to the dismay of some pilot's who longed for silk scarf days.

Seeing in the early 70's that the growth in cockpit display/controls with all new aircraft was relentlessly taking an increasingly steeper upward trend, various organisations in the U.K. and the U.S. began investigations into ways of reversing this trend. The first aircraft likely to enter service which will have benefitted from these studies are the McDonnell Douglas AV-8B and F18 Hornet. The AV-8B cockpit is shown in Fig. 10. On inspection one will note a Multi-Purpose Display on the left side. This display is a significant step, as it allows the pilot access to such systems as navigation, stores management, via the peripheral keys and displayed legend. It presents, on selection, weapon delivery, navigation and radar warning data. This display is also utilised during routine ground maintenance to display check-lists

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and to control/display the aircraft's built-in test facilities. The important innovation which has allowed the implementation of such a versatile display/controller is digital data transmission, the so-called 'data bus' concept, and it is important to dwell upon this for a moment. Fig. 11 shows a typical implementation. In philosophy the system can be likened to a telephone system by which various subscribers, in this case avionics sub-systems, may be interfaced. The data bus can be structured to operate in a number of different modes (there currently being a topic of intensive studies within the aerospace industry). For this example I will consider a data bus which operates in a command/response mode. In this mode, when a cockpit sub-system requires an action, e.g. a switch change, a status word is changed at the R/T. When the bus controller which continuously monitors the sub-systems reaches the changed status word it interrogates that sub-system to establish when contact can be made. Appropriate contact is established for a defined period of time. On completion of the task the status word is again changed and the bus controller removes the link. This provides a number of obvious system advantages. The most significant in terms of cockpit design is that sub-systems need no longer be linked by point-to-point wiring. This provides the ability to rationalise control panels, reduce switch body sizes and re-configure displayed data in the event of display head or driver failure.

The F.18 Hornet expands the concept of the AV-8B and for the first time has achieved a reversal in the trend towards more and more cockpit displays. Also, as will be seen from Fig. 12, the dedicated flight instrumentation has been relegated to a position low down on the right hand side. This cockpit has three displays; the Master Monitor-Display for presentation of caution/advisory information, air-to-ground weapon delivery and management, built-in test and navigation mode selection; the Multi-Function Display which presents radar, aircraft altitude and pertinent sensor or tactical data. Both of these displays provides a back-up for the other in the event of failure. The third is a Horizontal Situation Display which shows moving map and other short and long term navigation data.

At this point, let us summarize the theme of the paper. Since the

early days of flight the answer to the increasing sophistication of ground defences and the requirement for increased mission effectiveness has been to increase the displays and controls within the cockpit. Fig. 15 illustrates this growth. If this trend were to proceed unchecked it is inevitable (if not already the case!) that the pilot would be literally saturated with controls and displays. The F.18 Hornet shows that this trend has been quite significantly reversed, in fact, in the figure shown, to the level of the well-loved Hunter. I believe it should be possible to reduce this quantity of displays even further to below the Spitfire, for example.

## 3. Cockpit Design for the Future

Before the future cockpit can be discussed, a brief description of the future high performance fighter concept is required. Current studies within the U.K., U.S.A. and in Europe are directed towards aircraft which can perform close-turning combat over their full Mach number range from their lift limit to their structural design limits at altitudes up to at least 20,000 ft. These concepts employ combinations of such aerodynamic techniques as wing/body blending, swept-forward wings, forebody canards, etc. to allow exploitation of the high thrust/weight ratios now provided by the implementation of new engine technology and structures designed using advanced materials such as carbon fibre composites. The benefits of such advances show up in terms of turning capability. Fig. 14 shows how one new design, Rockwells HiMAT (Highly Manoeuvreable Aircraft Technology), has an expected turning capability twice that of the F.16. The future high performance fighter will also feel a significant impact on its system design caused by the introduction of cheap computing power and improving electro-optical display techniques.

The problem of the integration of these new technologies and the reversal of the old cockpit design philosophies is the one which is currently being addressed by design teams at various British Aerospace sites. As was indicated earlier, high sustained turning capability introduces physiological problems for the pilot. The anti 'g' suit, however, relieves these only up to the 5-6 'g' level. The turning capabilities being investigated range from 8-12 'g' sustained for up to 3 minutes. It is obvious that some additional 'g' alleviation

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mechanism is required. By reclining the pilot to the 'g' vector significant increases in 'g' tolerance can be obtained; this, however, causes problems relating to view, reach, ejection, etc. Our compromise approach is the adoption of the articulated seat. A particular seat geometry has been developed to allow the pilot to move from one posture to the other with no change in the relationship of the foot to the rudder, hands to stick or throttle, and to maintain a fixed eye to display distance. If the pilot has to initiate ejection from the reclined position the seat mechanism returns the seat to the upright position in 0.05 secs. This is physiologically acceptable (based upon the constraints used in the design of Command Ejection System) and is within the time needed to initiate "through-canopy" ejection or to jettison the canopy. The use of an articulated seat does, however, pose a number of design questions.

The major question relating to cockpit display layout is: "How much area above the pilot's knees and below the $15^{\circ}$ over the nose vision line remains when the pilot is in the reclined seat position ?". From our work on advanced cockpit anthropometry, it was defined that the critical design-case for this clearance was a small bodied pilot (i.e. 5 percentile sitting eye height) with both a large thigh and shin. This combination provided a clearance of 7.5 inches in which displays could be installed, Figure 15 illustrates this problem. Another major question is the location of the flight controller - must it be located on the side console ? Also, in the reclined position, the pilot's rearward view is impaired (though this is a problem with fixed reclined seats too). Finally, the pilot restraint system requires careful consideration to ensure it does not slacken during articulation.

The articulating seat then allows the pilot to withstand the extreme physiological environment but, without rationalisation of display/ controls, the pilot would still be mentally overloaded. To ensure that rationalisation of the cockpit control/display data is achieved, an extensive study has been made of information/task requirements for the aircraft. This employed a technique which defines a mission flow diagram in terms of broad mission functions such as Climb, Cruise, Ground Attack etc. and then defines within these functional system

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requirements, e.g. "Monitor and Control the Aircraft", "Navigate",
etc. These system functions are assessed in terms of the total
information/tasks required by the man/machine system to achieve these
functions, this process being followed by an assessment of which tasks
are best undertaken by the man and machine. Fig. 16 shows the concept.

The study is ongoing but it has allowed the adoption of the following
display/control system which is currently under evaluation. Fig. 17
shows the current layout. As stated previously, a side controller is
installed on the right console and present work in this area is
addressing the problem of forces and physical displacements. At the
forward end of the left console is the Main mission/system keyboard.
To aid data selection in the high vibration environment a sliding type
throttle has been developed which provides a wrist rest. This has also
had the beneficial effect of making the throttle less obtrusive. Both
of these controllers provide a HOTAS facility. The forward display
suite is designed to comply with various ergonomic requirements such
as optimised subtended visual angle at display, minimum eye scan times,
maximum view over the nose, inclusion of full aircrew population in
terms of anthropometry, and additionally to comply with the current
thoughts on Systems Reliability, Display Generation Redundancy,
Display Reconfiguration etc. The Head-Up Display (HUD) Unit to comply
with the previous ergonomic requirements, needs to take up little
space below the coaming line. There are currently two designs being
investigated, the Marconi Avionics Multi-Combiner and the Smith's/
Hughes Diffractive HUD. The latter, in an original version by
Hughes, has been flight-tested in the SAAB VIGGEN and received very
favourable pilot comment. Modelled in Fig. 17 is the Marconi Multi
Combiner. A Head Level Display (HLD) is installed directly below the
HUD, to achieve minimum eye motion and provide the pilot with the
ability to monitor essential flight data, while tracking a target for
example on the display. The display currently under consideration is
the Ferranti COMED unit. This unit has the capability to project a
variety of display formats, including radar, raster TV air-to-air and/
or air-to-ground, horizontal situation data and $\alpha$ - numeric information
from a CRT. A moving map unit is also included, the image from which
is overlaid on that of the CRT, thus allowing such data as navigation

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track, time-distance to way-points etc., to be over-written upon
the map image. The HUD and HLD present all essential flight data
within the pilot's near field of view.

Two Multi-Purpose Displays (MPD's) are positioned either side of the
HUD/HLD under the coaming. These displays represent the system work-
horses of the cockpit as they present all systems information and are
used in conjunction with the switch panels on the left console beside
the throttle to select Weapon, Communication and Navigation functions.
The selections are available, having been entered before flight via a
portable data store, the data being generated during the pre-flight
brief. The interactive switch-display concept has been developed in
an attempt to eliminate head-down selections which are a source of
erroneous inputs and also induce pilot vertigo, and remove the need to
reach forward to enter selection.

The display data is normally presented in mission phase packages,
e.g. take-off, cruise, air combat, etc. These are selected from the
keyboard located at the forward end of the left console. The mission
phase packages of information contain only that data relevant to the
particular phase of flight. Fig. 18 shows possible displays for
Cruise Mode, while Fig. 19 shows the changes caused by the selection
of Air Combat Mode. To allow the pilot access to the total packages
of data for a particular system such as engine, fuel, etc., a set of
dedicated keys is also available within the forward keyboard. Fig. 20
shows a display format for the aircraft fuel system. Also included
in this area is a numeric keyboard for the insertion of such data as
new waypoints, new communications channels, etc.

Referring back to Fig. 17, the right console has an interactive
display located at the forward end which will provide control of
Aircraft sensor systems and role change equipment. The other controls
are basically 'once a flight' in nature to reduce the need for the
pilot to remove his hand from the control stick.

The last area of interest is the pilot warning system, this being
positioned around the coaming edge. As the data packages present only
reduced systems information, the warning system takes on a more
significant role in the cockpit. Our current approach is that the

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lights are push-button selectors which, when depressed, would initiate corrective action and/or present appropriate actions/data to the pilot in the form of electronically displayed pilot's notes.

The current studies being undertaken on this cockpit relate to the development of a fundamental ergonomic design data base from which one can design future cockpits. To achieve this we are attempting to develop a model of the pilot's mental and physical abilities. Fig. 21 shows in a simple form which functions require consideration for such a model. It shows the pilot having input sensors, a central processor function and output motor function. Also requiring consideration are external modifying influences such as fatigue, the task, adaption, etc. For many years psychologists have investigated the human's performance and have produced various measures, the most common being the ability to process packages of data in computer technology - bits/sec. processing rate. We are presently attempting to apply this work to defining a quantitive measure of the pilot's performance during a typical mission. To achieve this we provide a prime flying task (e.g. a single axis tracking task), this is supplemented by a choice-reaction time light cancellation secondary task. We measure the "information" content of the flying task and the reaction time for the secondary task and allow the subject to achieve a consistent performance on these. A third task is then introduced such as reading a parameter for a display or changing a switch state. The difficulty of this task can be measured in terms of the amount of attention (thus degradation in performance) the subject diverts from the main tasks. Each task can then be modified to provide optimum attention allocation.

4. Future Consideration

As Technology advances, concepts in display, data entry and weapon-aiming etc., which have previously been impractical for the cockpit environment, began to become available. As aircraft manufacturers, the temptation to install new equipment "because it enhances the product and everybody else has it" must be resisted. The approach should be one in which each equipment is critically appraised in terms of the increase in operational capabilities it offers and the impact

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it has on the total system design.

If we start with displays, there are various display techniques
under development such as liquid crystal matrix and thin film
transistor (TFT), matrix displays and hardened colour CRT's.
Presently, liquid crystal and TFT panels offer reductions in the
installation volume required in the cockpit, while colour CRT's offer
the ability to reduce confusion by the presentation of colour coded
data and colour external video. Also in the display information
presentation area there is a growing trend towards the adoption of
predictive type displays. One type of landing display is shown in
Fig. 22 which shows the velocity vector superimposed on the desired
flight path data. Also shown are angle-of-attack, flight limitation
and energy status. By superimposing this on the outside world it has
shown that a significant reduction in work-load is achieved.

Recently it has become possible to make use of the concept of weapon-
aiming by means of head position sensing in conjunction with a sighting
reticle suitably collimated. These so-called Helmet-Mounted Sights
(HMS) have been evaluated in both fixed and rotary wing aircraft for
air-to-air and air-to-ground use. The current systems are limited by
the need to point the whole head towards the target. This is not a
totally natural motion since sighting normally consists of gross head
motion followed by fine pointing achieved by eye movements. Current
research is directed to the incorporation of eye motion detectors into
the HMS. A system under development is shown in Fig. 23 which is based
on Infra Red Techniques involving reflections from the cornea. Eye
motion causes fluctuations in the amounts of reflected light which
causes a corresponding voltage variation in a suitable detector.
These variations are inputs to equations which determine eyeball
position, thus line of sight.

5. Conclusions

Today's operational aircraft cockpit has evolved from the experience of
60 years of powered flight, into an environment in which the pilot is
presented with a very complex system management task. In some cases
the task is so complex that operational constraints have been placed
upon the aircraft because of the pilot's inability to cope. The

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development of techniques such as digital data transmission (the Data Bus) and systems such as the microprocessor during the 1970's has provided the opportunity to investigate new methods of presenting data and controlling systems from within the cockpit. These investigations have led to the introduction of the Data Bus and electronic multi-function head-down displays into the AV-8B and F.18. These systems, while increasing system flexibility, reduce the number of displays within the cockpit.

Present studies within the U.K. are developing this concept further and are producing cockpit layouts which bear little resemblance to present generation cockpit layouts. These developments pose a number of, as yet unanswered questions; such as:-

> How do we train the pilots ?
> How will the Services support the proposed
>    integrated Systems ?
> How does industry ensure the product which
>    is supplied is an improvement over that
>    which preceeded it ?

These and many other topics are as important as the technical issues discussed in this paper. It is only when an increase in capability based on an efficient operational and design compromise is reached that the type of general decline in aircraft numbers shown at the start of this paper becomes even moderately tolerable.

Finally, when considering any new cockpit design it is becoming very necessary to provide a co-ordinated multi-disciplinary design team at the conceptual stage who are capable of assessing mission/operational requirements, the human's capabilities and hardware technologies. This is a somewhat new approach but in this way a cockpit may be developed which will achieve the AIM (Fig. 24) of providing a powerful display/control system that reduces pilot workload rather than bamboozles him with new gadgets.
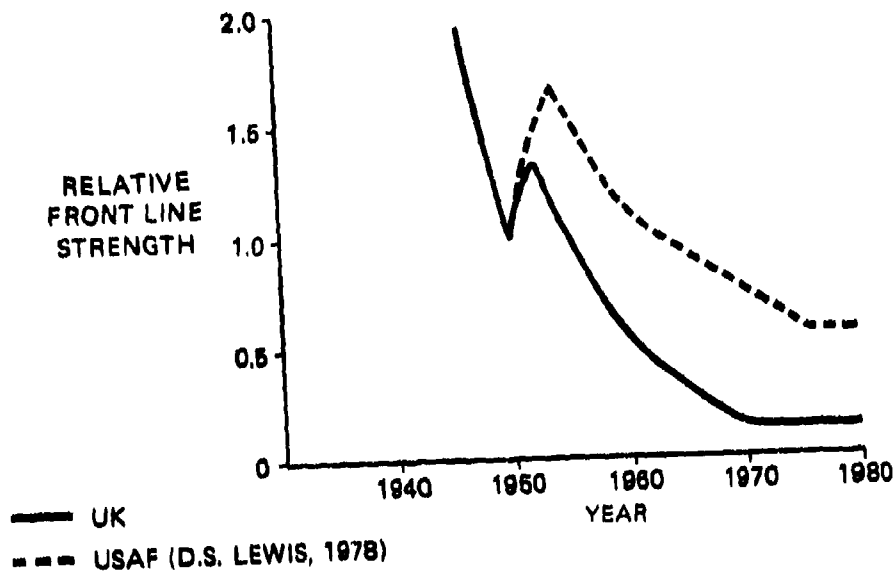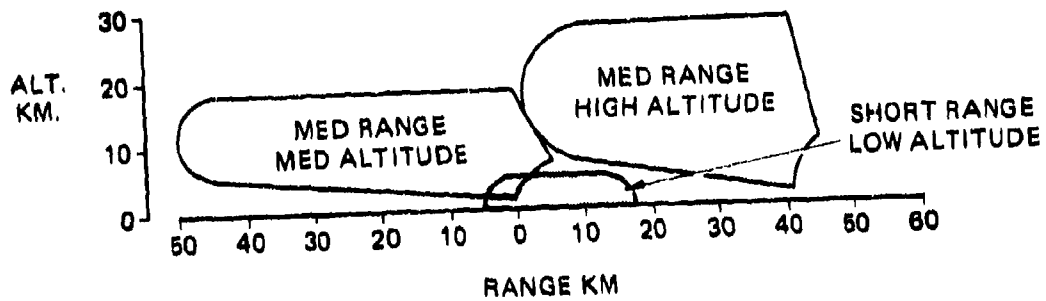
Fig.1  FRONT LINE AIRCRAFT STRENGTH
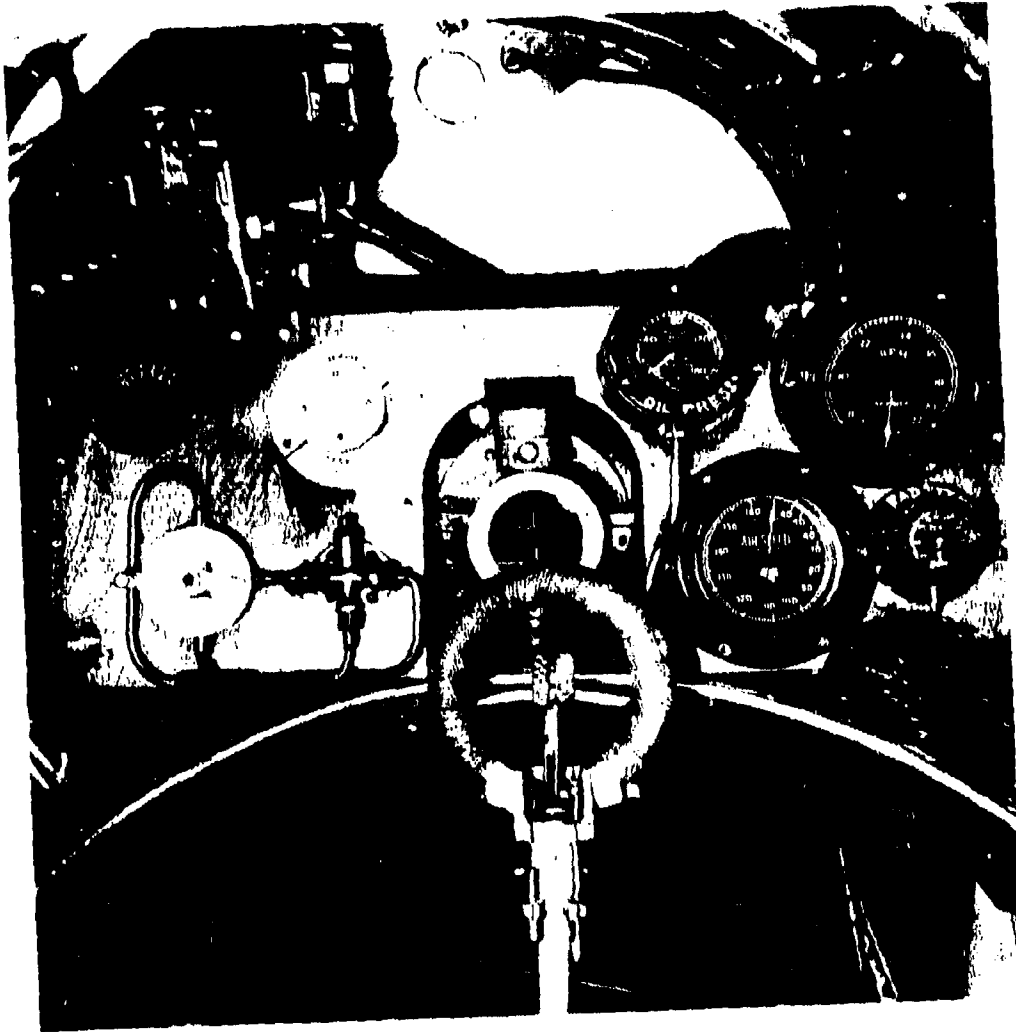


Fig.2  GROUND DEFENCE SCENARIO
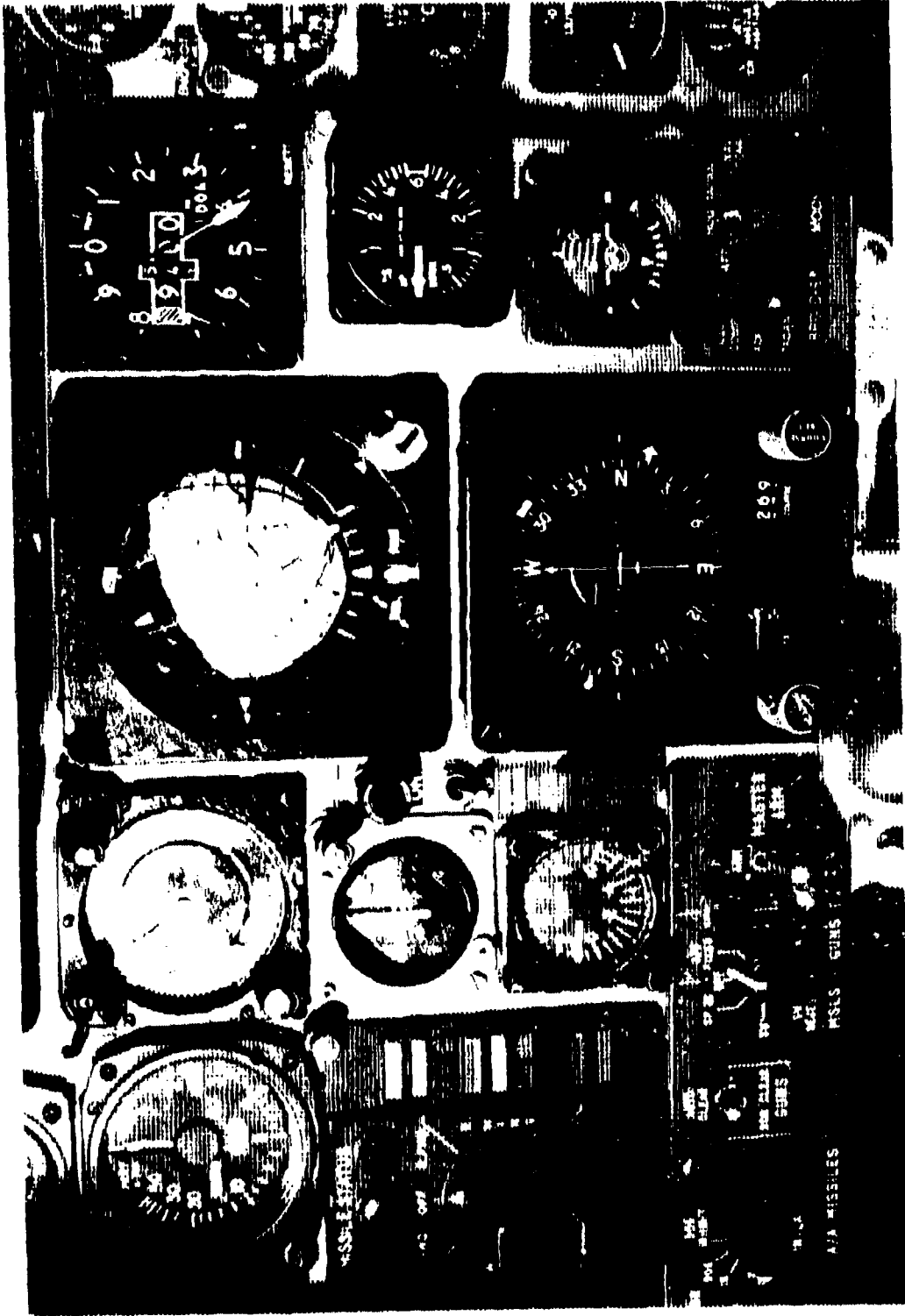
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Figure 5. REAR COCKPIT

FIG.1 BLIND FLYING PANEL

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FIG. 11. HUNTER COCKPIT

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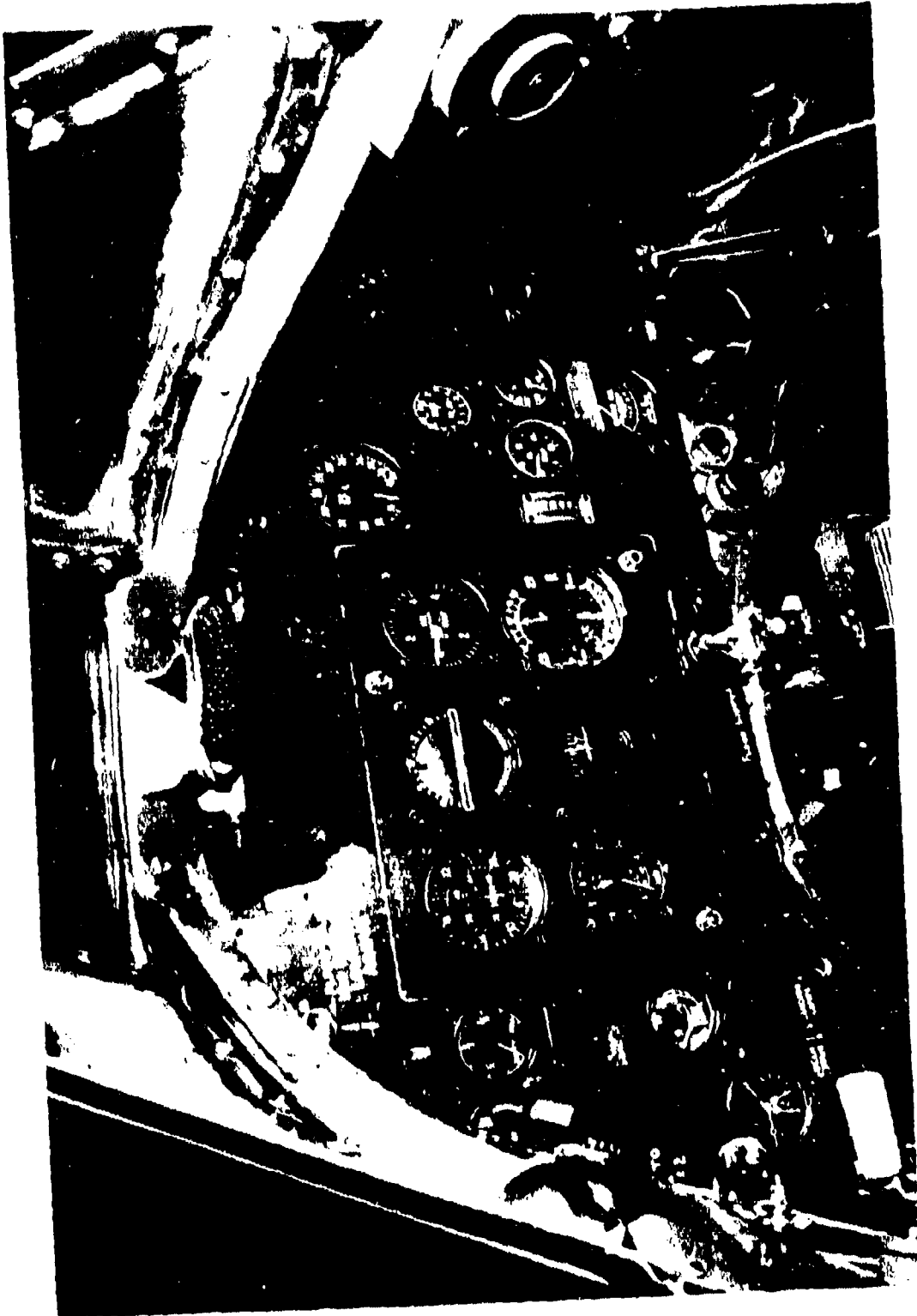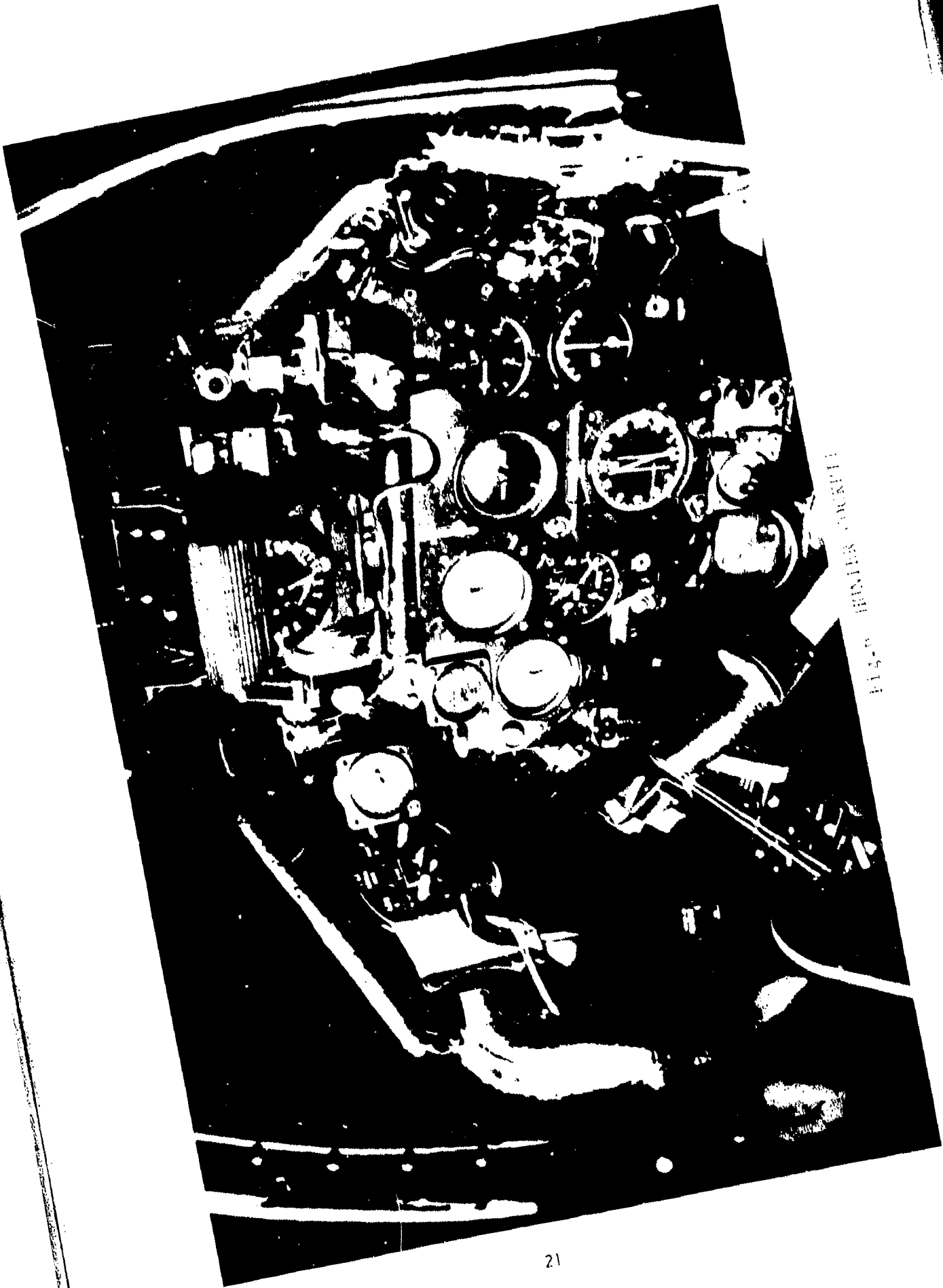
Fig.- LIGHTNING COCKPIT
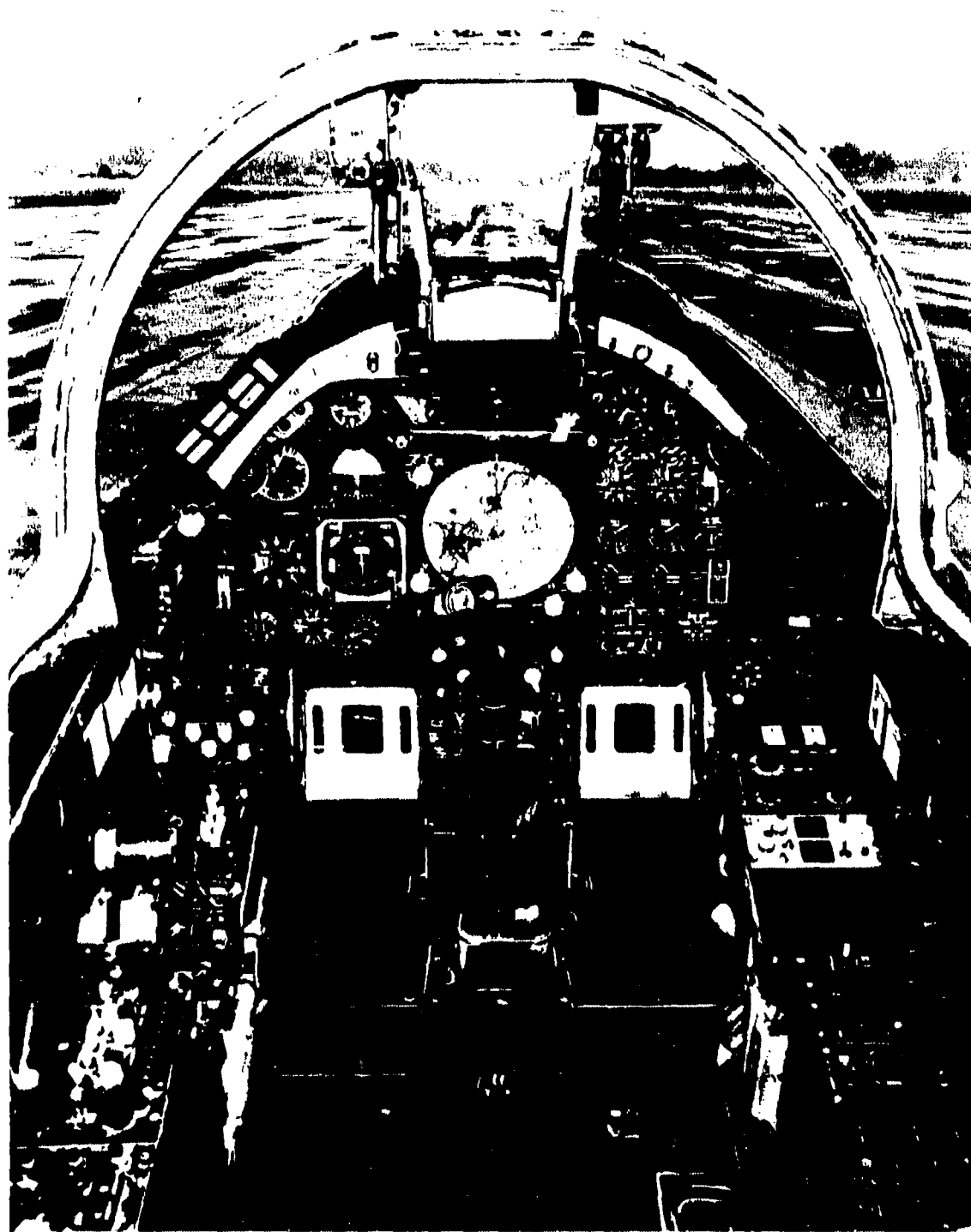
Fig. 8   JAGUAR COCKPIT
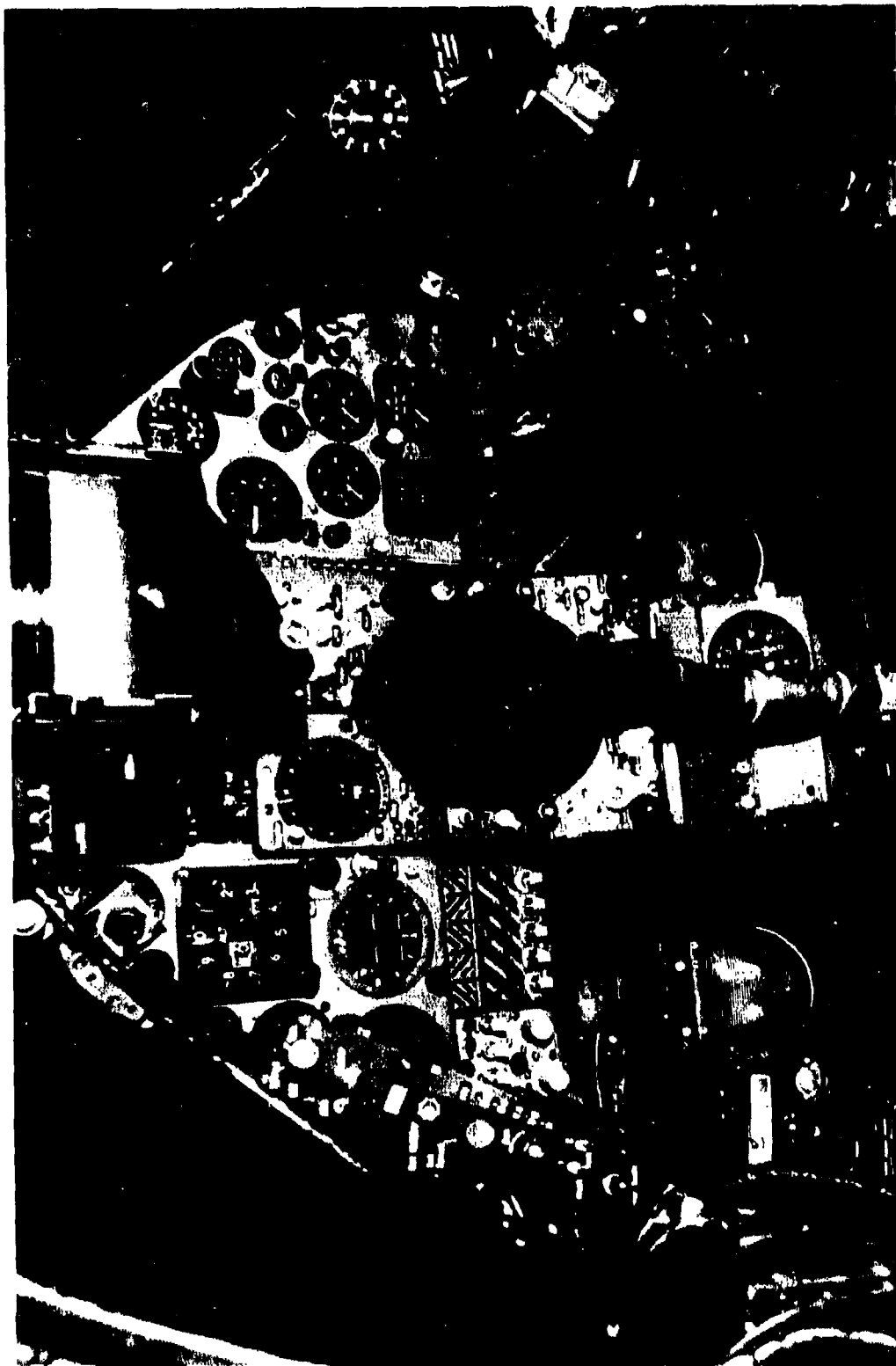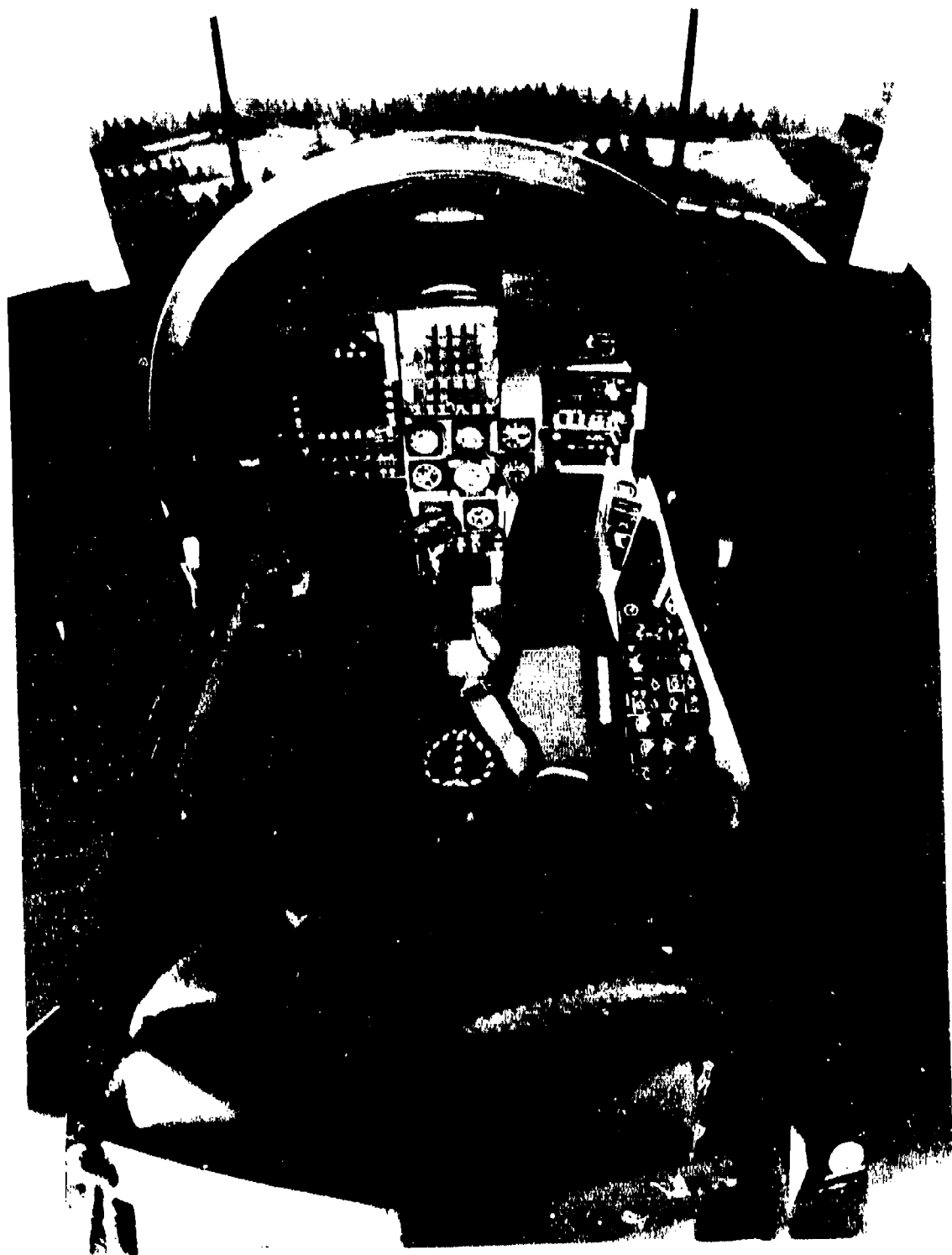
23

Fig. 3  HARRIER COCKPIT

Figure 11. Cockpit

25
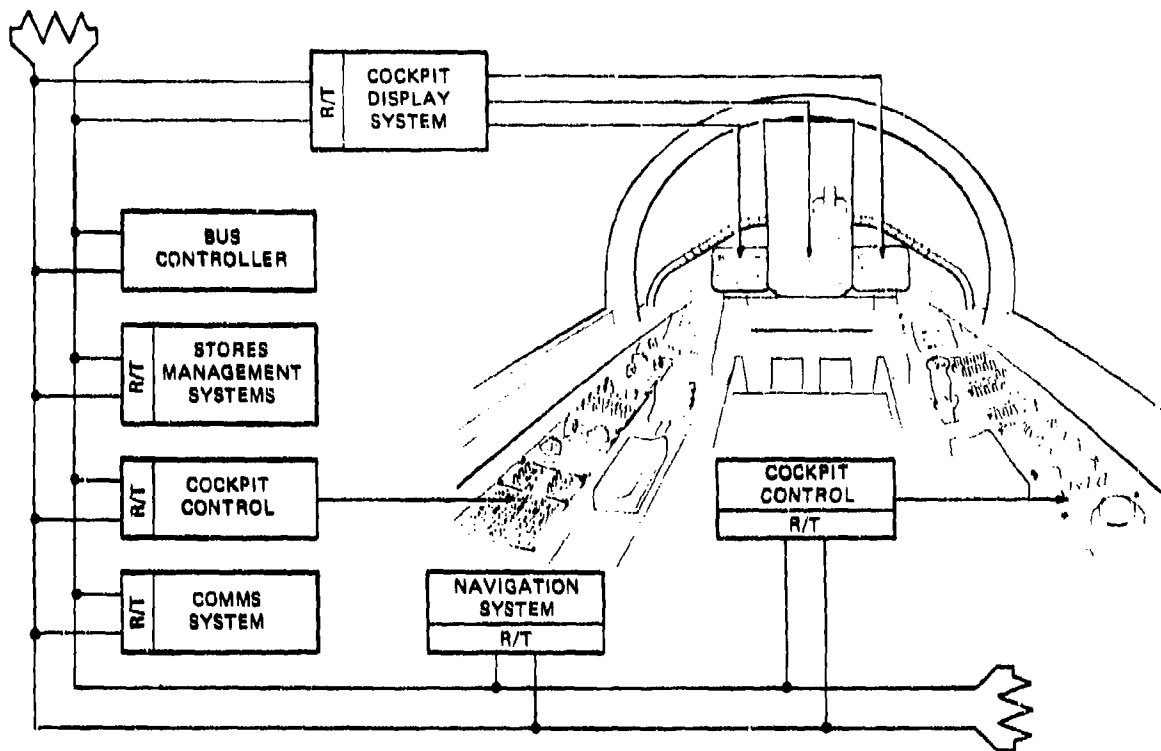
Fig.11 DATA BUS CONCEPT
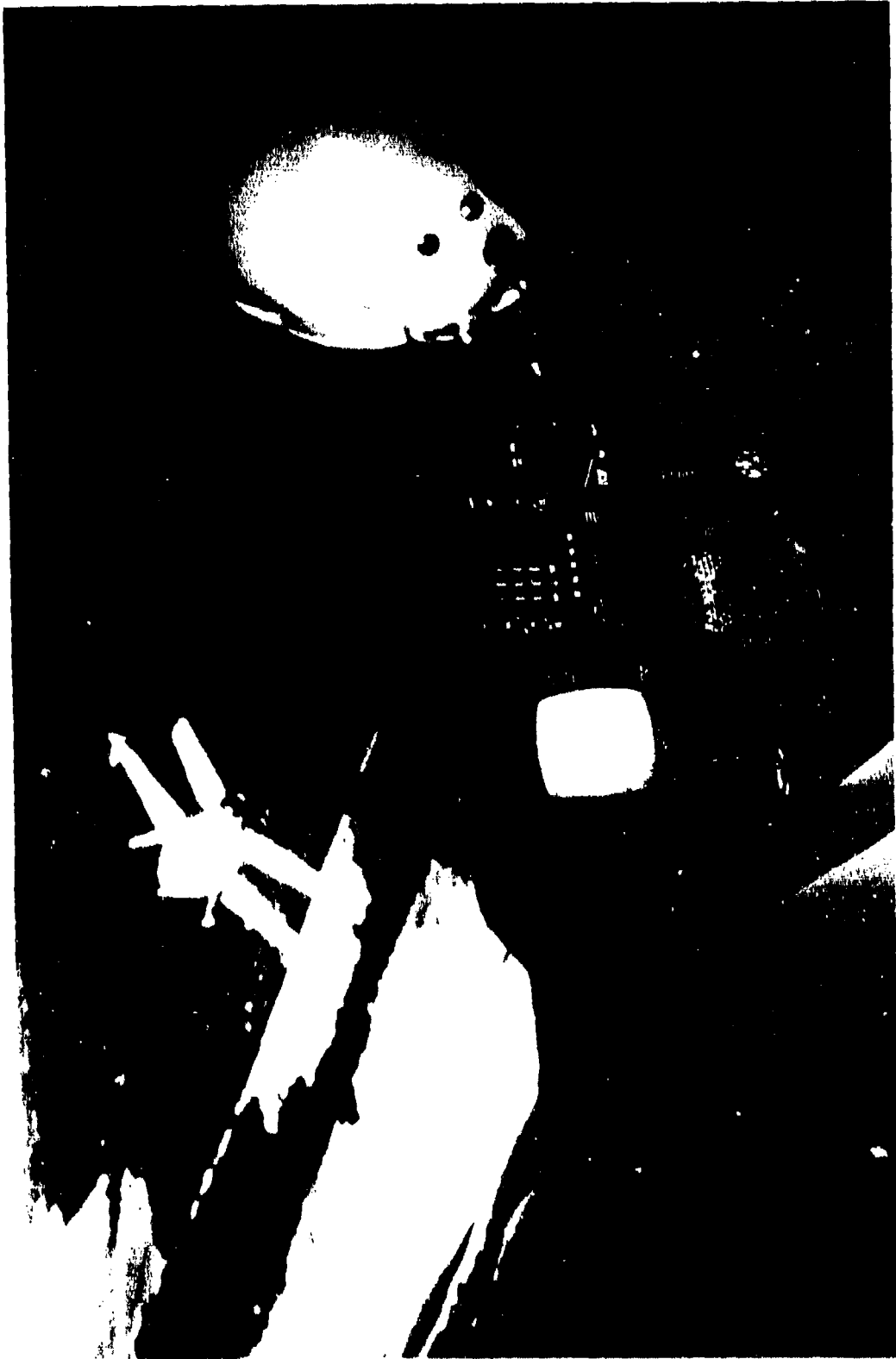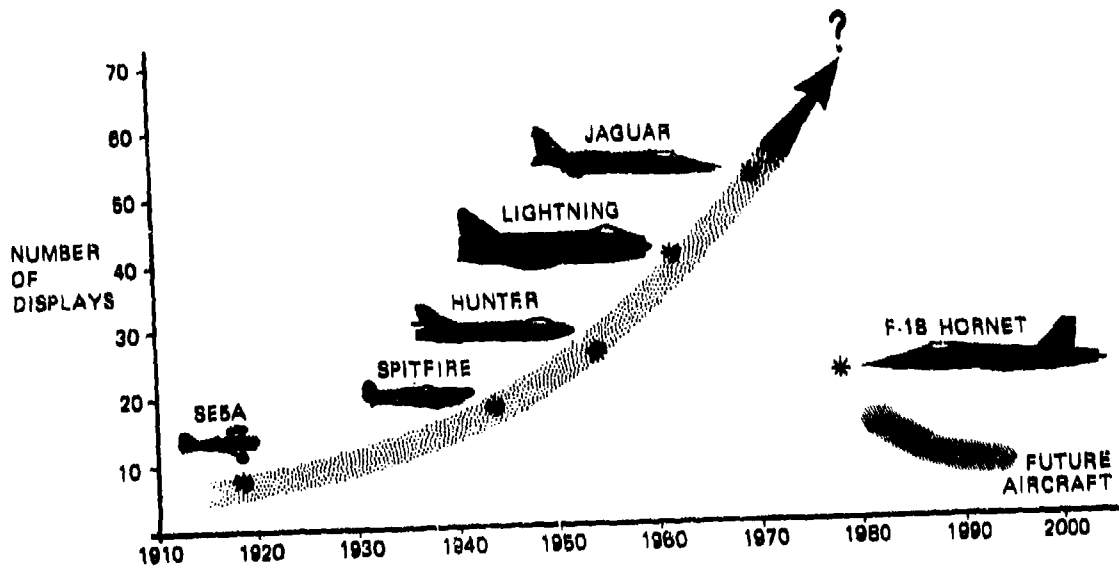
Fig.13 GROWTH OF COCKPIT DISPLAYS
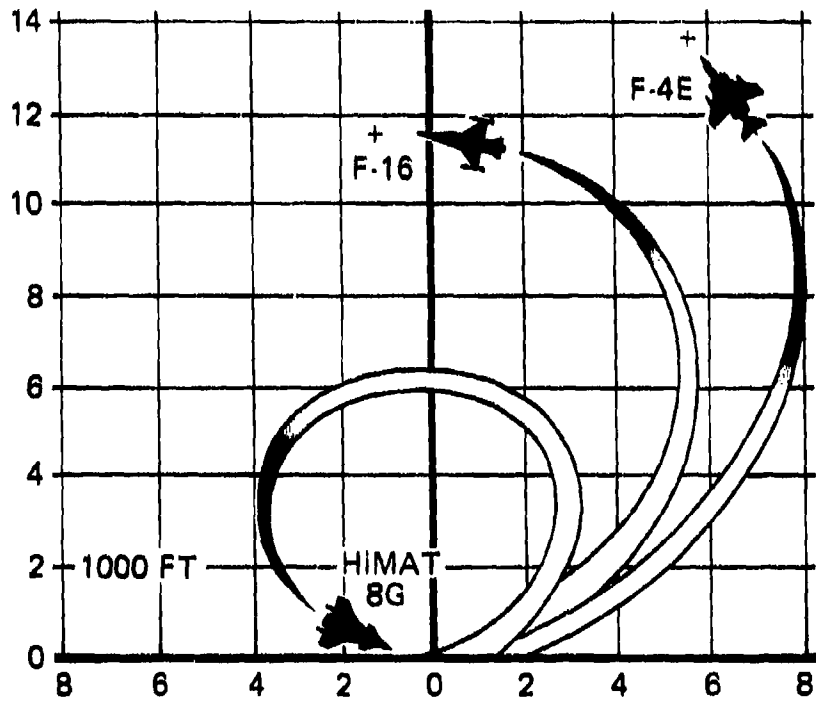
Fig.14  HIMAT  TURN  PERFORMANCE

AVAILABLE
DISPLAY
AREA

EJECTION
CLEARANCE

EYE LEVEL          15°

NORMAL FLIGHT POSITION
(BACK ANGLE 35°)

RECLINED COMBAT POSITION
(BACK ANGLE 55°)
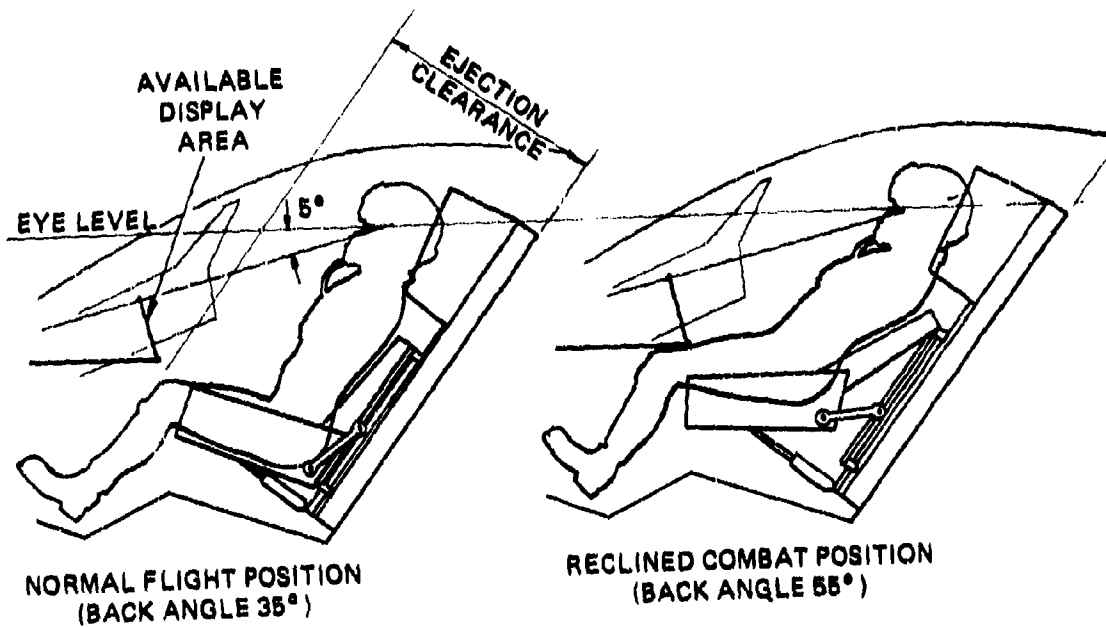
Fig.15  KNEES/COAMING  CLEARANCE

30

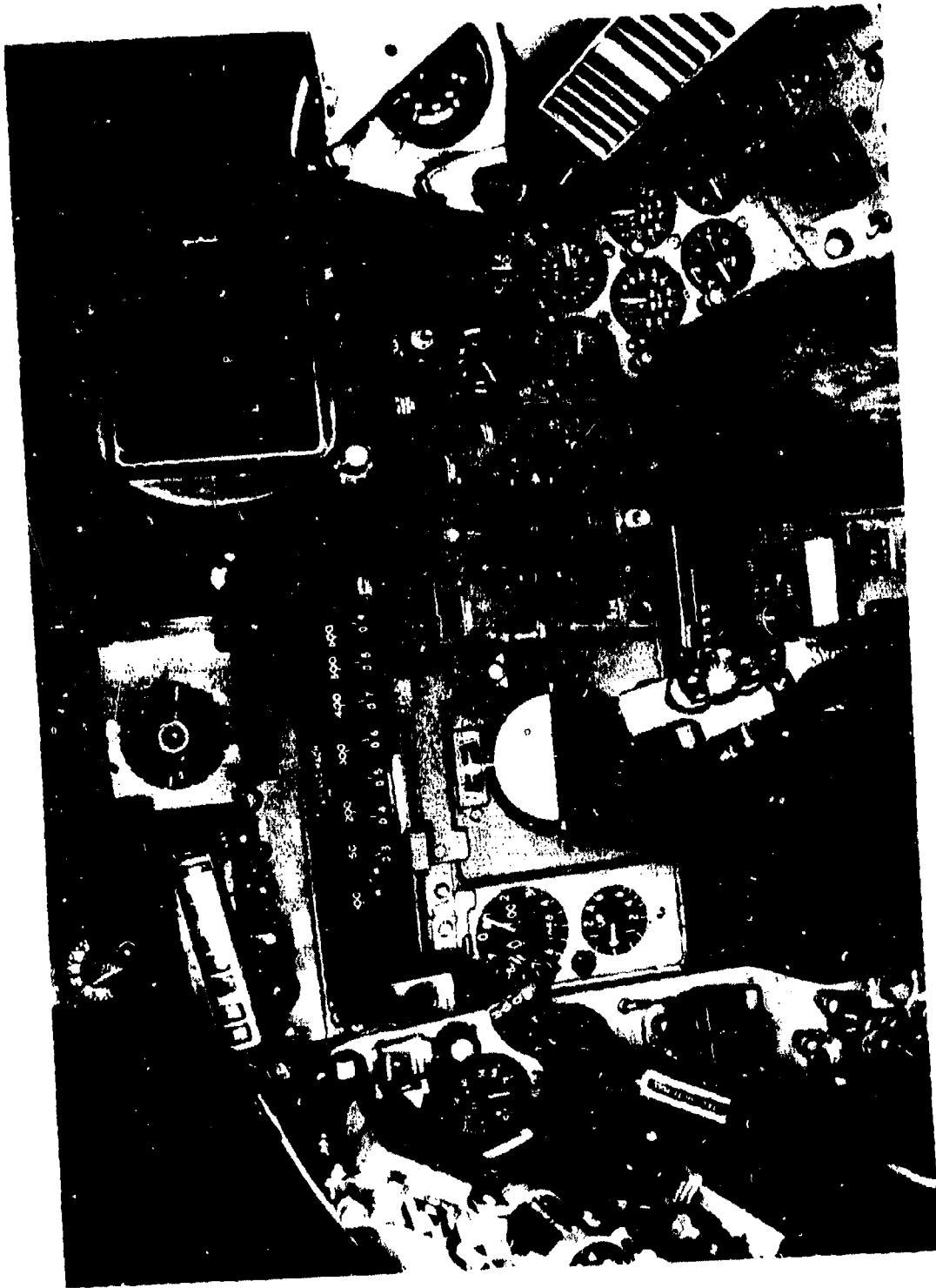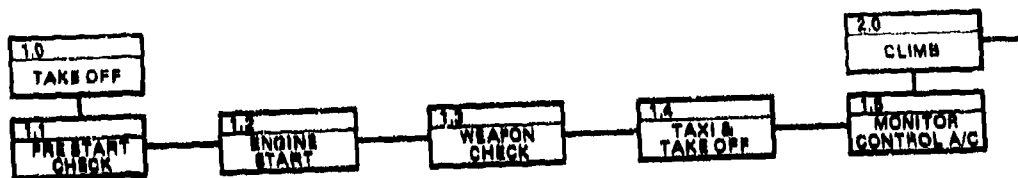| Function Number | Function Name | System Information Requirements | System Action Requirements | Machine Tasks | Man Tasks |
|---|---|---|---|---|---|
| 1.1 | Prestart check | Cockpit check<br><br>1 Integrity of system<br><br>2 Switches and controls 'safe' before power on<br><br>3 Position seat and rudder<br><br>4 Umbilicals<br><br>5 Straps<br><br>6 Brakes | 1 Place all switches and controls to safe<br><br>2 Adjust seat and rudder<br><br>3 Connect umbilicals<br><br>4 Connect straps<br><br>5 Ensure brake 'on' Measure, monitor, inform, select, test and warn | Measure, monitor inform, select, test and warn | 1 Inspect<br><br>2 All switches to safe<br><br>3 Adjust seat to attain eye level<br><br>4 Connect umbilicals<br><br>5 Fasten straps<br><br>6 Apply brakes 'on' |
| 1.2 | Power 'on' | | | | |

Fig.16 INFORMATION/TASK DEFINITION TECHNIQUE
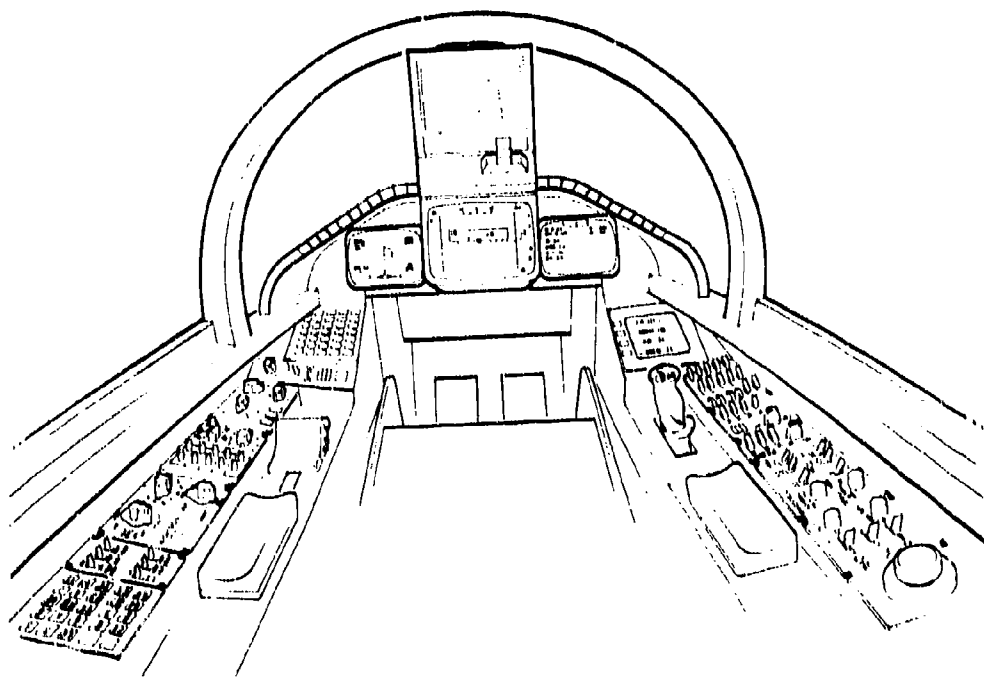
Fig.17 ADVANCED COCKPIT
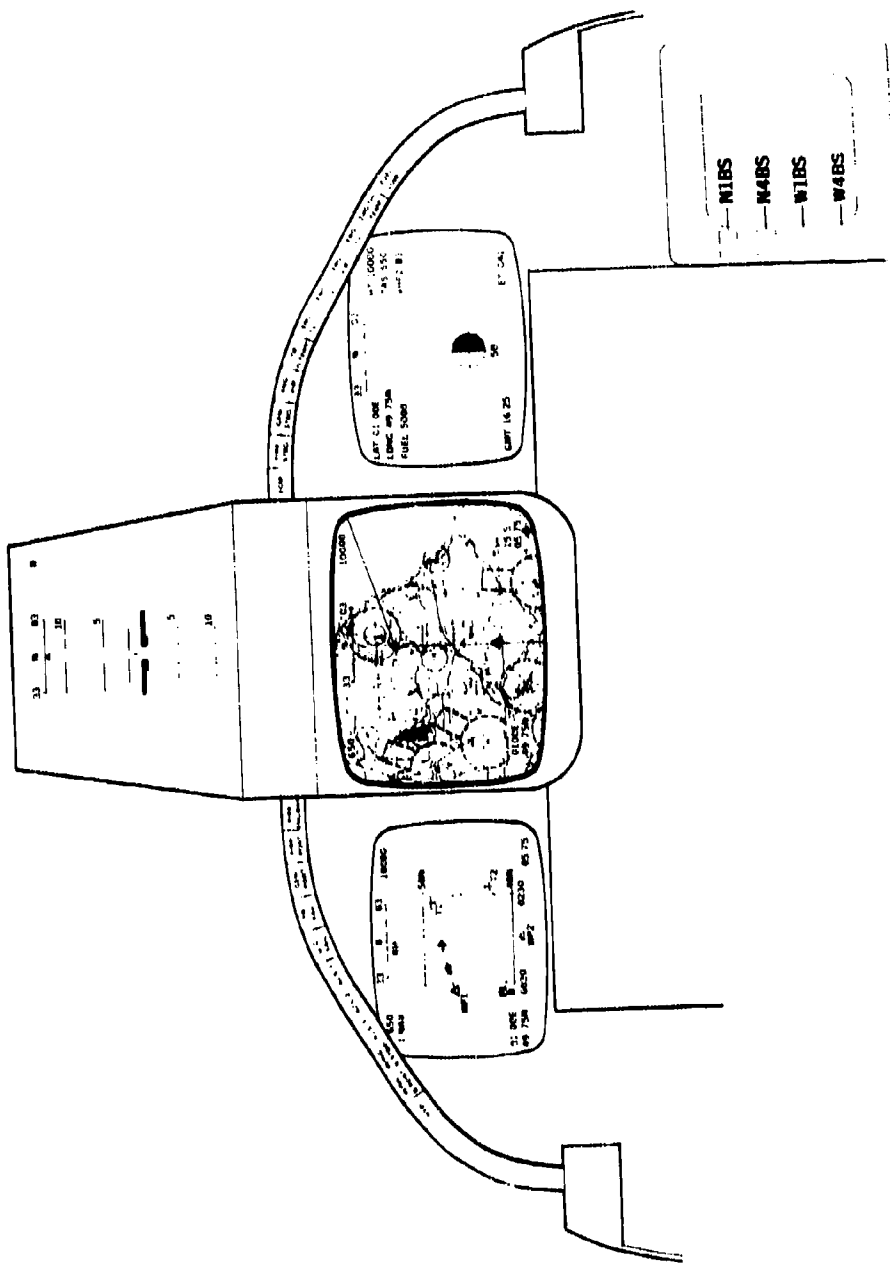
Fig. 18 CRUISE MODE

Fig.19 AIR COMBAT MODE

FUEL

TOTAL 10100

TEMP 50

WING

$C_L$

WING

2400

1300

2400

1000

1000

1000

1000

BINGO

FCE

FCA
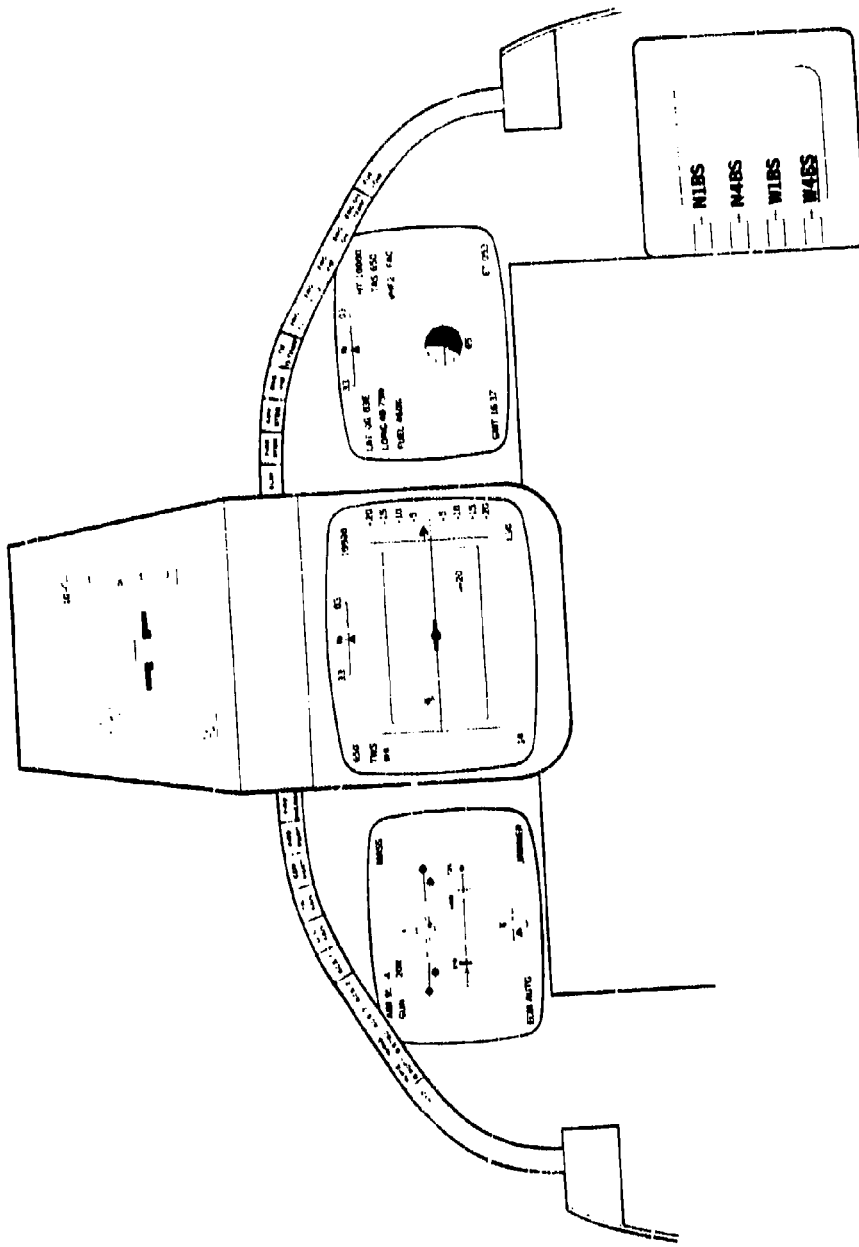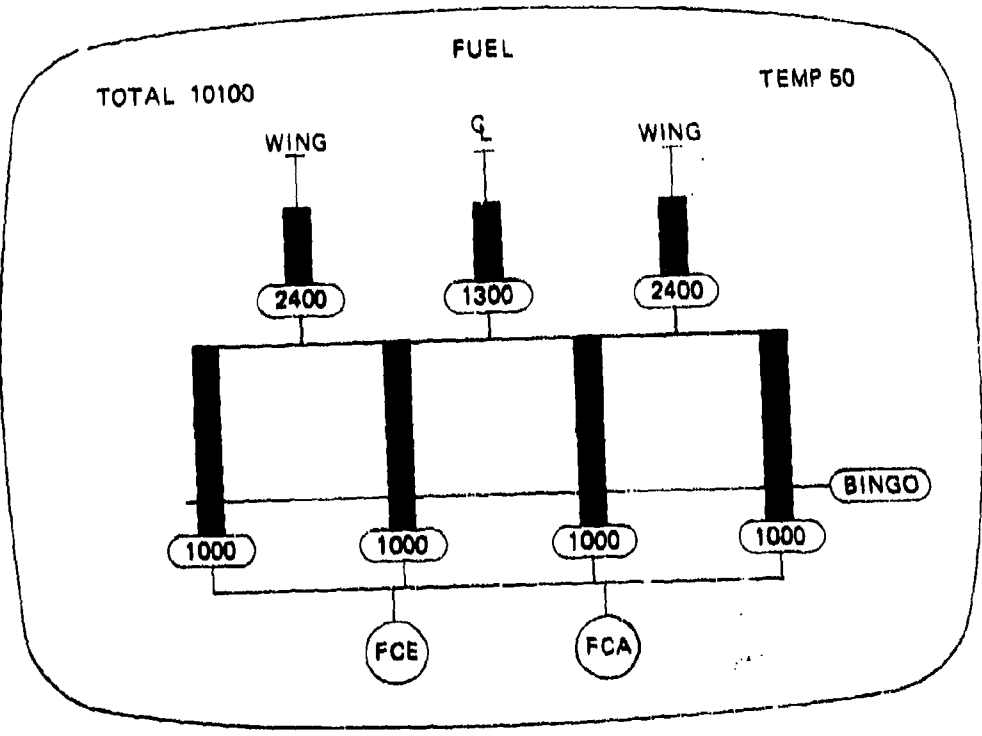
Fig. 20 FUEL SYSTEM
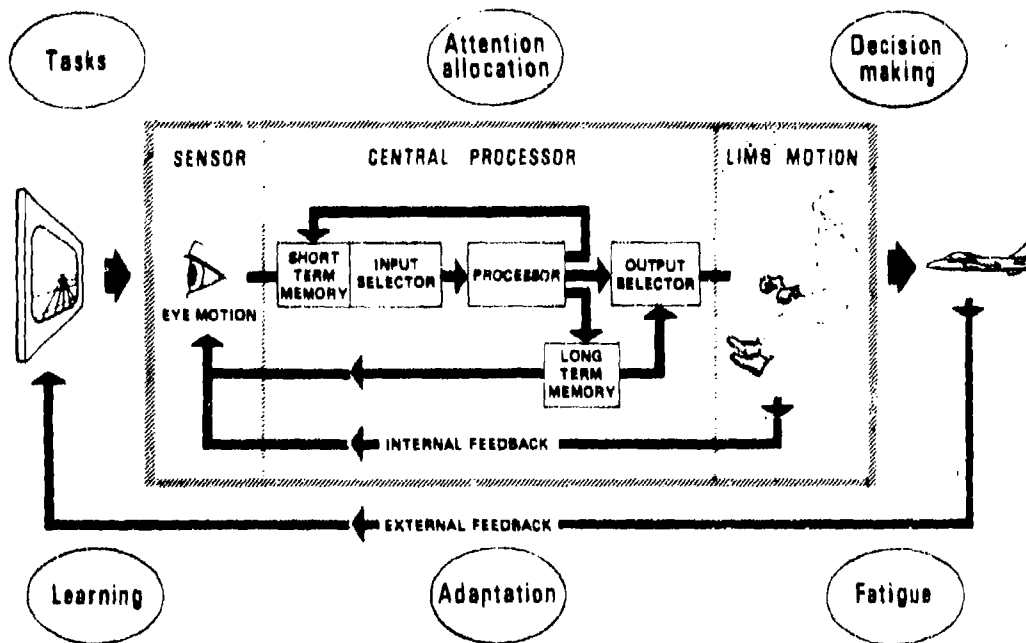
Fig.21 HUMAN OPERATOR MODEL

TRUE TRACK
HEADING SCALE
HORIZON BAR
POTENTIAL
FLIGHT PATH
MARKER
VELOCITY VECTOR
LIMIT OF THE TOTAL
FIELD OF VIEW
VALUE OF
SELECTED FLIGHT PATH
-2.7
AIRCRAFT SYMBOL
DESIRED TRACK
SYNTHETIC
RUNWAY
SELECTED
FLIGHT PATH
MARKER
ANGLE OF ATTACK
ON APPROACH
LIMITED
ANGLE
OF ATTACK
±10°  ±16°
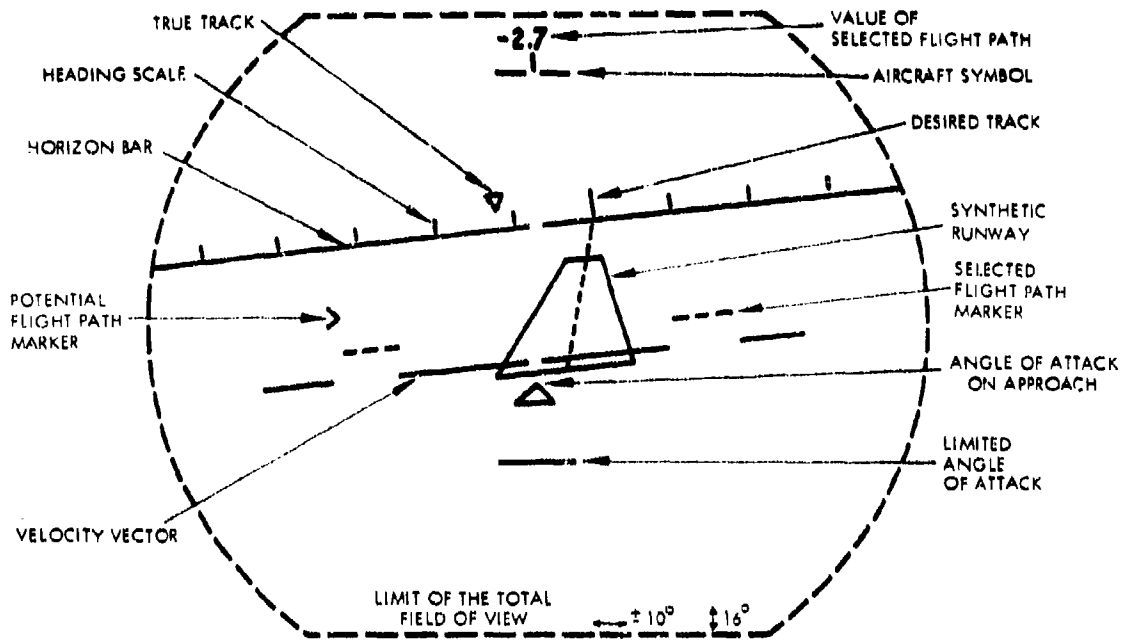
Fig.22 ADVANCED HUD DISPLAYS



DICHROIC
MIRROR
IR SOURCE
DETECTORS
TILT
MIRROR
LINE OF SIGHT
SIGHT
SURVEYING
UNIT
SIGHT
ELECTRONICS
UNIT
POINTING COMMANDS TO:
RADAR
CAMERA
EO SENSOR
MISSILE
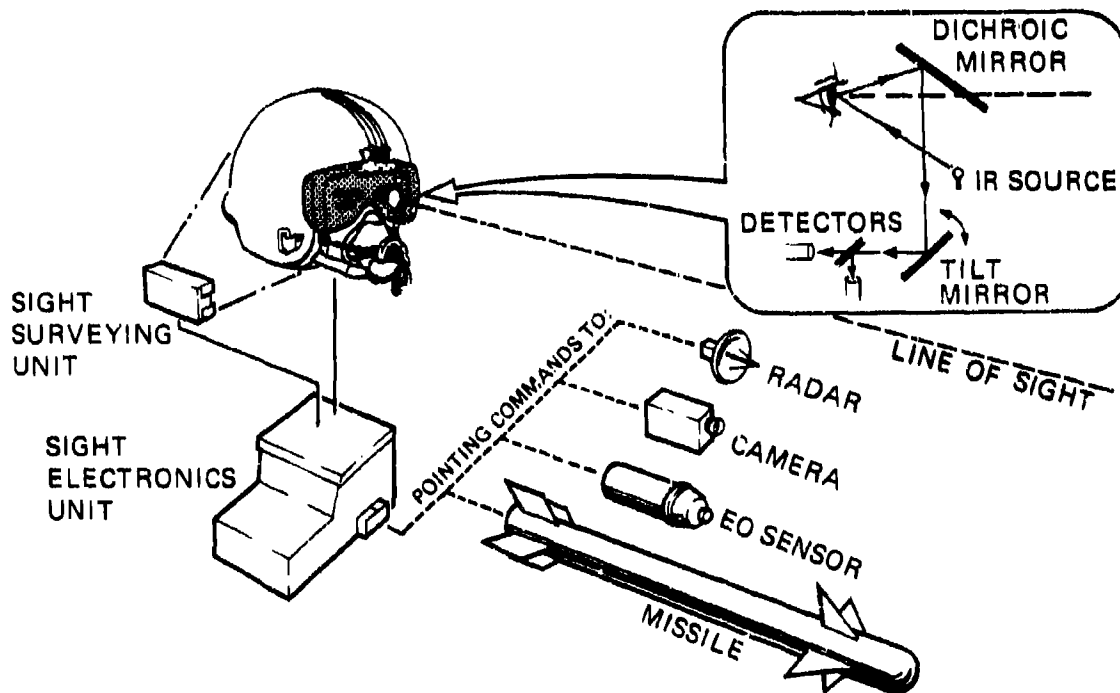
Fig.23 HELMET SIGHT WITH EYE POINTING

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NOW
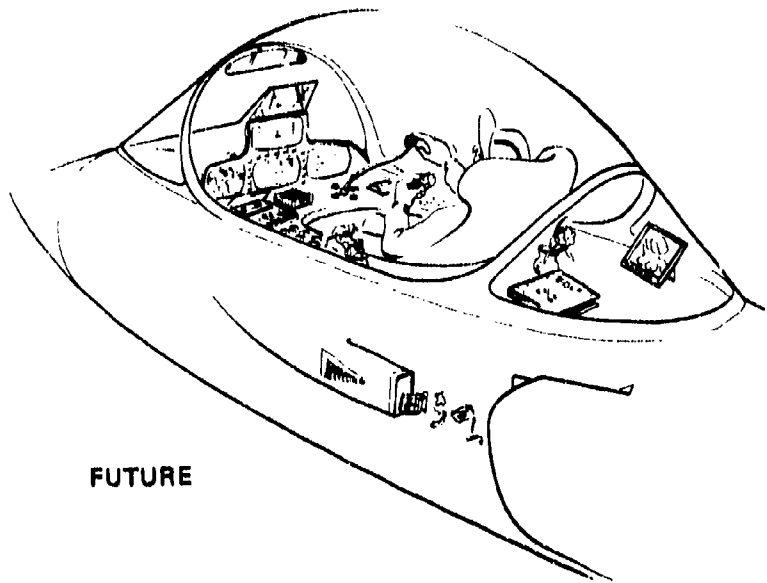
FUTURE

Fig.24 THE AIM

# COLOR SELECTION AND VERIFICATION TESTING FOR

# AIRBORNE COLOR CRT DISPLAYS

Louis D. Silverstein and Robin M. Merrifield

Boeing Commercial Airplane Company

Recent advances in Cathode Ray Tube (CRT) technology
have made the use of multi-color displays feasible for a
variety of applications. Despite the increased capa-
bility and potential advantages afforded by color
displays, there are inherent hardware and human factors
problems which must be confronted. One particularly
persistent problem in color display technology is the
specification and visual verification of a color reper-
toire. The utility of a color display is dependent upon
the display providing suitable chromatic differentiation
and image brightness to ensure reliable symbol visi-
bility and color discrimination under all operational
conditions. These criteria require special consider-
ation when the display must be used in dynamic and
severe lighting environments, such as the flight deck of
an aircraft. This paper details color selection and
visual testing methods used for the shadow-mask color
CRT displays on the Boeing Model 757/767 flight decks.
Topics include analytical methods for initial color
selection, visibility and other discrimination testing
under extreme high and low ambient lighting conditions,
color saturation effects, and special display design
considerations and limitations. The chromaticity and
brightness specifications for a seven color repertoire,
determined by the methods presented, are also described.

## BACKGROUND

Recent advances in Cathode Ray Tube (CRT) technology have made the use of
multi-color displays feasible for a variety of applications. Color offers a
number of distinct advantages for display design. First are the obvious
aesthetic benefits of color, supported by the general preference for color
over monochromatic presentations. Second, color has the potential for greatly
increasing information coding capability and flexibility, and for reducing
visual search time on complex displays. A third advantage is derived from the
addition of color contrast, which can increase symbol visibility and reduce
display brightness requirements.

Despite the increased capability and potential advantages afforded by
color displays, there are inherent hardware and human factors problems which

must be confronted. As Figure 1 illustrates, a color display analysis can be considered as a hierarchial process. At the top of the hierarchy are those visual and perceptual factors which constrain the utility of color. As one proceeds through levels of the hierarchy, increasingly complex and integrated human functions come into play. Obviously, the visual and perceptual requirements of the display user must be satisfied for a color display to be a viable concept.

One particularly difficult problem in color display technology is the specification and visual verification of a color repertoire. Additional complexities arise as the number of discriminable colors required increases and more elaborate display formats using color fields of varying size, brightness, and geometric arrangement are employed. The problem becomes critical when the display must be used in dynamic and severe lighting environments such as the flight deck of an aircraft, where complex interactions between display characteristics and the ambient environment make precise color and brightness specification essential. The focus of this paper is color selection and verification testing for airborne color CRT displays. Emphasis is placed on the visual and perceptual requirements for color visibility and discernability and the resulting display hardware considerations.

The selection of an effective color repertoire must be predicated on three fundamental attributes of a visual stimulus (Graham, 1965a; Wulfeck, Weisz, & Raben, 1958). On the display or transmitting side of the system, the physical light stimulus is characterized in terms of its wavelength distribution, luminance, and purity. For the display observer, these physical attributes correspond to the perception of hue, brightness, and saturation, respectively. Color specification is generally best accomplished by application of the CIE (Commission Internationale de l'eclairage) chromaticity system, which permits a replicable description of the appearance of any color through a set of chromaticity coordinates (see Wyszecki & Stiles, 1967). The basic color space, shown in Figure 2, was standardized in 1931 and provided a convenient method of specifying the dominant wavelength and purity of any colored sample (Figure 3). The other fundamental visual attribute, brightness, is measured and specified photometrically. The recognition that color discrimination was not uniform across the 1931 color space lead to transformations such as the 1960 Uniform Chromaticity Scale (UCS) shown in Figure 4, in which equal distances within the color space correspond more closely to equivalent perceptual differences in color. Other derivations exist for different size color fields and self-luminous versus reflective color sources. At this point it is important to recognize that color perception is a complex, multidimensional process. Changes in any one parameter of the color stimulus will modulate the perceptual effects of other parameters.

When selecting and specifying colors for critical applications, and especially for today's advanced CRT display systems in avionics, a number of additional factors related to color perception become important. First, color perception is strongly influenced by the size and brightness of the colored image; smaller images appear less saturated and sometimes appear shifted in hue relative to larger images. For small images, the ability to discriminate between colors is reduced, particularly along the blue/yellow continuum (Farrel & Booth, 1975). Likewise, changes in target luminance cause changes in both the perceived saturation and hue of the target (Farrell & Booth, 1975). A second major class of perceptual phenomena are related to simul-

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taneous contrast, whereby the appearance of a colored image is influenced by the hue and saturation of the surrounding visual field. In general, the color of a small target is shifted toward the complementary hue of the surrounding field (Hurvich, 1980). Third, the number of colors in the display set and the method of color coding will strongly affect color discrimination (Semple, Heapy, Conway & Burnette, 1971). As the number of colors increases, color discrimination becomes more difficult and tighter color control is required. Similarly, color display formats which require absolute color identification place greater demands on both the observer and display hardware than formats employing redundant forms of color coding and comparative color discrimination. Recommendations on the number of useable colors for coding purposes have been found to be in the range of four to six colors (Kinney, 1979; Krebs, Wolf, & Sandvig, 1978; Teichner, 1979). Finally, consideration must be given to the visual characteristics of the population of display users. For example, flight instrument displays must accommodate older pilots who may be characterized by a restricted range of visual accommodation (Southall, 1961), decreased contrast sensitivity (Blackwell, 1952), and a reduced ability to discriminate between colors. Color discrimination losses have been found to be most pronounced for the shorter wavelengths, due to changing ocular pigmentation with age (Burnham, Hanes, & Bartelson, 1963). Color display design criteria and related visual testing should represent the range of visual characteristics of the display user.

Color CRT characteristics, and interactions with the ambient operating environment, also act to determine the color experience of the display user. The shadow-mask color CRT, selected by Boeing for use in its new generation commercial aircraft, uses three separate primary phosphors with associated electron guns. The basic shadow-mask CRT concept is illustrated in Figure 5. Since color mixture with this type of color display is essentially accomplished by spatial color mixing at the retina of the eye, the convergence or alignment of the separate color images at the display face will affect the perceived color of composite images. Misconverged beams can result in a loss of color purity (hue shift) and produce color fringes on the borders of stroke-written symbology. Figure 6 shows the manner in which color purity is affected by improperly converged beams. The long term stability of the colors produced by a multi-gun system depends upon how impervious the convergence mechanism is to ambient vibration and any differential aging effects between the three color components.

Ambient lighting will also have a strong effect on display color, especially in a dynamic cockpit environment. Incident ambient illumination reduces both the brightness contrast and color contrast of displayed information via increases in display background brightness. As a result, the visibility and perceived saturation of colored symbology is reduced. The brightness of CRT-produced colors is not homogenous because of the differences in efficiency of the three primary phosphors and the spectral luminosity function of the eye (e.g., Hurvich, 1981). The degree to which a given color CRT is affected by ambient illumination depends largely upon the colors selected, symbol brightness, and the qualities of any contrast enhancement filters fitted to the display. Fortunately, some relief for the degrading effects of ambient illumination may be provided by the fact that the observers' contrast sensitivity and color perception are generally enhanced as display background and symbol brightness increase (Brown & Mueller, 1965; Burnham et. al., 1963).

Ultimately, the utility of a color display is dependent upon the display providing suitable chromatic differentiation and image brightness to ensure reliable symbol visibility and color discrimination under all operational conditions. The brief review of relevant visual factors indicates that color selection and brightness specification for airborne color CRT displays poses difficult problems for both the display designer and human factors specialist. At the present time, there are no analytical tools sufficient to solve these problems. Recent attempts to derive a model of photocolorimetric space (Galves & Brun, 1975; Martin, 1977), which includes both chromatic and brightness dimensions, have not received adequate experimental verification. Moreover, it is doubtful whether any model based solely on chromatic and luminance differences can provide suitable description of the perceptual factors inherent in complex color CRT presentations. Models offering overly conservative figures of merit for discrimination, which may indicate color and brightness specification that ensure performance, are likely to incur large penalties in hardware costs and display life. Such analytical techniques are useful engineering tools which must be supplemented with visual verification testing tailored to the particular display hardware and application. The remainder of this paper describes the analytical and experimental methods used in the Boeing color CRT development program.

## THE BOEING DISPLAYS

A significant step in commercial aviation was achieved when Boeing decided to integrate color CRT displays into the flight decks of the new 757/767 jetliners. After a review of a number of proposals, it was decided to pursue the development of a ruggedized, high-resolution shadow-mask type of display. The color and contrast capability of the shadow-mask system were primary advantages, but the final decision awaited demonstration of suitable ruggedness and resistance to vibration.

The shadow-mask display is the foundation of two major systems on the 757/767. The Electronic Flight Instrument System (EFIS) consists of electronic ADI and HSI primary flight instruments. A second system, also composed of two displays, combines Engine Indication and Crew Alerting functions (EICAS). Figure 7 shows typical display formats for the EADI and EHSI components. The EFIS displays are hybrids in that they write in both raster and stroke modes. Raster is used for sky/ground shading on the EADI and for weather radar imagery on the EHSI. Stroke and raster writing modes are combined such that stroke-written symbols may overlay color raster backgrounds. The EICAS system displays only stroke-written symbology.

Display color capability is illustrated in the CIE X-Y chromaticity space in Figure 8, where the triangular region defined by the three primary phosphor chromaticities and filter characteristics bounds the region of possible display colors. Symbol generator hardware allows the selection of up to seven stroke colors (and black) and four raster colors. Color mixing is controlled by amplitude modulation of the three component beams, which also permits selective color purity adjustments for each color. The displays are fitted with multi-band contrast enhancing filters tuned to the three phosphors and an anti-reflective coating. Separation between phosphor triads is .012", which corresponds to approximately 1.2 minutes of visual arc at the designed viewing distance. Other visually relevant features are an 80 Hz stroke refresh rate, 40 Hz frame/80 Hz field rates for raster, and automatic brightness/contrast

compensation via integral light sensors.

The incorporation of color CRTs on the new Boeing flight decks produced the need for a consistent color coding strategy. All displayed information is redundantly coded and absolute color identification is not required. Color is not used as a unitary coding dimension but is always combined with shape, alphanumerics, location, brightness or some other form of code. There are several reasons for adopting this strategy. Most prominent is the problem of partial display or color component failure. In this situation, coding redundancy permits a failure mode of monochromatic presentation without any loss of essential information. Color shifts as a function of display aging also have minimal impact on operator performance when color coding is used redundantly. Additional reasons concern the nature of color discrimination performance required of the display user. When color is used in concert with other coding dimensions, the basic perceptual mode required is one of relative or comparative color discrimination. The demands on both the display user and the display hardware itself are reduced when comparison between colors rather than absolute identification of each color is required (e.g., Krebs et. al., 1978). Color vision deficiencies in the user population are also less critical when all information is available through multiple codes.

OBJECTIVES AND APPROACH

Color selection and visual verification testing for the Boeing color CRT displays involved a number of major objectives. The first objective was chromaticity and brightness specification for a visually verified set of seven stroke-written colors and four raster colors. A second objective was the determination of the minimum brightness levels required for color discrimination under worst-case high ambient lighting conditions. It was recognized that these minimum levels would have a direct impact on CRT tube life and were a major factor in display brightness certification. Third, verification of color discrimination under low ambient viewing conditions was an important consideration. Investigation of preferred levels of color saturation for low ambient viewing was also part of this test phase, since highly saturated colors can produce exaggerated perceptions of apparent depth (chromostereopsis) and degrade visual acuity (Farrell & Booth, 1975; Riggs, 1965; Semple et. al., 1971). A final objective was the accumulation of supporting data for certification of displays and pilots' visual performance.

The approach to achieving these objectives consisted of four sequential phases:

o  Initial color selection by analytical computer model

o  Raster color and brightness optimization

o  Stroke/Raster color and brightness test - high ambient phase

o  Stroke/Raster color and brightness test - low ambient phase

Color discrimination performance was assessed by a comparative procedure which best reflects the operational use of color on the Boeing displays. Discrimination between all relevant stroke colors, raster colors, and combi-

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nations of stroke and raster was accommodated by the test procedures used.


## INITIAL COLOR SELECTION


DESCRIPTION OF ANALYTICAL COMPUTER COLOR MODEL

Historically, luminance contrast has been used as a means of predicting detection of a symbol against its background or discrimination between symbols on a common background. With the advent of narrow band phosphors and trichoric or notch filters, the discrepancy in using luminance contrast ratio as a figure of merit for a CRT display became apparent. Even a subjective comparison of a neutral-density filtered display with a notch filtered display of equal symbol and background luminance levels shows the neutral density display to have greater symbol to background discrimination. This is due to the chrominance contrast between symbol and background inherent through a neutral density filter but lacking in a notch filter.

Any prediction of the display operator's ability to discriminate and differentiate between luminous sources must take into account not only the luminous contrast but also the chrominance contrast between symbolic presentations and their backgrounds. This is especially true for shadow-mask CRT displays where a wide range of chrominance difference is used to code or enhance information.

Taking into account the extensive work of Judd and MacAdam on the visual perception of color difference (e.g., see Graham, 1965b) and the photocolorimetric grid system developed by Kowaliski (1969), Galves and Brun (1975) defined a model of photocolorimetric space in which the perception of luminance contrast and chrominance contrast are equivalent. In this space, an identical distance between two points, representing two different luminous sources, always represent an identical difference in visual impression. The derivation of the Galves and Brun model of photocolorimetric space is shown in Table 1 and Figures 9 and 10.

The model establishes two perceptually equivalent axes in photocolorimetric space which Galves and Brun call the Luminance Discrimination Index (IDL) and Chrominance Discrimination Index (IDC). Starting with two luminous sources with known luminance values and 1960 CIE-UCS color coordinates ($U_1$, $V_1$, $L_1$, AND $U_2$, $V_2$, $L_2$), the luminous difference can be expressed as the log of the luminance contrast ratio. Galves and Brun (1975) reported that the minimum discernable contrast ratio has been determined to be log 1.05. A comfortably discernable contrast ratio has been historically accepted to be a 3 dB luminance difference or $\log\sqrt{2}$. This is approximately seven times the minimum discernable contrast ratio. From this, Galves and Brun have defined the Luminance Discrimination Index (IDL) to be the log of the contrast ratio between two luminous sources divided by $\log\sqrt{2}$. By definition, the IDL will be one for a contrast ratio of $\log\sqrt{2}$ and can be considered a figure of merit for the luminous difference between two sources.

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The Chrominance Discrimination Index (IDC) is defined in a similar and perceptually identical manner. Using the 1960 CIE Uniform Chromaticity Scale (UCS), the chrominance difference between two luminous sources is defined as the root of the sum of the squares of the differences in U and V coordinates. Galves and Brun (1975) have reported that the smallest discernable color difference in terms of 1960 CIE UCS coordinates is 0.00384. Multiplying this value by approximately seven, as was done in the derivation of IDL, yields a comfortable chrominance difference of 0.027. Therefore, the Chrominance Discrimination Index (IDC) becomes the chrominance difference between luminous sources divided by 0.027. In this manner, both axes of photocolorimetric space should be perceptually identical and the root sum of squares value of IDL and IDC become the overall figure of merit of the discriminability between two luminous sources - the Index of Discrimination (ID).

## APPLICATION OF MODEL TO DISPLAY COLOR SELECTION

As a starting point for the selection of a color repertoire for the EFIS, EICAS and CAI displays, a computer program was created which predicted the Index of Discrimination between luminous sources of known primary luminance value mixes. It must be recognized that the x axis of a CIE (1931) Chromaticity Diagram is, by construction, an alcheny or locus of zero luminance values (Judd, 1951). All lines parallel to the x axis are therefore nomographic. Figure 11 shows a CIE (1931) Chromaticity Diagram with the nomographic color mix model which was programmed into the computer to predict chromaticity coordinates of any color contained in the CRT primary triangle. With this algorithm, the computer can mix any combinations of luminous sources with a raster and/or reflected ambient backgrounds of known luminance and chrominance values. The resultant program is capable of predicting IDL, IDC, ID, x, y, u, and v values from the x and y coordinates of the CRT phosphor primaries, the x, y, and luminance values of the reflected ambient illumination (i.e., display background), and the primary luminance mix of any secondary colors to be investigated.

The computer program described above was used to select those candidate colors which were equal in ID from their closest neighbors in an attempt to create a color repertoire which was perceptually balanced. The balancing procedures addressed the implicit assumption that the usefulness of the entire color repertoire is limited by the weakest link, in this case the smallest color difference. A large number of colors and backgrounds can potentially be accommodated by the color model. It also provided an excellent tool for investigating color shifts due to reflected ambient illumination and stroke/raster interactions. The nature and importance of these color shifts will become apparent in subsequent sections.

## RASTER COLOR AND BRIGHTNESS OPTIMIZATION

### Objectives

The second phase of color selection was related primarily to homogenous color raster fields used for sky/ground shading on the EADI and weather radar

imagery on the EHSI. Coding conventions dictated a blue for sky shading and a brown or black to represent the ground. Weather radar coding followed standards of green, amber, and red respectively for increasing severity of weather returns. Major objectives of this phase were: 1) to establish chromaticity specifications for the colors blue, green, amber, and red; 2) optimization of amber chromaticity to achieve maximal discrimination between amber and the green and red primaries; and 3) to determine the minimum raster brightness levels required to ensure reliable color discrimination between raster fields under worst-case high ambient illumination.

## Test Methods and Procedures

### Participating Subjects

Eight Boeing employees participated in the raster test. All of the subjects were male and ranged in age 25 to 48 years with a mean of 36.1 years. Subjects were screened for color vision deficiencies with the Abbreviated Color Vision Test consisting of American Optical HRR Pseudoisochromatic Plates.

### Test Equipment

Visual testing was conducted with engineering prototype units from the Rockwell-Collins EFIS 700 system. An EADI display unit, which has a useable display area of 2.35 x 2.10 inches, was chosen as the test display because of its built-in capability to present relatively large circular raster fields with independent selection of colors for the top and bottom halves of the field (i.e., a bipartite field). This circular raster field subtended a visual angle of approximately 5.5 degrees at the designed viewing distance (32 inches). The symbol generator hardware was modified to accommodate split-field raster patterns of any color, and also contained software for the test patterns used during all test phases. A specially constructed electronics board and test console was used to control the display system and provided the following functions: amplitude-modulated control of primary beam currents for the independent selection of seven colors; independent purity adjustment for all colors (except white) which allowed purity control from maximum through pastel to white along a vector passing through CIE Source C; separate display brightness controls for raster, stroke, and synchronous overall brightness; color switching for top and bottom raster half-fields; switching for up to 15 multi-color stroke symbol patterns; and total display blanking.

To create the high-ambient lighting environment required for testing, four Berkey-Colortran quartz halogen lamps fitted with dichroic filters were positioned at 45 degrees off-axis from the display face. The particular lighting arrangement was calibrated to produce 8000 footcandles (Ft.-c) of 5230 degrees Kelvin at the display face. The 8000 Ft.-c level, considered as the worst-case display illumination caused by sun shafting through the side windows of the 757/767 cockpit, was arrived at by using an estimate of 10,000 Ft.-c illuminance of sun in earth atmosphere (Semple et. al., 1971) and correcting this value by the coefficient of window transmissivity and the cosine of the smallest angle between the side windows and a line perpendicular to the display surface. Measurement of illuminance, luminance, and chromaticity were accomplished with a Pritchard 1980A photometer and a Gamma Scientific C-3 spectraradiometer equipped with a spectral scanning system. A diagram of the color display test setup is presented in Figure 12.

## Procedures

The colors green, amber, red and blue were first selected using the computer color model. Green and red chromaticity was fixed by the respective phosphor primaries, since maximum purity and sufficient luminance was available by using the primaries for these colors. This was not the case for blue. The luminous efficiency of short wavelength phosphors is relatively low due to the relative insensitivity of the eye to short wavelengths (Haeusing, 1976; Hurvich, 1981). In addition, visual acuity in the blue region is poor (Jones, 1961; Myers, 1967) and degrades further with increasing purity of the short-wavelength image. These problems can largely be overcome by increasing the luminance and decreasing the purity of the blue used, and large amounts of the primary green can be mixed with the primary blue without the resulting color perception being changed from blue (Hauesing, 1976). For these reasons, the blue primary alone was not used, but was mixed with green to produce a cyan of pleasing appearance. The color amber is a mixture of the primaries green and red. An effort was made to optimize discrimination between green, amber and red because of the significance of amber and red for caution and warning color coding. Five ambers were selected for testing. They were all located on the green-red chromatic axis and were of equal beam current and approximately equivalent luminance. The goal was to select that amber which offered maximal discrimination with red and green at the lowest luminance (best display efficiency).

Initial luminance values and chromaticity coordinates of the raster color set were balanced using the computer model to produce ID values of approximately .6 between all colors and between each color and the reflected ambient background. Galves and Brun (1975) have indicated that an ID of .6 would permit comfortable detection and identification under any ambient lighting. Figure 13 shows the four raster colors located in CIE X-Y coordinates, as well as the five ambers tested. The point marked RA indicates the chromaticity of the reflected ambient illumination. At the 8000 Ft.-c reference illumination, the display reflected 98.5 foot-lamberts (Ft.-L) at the indicated chromaticity. The vectors emanating from each color point illustrate the chromaticity shifts resulting from summation of the reflected ambient and display-generated phosphor emissions. Note that all of the colors decrease in purity and shift toward the reflected ambient.

All raster testing was conducted under 8000 Ft.-c of illumination. Since display brightness was a test variable, brightness steps were calibrated according to a scale based on the .6 ID value. The display was set such that the 50% brightness setting corresponded to the .6 ID value for each color. From that point, brightness adjustment was synchronous for all colors and varied according to a percentage scale.

Prior to beginning visual testing, the test subjects were shown all of the raster colors under both dark and high-ambient viewing conditions. The colors were named for them and they were given a chance to familiarize themselves with the test apparatus and the color test patterns. The experimental task consisted of a comparative, forced-choice color naming task. Upon presentation of a split-field raster pattern, subjects were required to name the color of the top half-field followed by the name of the color of the bottom half-field. Only the particular colors being compared and the word "blank" were permissible responses. The raster test pattern and a summary of

test conditions are illustrated in Figure 14.

The first test sequence involved the colors green, red, and the five
ambers, i.e., the set of rasters relevant to weather radar codes. Each sub-
ject was tested under all conditions in a within-subjects experimental design
(see Kirk, 1968). The split-field raster patterns were presented in a counter-
balanced fashion across the eight subjects to minimize order effects. Half of
the eight subjects began the test with the greenest amber (1) and proceeded in
sequence to the reddest amber (5). The other half of the subjects received
the amber sequence in reverse order. Brightness was manipulated within each
amber condition by decreasing the brightness after each series of eight test
patterns. The brightness values tested were 30%, 20%, 10%, and 5% on the
defined scale, a range determined in a brief pretesting procedure.

The second test sequence involved only cyan and blank half-fields, and
was designed to accommodate the relevant raster discriminations (sky/ground)
on the EADI display. The reason for testing with a blank rather than a brown
half-field for the ground texture was that the ground texture was defined to
be only cosmetic in nature since aircraft orientation can easily be determined
by the position of the cyan sky shading. In addition, brown is essentially a
blackish amber or yellow (Hurvich, 1981) and can only be produced on a
shadow-mask CRT by creating an amber of low luminance.

The EADI ground shading is a low-luminance amber which is not required to
be visible under the 8000 Ft.-c test conditions. As Figure 14 reveals, the
cyan-blank (reflected ambient) test involved only two patterns. Presentation
order of the patterns was radomized, and a within-subjects design with bright-
ness as the single independent variable was used. Each subject was presented
a series of six patterns at each brightness level, and brightness was in-
creased in steps according to the methods described earlier.

## Test Results

Figures 15 and 16 show the individual effects of amber chromaticity and
display brightness level on green-amber-red color discrimination performance.
An analysis of variance (e.g., Kirk, 1968) on the mean percent correct color
discrimination scores revealed that both affects significantly influenced
subjects' ability to discriminate between the three colors. Further statis-
tical tests indicated that the middle amber (3) produced better performance
than the other four ambers tested, and that increases in brightness beyond the
10% level do not significantly improve prformance. The most critical data for
this test may be found in Figure 17, which depicts the interaction of amber
chromaticity and brightness level. This interaction was also found to be
statistically significant, and basically points to the fact that the middle
amber (3) produced the best color discrimination performance at the lowest
brightness level. All of the test subjects demonstrated error-free color
discrimination between green, amber, and red with amber (3) at a 10% bright-
ness level.

The results of the cyan-reflected ambient color discrimination test are
shown in Figure 18. Mean percent correct color discrimination performance
increased with display brightness increments, but an analysis of variance for
these data did not indicate a significant effect of brightness level. At some
point between the 10% and 20% levels, subjects would presumably reach an error-

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free level of performance. Since the data did not allow a clear decision as to the required brightness level for the cyan raster, it was decided to accept the same level (10%) that was found sufficient for the other raster colors.

Operationally, the pilots using EFIS displays will be confronted with color raster fields considerably smaller than the 5.5° test field in the present study. This is especially true for weather radar imagery on the EHSI, where returns from small or distant storm cells can produce a small color image. Hardware limitations in the experimental test setup precluded testing with a variety of field sizes, so a field-size correction factor was applied to the raster test results. An estimated minimum raster size of 5' of visual arc was used as a reference. The classic contrast threshold data of Blackwell (1946) were consulted, and it was found that an approximate 3 to 1 increase in contrast was required when extrapolating from a 5.5° to a 5' visual field size for a background brightness of 100 Ft.-L. Following this rationale, brightness values determined in the present test were multiplied by three. Brightness requirements for raster fields were clearly overestimated by the computer model. For the large fields tested, the brightness values (10%) resulting in essentially error-free color discrimination performance were only a fifth of the required brightness values predicted by the computer model (50%). Even after application of the small-field correction factor, the psychophysically determined brightness requirements were significantly less than the model's predictions.

Actual chromaticity coordinates and brightness values for the four raster colors tested may be found at the bottom of Table 2. It is important to note that these values are directly applicable only to the particular displays under test. Chromaticity and brightness requirements for any color CRT display must take into account phosphor characteristics, screen geometry, and the properties of contrast enhancement filters and anti-reflective coatings fitted to the display.


## STROKE/RASTER COLOR AND BRIGHTNESS TEST

### HIGH AMBIENT PHASE


## OBJECTIVES

The third phase of color selection and verification testing was designed primarily to complete the specification of a seven color repertoire and determine the minimum brightness requirements for stroke-written symbology. The visual factors involved in producing acceptable color stroke-written images are somewhat more critical than for raster fields. Images composed of narrow lines or strokes require higher brightness to assure adequate visibility and are more demanding of subjects' abilities to resolve fine details. With respect to color, the ability to discriminate color differences for small images is reduced. Moreover, two aspects of the shadow-mask type of color display and the combined use of stroke and raster writing techniques are significant.

First, stroke-written lines which are a mixture of more than one primary will inevitably contain some col... fringes produced by misconvergence. The extent to which color perception is affected will be determined by the amount of misconvergence, the stroke width, and viewing distance. Color discrimination performance must therefore be tested within the specified operating ranges for convergence and linewidth. Second, stroke-written symbols which overlay raster fields of a different color will shift in color. The additivity of luminances at the intersection of the images will result in a stroke symbol of increased brightness whose color is shifted along a vector connecting the stroke and raster chromaticities. The integrity of the intended stroke color will depend largely upon the brightness contrast existing between the stroke and raster images. Obviously, stroke color discrimination must be tested against all anticipated raster backgrounds.

Having established chromaticity specifications for four of the seven colors in the previous raster tests, major objectives for this test phase were: 1) to establish chromaticity specifications for three remaining stroke colors; 2) to determine the minimum stroke brightness levels required to ensure reliable color discrimination between stroke-written colors under 8000 Ft.-c of ambient illumination; and 3) verification of stroke color integrity on all raster backgrounds.

## Test Methods and Procedures

### Participating Subjects

Ten Boeing pilots and flight engineers participated in the testing. All of the subjects were male and ranged in age from 23 to 62 years with a mean of 43.3 years. They were randomly selected from the population of Boeing pilots and flight engineers possessing current Class I medical certificates, and therefore met the same minimum criteria for visual functions demanded of the airline pilot population.

### Test Equipment

The basic test setup was the same as in the raster study. Prior to testing, measurements of convergence and line width were taken to confirm that they were within specified limits. Convergence specifications were defined in prior psychophysical tests (Merrifield, Haakenstad, Ruggiero, and Lee, 1979), which revealed that image separations up to .008 inches resulted in acceptable stroke-written color symbols. Display convergence was within .006 inches and met the display specifications. At the 32 inch viewing distance, .006 inches of misconvergence results in a stroke image separation which subtends only .64 minutes of visual arc. Line widths were also found to be within the specified range of .008 to .020 inches. For the higher brightness levels used during testing, line widths tended toward the upper end of this range.

### Procedures

The initial procedural step was to consult the computer color model in an attempt to locate those chromatic regions best suited for the remaining colors. The red-green and green-blue chromatic axes already contained the secondary colors amber and cyan, respectively; however, the red-blue axis was unused. A plot of the CRT chromaticity triangle in 1960 UCS coordinates

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revealed that the axis between the red and blue primaries was the longest of the three chromatic axes (i.e., the greatest perceptual spacing), and the fact that the blue primary was not used left a large area of potential chromatic differentiation untouched. For these reasons, it was decided to select two secondary colors on the red-blue axis. The last free chromatic region was the central area of the CRT color triangle, dictating that the seventh color should be a white. Chromaticity coordinates of the colors red, green, amber, and cyan and raster brightness values, which were all established in the previous test phase, were input to the computer model along with the general regions for the last three colors. The model selected the precise chromaticity coordinates for the remaining colors based upon a balanced perceptual set of seven stroke colors. Balancing involved selecting the chromaticities and relative luminances of the seven stroke colors such that the ID between all paired combinations of colors on their worst-case raster backgrounds and under 8000 Ft.-c of illumination were approximately equal. The colors magenta (reddish purple), purple, and white completed the seven color repertoire.

Visual testing was designed to assess color discrimination performance for the following display combinations:

o  Stroke colors to reflected ambient

o  Stroke color to stroke color

o  Stroke colors to raster colors

o  Raster colors to reflected ambient

o  Raster color to raster color

o  Stroke color to stroke color overlaying raster colors

To accommodate all of these comparisons, a series of 10 split-field raster patterns was combined with 10 stroke symbol patterns. Each stroke pattern consisted of 18 diamond-shaped symbols arranged in two rows of 9 symbols each. Within a row, symbols of different colors were randomly ordered such that each of the seven stroke colors was represented at least once in every row. The diamond-shaped stroke symbols subtended a visual angle of approximately 20' of arc and were chosen because their small size was representative of the smallest symbology elements used for the Boeing display formats. The test pattern configuration is shown in Figure 19.

The experimental design consisted of a 10 x 10 Latin Square (Winer, 1971) to counterbalance order effects across the 10 subjects. Rows of the Latin Square were composed of balanced orderings of the 10 split-field raster patterns shown at the bottom of Figure 19. The 10 stroke symbol patterns were combined with this Latin Square such that each of the 10 stroke patterns appeared once in each row and equally often with each raster pattern across the 10 rows. The effect of the balancing procedure was to produce equivalent test rows such that each stroke-background combination was replicated four times per row. Each subject began the test with a different row of the balanced Latin Square, and the stroke/raster brightness contrast ratio was manipulated between rows. A within-subjects statistical model with repeated measures characterized the design (see Kirk, 1968), with stroke color, back-

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ground color (rasters or reflected ambient), and stroke/raster brightness contrast ratio as the independent variables. Mean percent correct color discrimination was the dependent measure.

Since the determination of the minimum stroke brightness levels required to ensure reliable discrimination between stroke-written colors on all backgrounds was a major test objective, stroke brightness steps were calibrated according to a scale based on the brightness contrast ratio between stroke and raster colors. Raster brightness was fixed at the level determined in the previous test phase, and stroke brightness was manipulated synchronously for all stoke colors according to equal steps in the stroke/raster contrast ratio. The contrast ratio was incremented after each test row (10 test patterns) until an error free series was completed or maximum display brightness was reached. The starting contrast ratio value was always a nominal 4.0 on the defined scale.

Prior to beginning visual testing, the test subjects were shown all of the stroke and raster colors under both dark and high-ambient viewing conditions. The colors were named for them and they were given a chance to familiarize themselves with the test apparatus and sample test patterns. As in the previous test phase, the experimental task consisted of a comparative, forced-choice color naming task. Upon presentation of a test pattern, subjects were required to name in order: 1) the color of the top half-field background; 2) the color of the bottom half-field background; 3) the colors of the top row of stroke symbols from left to right; and 4) the colors of the bottom row of stroke symbols from left to right. Only the seven display colors being tested and the word "blank" were permissible responses.

Due to the complexity and length of the test, it was decided that a criterion of 100% correct color discrimination was unrealistic. Random errors resulting from subject fatigue or other factors unrelated to color perception (i.e., "experimental noise") are likely to influence the data under such conditions, and a criterion demanding error-free performance from all subjects would either be unattainable or artifactually result in unnecessarily high brightness levels. For these reasons, a criterion of 95% mean correct color discrimination for all stroke and raster colors was adopted.

## Test Results

The major results are summarized in Figures 20-22. Each bar in these figures represents the mean of 200 trials. Stroke color discrimination is shown averaged across backgrounds (raster colors and reflected ambient) since an analysis of variance on the complete data set revealed that the background did not significantly influence stroke color discrimination performance. This factor will not be considered further. The obvious trend toward improving performance with increases in the stroke/raster contrast ratio was found to be statistically significant. Further statistical tests on this factor indicated that stroke color discrimination improved significantly when the contrast ratio increased from 4.0, but that further increases beyond a contrast ratio of 5.0 produced no reliable improvements in performance. All seven stroke colors met or exceeded the 95% criterion at a nominal stroke/raster contrast ratio of 5.0. The main effect for stroke colors was significant as was the interaction between stroke colors and contrast ratio. These two effects reflected the fact that the colors magenta, purple, and cyan produced the

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poorest color discrimination performance at the lowest contrast ratio, and therefore benefited the most from increases in stroke/raster contrast ratio. Mean color discrimination performance for the raster colors was 97.6%, replicating the results of the previous raster test.

Figure 23 shows a confusion matrix which indicates the ID values and errors between the seven stroke colors at a stroke/raster contrast ratio of 5.0. The matrix reveals three important facts: 1) errors were not uniformly distributed between color combinations; 2) numbers of errors between colors were not highly correlated with the ID values between colors; and 3) the ID values between colors were all considerably higher than the figure of merit (ID = .6) proposed by Galves and Brun (1975). In contrast to the overestimated brightness values for large raster fields, the computer color model tended to underestimate brightness requirements for small, stroke-written color images.

A further inspection of Figure 23 shows three regions of disproportionately high error rates. Color confusions between cyan and green may be attributable to small-field tritanopia, a loss of color discrimination ability with small visual fields often resulting in blue-green confusions (see Farrell & Booth, 1975). The present findings support the general recommendation that small color fields, particularly in the blue region, be avoided (Krebs et. al., 1978; Semple et. al., 1971). The two other regions of relatively high color confusion were between red and magenta and between magenta and purple. The reasons for confusion in these regions are less clear, but may be partly explained by the relative unfamiliarity of colors in the purple family. In any event, all ten of the pilots tested found the color purple objectionable. Pilots' comments indicated that the brightness and clarity of the small purple images was unacceptable. Based on these findings, it was decided to eliminate purple from the repertoire of stroke colors but retain the capability to use purple for future raster applications.

The final, verified repertoire of seven stroke colors is shown plotted in CIE X-Y coordinates in Figure 24. The vectors emanating from each color point illustrate the chromaticity shifts resulting from 8000 Ft.-c of display illumination. Post test chromaticity and brightness measurements for all stroke colors may be found in the top section of Table 2. Again, these data are directly applicable only to the particular display hardware tested. They are not intended as general guidelines or specifications for all color CRT display systems.

The brightness specifications presented in Table 2 are the minimum brightness levels required for criterion color discrimination performance. As such, they represent display performance requirements. When available, display brightness falls below these levels, whether by display aging or some malfunction, color coding of displayed information will be rendered less effective due to degraded color discrimination performance. In practice, available new display brightness should be some multiple of these minimum levels to allow for decreasing brightness capability as the display ages. The usable life of a color CRT display is directly related to the ratio of available display brightness and minimum required brightness. For the Boeing systems, available brightness for a new color CRT is in excess of twice the minimum brightness levels determined in the present tests. Useable display life has been projected to be in the range of 10,000 to 15,000 hours.

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# STROKE/RASTER COLOR AND BRIGHTNESS TEST

## LOW AMBIENT PHASE

### OBJECTIVES

The final phase of color selection and verification testing investigated color display characteristics under low ambient viewing conditions. The verification of color discrimination performance with the specified seven color repertoire was one major objective. In general, an observer's contrast sensitivity and color perception deteriorates as display background and symbol brightness decreases (Graham, 1965b; Burnham et. al., 1963). Colors displayed against a dark background are often perceived as being less saturated or pure than when a light background is present (Pitt & Winter, 1974). Thus, although a color CRT display exhibits greater brightness contrast and color purity in a low-ambient lighting environment, an observer's sensitivity to color differences diminishes. The second major objective of low ambient testing was the investigation of subject-preferred levels of color saturation, since highly saturated colors can produce exaggerated perception of apparent depth (chromostereopsis) and degrade visual acuity (Farrell & Booth, 1975; Riggs, 1965; Semple et. al., 1971). Increases in pupil size for the dark-adapted eye would tend to enhance any undesirable visual effects caused by high color saturation.

### Test Methods and Procedures

#### Participating Subjects

Ten Boeing pilots and flight engineers participated in this last test phase. All of the subjects were male and ranged in age from 38 to 62 years with a mean of 46.6 years. They were randomly selected from the population of Boeing pilots and flight engineers possessing current Class I medical certificates. Four of the subjects had participated in the previous high-ambient color testing.

#### Test Equipment

The basic test setup has been described in earlier sections. However, two features were unique to this test phase. The first involves the control of color purity. The electronics board and test console contained circuitry and calibrated potentiometers enabling independent color purity adjustment for all of the colors except white (by definition white is a color of minimum purity). The range of adjustment allowed purity to be varied for each color from its specified zero-ambient chromaticity (i.e., its location on the boundary of the CRT color triangle) through pastel to white along a vector passing through CIE Source C. The second equipment feature, unique to this test phase, pertains to the production of the low-ambient lighting environment. A reasonable night time level of cockpit illumination was estimated to be .1 Ft.-c. This ambient illumination was produced by adjustment of both fluorescent and incandescent lighting in the test area until .1 Ft.-c was

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measured at the face of the test display.

Procedures

Visual testing was conducted in two parts. In the first part, color discrimination performance was measured with the fully saturated color set. The test patterns, experimental task, and basic procedures were identical to those used for high-ambient testing. Since display brightness was not a critical factor with such dark viewing conditions, subjects were permitted to adjust the brightness of the display to a comfortable level. The stroke/raster contrast ratio was fixed at the previously determined value. An abbreviated series of counterbalanced test patterns which contained all of the critical color combinations was used.

Part two involved the determination of subject-preferred levels of color saturation. Special test patterns were developed for this purpose and are graphically described in Figure 25. Each of the seven stroke colors was presented once on both top and bottom half-fields, and the stroke symbols of each color were vertically aligned such that a given color appeared in the same position on both top and bottom fields. The top half-field was always one of the four raster colors and the bottom half-field was always blank. The patterns allowed a direct comparison between stroke color appearance on the dark and colored backgrounds, and provided a reference for the effects of color desaturation. An EADI test pattern was also used, and was modified so that it contained all colors. The stroke/raster contrast ratio was fixed at the nominal 5.0 value.

The four steps in the desaturation test procedure are described at the bottom of Figure 25. Subjects were instructed to request changes in color saturation individually for each color (either more or less color purity) according to their preference and changes in display brightness were permitted at any time. The instructions to subjects emphasized that the image quality or focus of the displayed symbols could be varied by changes in color saturation and that perceptions of apparent depth between colors could also be modified in this manner. They were instructed to attempt to minimize any undesirable image blurring or depth effects by requesting color saturation changes. Repetitions of each pattern provided a means of checking the consistency of subjects' adjustments. Color saturation and display brightness adjustments were recorded after each test pattern presentation.

Prior to beginning the tests in this phase, subjects were shown example test patterns and all stroke and raster colors. The effects of changing color purity were also demonstrated for each of the colors. Testing began after a dark adaptation period of 15 minutes had elapsed.

Test Results

Color discrimination performance under the .1 Ft.-c ambient viewing conditions is illustrated in Figure 26. Each bar represents the mean of 100 trials. The 95% performance criterion was satisfied for all seven colors.

Figure 27 summarizes the results of color saturation testing. The numbers in the columns corresponding to each test subject indicate whether that subject chose to desaturate a particular color in either the first or

second test sequence. The absence of a number in any position means that the
subject chose to leave the color in its most saturated form. In a number of
cases, subjects requested more color purity than was available. The data,
therefore, show subjects' tendencies to desaturate the individual colors and
not the magnitude of saturation adjustments.

Several facts are apparent from Figure 27. The tendency to desaturate
colors was primarily limited to the colors green, red, and cyan. Desaturation
adjustments were not very consistent; within any given color only three sub-
jects at most elected to desaturate that color in both test sequences. While
there was a slightly higher frequency of saturation adjustments in the second
test sequence, there were no statistically reliable difference in the tendency
to desaturate colors between the first and second sequences.

Subjective comments from the group of pilots tested indicated that
slightly blurred images and apparent differences in depth between colors were
perceived by some of the pilots. However, none of the pilots found these
effects particularly objectionable or distracting. In general, pilots
preferred maximally saturated, vivid colors and were unwilling to sacrifice
color purity for any potential benefits in image quality. Subsequent opera-
tional testing of the Boeing displays, with many hours spent viewing the color
CRTs in a dark simulator environment, has shown that the colors selected are
highly acceptable for prolonged periods of low-ambient viewing.


## OVERVIEW AND CONCLUSIONS


The present paper has described the human factors and display hardware
considerations which impact the selection of colors for today's modern air-
borne color CRT displays. The analytical and experimental methods employed by
Boeing in the development of color CRT display systems for the new 757/767
commercial jetliners were presented in detail. More important than the spe-
cific data presented is an awareness of the critical factors which constrain
the use of color and the methodology for confronting them. The color CRT
display offers great potential advantages for a variety of airborne applica-
tions; however, the viability of any color display concept rests on the assump-
tion that the visual and perceptual requirements of the display user can be
satisfied.

The proliferation of color display technology in commercial aviation does
not lighten the task of the military. Problems of display visibility and
color perception caused by dynamically changing ambient illumination will be
even more severe in the bubble-canopy cockpits of many military aircraft.
Color will likely be used to code information in a way which is more
critically demanding of accurate color perception. Recognition of the
complexity and importance of these issues is mounting as advances in color
display technology open up new areas of application (e.g., Waruszewski, 1981).

There is a real and immediate need for more programmatic research
activity on the human factors aspects of color displays. Continued reliance
on extensive human performance testing to verify new display concepts and

define specifications will hinder future developments. In the area of color selection, there has been a recent trend toward the development of analytical models of color perception with the hope that such techniques can solve the problems confronting the display designer. Currently available analytical models, while certainly a step in the right direction, are not sufficiently precise to accomplish this task. There is a basic failure to account for the complexity of the visual process. Future research must strive to integrate such factors as field size, number of colors, and mode of color discrimination performance into the present formulations. The incorporation of more parameters characterizing a visual display will ultimately produce analytical techniques which minimize the need for repetitive and expensive human performance testing. The design of more effective color display formats and color coding applications will also benefit from more programmatic research efforts. The payoff is that today's rapid advances in color technology will permit the development of more integrated, efficient methods of information display for tomorrow.

Airborne color displays are here to stay. The burden is on us, the human factors specialists and display designers, to see that their full potential is realized.

## ACKNOWLEDGEMENTS

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# Table 1
## Discrimination Index Between Two Luminous Sources

### Luminance Discrimination Index

Luminance Difference $= \mathrm{Log}\,\dfrac{L1}{L2} = \mathrm{Log\ CR}$

Perception Threshold $= \mathrm{Log}\ 1.05$

Unitary Luminance Difference $= \mathrm{Log}\sqrt{2} = \mathrm{ELU}$

Ratio of $\dfrac{\text{Unitary Luminance Difference}}{\text{Perception Threshold}} = 7$

Index of Luminance Discrimination (IDL) $= \dfrac{\mathrm{Log\ CR}}{\mathrm{ELU}}$

### Chrominance Discrimination Index

Chrominance Difference $= \sqrt{\Delta u^2 + \Delta v^2}$

Perception Threshold $= 0.00384$

Unitary Chrominance Difference $= 0.027 = \mathrm{ECU}$

Ratio of $\dfrac{\text{Unitary Chrominance Difference}}{\text{Perception Threshold}} = 7$

Index of Chrominance Discrimination (IDC) $= \dfrac{\sqrt{\Delta u^2 + \Delta v^2}}{\mathrm{ECU}}$

### Index of Discrimination in Photocolorimetric Space

$$ID = \sqrt{IDL^2 + IDC^2}$$

60

TABLE 2

Color Verification Test Results

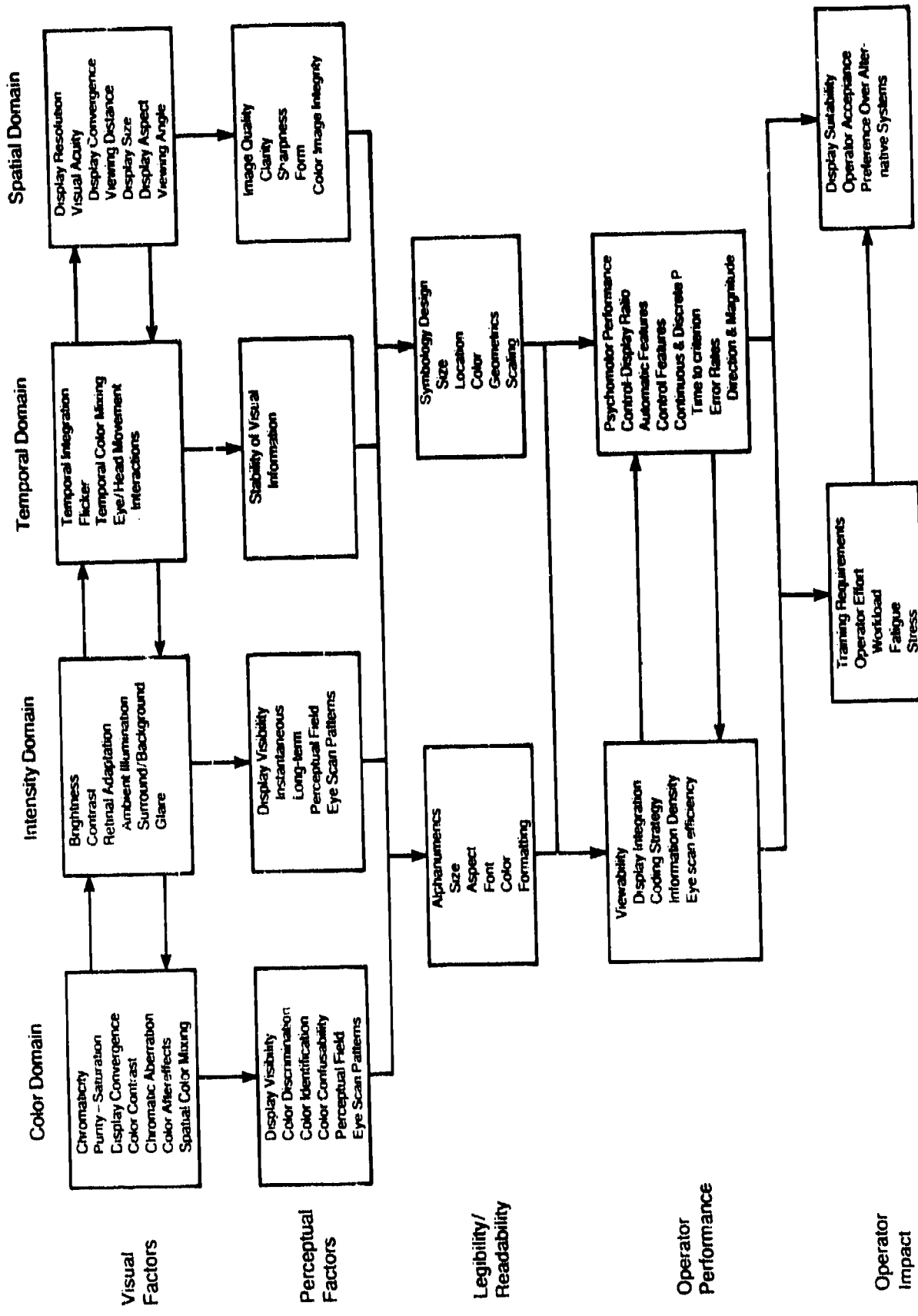| Color | Chromaticity Coordinates | | | | Primary | Percent Primary Luminance | Primary Luminance Level (F-L) |
|---|---|---|---|---|---|---|---|
| | X | Y | U | V | | | |
| Green | .3000 | .5900 | .1266 | .3734 | G<br>R<br>B | 100<br>0<br>0 | 30.0<br>0<br>0 |
| Red | .6530 | .3230 | .4689 | .3479 | G<br>R<br>B | 0<br>100<br>0 | 0<br>14.0<br>0 |
| Amber | .4681 | .4628 | .2457 | .3644 | G<br>R<br>B | 83.3<br>88.6<br>0 | 25.0<br>12.4<br>0 |
| Cyan | .1925 | .2077 | .1504 | .2434 | G<br>R<br>B | 64.0<br>0<br>100 | 19.2<br>0<br>5.1 |
| Magenta | .3216 | .1494 | .3107 | .2160 | G<br>R<br>B | 0<br>100<br>100 | 0<br>14.0<br>5.1 |
| Purple | .2027 | .0871 | .2227 | .1436 | G<br>R<br>B | 0<br>22.1<br>100 | 0<br>3.1<br>5.1 |
| White | .3155 | .2750 | .2226 | .2910 | G<br>R<br>B | 100<br>100<br>100 | 30.0<br>14.0<br>5.1 |
| Green Raster | .3000 | .5900 | .1266 | .3734 | G<br>R<br>B | 100<br>0<br>0 | 5.8<br>0<br>0 |
| Red Raster | .6530 | .3230 | .4689 | .3479 | G<br>R<br>B | 0<br>100<br>0 | 0<br>2.7<br>0 |
| Amber Raster | .4681 | .4628 | .2457 | .3644 | G<br>R<br>B | 83.3<br>88.9<br>0 | 4.8<br>2.4<br>0 |
| Cyan Raster | .1925 | .2077 | .1504 | .2434 | G<br>R<br>B | 64.0<br>0<br>100 | 3.7<br>0<br>.97 |

FIGURE 1. HIERARGHIAL HUMAN FACTORS ANALYSIS OF SHADON-MASK COLOR CRT DISPLAY
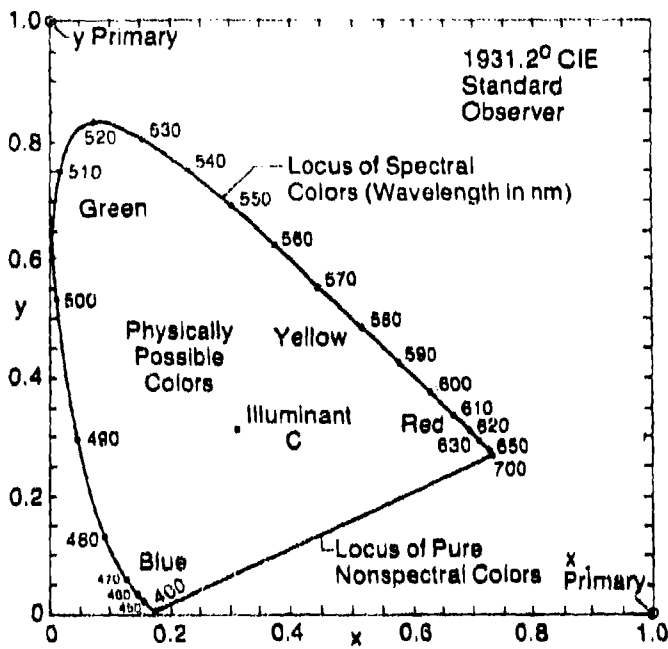
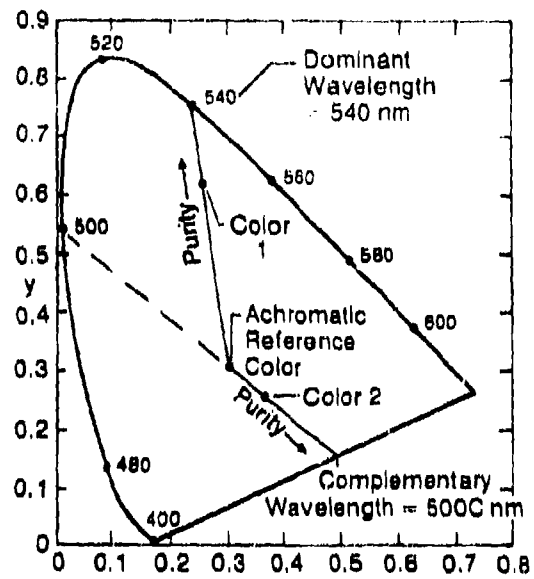FIGURE 2. THE BASIC CIE CHROMATICITY DIAGRAM



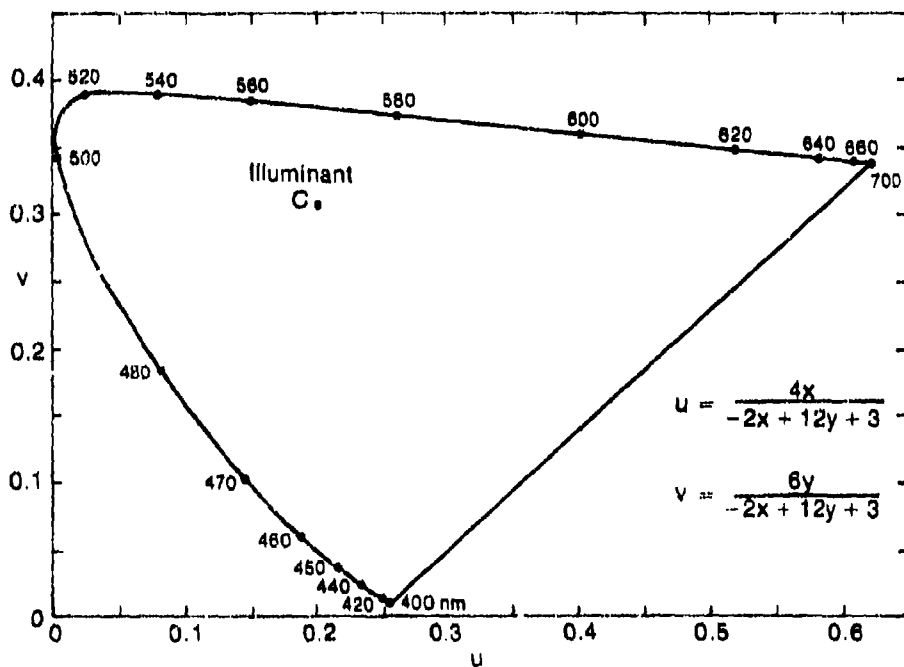FIGURE 3. DOMINANT WAVELENGTH AND PURITY SPECIFICATION



FIGURE 4. THE CIE 1960 UNIFORM CHROMATICITY SPACING (UCS) DIAGRAM
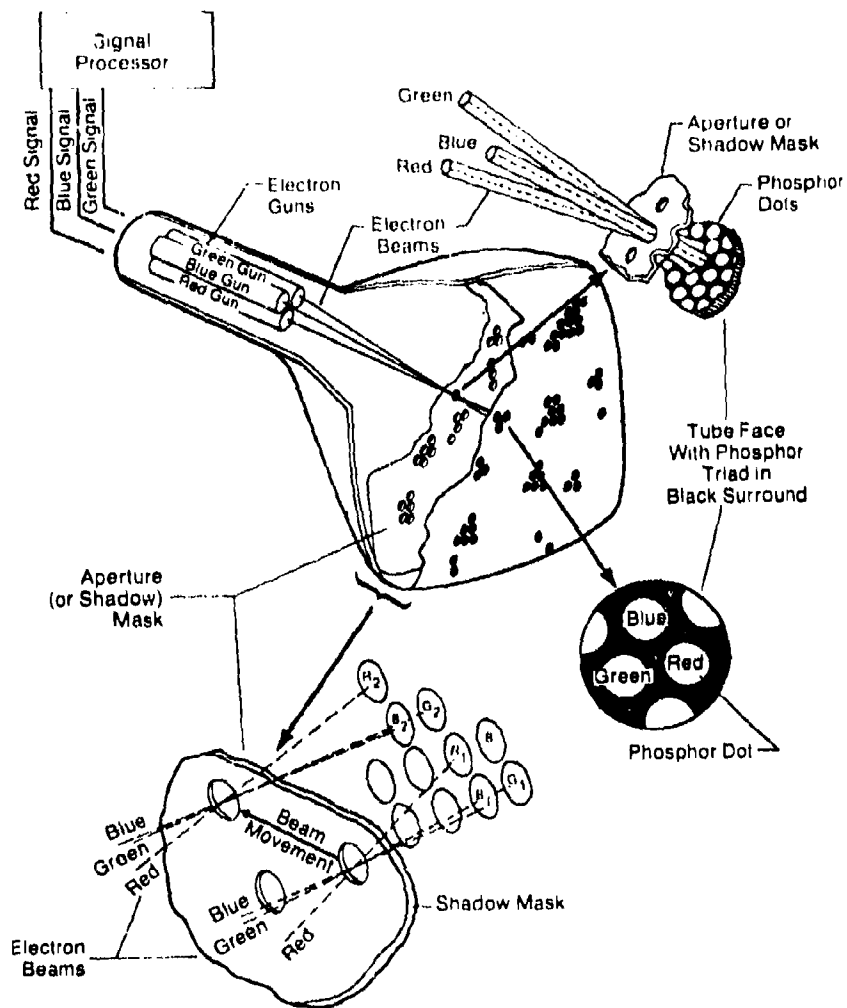
FIGURE 5.    SHADOW-MASK COLOR CRT WITH DELTA GUN GEOMETRY
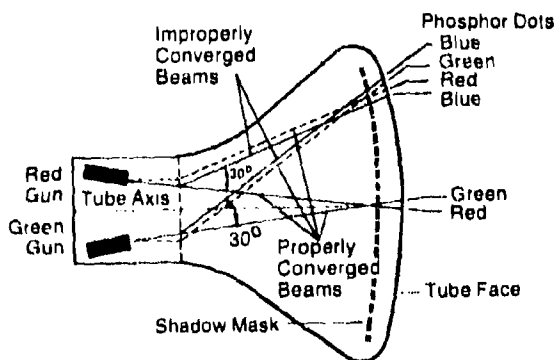


FIGURE 6.    COLOR PURITY LOSS DUE TO BEAM MISCONVERGENCE

ELECTRONIC ATTITUDE DIRECTOR INDICATOR (EADI)

GS397

MACH        CMD

VNAV        LNAV

9.7NM    TRK ⌊016⌋ M    1335.3z

3

LENNA

CMD

KOMC

40

AVL        OAK

20
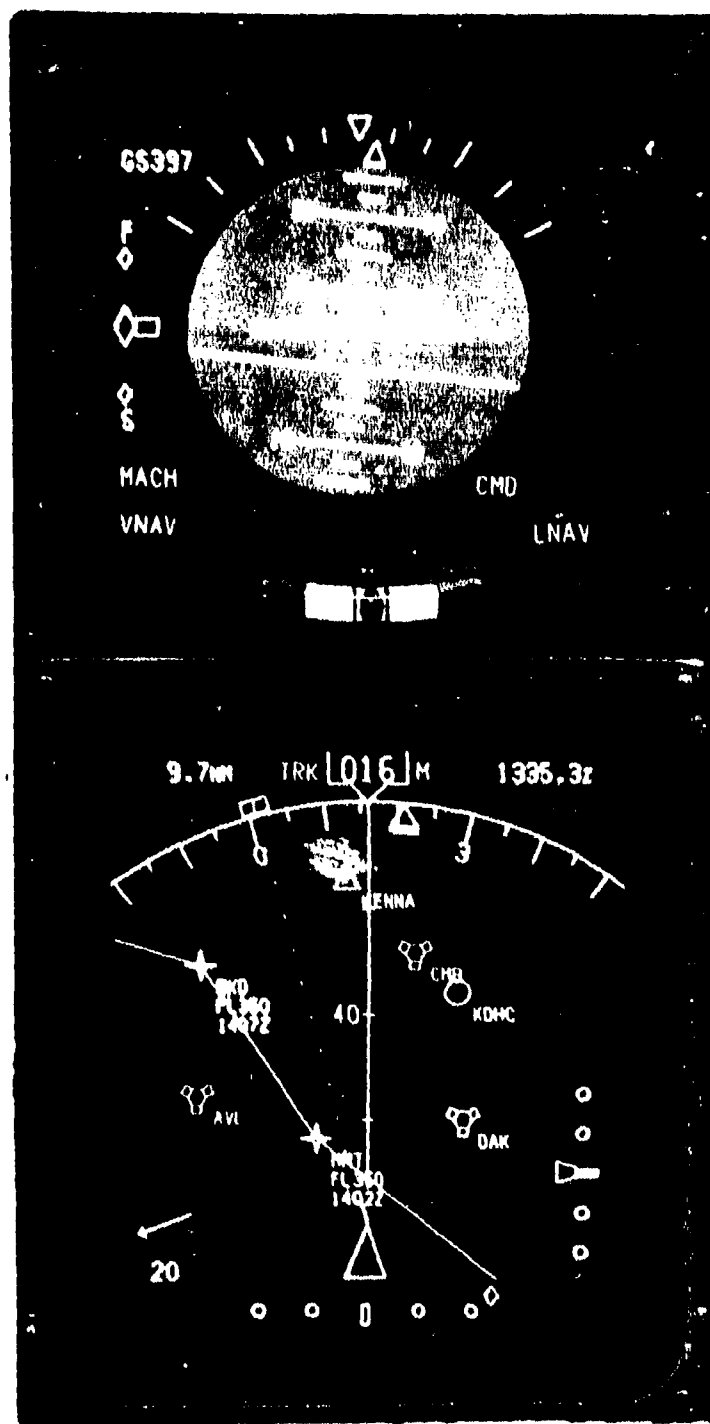
ELECTRONIC HORIZONTAL SITUATION INDICATOR (EHSI)

FIGURE 7. TYPICAL ENROUTE EADI AND EHSI DISPLAY FORMATS. EHSI SHOWN IN MAP MODE WITHOUT WEATHER RADAR IMAGERY.
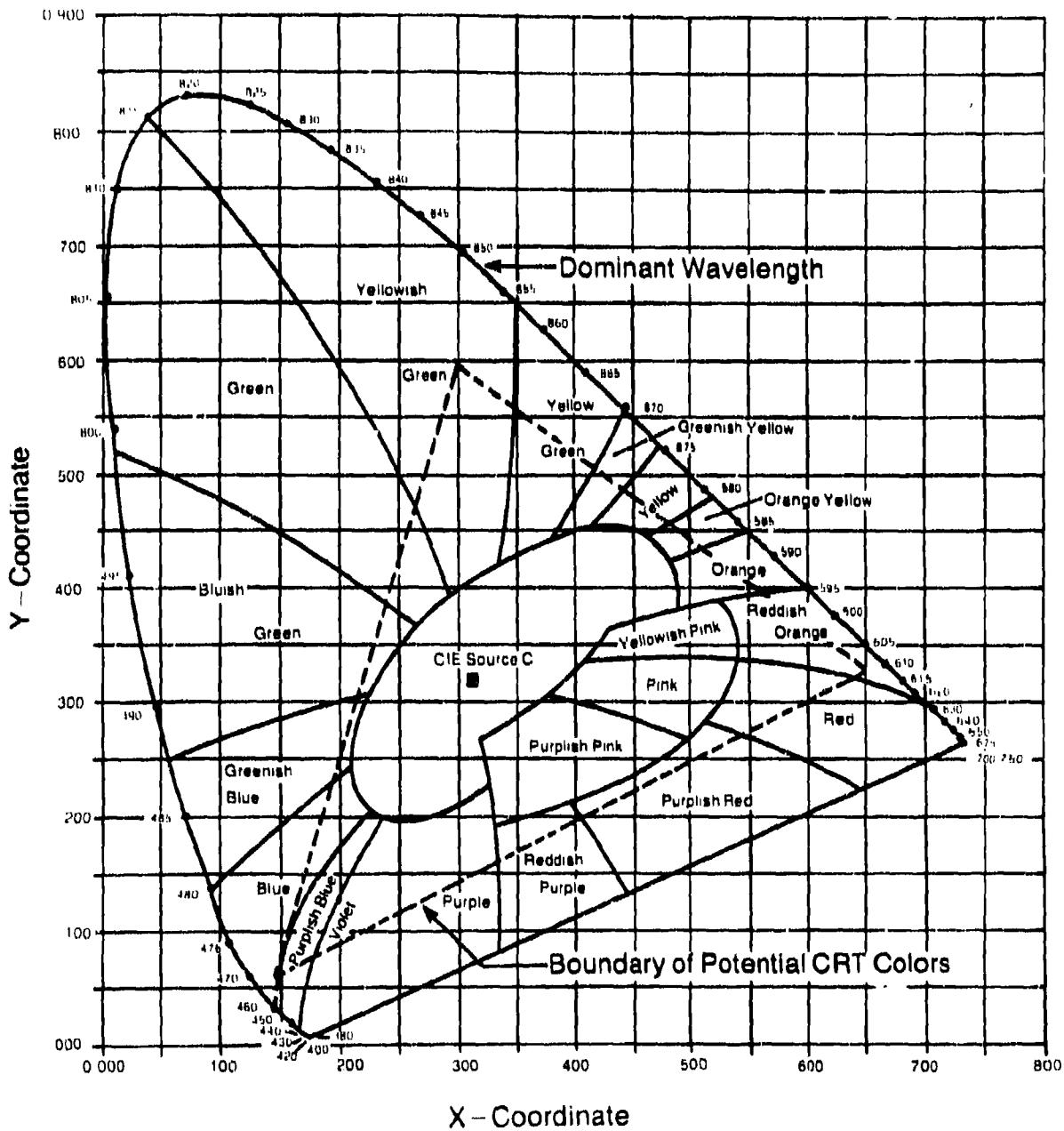
FIGURE 8.    COLOR CAPABILITY FOR THE BOEING DISPLAY SYSTEMS

66
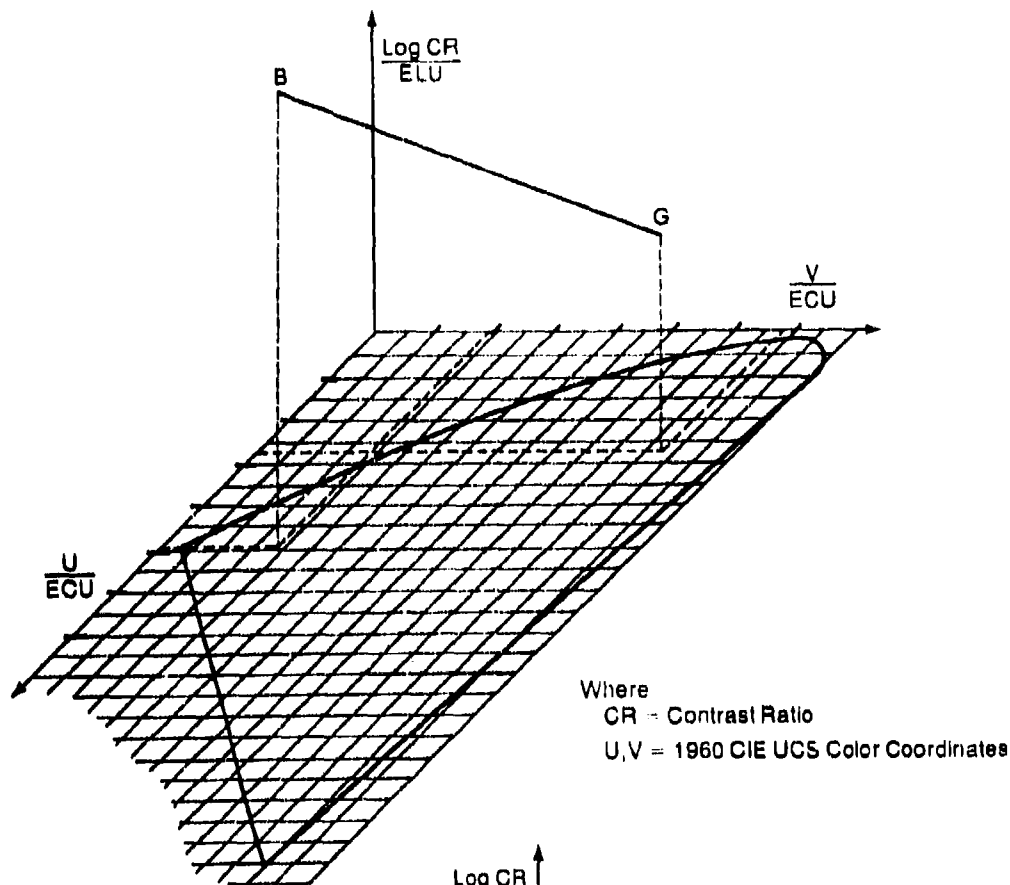
FIGURE 9. PHOTOCOLORIMETRIC SPACE

Where
  CR = Contrast Ratio
  U,V = 1960 CIE UCS Color Coordinates
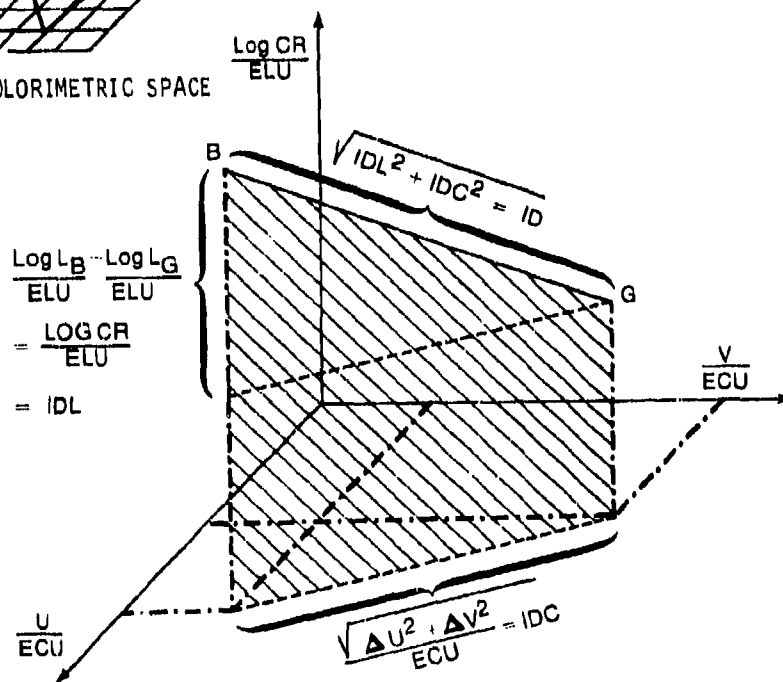


FIGURE 10. INDEX OF DISCRIMINATION IN PHOTOCOLORIMETRIC
SPACE

67
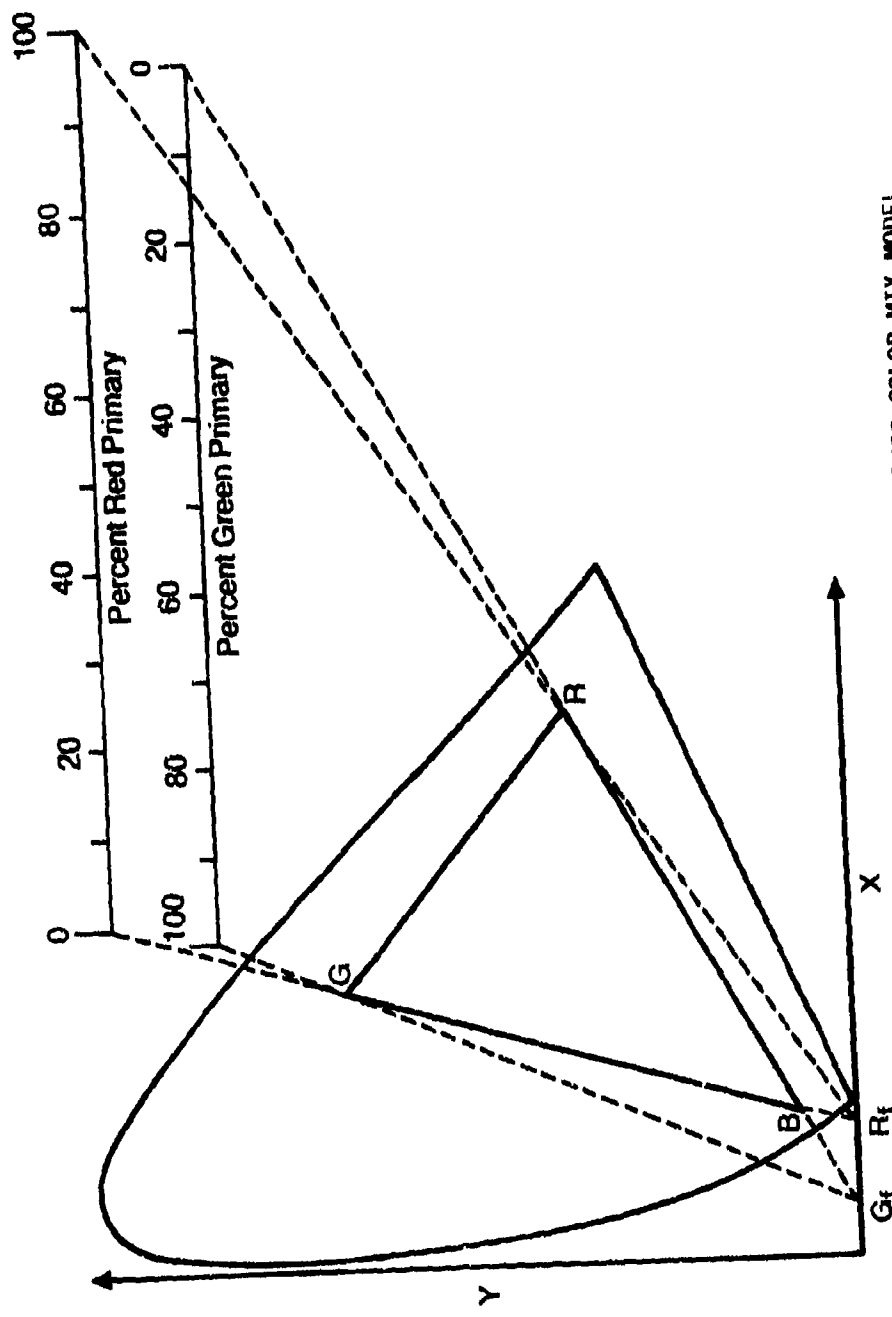
FIGURE 11. CIE 1931 CHROMATICITY DIAGRAM WITH NOMOGRAPHIC COLOR MIX MODEL

68
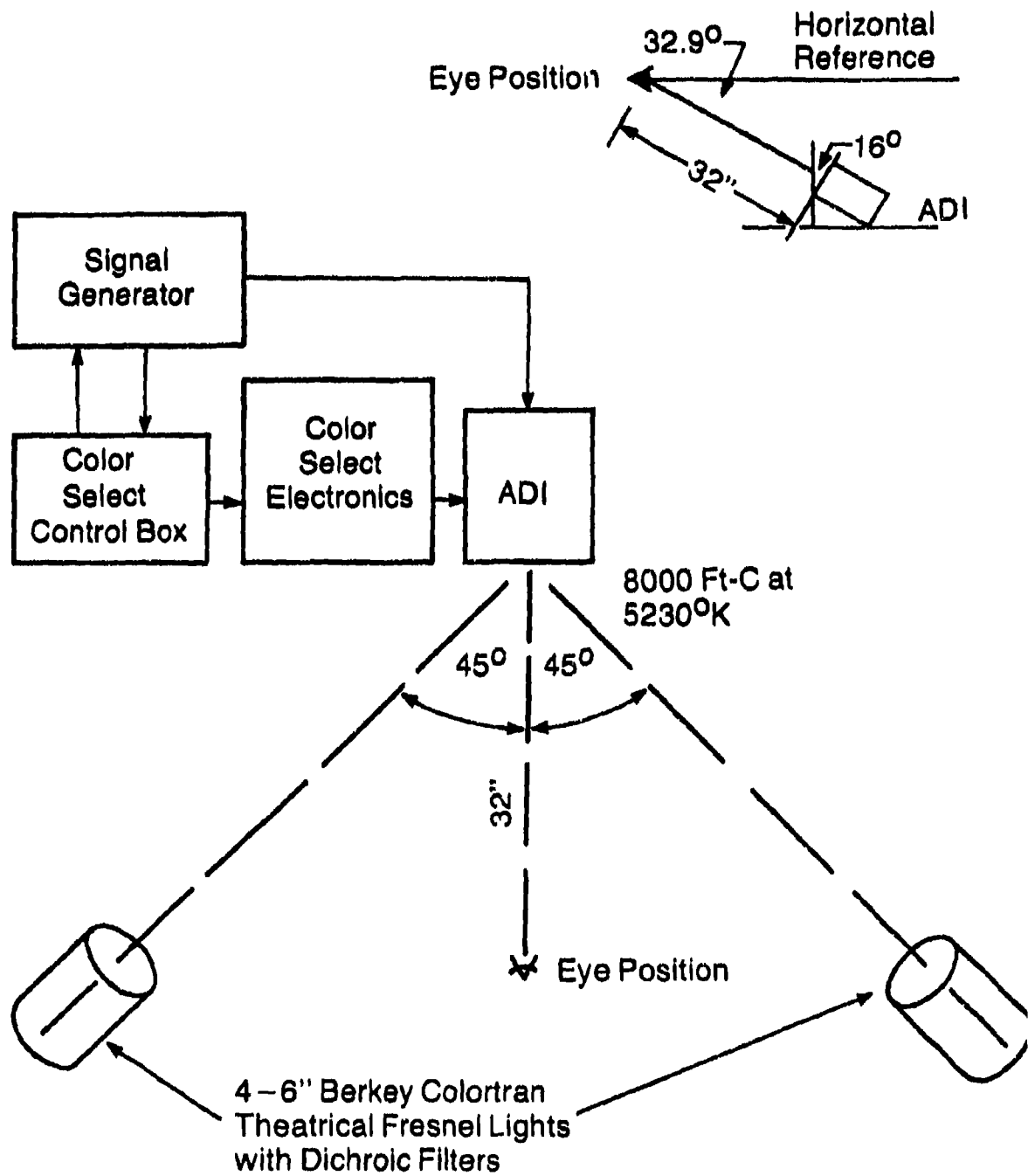
FIGURE 12.  COLOR DISPLAY TEST SET-UP
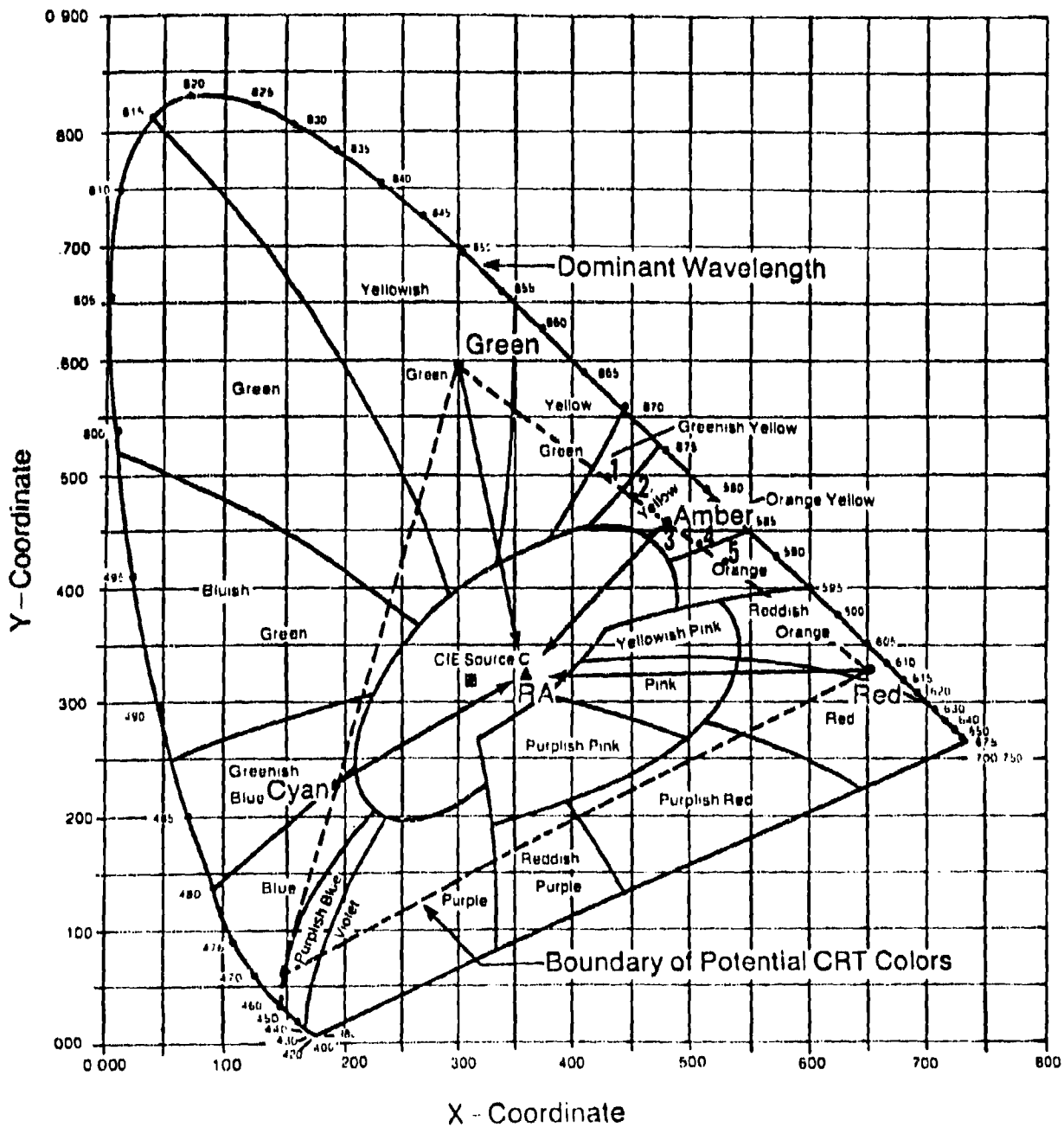
FIGURE 13. RASTER COLORS LOCATED IN CIE 1931 COORDINATES

The numbers 1-5 on the RED-GREEN axis indicate the location
of the 5 AMBERS tested. The point marked RA designates the
coordinates of the Reflected Ambient Illumination.
Directional Vectors show color shifts due to 8000 Ft.-C of
Ambient Illumination.

70

# Raster Field Test Pattern

Raster Half-Fields
Green
Red
Amber (1, 2, 3, 4, 5)
Cyan
Blank (Ambient)
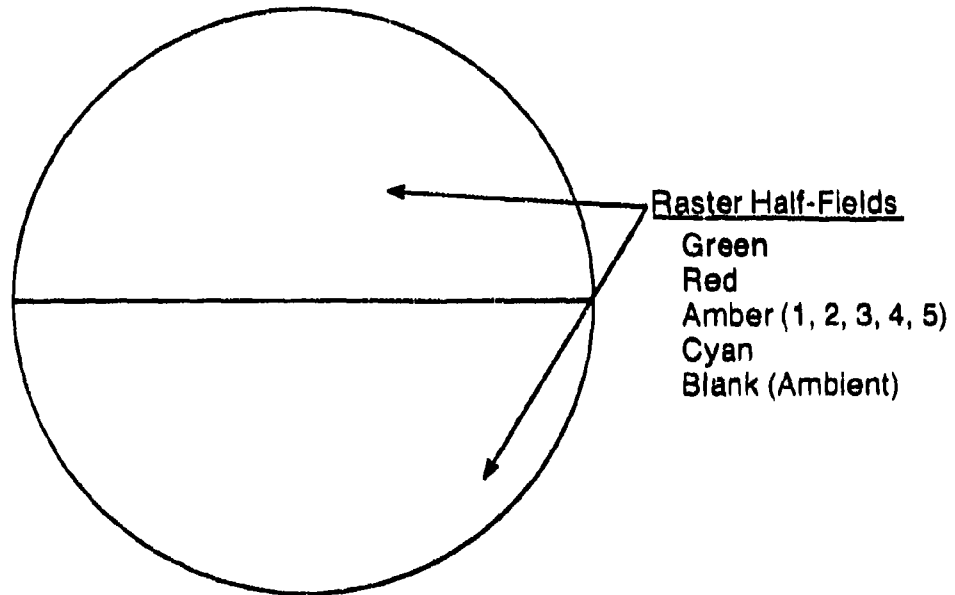
## Test Conditions

Ambient Illumination = 8000 ft C
Test Subjects = 8 Boeing Employees – Color Vision
  Screen With American Optical HRR Abbreviated Color Vision Test

## Red-Yellow-Green Test

Each Subject Tested With Family of 5 Ambers in Counterbalanced Design

| Green | Blank | Red | Blank | Amber | Red | Amber | Green |
|-------|-------|-----|-------|-------|-----|-------|-------|
| Blank | Green | Blank | Red | Red | Amber | Green | Amber |

## Cyan-Ambient Test

Randomized Presentation Order

| Blue | Blank |
|------|-------|
| Blank | Blue |

FIGURE 14.   RASTER TEST PATTERN AND SUMMARY OF RASTER TEST CONDITIONS
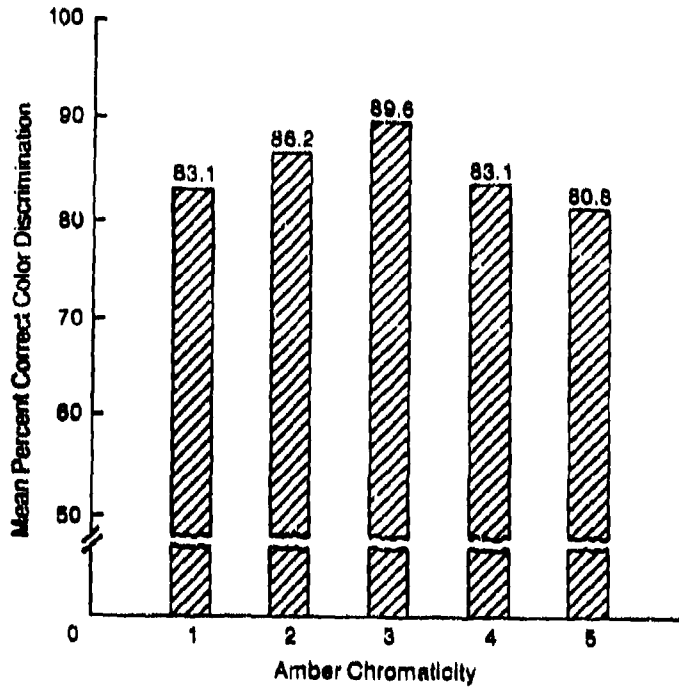
FIGURE 15. RED-AMBER-GREEN RASTER COLOR
DISCRIMINATION PERFORMANCE AS
A FUNCTION OF AMBER CHROMA-
TICITY
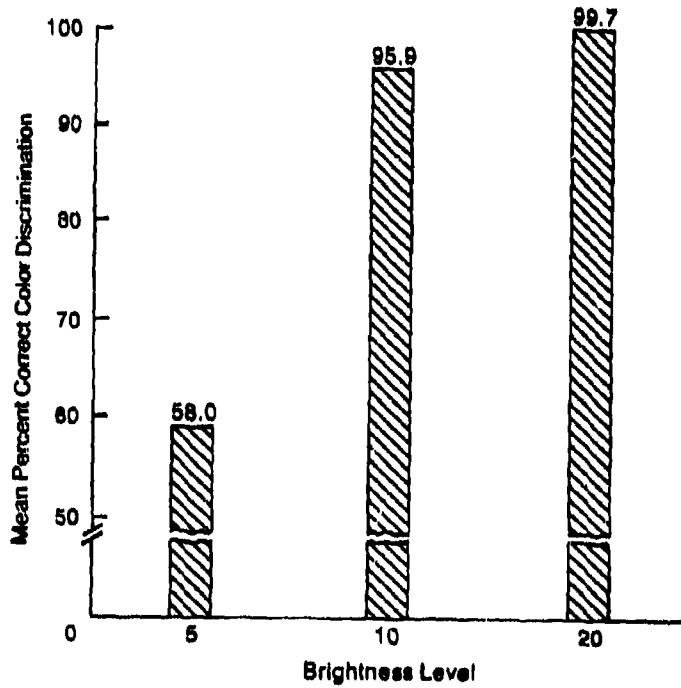


FIGURE 16. RED-AMBER-GREEN RASTER COLOR
DISCRIMINATION PERFORMANCE  AS
A FUNCTION OF DISPLAY BRIGHTNESS
LEVEL

72
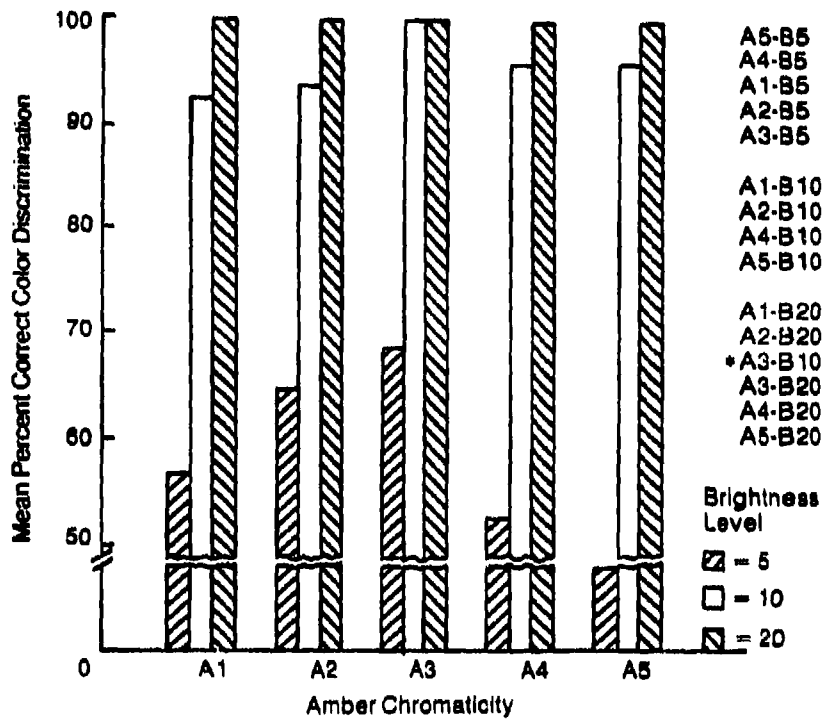
FIGURE 17. RED-AMBER-GREEN RASTER COLOR DISCRIMI-
NATION PERFORMANCE AS A FUNCTION OF BOTH AMBER
CHROMATICITY AND DISPLAY BRIGHTNESS LEVEL
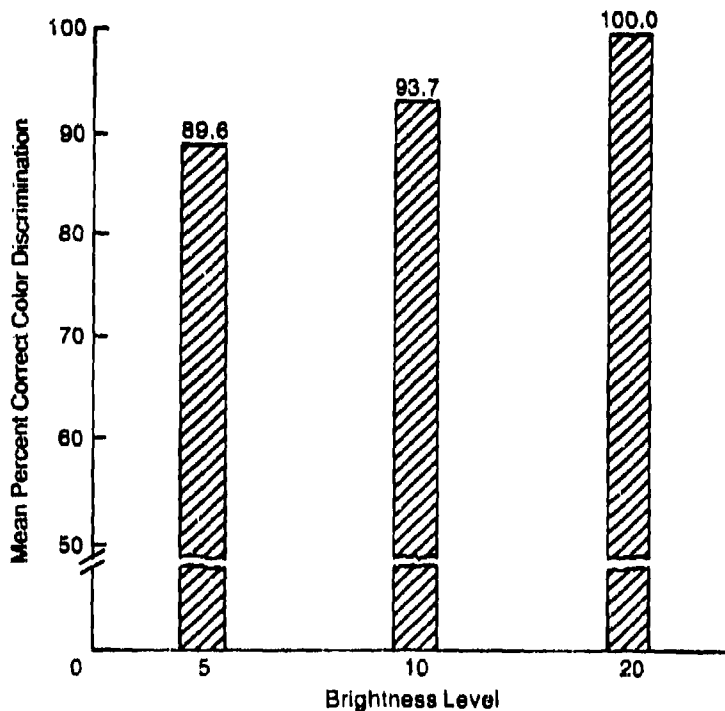


FIGURE 18. CYAN-REFLECTED AMBIENT DISCRIMINATION
PERFORMANCE AS A FUNCTION OF DISPLAY BRIGHTNESS
LEVEL

73

# Discrimination Test Pattern

**Raster Half-Fields**
Green
Red
Amber
Cyan
Blank (Ambient)

**Stroke Symbols**
Green
Red
Amber
Cyan
White
Magenta
Purple
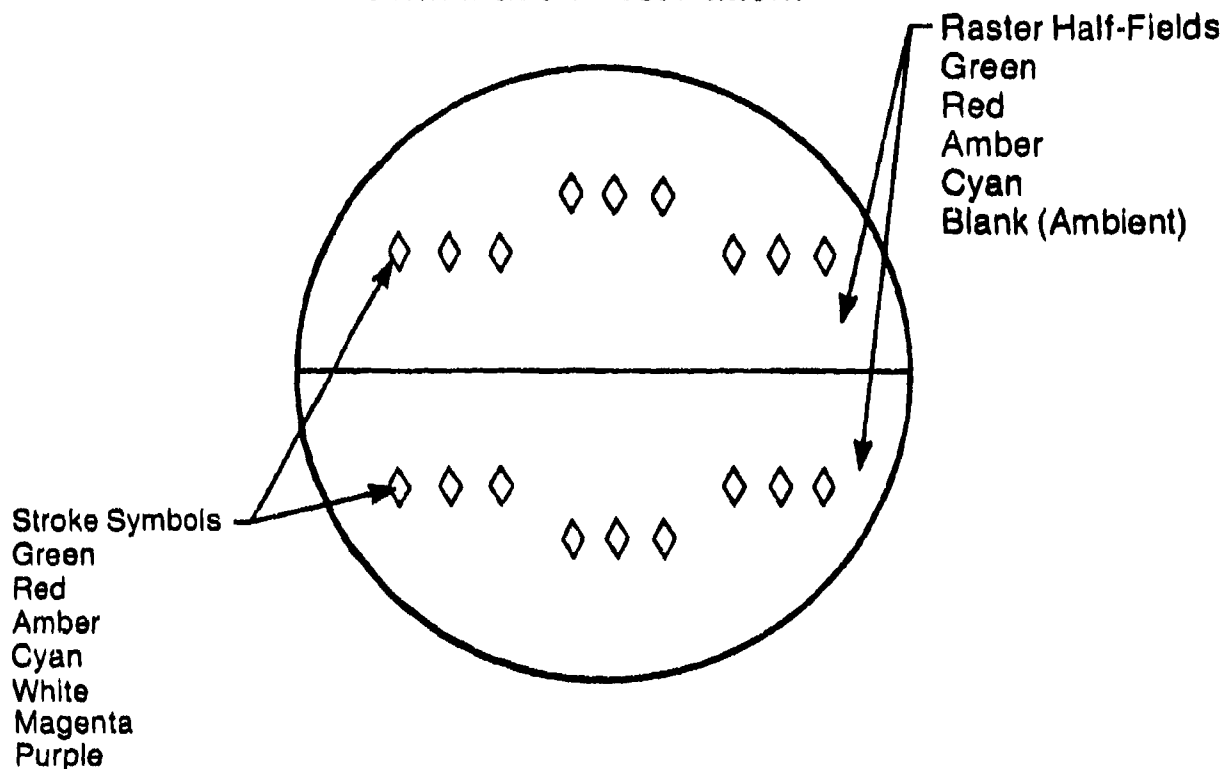
Test Conditions
Ambient Illumination = 8000 Ft-C
Test Subject = 10 Boeing pilots and flight engineers
Raster Background Conditions:

Upper Half-Field

| Green | Green | Cyan | Blank | Red | Red | Blank | Amber | Amber | Cyan |
|-------|-------|-------|-------|-------|------|-------|-------|-------|-------|
| Red | Amber | Green | Green | Amber | Cyan | Red | Cyan | Blank | Blank |

Lower Half-Field

FIGURE 19.   STROKE/RASTER COLOR TEST PATTERN AND SUMMARY OF TEST CONDITIONS
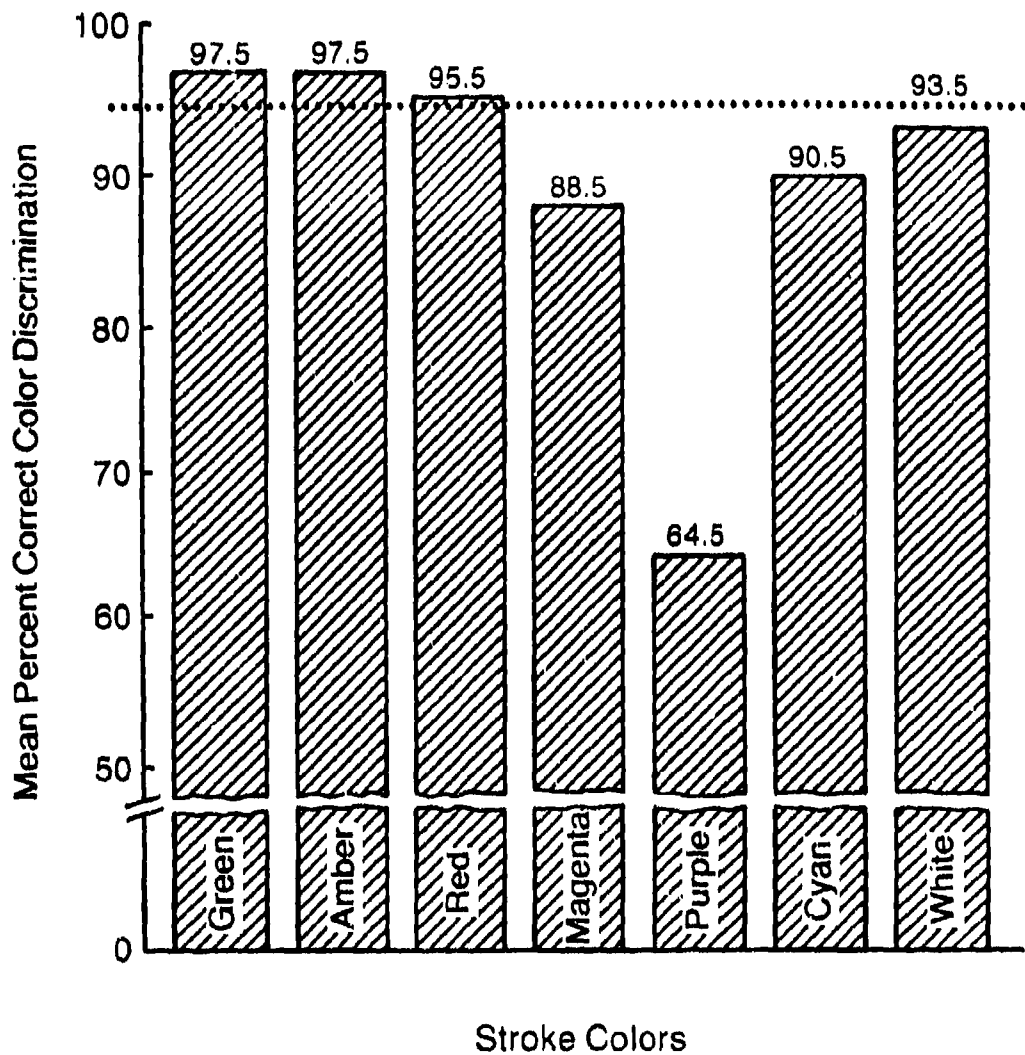
FIGURE 20.  STROKE COLOR DISCRIMINATION PERFORMANCE
(AVERAGED ACROSS COLOR RASTER AND REFLECTED
AMBIENT BACKGROUNDS).  STROKE/RASTER
CONTRAST RATIO = 4
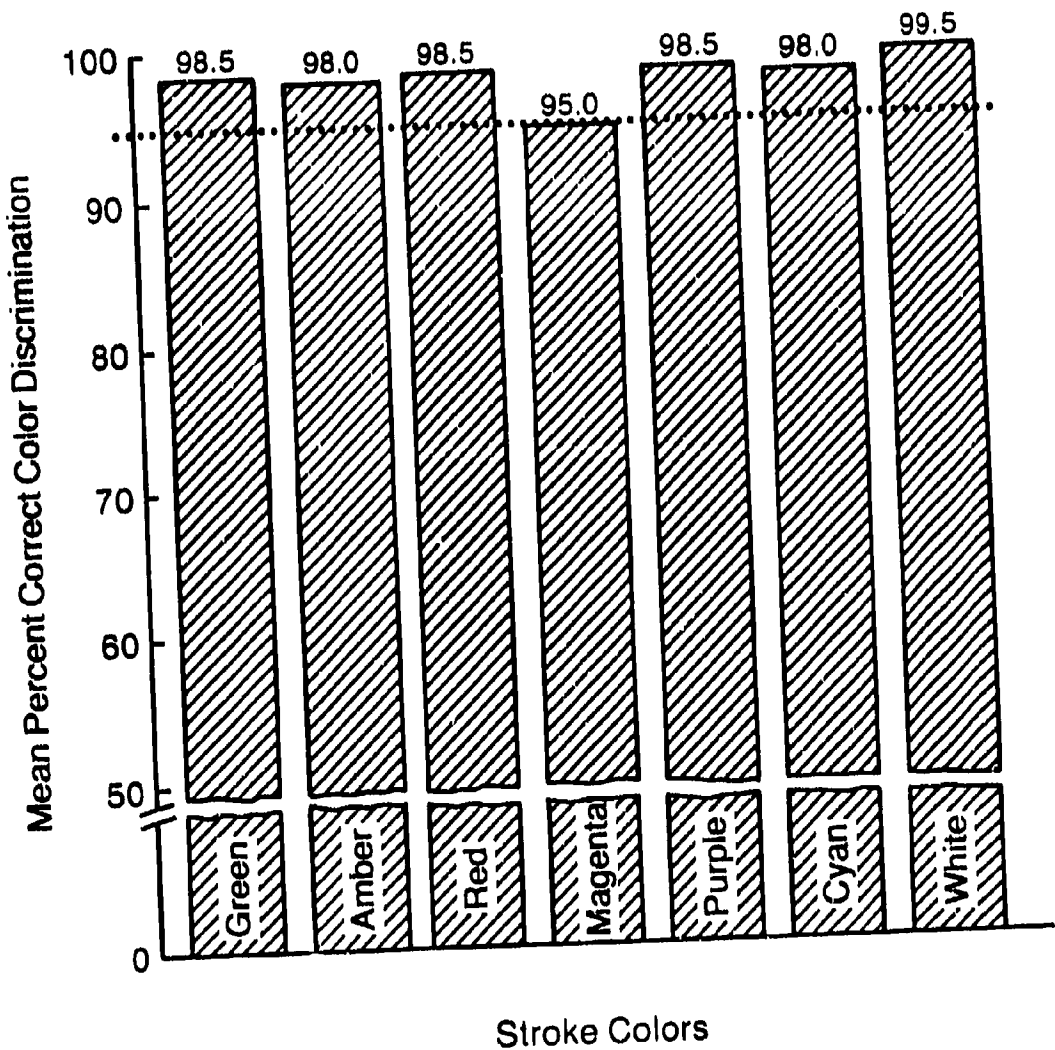
FIGURE 21. STROKE COLOR DISCRIMINATION PERFORMANCE (AVERAGED ACROSS COLOR RASTER AND REFLECTED AMBIENT BACKGROUNDS). STROKE/RASTER CONTRAST RATIO = 5
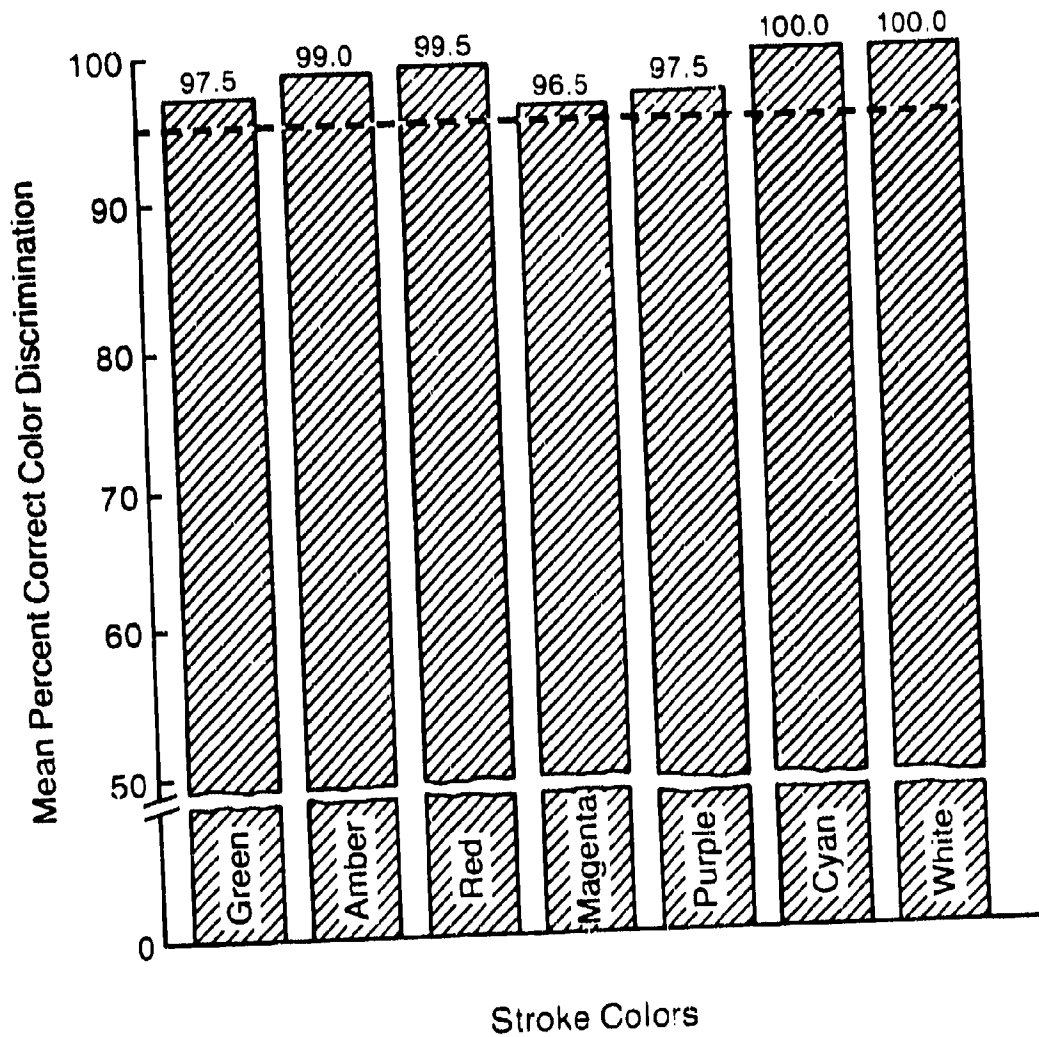
FIGURE 22. STROKE COLOR DISCRIMINATION PERFORMANCE (AVERAGED ACROSS COLOR RASTER AND REFLECTED AMBIENT BACKGROUNDS). STROKE/RASTER CONTRAST RATIO = 6

77
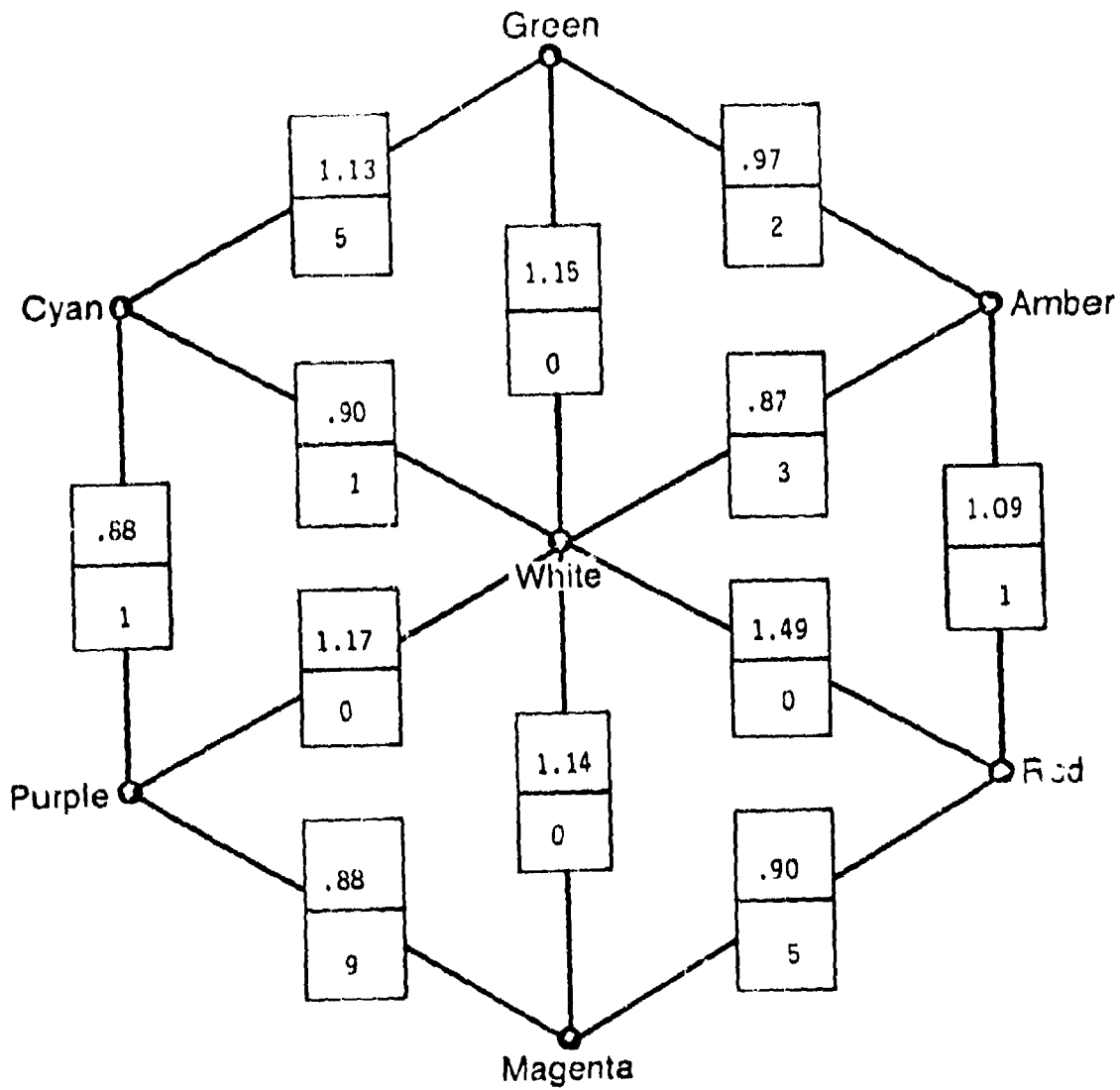
FIGURE 23. INDEX OF DISCRIMINATION (ID) VALUES (AVERAGED ACROSS COLOR RASTER AND REFLECTED AMBIENT BACKGROUNDS) AND SUMMED STROKE COLOR CONFUSION ERRORS AT STROKE/RASTER CONTRAST RATIO = 5

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FIGURE 24. STROKE COLORS LOCATED IN CIE 1931 COORDINATES. THE POINT
MARKED RA DESIGNATES THE COORDINATES OF THE REFLECTED
AMBIENT ILLUMINATION. DIRECTIONAL VECTORS SHOW COLOR
SHIFTS DUE TO 8000 Ft.-C OF AMBIENT ILLUMINATION

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## Desaturation Test Pattern

Top Raster Field
Green
Red
Amber
Cyan

Stroke Symbols
Green
Red
Amber
Cyan
White
Magenta
Purple

Bottom Raster Field
Blank
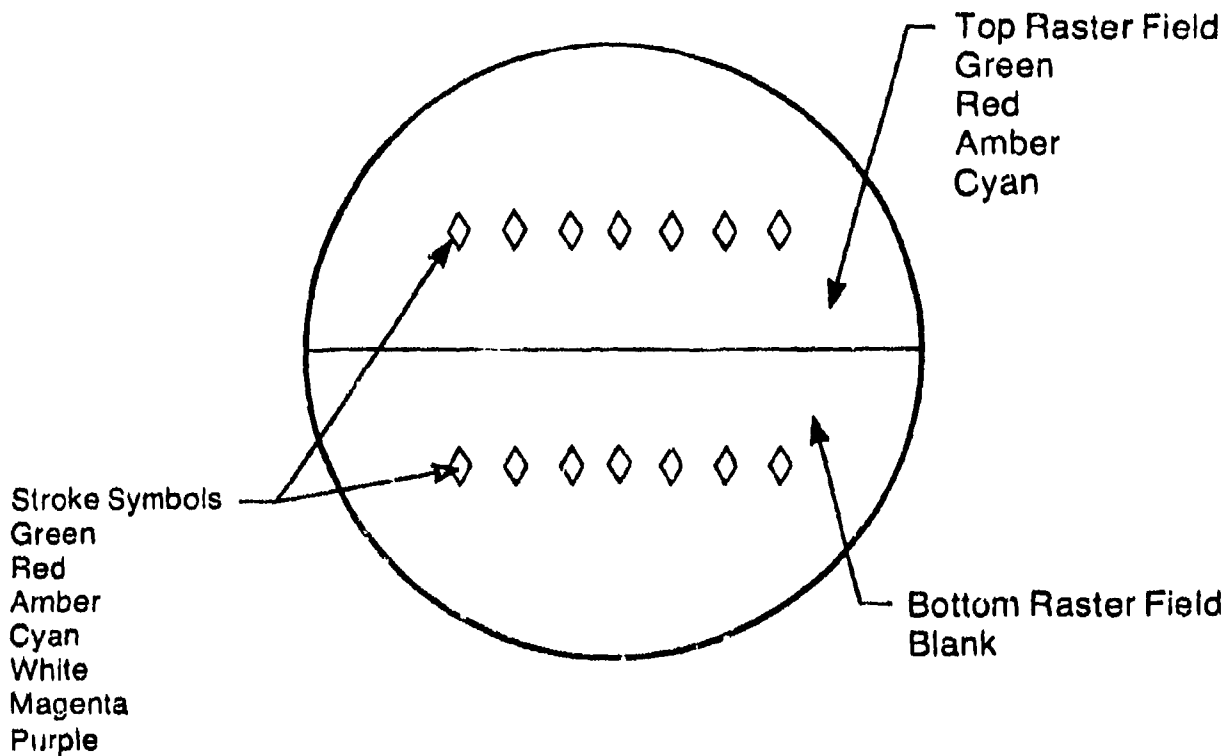
Test Conditions
Ambient Illumination = 0.1 Ft-C
Test Subjects: = 10 Boeing pilots and flight engineers

Test Sequence
1. Low ambient color verification using phase I test patterns
2. Color saturation adjusted individually for each color on
   Desaturation Test Pattern according to pilot preference
3. Color saturation adjusted individually for each color on Modified ADI Test
   Pattern according to pilot preference
4. Repeat step 2.
5. Repeat step 3.

FIGURE 25.  COLOR DESATURATION TEST PATTERN AND SUMMARY OF
LOW-AMBIENT TEST CONDITIONS
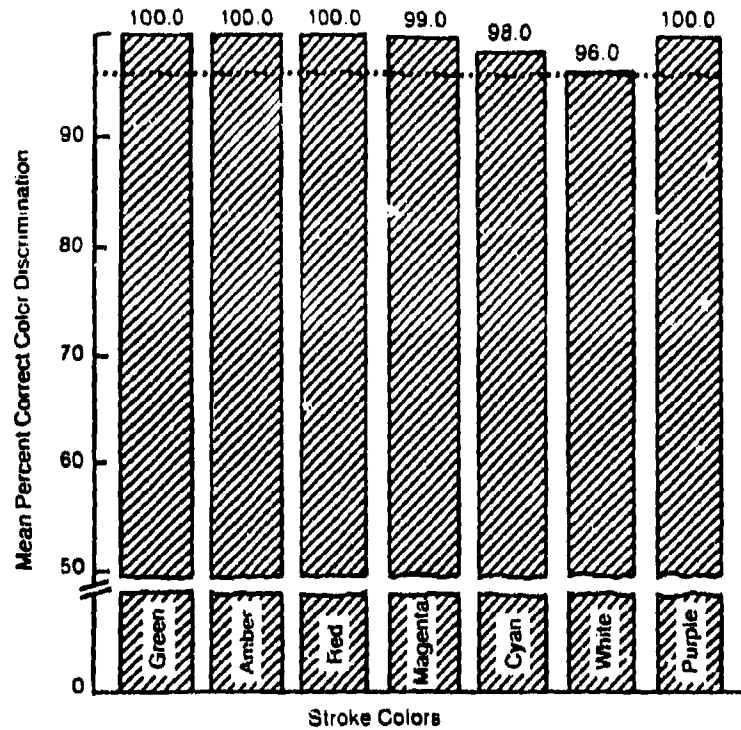
FIGURE 26. STROKE COLOR DISCRIMINATION
PERFORMANCE UNDER LOW-AMBIENT
VIEWING CONDITIONS

1 = First Test Sequence
2 = Second Test Sequence
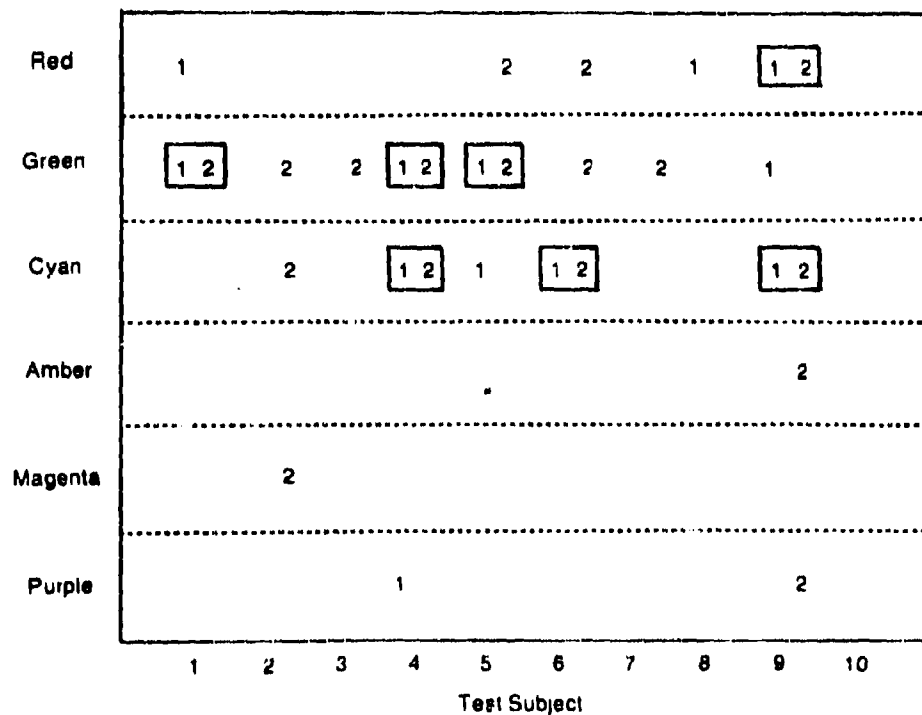


FIGURE 27. DISTRIBUTION TENDENCY TO DESATURATE COLORS
UNDER LOW-AMBIENT VIEWING CONDITIONS

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F/A-18 HORNET CREW STATION
Eugene C. Adam
McDonnell Aircraft Company

## ABSTRACT

The F/A-18 Hornet Crew Station represents a considerable step forward in the application of integrated controls and computer controlled displays to the reduction of pilot workload and enhancement of mission success. The Hornet crew stat'on design requirements was to essentially provide the capability contained in both the F-4 and A-7 weapon systems so as to perform both the fighter and attack roles, make it operable by one pilot, and increase mission reliability by a combination of improved hardware reliability and functional redundancy.

To put this requirement in perspective, the F/A-18 cockpit has 40% less usable area than any of its contemporaries. This area constraint necessitated extensive integration of the weapon system controls and displays. The resultant crew station features four multipurpose cathode-ray displays driven by two mission computers, an integrated upfront control panel, and numerous automatic functions on the "stick and throttle". This paper describes the rationale leading up to the configuration and presents a few examples of the one-man-operability features of the Hornet and how they would be used by the pilot. The crew station design was generated and validated by a vigorous process of analysis and simulation and is currently undergoing flight evaluation in eleven Hornet Aircraft at the Navy test facility at Patuxent River, Maryland.

## INTRODUCTION

The Navy and Marine F/A-18 Hornet strike-fighter (Figure 1) being developed by McDonnell Douglas uses integrated controls and four computer aided displays to allow the pilot to perform both the fighter and the attack roles of the F-4 Phantom and A-7 Corsair from one cockpit. No internal hardware or software reconfiguration is necessary to switch fighter and attack roles. The role the aircraft will perform is determined solely by the external sensors and weapons loading and in fact, the Hornet can be configured to carry missiles, bombs, and gun ammo to perform the combined strike/fighter mission. This dual role capability is made possible by the use of multi-function displays with programmable switches surrounding each display, a programmable Up-Front Control that integrates many previously separate control and sensor panels and the implementation of numerous software controlled computers and microprocessors distributed throughout the various elements of the weapon system. One-man-operability was of paramount concern during the weapon system definition and integration phases and it was validated by a continuing series of pilot-in-the loop simulations at the McDonnell simulation facility.



FIGURE 1
F/A-18 HORNET

## COCKPIT SIZE

The quest for good aerodynamic performance, fishbowl visibility, and minimum weight resulted in an airframe whose cockpit instrument panel and console area was 40% less than contemporary aircraft such as the F-4, A-7, or F-15, yet there were more systems to control and display in that smaller area. It was clear that to achieve one-man-operability of the numerous sensors and weapons on board, maximum advantage had to be taken of the recent trend toward programmable digital weapon systems and computer aided control and display techniques, human factors analysis, simulation, and functional automation.

## APPROACH RATIONALE

The Cathode Ray Tube (CRT) was chosen as the display medium for the three identically formatted indicators shown in Figure 2. The CRT has undergone steady design improvements during the past 40 years and presently offers the best combination of contrast and resolution in bright sunlight. Acceptable reliability can be achieved after a combination of vibration and burn-in cycles. These multi-purpose displays, in conjunction with the Head Up Display (HUD), provide the pilot with all essential flight information for air to air, air to surface, and navigation phases of the mission.



FIGURE 2
F/A-18 CREW STATION LAYOUT
(MORE FUNCTIONS IN 40% SPACE
THAN CONTEMPORARY AIRCRAFT)
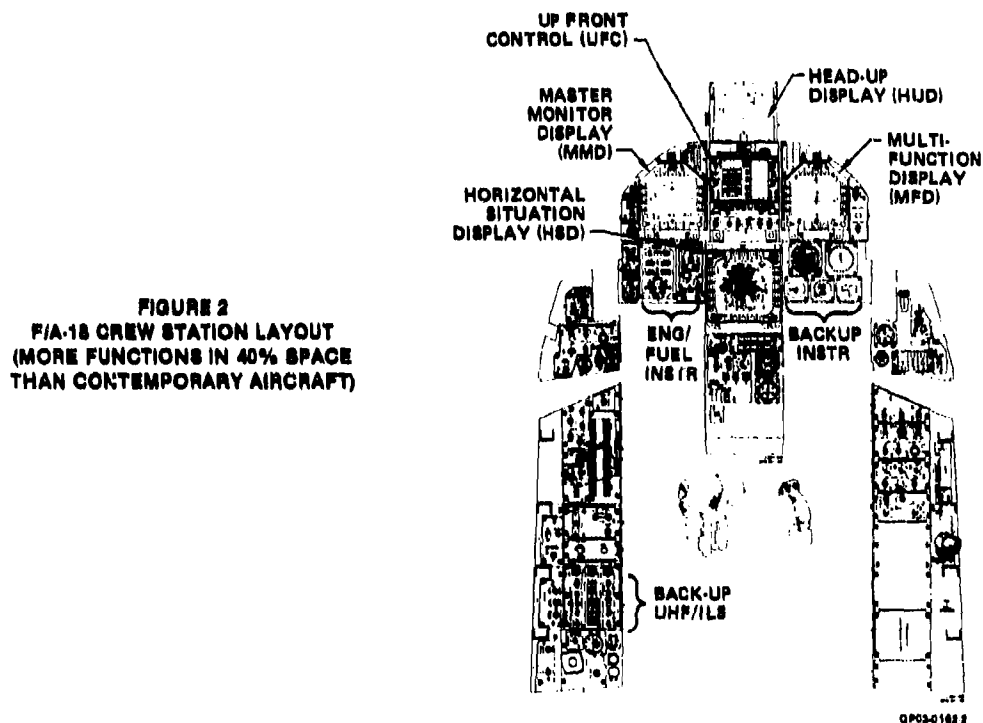
The HUD is the primary flight instrument for weapon delivery and navigation including manual and automatic carrier landing modes. All essential flight data such as speed, altitude, heading, attitude, alphanumeric cues, and steering commands are projected on the HUD combiner and focused at infinity for easy assimilation by the Pilot. The Multi-function Display (MFD) is the primary sensor display for radar attack, radar mapping, and backup for the Master Monitor Display (MMD). Superimposed on the sensor data is own-aircraft data such as attitude, speed, altitude, weapon status, and other alphanumeric cues. This reduces pilot scan time and allows search-through-reattack segments to take place on one display. The MMD is the primary warning, caution, EO and IR sensor, armament, built-in-test, and scratch pad display. The Horizontal Situation Display (HSD) presents CRT generated plan-view navigation information superimposed on a color film-projected moving map for easy navigation by the pilot. The HSD improves target finding accuracy during attack missions, simplifies navigation updates and radar map matching, and provides growth for display of other tactical data such as EW, electronic order of battle, navigation segments, and approximately 200 filmed data frames relating to aircraft systems.

Direct benefits of multiple CRT display of flight parameters, armament control, navigation, and other conventional parameters are: 1) Pilot scan times are reduced because sensor, weapon, and own-flight information is grouped together as required on each display; 2) An armament panel and more than a dozen low reliability, electro-mechanical servoed instruments have been deleted from the aircraft, reducing life cycle costs and freeing valuable cockpit space; 3) Mission reliability is enhanced because each of the display formats can be presented elsewhere thus precluding a single and even dual display failures from causing a mission abort.

The lower left corner of the instrument panel contains engine and fuel instruments necessary for pilot monitoring during aircraft self-start on battery power. The lower right corner of the instrument panel contain pneumatic standby airspeed, altitude, and vertical speed indicators and a 3" Attitude Director Indicator (ADI) with a self contained gyro for use in the unlikely event of total power or display loss.

The displays are mechanized (Figure 3) such that the MMD and MFD are identical and interchangeable black boxes thus reducing unit recurring costs and logistic support. Each contains symbol generators capable of driving two or three displays depending on the complexity of the modes. Thus either the MMD or the MFD can drive itself, the HUD, and essential data on the HSD in a backup mode. This dual drive feature provides a significant reliability improvement for the primary flight instrument function (HUD) and allows the pilot the tactical flexibility and mission reliability of putting sensor data where he wants it. The two seat trainer version (TF-18) uses three repeater type CRT displays in the rear seat which display information corresponding to their counterparts in the front seat. These hardware identical repeaters use the same modules contained in the front end of the MMD/MFD, further reducing life cycle costs.



FIGURE 3
F/A-18 DISPLAYS BLOCK DIAGRAM
(MMD OR MFD CAN DRIVE UP
TO THREE DISPLAYS)
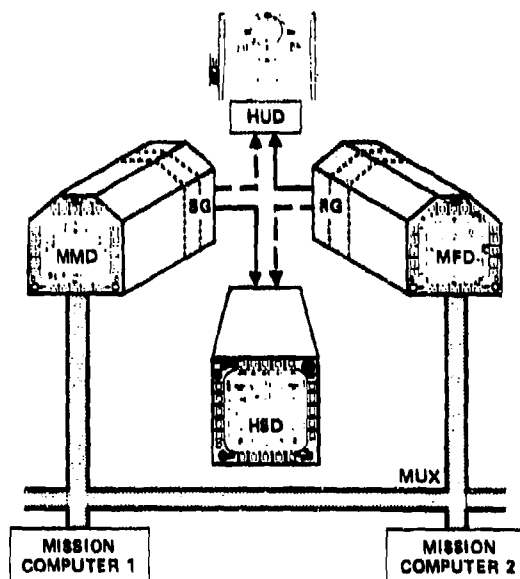
## ONE MAN OPERABILITY

The one-man-operability problem was approached with a clean slate. The small cockpit, numerous sensors to control and display, the Navy's new look in reliability, maintainability, and lower ownership costs required a fresh, integrated approach to the cockpit design. Five years of effort went into the cockpit design starting with mission analysis and simulation and ending with flight verification by a twelve member Navy/Marine and MCAIR flight team.

The problem was broken down into three major workload areas: 1) Time-critical weapon and sensor management during combat; 2) COMM, NAV, and Ident (CNI) management during all phases of flight, especially low visibility carrier operations; 3) Moding and miscellaneous requirements, usually not time critical but nevertheless cockpit space and task consumers in previous aircraft.

The solution to these three problems was to use computer aided controls and displays to minimize vertigo and error-including console activity by: 1) Weapon and sensor management via a hands-on-throttle-and-stick (HOTAS) concept; 2) CNI management via the up-front control (UFC) immediately in front of the pilot; 3) Master Monitor Moding via the switches surrounding the three head-down CRT displays.

## HANDS ON THE THROTTLE & STICK (HOTAS)

The HOTAS concept utilizes switches on the stick and throttle (Figure 4) to allow the pilot to control the weapon, sensors, and displays during time critical portions of the attack while maintaining full control of the aircraft. Although at first glance the number of switches might appear to be complex and confusing to operate, MCAIR simulation and flight experience using fleet pilots indicates they are easily learned because the constant availability of the switches under the pilots' fingers encourages practice and there is always a specific visual feedback of each selection on one or more of the displays. Thus an incorrect selection can be corrected in fractions of a second.

The three primary HOTAS switches are the Weapon Selector and Auto Lock-On selector on the stick, and the Target Designator on the throttle. Weapon selection automatically conditions the radar to nominal parameters for range, azimuth, elevation and Pulse Repetition Frequency (PRF) for Sparrow, Sidewinder, or Gun search. In effect, this allows the pilot to conveniently vary the radar search pattern with his right thumb. The HUD, MFD, and MMD each display sufficient portions of those parameters for the pilot to verify his selection immediately. The three Position Automatic Lock-On switch on the stick is used for visual lock-on and offers a 3° boresight circle on the HUD for pinpoint fly-to lock-on, a 20° circle on the HUD for fast search/acquisition within the HUD field-of-view, and a vertical scan racetrack symbol opening off the top of the HUD for off-boresight lock-on whereby the pilot rolls the aircraft until the target is centered above the rear-view mirror on the canopy bow. Lock-on is automatic in all modes and is conveyed symbolically to the pilot on the HUD and MFD and via a "LOCK" light on the canopy bow.

The Target Designator Control (TDC) on the throttle is a force controlled switch which moves the appropriate designator symbol on the displays in any direction. Computer and sensor designation is accomplished by pressing and releasing the TDC switch. The small cockpit space available and the easily learned use of the TDC prompted some early simulator experimentation with TDC control of essentially all radar control panel functions. In a nutshell, when the pilot wishes to change radar, azimuth, mode, bar scan, or any of the numerous selections normally available on a dedicated radar panel he simply slews the MFD TDC symbol over the displayed quantity he wishes to change and cycles the TDC button until the desired quantity appears. After a little practice, fleet pilots have demonstrated the capability of changing a radar parameter in less than a second elapsed time without removing their hand from the throttle. This feature not only increases pilot effectiveness but also deletes a complex radar control panel and, because of the display redundancy, actually increases the reliability of the function.
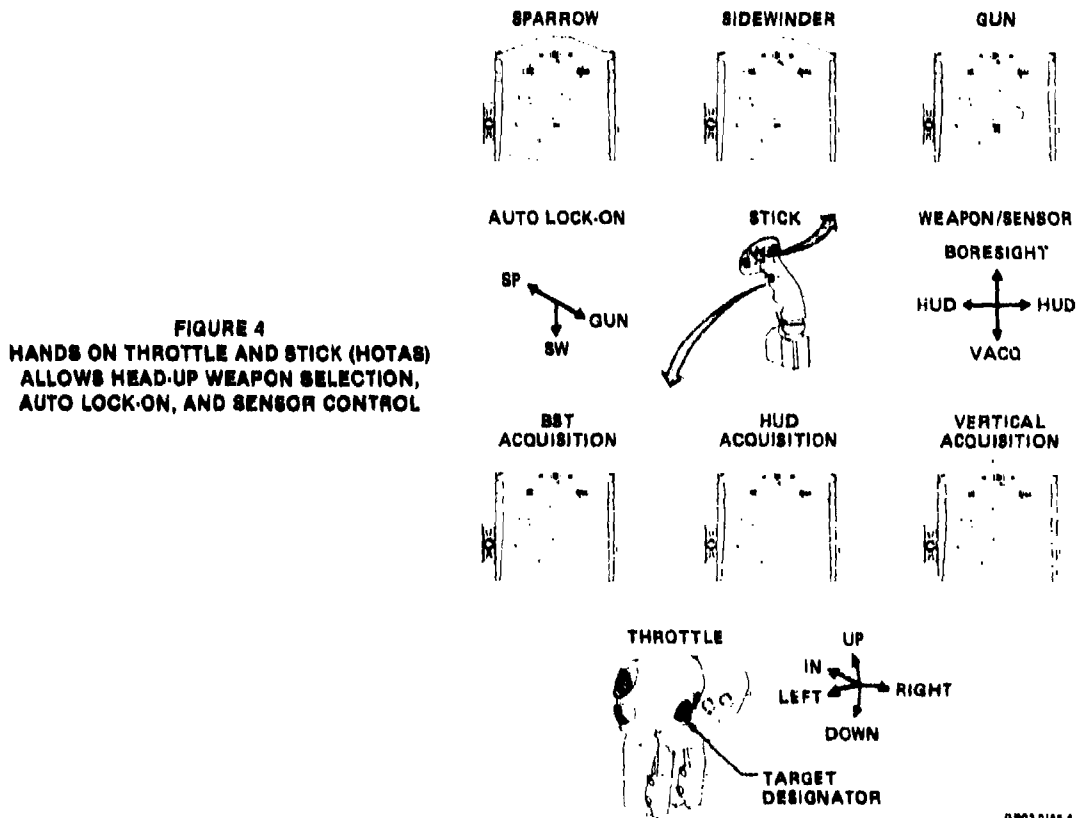
FIGURE 4
HANDS ON THROTTLE AND STICK (HOTAS)
ALLOWS HEAD-UP WEAPON SELECTION,
AUTO LOCK-ON, AND SENSOR CONTROL



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The HOTAS concept allows the pilot to perform a complete head-up, sensor aided gun or missile attack from detection through weapon delivery without removing his hands from the stick or throttle. Similar HOTAS functions are performed for air-to-surface weapon delivery and the pilot need only select Sparrow, Sidewinder, or Gun to revert to air-to-air when coming off the target.

## CNI MANAGEMENT

The Up Front Control (UFC) panel (Figure 5) allows head-up, either hand control of two UHF/VHF radios, ILS, Data Link, TACAN, Beacon, ADF, or auto pilot modes. The panel is mounted on the front face of the HUD within easy reach and view of the pilot. The bottom row of switches select functions and the upper area is composed of a keyboard and scratch pad readout, and five option windows on the right side with associated select buttons. For the example shown, the pilot has selected a TACAN function with channel 125 entered in the keyboard scratchpad and the five TACAN modes are shown in the option windows for pilot selection as desired. After the "enter" button is depressed, all data is entered and the UFC clears. The status of any system or channel frequency is available by simply pressing the appropriate function button. The UFC panel is located so near the over-nose vision line that the pilot can easily perform numerous CNI functions during IFR conditions in formation flight.



**FIGURE 5**
**UP FRONT CONTROL OF RADIOS, ILS, DATA LINK,**
**BEACON, IFF, TACAN, AND ALL NUMERIC ENTRIES**
**CAN BE ACCOMPLISHED WITH EITHER HAND**
**WHILE THE HEAD IS LOOKING FORWARD**

GP03-0182-9
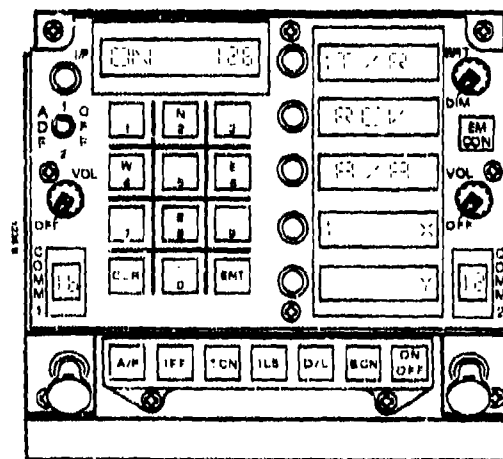
## MODING

Each of the multifunction displays have 20 push-button switches around their periphery. The display (Figure 6) is formatted such that when sensor data is called up, a quarter inch strip of the perimeter of the CRT is available for display of the primary controls for that sensor. The example shown allows pilot selection of wide or narrow field-of-view, positive or negative picture format, freeze, snowplow, a pitch ladder, and other functions important to the effective use of that sensor without diverting the pilot's attention from the sensor. The primary controls and displays extend from the instrument panel about four inches but still outside of the ejection envelope to allow the pilot to reach them without unlocking or straining against the shoulder harness (Figure 7).
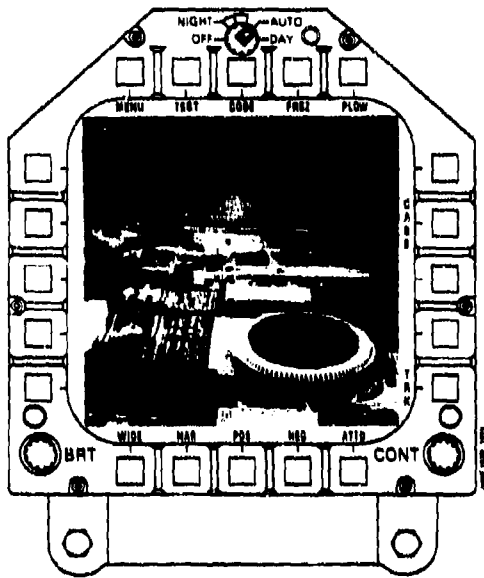
**FIGURE 6**
THE THREE CRT DISPLAYS EACH HAVE 20 SWITCHES
AROUND THEIR PERIPHERY TO ALLOW PILOT
SELECTION OF RELATED SENSOR FUNCTIONS
WITHOUT DIVERTING ATTENTION FROM THE SENSOR



**FIGURE 7**
F/A-18 HORNET COCKPIT

## MEAGER CONSOLE ACTIVITY

The HOTAS concept, UFC, and display Moding techniques essentially eliminate console activity except for infrequent, low priority items such as instrument lighting, temperature control, some sensor ON/OFF and NAV alignment functions all of which are not time critical, thus significantly reducing the chance of pilot error and vertigo.

## SIMULATOR VERIFIED

The simulator program began long before the award of the F/A-18 contract to McDonnell Douglas to verify the HOTAS, Up-Front, and Moding concepts to ensure credibility of the proposed approach.

The present simulator configuration represents the full-up aircraft weapon system with all the controls and displays operational. It is housed in a 40 foot diameter dome on which out-the-window graphics are displayed for air-to-ground, air-to-air, and carrier landing. This simulator, in conjunction with one or two other domes, is used for one-on-one and two-on-one air combat engagements.

In addition to continuous refinement of the one-man-operability techniques by MCAIR pilots, a seven member system advisory panel consisting of fleet pilots from the Navy and Marine fighter and attack community fly the simulator for periods up to one week, numerous times a year to verify that fleet operational doctrine and experience are brought to bear on the design as early as possible. These simulations are fully instrumented and provide a statistical and qualitative figure of merit for alternate approaches to one-man-operability concepts.

The final phases of the simulator program included the installation of the actual aircraft hardware into the simulator for integration and closed loop dynamic operation by MCAIR and fleet pilots prior to the initiation of flight testing.

## FLIGHT TESTING

The Hornet full scale development program consists of nine single place and two trainer (two place) aircraft. The first Hornet flight took place at the McDonnell facility in St. Louis on November 18, 1978 with Chief Test Pilot Jack Krings at the controls, and since that time the Flight Test Program has been progressing steadily at Patuxent River Maryland, and Point Mugu California presently accumulating over 4,000 hours flight time. It is the general consensus of the MCAIR and Navy Marine pilots that the display concept and weapon system is indeed versatile, reliable, and one-man-operable. The flight test program will continue through mid-1982 at which time fleet introduction will begin.

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## BIG R, EASY M

The new look in the U.S. Navy calls for reliability improvements of three to five times those currently experienced in the fleet, and maintenance levels of one-half those of present carrier aircraft. The meeting of this requirement was pursued in a variety of ways:

1.  R, M, and cost were considered equivalent to performance and weight in all design decisions.

2.  R & M requirement guarantees (not goals) imposed on MCAIR and subcontractors.

3.  Incentives were available to MCAIR and selected subcontractors for exceeding the R & M requirement.

4.  A stringent parts screening program, derating requirements, and detailed reliability design guidelines was implemented.

5.  Early hardware reliability development, test, analyze, and fix required on all major systems giving a two year jump on most past reliability programs.

6.  Realistic aircraft operational mission environments were imposed during design and development tests on key systems.

Mission reliability is further enhanced by the display and computer redundancy. Life cycle costs are reduced by common display modules and test programs. The readiness of the weapon system is continually monitored by built-in-test providing 98% failure detection and 99% failure isolation. The MMD in the cockpit presents suitable failure indications to the pilot for easy degraded mode assessment and a Maintenance Monitor Panel in the wheelwell indicates the failed unit to be replaced by the maintenance personnel.

## FLEXIBILITY

Long term flexibility is built into the F/A-18. All essential systems and their parameters are available on the multiplex bus, each of the computers and displays have memory and time growth capacity, and the display formats are programmable. This flexibility provides growth for new systems, weapons, and missions. Examples of easily assimulated systems include a new EW suite, modern data transmission methods (JTIDS), and recce/sensor controls and displays. Of immediate benefit to the F/A-18 Hornet is that quick modifications were accomplished during development flight testing by this built-in weapon system flexibility.

# SYSTEMS INTEGRATION OF PRIMARY FLIGHT INFORMATION

LEE PERSON

&

GEORGE STEINMETZ

# 2nd GENERATION

# PRIMARY FLIGHT DISPLAY CONCEPT

- LIMITED RESEARCH EFFORT
  - SPIN OFF OF TCV
  - SIMULATION EFFORT - TCV SIMULATOR
  - RESULTS GOOD ENOUGH TO SHARE

- ASSUMES AN INTEGRATED ELECTRONIC AIRCRAFT
  - PRECISE NAVIGATION SOLUTIONS
  - ELECTRONIC DISPLAY CAPABILITY
  - CONTROL AUGMENTATION OR AUTOMATION

- REVIEW DISPLAY EVOLUTION
  - OUT THE WINDOW
  - ELECTRO MECHANICAL
  - BASIC ELECTRONIC "REAL WORLD"

- 1ST GENERATION ELECTRONIC DISPLAY
- 2ND GENERATION ELECTRONIC DISPLAY
- VIDEOTAPE OF DISPLAY DYNAMICS

90

515

LANGLEY RESEARCH CENTER

NASA
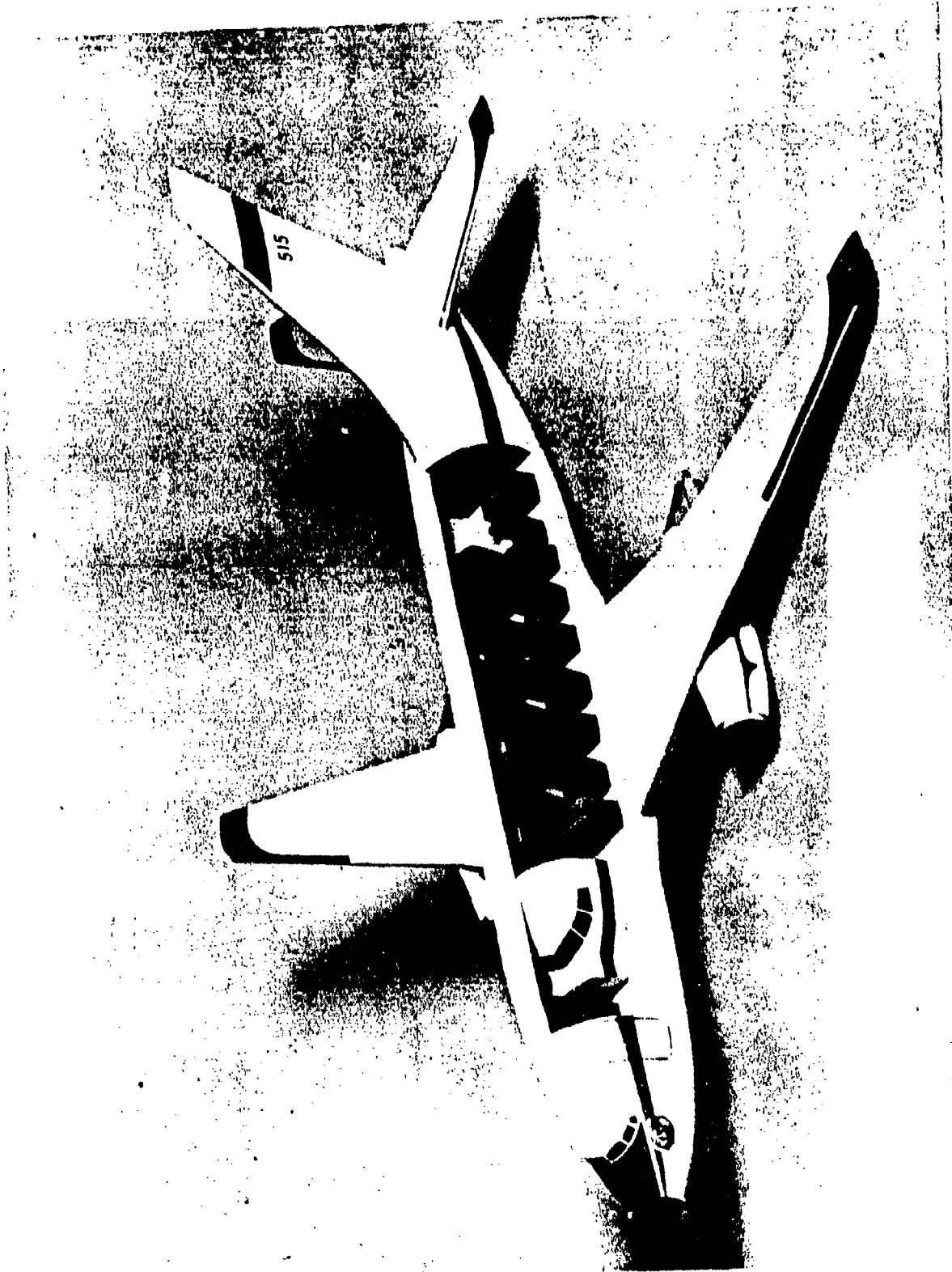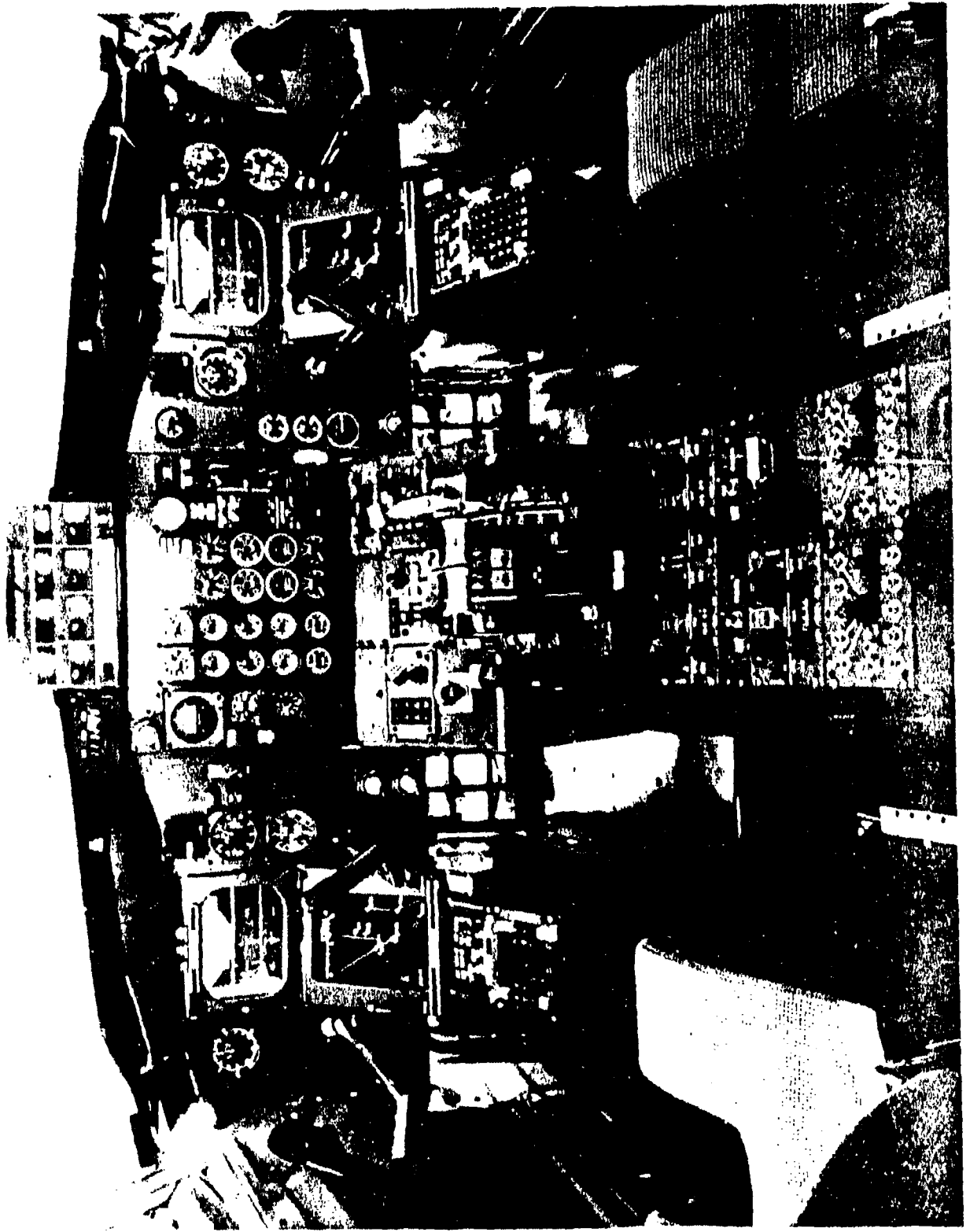
# ADVANCED AIRCRAFT SYSTEM
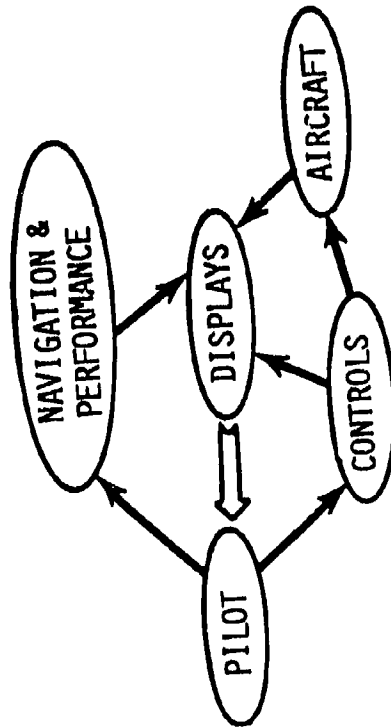


OPERATIONAL PHILOSOPHY

- PROVIDE ADEQUATE SITUATION & PREDICTIVE INFORMATION
- PILOT IN THE CONTROL LOOP

# HANDLING QUALITIES OF A
# VELOCITY VECTOR CONTROL SYSTEM

**STABILITY**

- COMPUTER STABILIZATION OF
  - FLIGHT PATH ANGLE
  - TRACK ANGLE
  - ATTITUDE

**CONTROL**

- NORMAL RATE RESPONSE
- INERTIAL REFERENCE ~ NO WIND WORLD

95
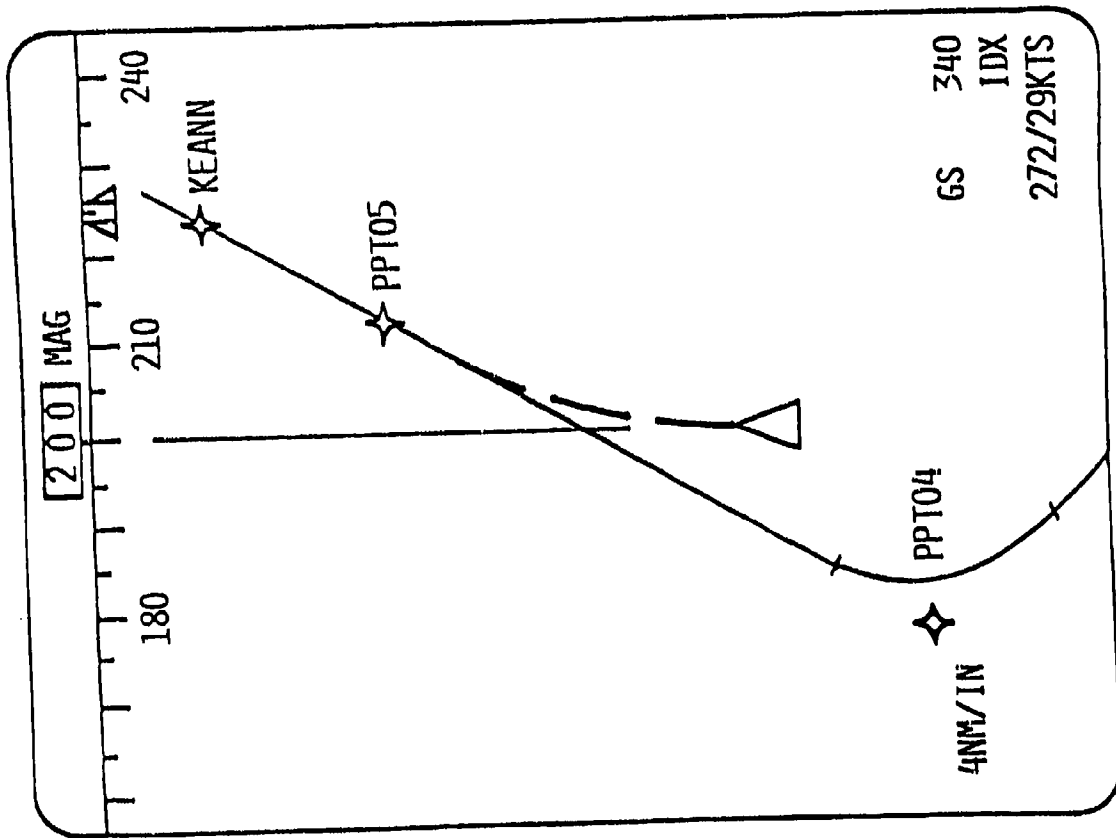
COMPARISON OF ELECTRONIC DISPLAYS AND
VISUAL APPROACH INFORMATION
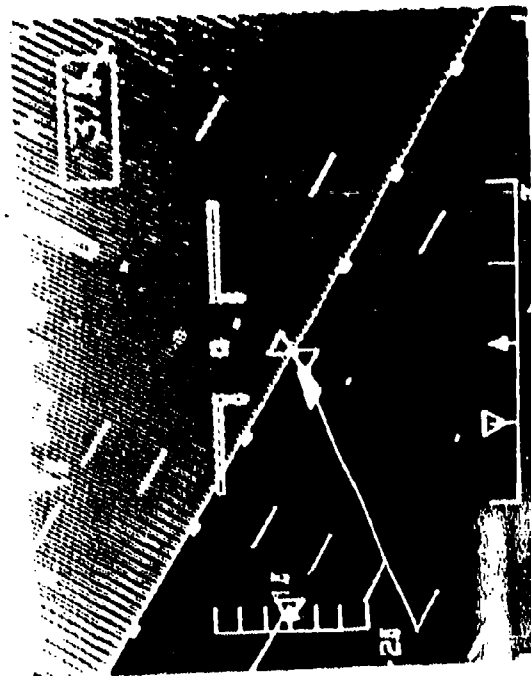
# 1st GENERATION
# ELECTRONIC DISPLAY

## NEW AND USABLE INFORMATION

- PERSPECTIVE RUNWAY
- INERTIAL FLIGHT PATH ANGLE
- FLIGHT PATH ACCELERATION

## PROBLEM AREAS

- ATTITUDE ORIENTATION
  - ABNORMAL CROSSWIND PICTURE
  - SYMBOLOGY JITTER IN TURBULENCE
- AWKWARD SCAN PATTERN

98

# EADI FORMAT ORIENTATION
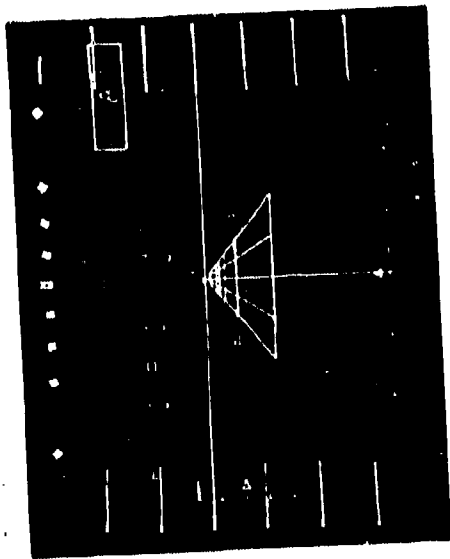


FLIGHTPATH CENTERED
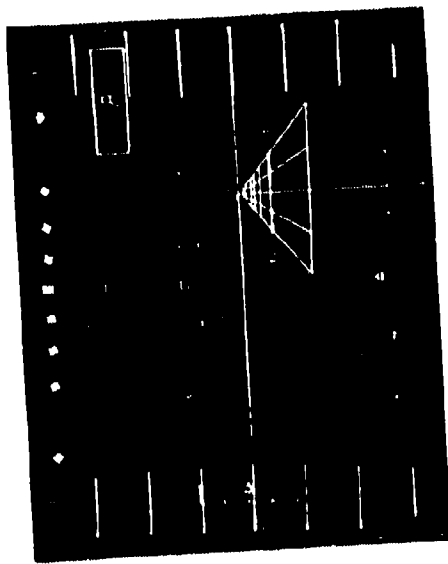
ATTITUDE CENTERED

RUNWAY

99
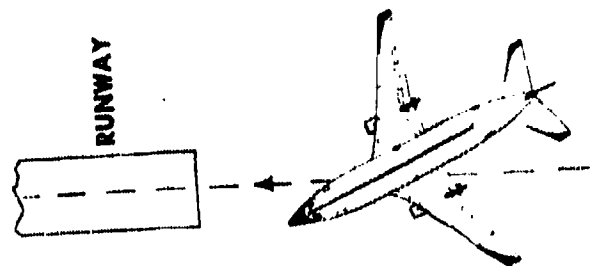
# 2nd GENERATION ELECTRONIC DISPLAY

- ORIENTATION ABOUT AIRCRAFT VELOCITY VECTOR
    - PILOTS REAL WORLD PICTURE
    - SYMBOL STABILITY IN TURBULENCE
    - ROLL CUES FROM VELOCITY VECTOR SYMBOL

- INFORMATION FORMAT IMPROVEMENTS
    - DEEMPHASIZED ATTITUDE SYMBOL
    - ADDED REFERENCE & ACTUAL AIRSPEED
    - AIRSPEED ERROR ON ACCELERATION SYMBOL
    - MOVED RADAR ALT READOUT & ADDED BARO
    - REFERENCED VERTICAL SCALE TO VERTICAL PATH
    - ADDED STATUS & FLIGHT CRITICAL MESSAGE AREAS
    - LAND MODE DECLUTTER
    - ADDED FLARE GUIDANCE

- IMPROVED SCAN PATTERN

- PRIMARY FLIGHT DISPLAY

100

RWY 7 | VV | CAS | 120

G/S

180 R

120

D/H

120

-10
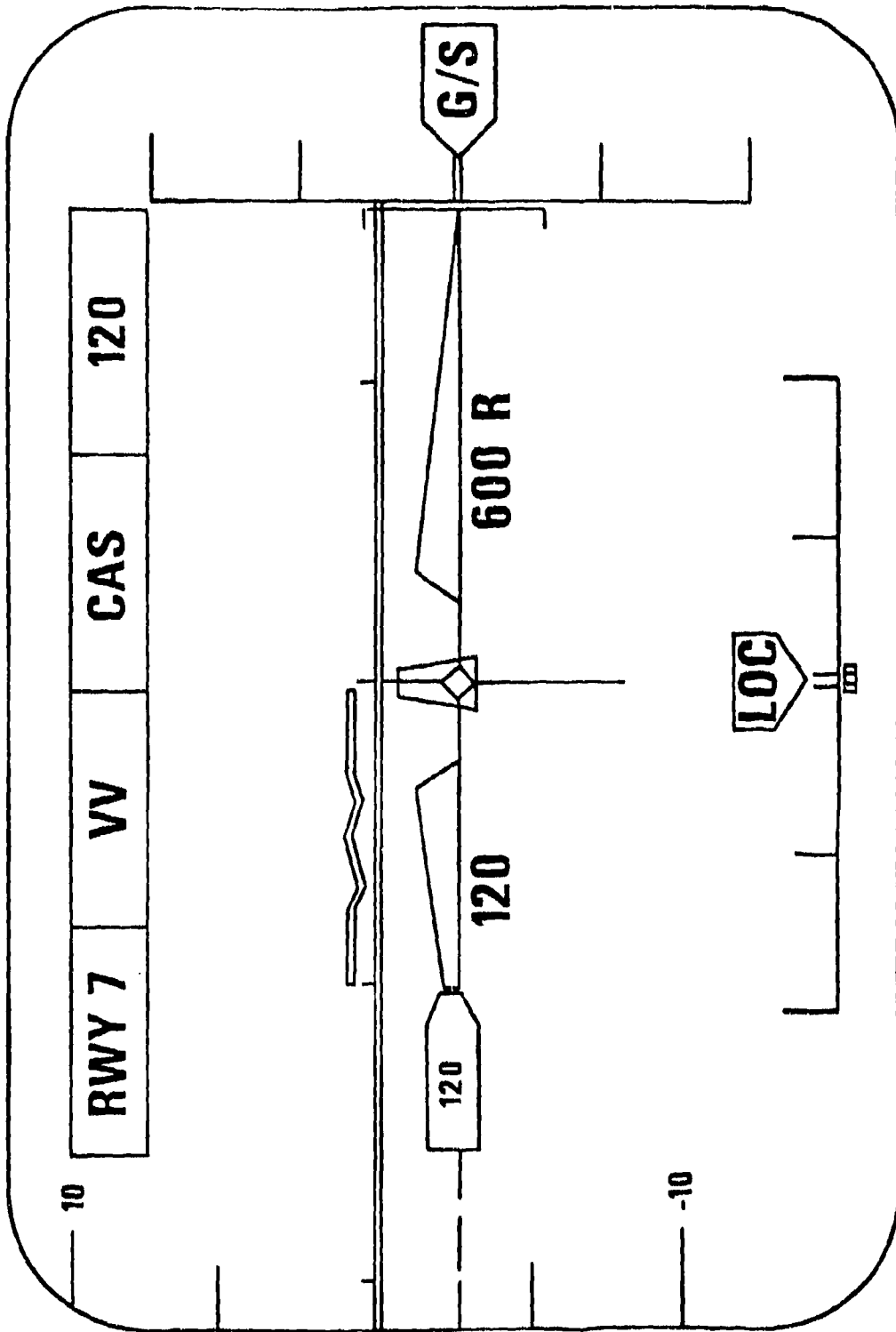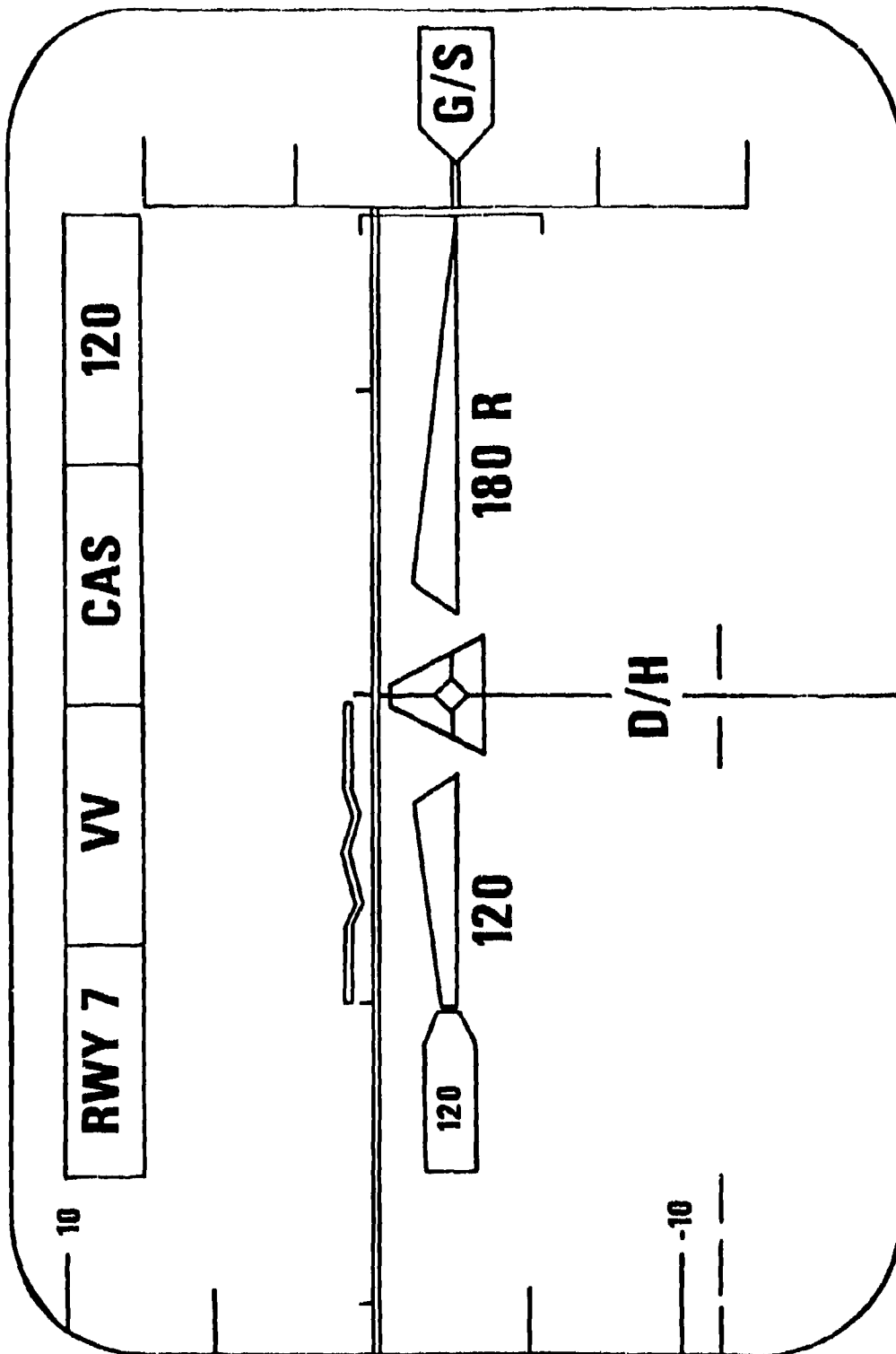
# CONCLUDING REMARKS

- 2ND GENERATION ELECTRONIC DISPLAY LOOKS GOOD

  AT PRESENT LEVEL OF DEVELOPMENT

- VELOCITY VECTOR ORIENTATION PROVIDES

  A MORE NATURAL REAL WORLD SCENE FOR PILOTS

  SYMBOL STABILITY IN TURBULENCE

- INTEGRATION OF ADDITIONAL PRIMARY FLIGHT INFORMATION

  ENHANCES PILOT SITUATIONAL AWARENESS

  REDUCES PILOT SCAN REQUIREMENTS

- LIMITED PILOT EVALUATION

- FOR THE FUTURE

  OUTSIDE PILOT EVALUATION

  IMPLEMENTATION IN TCV UPGRADE

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# HEAD-UP-DISPLAY FLIGHT TESTS

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and
Rogers E. Smith (AM)
Calspan Advanced Technology Center

This paper describes Head-Up-Display (HUD) flight tests conducted for the United States Navy and the United States Air Force by the Flight Research Branch of the Calspan Advanced Technology Center. The flight test system is outlined, followed by a discussion of HUD flight testing to date, and finally, future HUD flight test activities.

## HUD FLIGHT TEST SYSTEM

The HUD flight test system includes the NT-33A variable "Fly-By-Wire" research aircraft, a programmable HUD, and a workload assessment device.

## NT-33A Aircraft

The NT-33A in-flight simulator (Figure 1) is operated by Calspan for the USAF Flight Dynamics Laboratory, and has been used for fighter aircraft flying qualities research for many years. An analog/digital
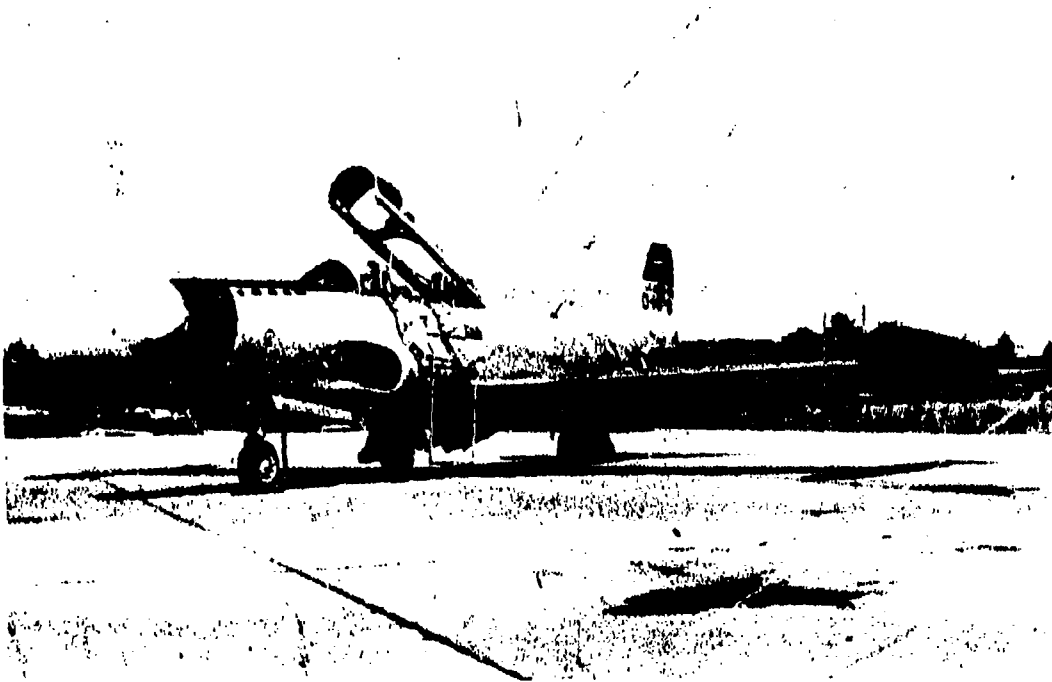


Figure 1 NT-33A RESEARCH AIRCRAFT

response feedback variable stability system, together with a center
stick/side stick variable force feel system, are used for simulation
of a wide range of stability and control characteristics.  A digital
data recording system collects data for post flight analysis.

## Programmable HUD

A programmable HUD was designed by the General Electric Corporation
Aircraft Equipment Division and installed in the NT-33 by Calspan,
under a program funded and directed by the U.S. Naval Air Test Center
(NATC).  This program and the resulting variable display system were
called "DEFT" for Display Evaluation Flight Test.

The core of the programmable HUD is a general purpose digital
computer.  Signals from various sensors are input to the computer
(Figure 2).  These signals include air data; inertial position, veloci-
ties, and accelerations; and aircraft angles, angle rates, and accelera-
tions.  The general purpose computer outputs information to the pro-
grammable display generator, a separate digital computer.  The pro-
grammable display generator produces the symbology which is displayed
on the AVQ-7 HUD optics (Figure 3).  A TV monitor/repeater in the rear
cockpit allows the rear cockpit safety pilot to observe the HUD sym-
bology.  Mode control is achieved with a rear cockpit mode control
unit, and with front cockpit declutter and flight director buttons.
Magnetic tape drives are used to program the general purpose computer,
and for data collection.  Computer programs, which control the HUD
format, are developed on a ground integrated test bench.
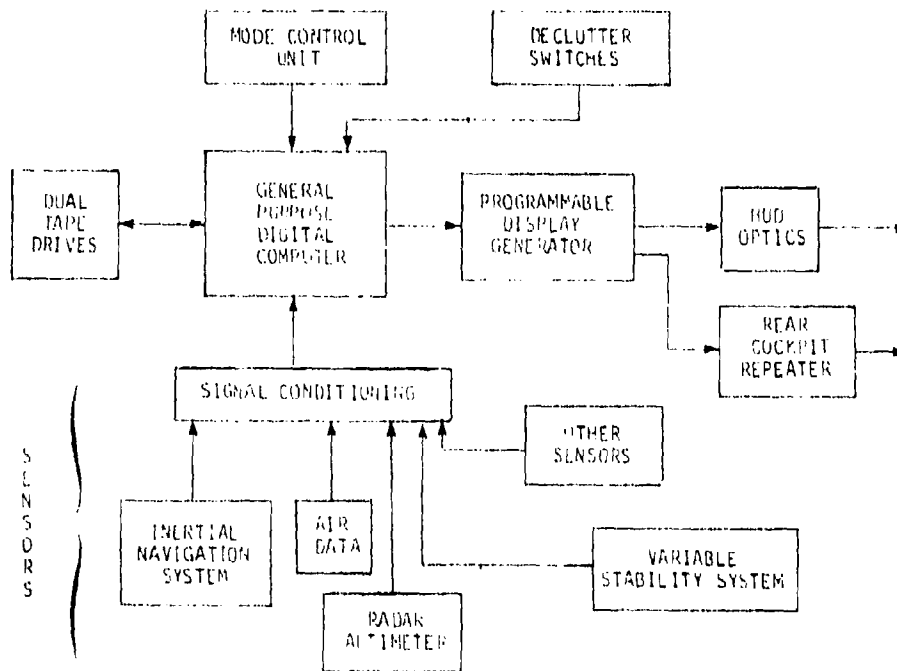
Figure 2    DISPLAY EVALUATION FLIGHT TEST SYSTEM

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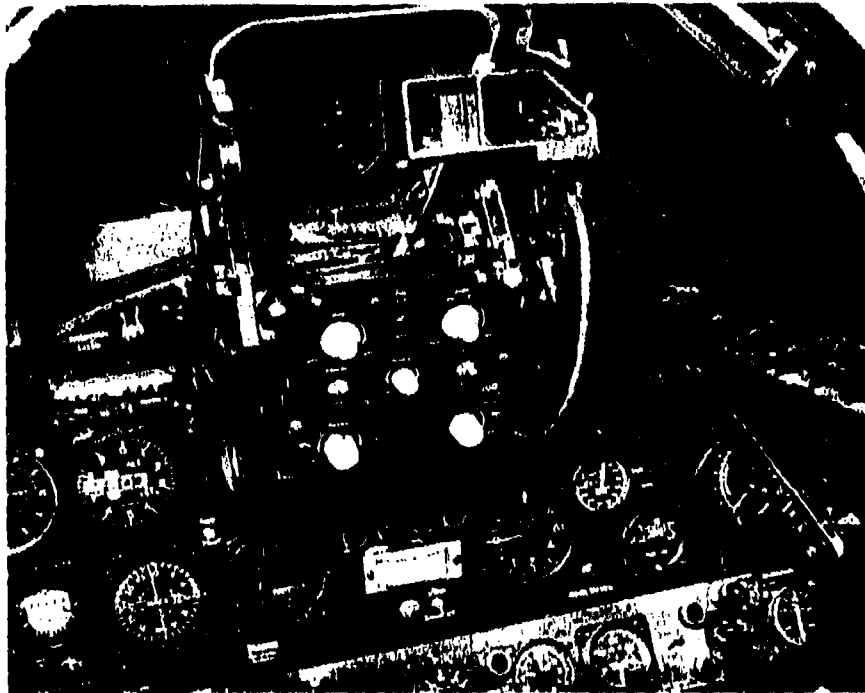
Figure 3    NT-33 HEAD-UP-DISPLAY

## Workload Assessment Device

A Workload Assessment Device (WAD) was also installed in the NT-33
as part of the Naval Air Test Center DEFT program. The WAD, designed
by the Systems Research Laboratory, provides a quantitative measurement
of a pilot's reserve mental processing capacity. This measurement is
the result of a secondary task which the pilot performs at the same
time he performs the primary flight task. A rear cockpit control panel
allows in-flight control of the WAD. When actuated, the WAD system
causes the HUD to display a single randomly selected letter at seven
second intervals.

During flight the pilot must decide, as quickly as possible, whether
the displayed letter belongs to a set of "positive" letters he memorized
during the mission briefing. Three sets, containing one, two and four
letters, respectively, are used. The evaluation pilot indicates posi-
tive and negative decisions with control stick switches. The letter is
removed from the HUD when the pilot depresses a response switch, or
after five seconds, whichever occurs first. Pilots are carefully
instructed to consider the WAD as a secondary task to be accomplished
without interfering with performance of the primary task. A complete
workload assessment requires four repetitions of the primary task. On
the first repetition of the primary task, no WAD letters are displayed.

WAD data consists of pilot reaction time and error rate, as a
function of memory set size (one, two, or four letters). The basic
concept is that the increase in reaction time, as memory letter set

size is increased, will be greater when primary task pilot workload
is high than when primary task workload is low.  In-flight WAD data
is compared with baseline WAD data acquired on the ground prior to
flight.

## HUD FLIGHT TESTS TO DATE

During the past year Calspan has conducted four HUD flight tests:

- Instrument Landing HUD Format Test
- Visual Carrier Approach HUD Format Test
- Evaluation of HUD Pitch Ladder Scaling
- A HUD Based Lateral Flying Qualities Evaluation Task

### Instrument Landing HUD Format Test

The objective of the Instrument Landing HUD Format Test, sponsored
by the Naval Air Test Center, was to compare two HUD formats during
blind Instrument Landing System (ILS) approach and visual flare and
landing, from the standpoint of pilot performance and workload.  Two
NATC test pilots served as evaluation pilots.

The primary task was divided into two subtasks.  The first subtask
was to fly a "blind", or no visual reference, ILS approach using the
HUD as the primary control and performance instrument.  This subtask
began (for analysis purposes) at glide path interception and ended at
decision height.  The second subtask was to perform a visual flare and
landing, or low approach, using the HUD as the primary performance
reference.  The second subtask began at decision height and ended at
touchdown, or at waveoff.

The secondary task was the previously described WAD task.

A transparent amber film on the NT-33 canopy and a blue visor on
the evaluation pilot's helmet allowed the simulation of blind instru-
ment flight.  With the blue visor down, the evaluation pilot could not
see outside the aircraft, but could see all aircraft instruments and
the HUD display.  With the visor up, the pilot could see outside
normally.

Two different HUD formats were evaluated:  the first was a con-
ventional display similar to that used in the U.S. Navy/McDonnell
Douglas F/A-18 aircraft; the second display was designed by Gilbert
Klopfstein, French Service Technique Aeronautique.

Conventional Display:

The conventional display, shown in Figure 4, used a combined digital
and analog format.  An inertial flight path marker and pitch ladder
(scaled 1:1 with the real world) showed inertial flight path angle.
During a blind ILS approach, horizontal (localizer) and certical (glide
path) position guidance was provided by horizontal and vertical devia-
tion indicators, referenced to the flight path marker.  The aircraft was
on course and on glide path when the deviation indicators were aligned
with the flight path marker.  Displacement of the deviation indicators
from the flight path marker showed the angular localizer and glide
path errors (the deviation indicators did not show the bank or pitch

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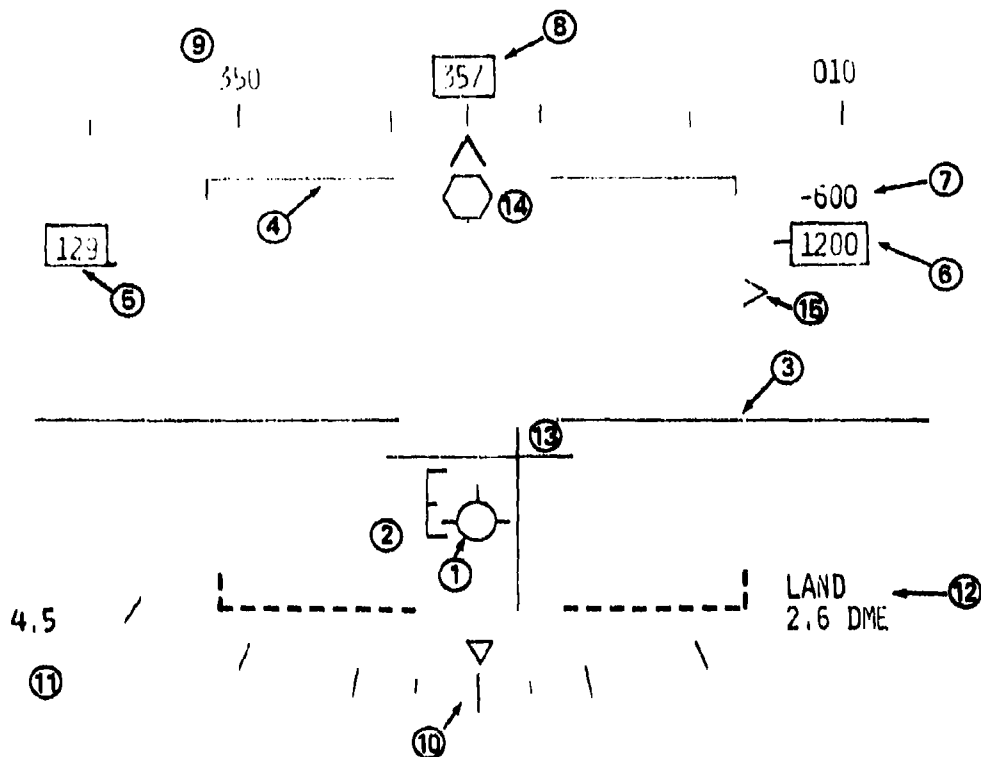
Figure 4   CONVENTIONAL HUD FORMAT

1. INERTIAL FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
2. ANGLE OF ATTACK BRACKET ($\alpha$ GREATER THAN COMMAND. $\alpha$ = COMMAND WHEN BRACKET IS ALIGNED WITH FLIGHT PATH MARKER).
3. HORIZON LINE
4. PITCH LADDER
5. INDICATED AIRSPEED
6. BAROMETRIC ALTITUDE
7. VERTICAL VELOCITY
8. MAGNETIC HEADING
9. HEADING SCALE
10. BANK ANGLE SCALE (30 DEG. MAX.)
11. ANGLE OF ATTACK
12. MODE AND RANGE TO TOUCHDOWN
13. ILS DEVIATION BARS
14. LATERAL ACCELERATION BALL
15. DECISION HEIGHT INDICATOR

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angle changes required to return to the ILS course and glide path.)
Digital heading, altitude, and vertical velocity displays provided
additional positional guidance.

Digital angle of attack and indicated airspeed, together with an
angle of attack bracket, provided speed guidance. The desired approach
angle of attack was achieved when the bracket was aligned with the flight
path marker. Displacement of the bracket from the flight path marker
showed angle of attack error.

Klopfstein Display:

The Klopfstein display, shown in Figure 5, was an all-analog dis-
play optimized for adverse weather takeoffs and landings. An air mass
flight path marker referenced to a horizon line showed air mass flight
path angle. Programmed runway data and ILS receiver information were
used to generate a synthetic runway display which, in effect, overlayed
the actual runway. During a blind ILS approach, the orientation of the
synthetic runway provided the pilot with horizontal (localizer) error
cues similar to those used during visual landings. Runway heading and
aircraft track markers on the HUD horizon line provided additional
horizontal guidance.

Vertical (glide path) ILS guidance was provided by the position of
a Selected Flight Path Marker (SFPM) relative to the synthetic runway.
The adjustable SFPM was depressed below the HUD horizon line at the
appropriate ILS glide path angle, and was aligned with the touchdown
point when the aircraft was on glide path.

A HUD angle of attack display and a Potential Flight Path Marker
(PFPM) provided speed guidance. The angular displacement between the
air mass flight path marker and the longitudinal reference marker, or
waterline marker, was, by definition, angle of attack. Increasing angle
of attack was shown by increasing displacement between the waterline
marker and air mass flight path marker. The display included an index
displaced from the waterline marker an angle equal to the desired
approach angle of attack, and an index displaced to show maximum allow-
able angle of attack. When the aircraft was flown at the desired
approach angle of attack, the air mass flight path marker was aligned
with the apex of the approach angle of attack index. The PFPM, when
referenced to the air mass flight path marker, showed the aircraft's
acceleration along the air mass flight path. When the PFPM was aligned
with the air mass flight path marker, the aircraft maintained a constant
inertial speed.

For this test, the variable "fly-by-wire" system was programmed to
yield "Good," "Fair," or "Poor" landing approach longitudinal flying
qualities.

Ten evaluation flights were flown in September 1979.

Task performance was evaluated using ILS and angle of attack error
data. Performance results could not be consistantly related to changes
in HUD format or flying qualities configuration. Pilot workload was
evaluated using numerical control stick force, pitch angle, and bank
angle data; pilot ratings and comments; and WAD data (Figure 6).
Although pilot ratings and numerical data were inconclusive, pilot
comments and WAD data showed that pilot workload was lower during ILS
approaches flown with the Klopfstein HUD format, as compared to

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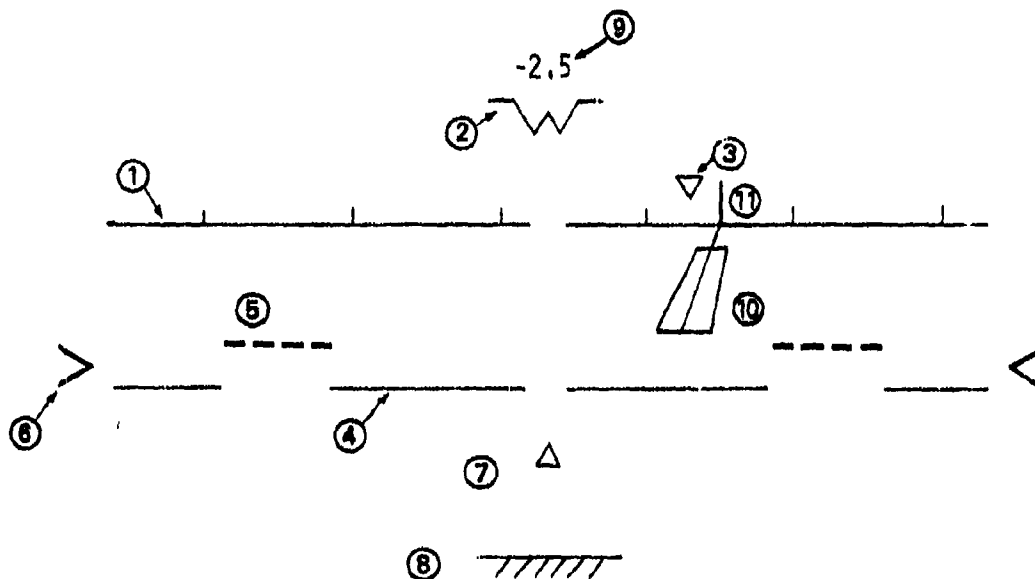
**Figure 5   KLOPFSTEIN HUD FORMAT**

1. HORIZON LINE WITH 2 DEG. HEADING MARKS (OVERLAYS REAL HORIZON).
2. WATERLINE SYMBOL.
3. TRACK MARKER
4. AIR MASS FLIGHT PATH MARKER
5. SELECTED FLIGHT PATH MARKER (DEPRESSED BELOW HORIZON LINE AT GLIDE PATH ANGLE).
6. POTENTIAL FLIGHT PATH MARKER (AIRSPEED INCREASING. AIRSPEED INCREASE WILL STOP IF THRUST IS REDUCED TO LOWER POTENTIAL FLIGHT PATH MARKER TO ALIGN WITH FLIGHT PATH MARKER, OR IF FLIGHT PATH MARKER IS RAISED TO ALIGN WITH POTENTIAL FLIGHT PATH MARKER).
7. ANGLE OF ATTACK TRIANGLE. (ANGLE OF ATTACK LESS THAN COMMAND. COMMAND ANGLE OF ATTACK IS ACHIEVED WHEN APEX OF TRIANGLE IS TOUCHING THE FLIGHT PATH MARKER).
8. LIMIT ANGLE OF ATTACK. (LIMIT ANGLE OF ATTACK IS ACHIEVED WHEN LIMIT SYMBOL IS ALIGNED WITH FLIGHT PATH MARKER).
9. SELECTED FLIGHT PATH ANGLE (ANGLE BETWEEN HORIZON LINE AND SELECTED FLIGHT PATH MARKER = GLIDE PATH ANGLE).
10. SYNTHETIC RUNWAY (THRESHOLD AT GLIDE PATH INTERCEPT POSITION).
11. EXTENDED RUNWAY CENTERLINE.

approaches flown with the conventional format. Pilot workload during
visual flare and landing was not related to HUD format, but was related
to flying qualities configuration. As expected, pilot workload was
higher for the poor flying qualities aircraft during flare and landing.

Flight test results indicated that the Klopfstein HUD format was
better than the conventional format for ILS approaches because of
reduced pilot workload. WAD pilot workload results correlated with
pilot comments. This correlation may be of importance to future
flight test programs.
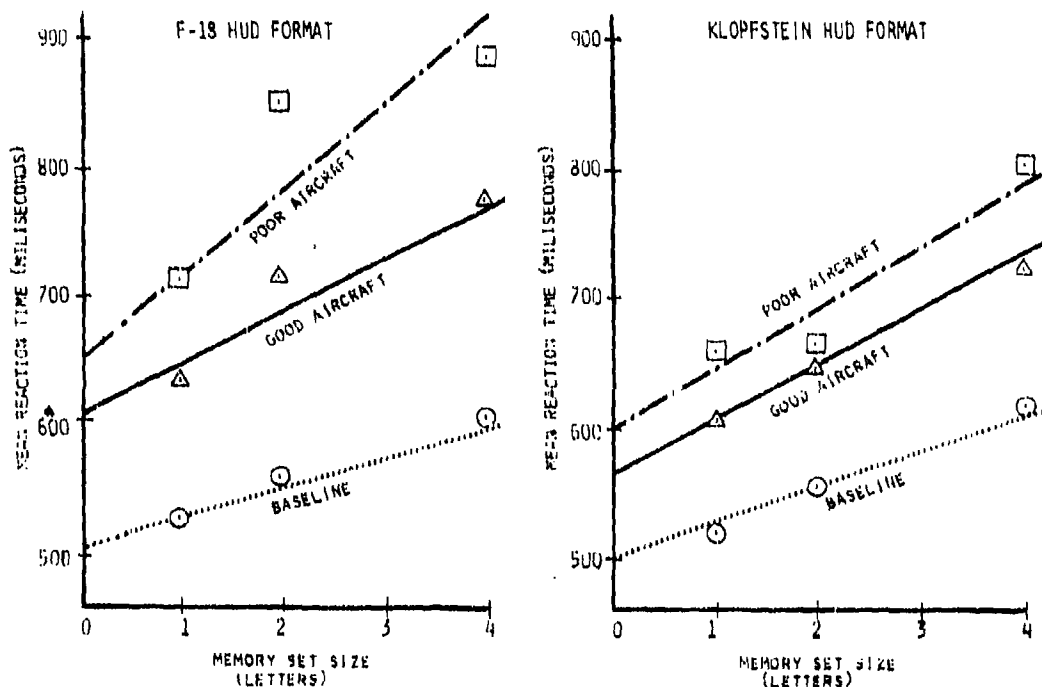


Figure 6   WAD RESULTS FOR ONE EVALUATION PILOT

Visual Carrier Approach HUD Format Test

The Visual Carrier Approach HUD Format Test was also sponsored by
NATC. The objective was to determine, within test constraints, if the
Klopfstein HUD format improves task performance and reduces pilot work-
load during visual carrier approaches, compared to a conventional HUD
format. Three NATC test pilots served as evaluation pilots.

The primary task was a land based simulated carrier approach to
minimum altitude waveoff, using an optical landing system. The second-
ary task was the WAD task. The two HUD formats were the previously
described Klopfstein and conventional formats, modified for visual
approaches. The ILS error pointers were removed from the conventional
format, and the synthetic runway was removed from the Klopfstein format.
Seven test flights were flown in April 1980.

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Glide path and line up errors, determined from laser tracker data, and angle of attack errors were used to measure task performance. Pilot workload was evaluated using pilot ratings and comments and WAD data.

Results showed no real performance or workload advantages of one format with respect to the other. However, pilot comments indicated that the potential flight path marker was very helpful for angle of attack control. Also, the selected flight path marker may be a backup glide path aid in the event of optical landing system failure.

## Evaluation of Pitch Ladder Scaling

Recent "lost wingman" accidents involving tactical aircraft which employ a HUD as the primary instrument reference, and recent ground simulator HUD research, indicate that pilots may have less attitude awareness when using a HUD as a primary instrument reference, than when using a conventional attitude indicator. To date, HUDs in U.S. tactical aircraft have generally had 1:1 pitch ladder scaling, and a flight path marker control index. This format maximizes precise flight path control, perhaps at the expense of attitude awareness. Some non U.S. aircraft, for example, the British Sea Harrier, have been equipped with different pitch ladder scaling and control index formats, in an attempt to improve the pilot's attitude awareness during maneuvers in instrument meteorological conditions.

These considerations resulted in the third HUD flight test: an evaluation of HUD pitch ladder scaling, conducted as part of the USAF Test Pilot School curriculum for Class 79B. The objective was to compare pitch ladder scale options and flight index options during large amplitude maneuvering and during instrument approaches.

The conventional HUD format, with the following three pitch ladder scale options and three flight index options, was used:

### Pitch Ladder Scaling

- 1:1    (NORMAL) pitch ladder lines correspond to the real world at all times.
- 6:1    (COMPRESSED) only $30^\circ$, $60^\circ$, and $90^\circ$ pitch ladder lines are shown (Figure 7). With respect to the horizon line, the $30^\circ$, $60^\circ$, and $90^\circ$ pitch lines are located in the same position on the 6:1 pitch ladder scale as the $5^\circ$, $10^\circ$, and $15^\circ$ lines on the 1:1 scale. Pitch ladder scale does not correspond to the real world.
- 1:1/2:1    (DUAL SCALES) pitch ladder scaling is 1:1 when pitch attitude is less than $\pm 20^\circ$, and compressed 2:1 when pitch attitude exceeds $\pm 20^\circ$

### Index Formats

- Flight Path Marker (Velocity Vector)
- Pitch Marker (Fixed Reference Mark)
- Combined Pitch and Flight Path Markers
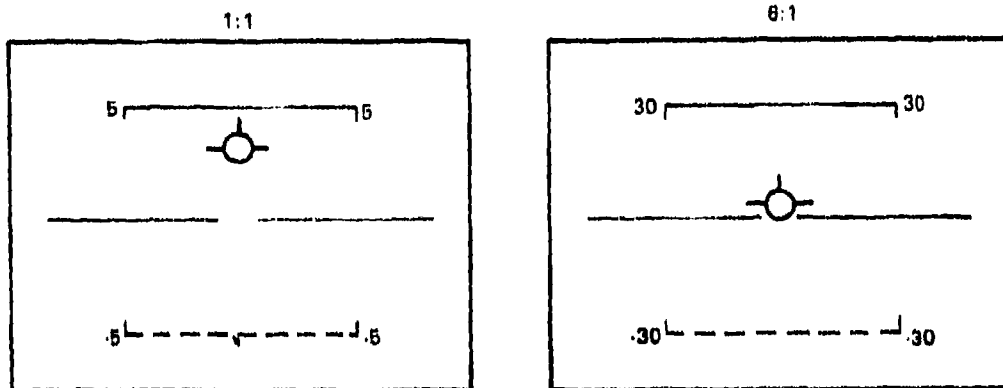
DETAILS OMITTED FOR CLARITY

Figure 7   HUD PITCH LADDER SCALING

A sequence of maneuvers in simulated Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC) was performed with pitch ladder scale/flight index combinations.  IMC flight was simulated with the blue/amber vision restriction system.  IMC maneuvers included aerobatics and unusual  attitude recoveries.  VMC maneuvers included aerobatics and simulated weapons deliveries requiring precise flight path control.  Sixteen evaluation flights were performed in June 1980.

Pilots completed opinion questionnaires following each evaluation flight.  All agreed that the 6:1 pitch ladder scale resulted in improved attitude awareness compared to the 1:1 scale, although precision flight path control was somewhat more difficult.  The majority of participating pilots preferred 6:1 pitch ladder scaling over 1:1 scaling, and the pitch marker over the flight path marker, for the large amplitude IMC and VMC maneuvers performed during evaluation flights.  All pilots preferred 1:1 pitch ladder scaling and most pre ferred the flight path marker for IMC instrument approaches.  Thus, optimum pitch ladder scaling and optimum flight index appear to depend on the task and on the environment.

The results of this limited evaluation suggest that U.S. tactical aircraft may not be equipped with optimum HUD formats for IMC attitude awareness.  Existing formats emphasize precision flight path control even when the aircraft are equipped with automatic weapons aiming systems.

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## Lateral Flying Qualities Evaluation Task

HUD based tasks were used to evaluate lateral flying qualities during a recently completed USN/USAF NT-33 research program. The purpose of this flight test program was to investigate the lateral-directional flying qualities of fighter aircraft with highly augmented flight control systems. A secondary program objective, associated with the HUD, was to determine if selected HUD based tasks yield lateral flying qualities evaluation results similar to results for precise maneuvering fighter tasks such as formation, gun tracking, air refueling, instrument approach, and visual landing. Heading tracking and bank angle tracking tasks were therefore superimposed on the conventional HUD format.

HUD based flying qualities evaluation tasks are useful because no support aircraft is required; further, HUD based tasks are repeatable and tracking errors can be easily recorded for post flight analysis.

Command heading or bank angle, as a function of time, was programmed in the DEFT general purpose computer (Figure 8). Step changes and ramp changes of command angle were programmed. For heading tracking, a heading error cross (Figure 9) was displaced along the HUD horizon line away from the flight path marker a distance proportional to heading error (the difference between command heading and actual heading.) The pilot turned towards the heading cross to eliminate heading error. For bank angle tracking, a command bank angle line (Figure 10) which intersected the center of the HUD horizon line, was rotated with



TIME SCALE SHOWN FOR
BANK ANGLE TRACKING.
TIME SCALE EXPANDS TO
270 SECONDS FOR HEADING
TRACKING.
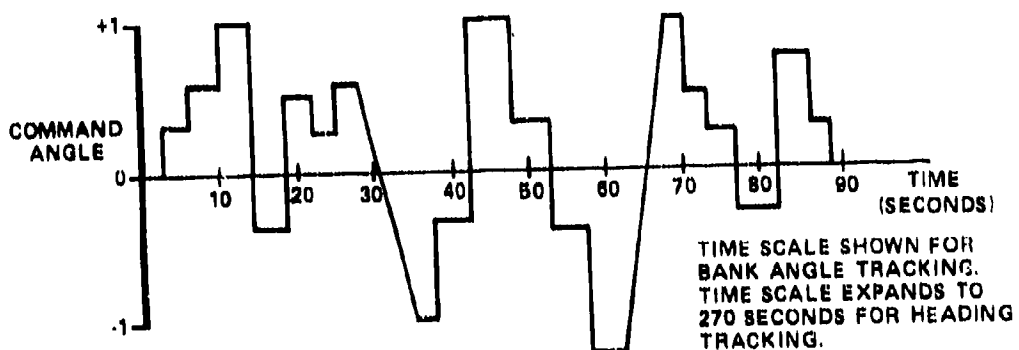
1.0 COMMAND ANGLE = 60°, BANK ANGLE TRACKING, LANDING GEAR UP
30°, BANK ANGLE TRACKING, LANDING GEAR DOWN
30°, HEADING TRACKING, LANDING GEAR UP
15°, HEADING TRACKING, LANDING GEAR DOWN

Figure 8. COMMAND ANGLE VS. TIME

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DETAILS OMITTED FOR CLARITY
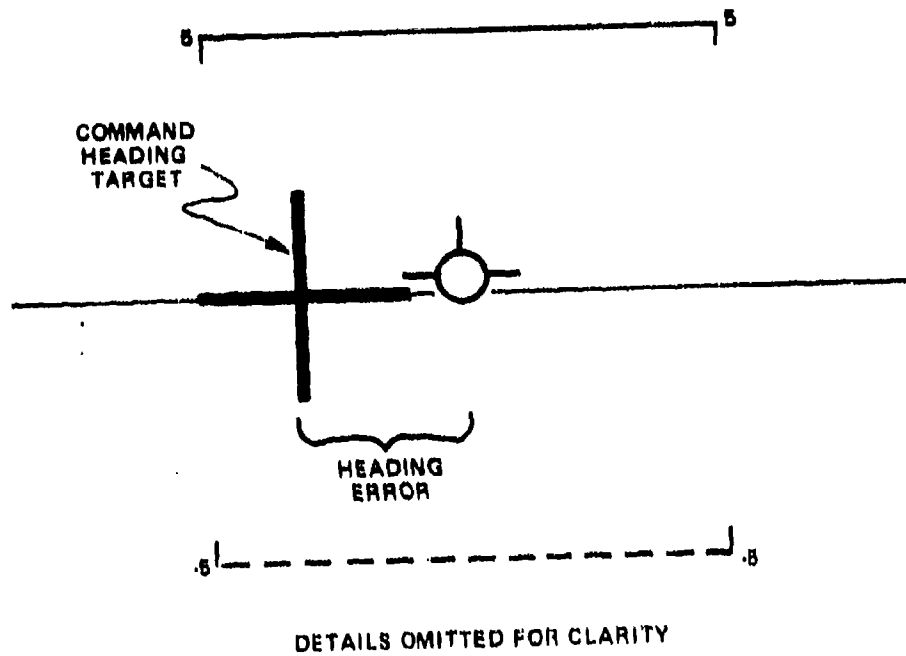
Figure 9   HEADING TRACKING TASK FORMAT



DETAILS OMITTED FOR CLARITY
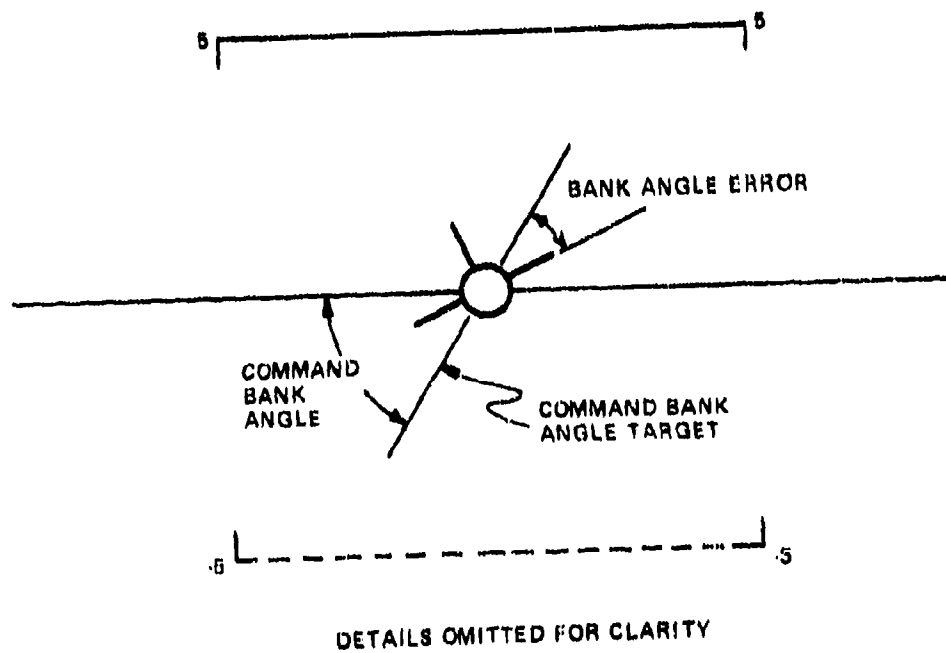
Figure 10   BANK ANGLE TRACKING TASK FORMAT

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respect to the horizon line to show command bank angle. The pilot banked the aircraft until the "wings" of the flight path marker symbol were parallel to the command bank angle line, thereby matching actual bank angle to command bank angle. The magnitude of command angle changes, and the interval between changes, were chosen to require the evaluation pilot to fly the HUD tasks as precisely and agressively as the primary fighter maneuvering evaluation tasks.

Initial results indicate that the HUD bank angle tracking evaluation task yields pilot ratings and comments, for a given lateral-directional flying qualities configuration, similar to those for air-to-air gun tracking and probe and drouge air refueling.

Of course flying qualities research must be primarily based on actual mission representative evaluation tasks; however, HUD based tasks may be useful as secondary tasks. Also HUD tasks may assist comparison of ground simulation results with in-flight flying qualities evaluation results.

## FUTURE HUD TESTS

Possible future DEFT programs include:

- Missile launch envelope display. This display would provide the pilot with information on the probable success of an air-to-air missile launch against a target with constant maneuver parameters, and with worst case maneuver parameters.

- USN and USAF Test Pilot School DEFT programs.

- Evaluation of proposed changes to operational HUDs.

- Improved HUD target. This HUD target would have three dimensional perspective, and would be programmed to maneuver in an earth based reference system.

- Improved WAD. The WAD is being modified to include a "Computalk" aural letter presentation over the aircraft interphone system simultaneously with the existing HUD visual letter presentation. Also, the interval between WAD letters will be automatically adapted to the pilot's WAD reaction time and error rate. When the pilot is responding correctly and quickly to the WAD, the interval between letters will be reduced.

## CONCLUSION

Head-Up-Display flight testing involves not only the display itself, but also the total environment, including aircraft flying qualities. Results must address pilot workload as well as task performance.

The integration of the Display Evaluation Flight Test system and the Workload Assessment Device with the NT-33 in-flight simulation aircraft has resulted in an advanced systems research aircraft for USAF and USN flight research. During the past year, this aircraft has proved to be a powerful tool for investigating the relationships between displays, flying qualities, and pilot performance and workload.

EVALUATION OF A PILOT WORKLOAD ASSESSMENT DEVICE
TO TEST ALTERNATE DISPLAY FORMATS AND
CONTROL HANDLING QUALITIES

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## SUMMARY

This in-flight research project evaluated the utility of a Workload
Assessment Device (WAD) to measure pilot workload for approach and landing
tasks under simulated instrument meteorological conditions, alternate HUD
formats and control stability variations. The flight tests were conducted
in an NT-33A research aircraft, extensively modified for the U. S. Air Force
and U. S. Navy by the Display Evaluation Flight Test program. The hardware,
software, and test procedures associated with the WAD functioned efficiently
with only minor discrepancies and minimum pilot distraction. The project
established the feasibility of using an item-recognition task as a measure
of sensory-response loading and reserve information processing capacity
while flying precision approaches. In a descriptive statistical treatment
of the data, the results indicate an appreciable increase in reaction time
and errors with degraded handling qualities as compared to ground baseline
measures and good handling qualities. The preliminary findings also reveal
consistent trends toward the availability of more mental reserve capacity
when flying predominantly pictorial/symbolic HUD configurations as compared
to conventional HUD formats with scales and alphanumerics. It is
recommended that further evaluations be conducted to establish the efficacy
of utilizing the WAD to measure mental workload in a wide variety of
aircrew tasks.

## INTRODUCTION

### BACKGROUND

New developments in cockpit display designs and integrated weapons system avionics
have significantly altered the role of the pilot from that of a skilled, manual control
operator to an executive manager of an integrated weapons system. Emphasis on psycho-
motor control has been augmented by an interest in more cognitive skills represented by
such functions as short-term memory, information processing, and decision making. Few
measurement techniques exist which are able to provide an objective, reliable, and valid
estimate of the subtle differences in workload introduced by these new systems. To date,
methodology for objectively quantifying workload has not been effectively applied to the
flight test and evaluation of aircrew systems (references 1 and 2).

This project introduced a novel approach to the traditional manner of measuring pilot
workload. Aircrew workloads are typically measured by subjective assessment rating scales
which are based on pilot opinions that relate operational task demands to system response
characteristics, e.g., Cooper-Harper Handling Qualities Rating Scale. The new approach
applied in this project is an item-recognition task first identified by Sternberg
(reference 3) and modified by the U. S. Air Force (reference 4) to measure the reserve
capacity of the pilot. The approach assumes that an upper bound exists on the ability of
the pilot to gather and process information. As the pilot's workload increases on the
primary task, i.e., flying the aircraft, reserve capacity for processing secondary
information decreases until a point of overload is reached by the pilot. At this point,
the information processing demands of the task exceed the pilot's total workload capacity
and is manifested by degradation in performance (i.e., increase in errors and response
times) on the secondary item-recognition task.

The theoretical formulation of the item-recognition task, as proposed by Sternberg
(figure 1), has several attractive features which make it ideally suited for evaluating
the source of increase in task-loading in aircraft test environments. The theory assumes
a least-squares, linear regression fit of the data where the intercept represents the
input/output component and the slope depicts the mental information processing component
of the item-recognition task. If, for example, the sensory-response mode (i.e., input/
output), is response overloaded the theoretical expectation is a change in the y-intercept
of the regression line with no change in slope. Conversely, if the source of task-loading
was one which affected the pilot's mental information processing capabilities (e.g., short-
term memory overload), the expectation is a change in the slope of the curve without a
corresponding change in the intercept value. Either result would be a decrease in the
pilot's reserve capacity for processing information.

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The use of the item-recognition task to assess primary task workload is not a new concept in aircrew flight simulation studies (references 5 and 6). However, the uniqueness of its application in this project is that a Workload Assessment Device (WAD) that generates and controls the secondary item-recognition task was designed, fabricated, and installed in a NT-33A research aircraft to measure and analyze the pilot's reserve workload capacity for the Display Evaluation Flight Test (DEFT) program as reported in reference 7.

## PURPOSE

The purpose of this project was to evaluate the utility of the WAD to measure pilot workload for approach and landing tasks under simulated Instrument Meteorological Conditions (IMC's) for alternate HUD formats and aircraft control stability variations.

## DESCRIPTION OF AIRCRAFT/EQUIPMENT

The NT-33A variable stability aircraft is an extensively-modified, T-33 jet trainer. The elevator, aileron, and rudder controls in the front cockpit were disconnected from their respective control surfaces and connected to separate servo-mechanisms that comprise an "artificial feel" system. In addition, the elevator, aileron, and rudder control surfaces were connected to individual servos which were driven by a number of different electrical inputs. This arrangement, through a response-feedback system, allowed the normal T-33 stability derivatives to be augmented to the extent that the handling qualities of the hypothetical research configurations could be simulated. A more comprehensive description of the NT-33A can be found in reference 8.

The DEFT program also provided a fully software-programmable display system to complement the variable stability features of the host-modified NT-33 Aircraft. Relative to the aircraft configuration, the DEFT system provided the capability of changing display formats and changing the algorithms and dynamics of the display driving signals. The display system consisted of a HUD, two digital computers, a magnetic tape system, INS sensors to augment the existing aircraft sensors, and a display repeater and mode control unit for the aft cockpit.

The software programs provided an in-flight choice of two uniquely different display configurations for use in the approach and landing phases of flight. These displays were of a conventional HUD format (figure 2) and the predominantly symbolic Klopfstein format (figure 3). As depicted in the figures, the conventional display used a HUD format with a flight path ladder, scales, and alphanumeric readouts of various flight parameters. The Klopfstein display, however, is predominantly symbolic/pictorial depicting the horizon, and artifical runway overlaying the actual runway, and other flight guidance symbols.

## METHOD

After several practice sessions and prior to the start of the evaluation flights, a baseline measurement was obtained on the item-recognition task. Each pilot was given the item-recognition task for each memory set size while sitting in the cockpit of the aircraft stationed on the ground. The task required the pilot to memorize sets of one, two, or four letters, i.e., A, RJ, ZPNW. The pilot was then instructed, prior to testing with each memory set, which set of letters would be presented for memory recall. The prememorized letters (positive) or other letters (negative) were presented on the HUD one at a time every 7 sec. The positive and negative letters were presented individually with a .5-probability of occurrence. Each letter appeared on the HUD one at a time until the pilot responded or 5 secs. elapsed. The pilot responded to a letter presentation by pressing one of two designated buttons on the control stick. One button indicated that the letter was a member of the prememorized set (positive) and the other indicating it was not a member of the prememorized set (negative). Positive letters never appeared as negative letters and the same positive letter sets were used throughout the test. A total of 30 letters, 15 positive and 15 negative, was presented for each memory set for the baseline conditions.

The same procedures were used in flight as during the baseline test conditions with the exception that the pilot was flying the aircraft while performing the secondary task. An additional experimental control allowed one approach per handling quality/display format combination to be flown without any letter presentations to evaluate the impact of the secondary task on the primary task of flying the aircraft

The reaction times and response errors were collected and analyzed by the WAD controller and ground-based analysis system. After each response, the reaction time was measured from the onset of a letter to the physical response of pressing the correct button. The reaction times for both the positive and negative letters were stored on cassette tapes. The reaction times for the correct responses were then averaged and plotted as a function of the memory set sizes. The response errors were coded, tabulated, and categorized by type of error and frequency of occurrence. A response was considered an error if the pilot pressed the wrong key (reversal error), responded correctly but after 1,500 msec (out-of-bound error), or did not respond before 5 sec (time-out error).

The basic flight scenario for each approach and touch-and-go was as follows. The Evaluation Pilot (EP) was given control of the aircraft by the Safety Pilot (SP) with the desired display-aircraft handling quality combination. The EP then flew on instruments while using an orange filter over the windscreen and a blue visor attached to the helmet

to simulate IMC.[1] After intercepting the glide slope, the EP descended to 1,800 meter MSL to intercept the localizer at 8 nmi. At this point, the SP turned on the digital recorder and the WAD controller which were used to record the primary flight measures and the secondary task measures, respectively. The EP proceeded to fly the glide slope and the localizer to perform the approach. The outer marker was at approximately 4 nmiles. At 200 meter AGL and approximately 1/2 nmi from the runway threshold, the EP "broke out" (i.e., he lifted the blue visor) and flew visually for the remainder of the low approach (7 meters AGL). If conditions permitted (fuel state, crosswind, etc.), the EP then performed the touch-and-go landing, minimizing the sink rate on touchdown to less than 1 meter/sec. The touchdown point was a 170-meter zone, 500 meters from runway threshold. After liftoff and at approximately 70-meter AGL, the SP turned off the WAD controller and the digital recorder. After four approaches, the SP assumed control of the aircraft, then changed the pitch handling quality to the next desired setting and again released control of the aircraft to the EP.

After each block of four approaches was completed under the same pitch handling quality, the EP and SP rated the approach and flare/landing segments of the flight profile using the Cooper-Harper pilot rating scale. Additional commentary data were gathered from the EP and SP throughout the flight tests by use of an audio tape recorder, e.g., comments on degree of air turbulence.

The WAD consists of two basic units: the airborne controller and the ground-based analysis center. The controller is configured for installation in the front avionics bay of the NT-33A research aircraft. The unit provides the electronics, power supply, software, interfaces to the HUD and the aircraft intercom, rear cockpit initialization switches, control stick response switches, and data recording system necessary to perform a complete series of item-recognition experiments. In addition, the controller can operate as a stand alone laboratory system capable of performing the same tasks as when airborne. The ground-based data analysis center is used to initialize several software options of the controller and to reduce and analyze response time data. A description of the functional capabilities of the hardware and software is discussed in appendix A. A detailed description of the complete WAD system is contained in reference 9.

## SCOPE

Each pilot flew two evaluation flights using the conventional HUD format and two with the Klopfstein format. During each evaluation flight, a pilot performed eight approaches terminating in either a low approach or touch-and-go landing for a total of 32 approaches per pilot. One-half of the approaches for each flight were made using "good" handling qualities, the other half were made using either "fair" or "poor" handling qualities. The handling qualities were manipulated by changing the pitch response (150 msec or 200 msec time delay) of the aircraft after every four approaches. The response of the roll and yaw axes was held constant throughout the tests.

## RESULTS AND DISCUSSION

### GENERAL

The test and evaluation paradigm used in this project was a repeated measures design in which type of display format (conventional versus Klopfstein), flight handling quality (good versus poor), and secondary task difficulty (memory set sizes, 0, 1, 2, and 4) were fractionally combined to form 16 different conditions. It was planned that the two EP's would be exposed to each of the 16 conditions twice. However, each EP was able to complete all combinations of the test conditions only once. Out of a total of eight 1.5-hr evaluation flights, a complete set of secondary task data was analyzed for four flights only.

The results showed that the general procedures established for the conduct of the evaluation flight tests of the WAD were acceptable to the pilots. The in-flight test procedures provided the EP's and SP's with reliable guidelines for efficient and safe crew coordination during successful approaches and during incidents of all equipment malfunctions. Pilot comments aided in the investigation of the most salient characteristics of the item-recognition task including the selection, location, and timing of the letters as presented on the HUD. A thorough testing of the WAD procedures during the project resulted in only minor software changes and hardware replacements and clearly established the feasibility of using the item-recognition task for in-flight tests.

### PRIMARY FLIGHT MEASURES

The primary flight measurement data taken from the digital recorder were divided into two defined categories of approach and flare/landing. Because of the length and complexity of the analyses of the primary flight measurement data, the results were published under separate cover in reference 10.

The summary results of those analyses indicate that the primary flight performance parameters and Cooper-Harper ratings showed a general inconsistency between displays and handling qualities during the approach and flare/landing phases of the flight task.

Overlaying the two complementing colors produced a perceptual environment similar to night IMC when the pilot attempted to view the external world.

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Lack of systematic differences in the primary flight measures and Cooper-Harper ratings suggests that pilot performance remained the same for all conditions. That is, no significant differences were found in the primary flight measures between display formats, handling qualities, or memory set sizes. These findings indicate that the pilots compensated for the increased task difficulty by maintaining primary flight performance at an acceptable level. However, this pilot compensation was not without cost. A loss of information processing reserve capacity can be clearly shown from the results of the secondary task measures.

## SECONDARY TASK MEASURES

Secondary task measures consisted of reaction times in which slopes and intercepts were calculated after solving linear regression equations for each set of data. Secondary task errors for the item recognition task were calculated for all incorrect responses, late responses, and no responses.

## REGRESSION EQUATIONS (REACTION TIMES)

The reaction times associated with each correct response were averaged for the complete flight profile for each m-set size (letters 1, 2, or 4), handling quality (good or poor), and display format (conventional or Klopfstein). Linear regression equations were then calculated to indicate the slope and intercept of the plotted data as shown in figures 4 and 5. The data reveal that both the intercept and slope of the curves for each pilot increased from baseline conditions when the handling qualities were degraded. The results indicate that the WAD is sensitive to the increased sensory/response and mental processing requirements imposed by the addition of a secondary task and to the level of difficulty of that task. For example, the largest intercept and slope changes occurred between each subject's relative baseline and poor handling quality condition.

A closer examination of the data reveals that the differences in the magnitude of change in the slopes were consistently larger for the conventional HUD format than the pictorial Klopfstein HUD format under either good or poor handling qualities. This trend, relative to each subject's shift in slope magnitude, suggests that more mental reserve capacity was available to process information while flying the Klopfstein display than the conventional HUD format and while good handling qualities independent of the type of display format used.

Reviewing the resulting changes in intercepts revealed a similar trend with regard to the handling quality parameter. The average increase in the magnitude of change in intercept was less for conditions of good handling qualities than for poor handling qualities. However, with regard to the display variable, the trend was reversed from that observed for the changes in slope; i.e., the average intercept value changed less for the conventional format than for the Klopfstein. Assuming the observed trends would persist in a larger data sample, the results indicated that degrading the handling qualities had a consistent effect on the input/output stages of the item-recognition task, whereas the effect of the display format variable on the input/output stages of the task was subject to inconsistent individual differences. The lack of consistent trends in the changes in intercept relative to the display variable may be due to: (1) individual differences in establishing a time-error tradeoff,[2] (2) locations of the letter in relationship to differences in eye scan patterns, and/or (3) different strategies of memory recall.

These results suggest that degrading handling qualities had a consistent and predominant effect of reducing the pilot's reserve capacity for all three stages of the information-processing, secondary task. Changing the display formats appeared to yield similar results but are subject to the influences of individual differences with regard to the mental component of the information processing task.

The reader is reminded that these data reveal only trends and were gathered from a sample of two pilots. Additional flight data are required with a larger pilot sample and more replications of test conditions before definitive conclusions can be made concerning the reliability of the results of these measures. A further discussion of the reliability of the item-recognition task that questions the day-by-day stability of the slope and intercept is found in reference 11.

## PERCENT ERRORS

The WAD provided an accumulative record of the number of errors, sequence of occurrence, type of error, and reaction time associated with each error for both positive and negative letters. The combined percent of secondary task errors for both pilots is shown in figure 6. The error data show that as the difficulty of the secondary task was increased, i.e., as the m-set size increased, a corresponding decrease in response accuracy was observed which supports the expectation of increased error rate under conditions of task overloading.

The increases found in secondary task response errors under conditions of poor handling qualities for both display formats are consistent with the results of the slope and intercept reaction time data with regard to the influence of degraded handling qualities.

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[2] The EP's were only instructed to respond as quickly and accurately as possible to the secondary task while flying a precision approach and landing.

That is, under test conditions producing a reduction in reserve capacity, a corresponding increase in response errors occurred.

In contrast, the reaction time data indicated that the type of display format differentially influenced both the input/output and mental stages of the information processing tasks, whereas response error data showed a consistently higher degree of response accuracy under conditions of the pictorial Klopfstein display format.

To further explore these results, the total percent errors were classified into type of error for each handling quality and display format. The secondary task errors reveal that the total percent errors were evenly distributed between incorrect responses (reversals), late responses (out-of-bounds), and no responses (time-outs). However when the total percent errors are differentiated between display type and handling quality, it clearly shows that three times as many reversal errors were committed by the EP's flying the conventional HUD than the Klopfstein display format. Degrading the handling qualities increased the percentage of time-out errors for the EP's flying with the conventional display and increased the out-of-bounds under the Klopfstein display format. Since it was assumed that a time-out error would reflect a greater decrement in reserve capacity than an out-of-bounds error, these results would imply that the EP's had less reserve capacity while flying under the conventional HUD and degraded handling qualities than the Klopfstein display format.

In summary, the percent of secondary task errors increased whenever the memory set size increased, the handling qualities were degraded, and the task was performed in flight under the conventional display format conditions. Poor handling qualities primarily induced errors of delay or no response while the type of display affected mainly the accuracy (correctness) of response.


## CONCLUSIONS

The hardware, software, and test procedures associated with the Workload Assessment Device (WAD) functioned efficiently with only minor discrepancies and minimum pilot distraction.

The project established the feasibility and sensitivity of using a secondary item-recognition task as a measure of sensory/response loading and reserve information processing capacity while flying precision instrument meteorological conditions approaches.

The pilots showed an appreciable increase in reaction time and percentage of errors on the secondary task flown under poor handling qualities as compared to good handling qualities and ground baseline conditions.

The WAD revealed that the pilots had less secondary task errors, more mental reserve capacity, but longer reaction times attributed to sensory/response delays while flying with pictorial/symbolic HUD configurations (Klopfstein) than conventional HUD formats.


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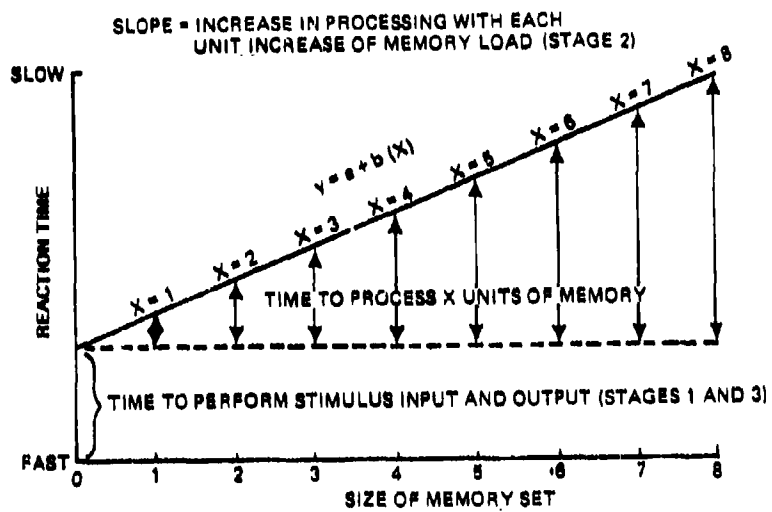
Figure 1    Theoretical Components of the Item
Recognition Task Proposed by Sternberg

Figure 2   Conventional HUD Format



Figure 3   Klopfstein HUD Format

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CONVENTIONAL DISPLAY

KLOPFSTEIN DISPLAY

MEAN REACTION TIME (MSEC)

POOR HANDLING

GOOD HANDLING

BASELINE
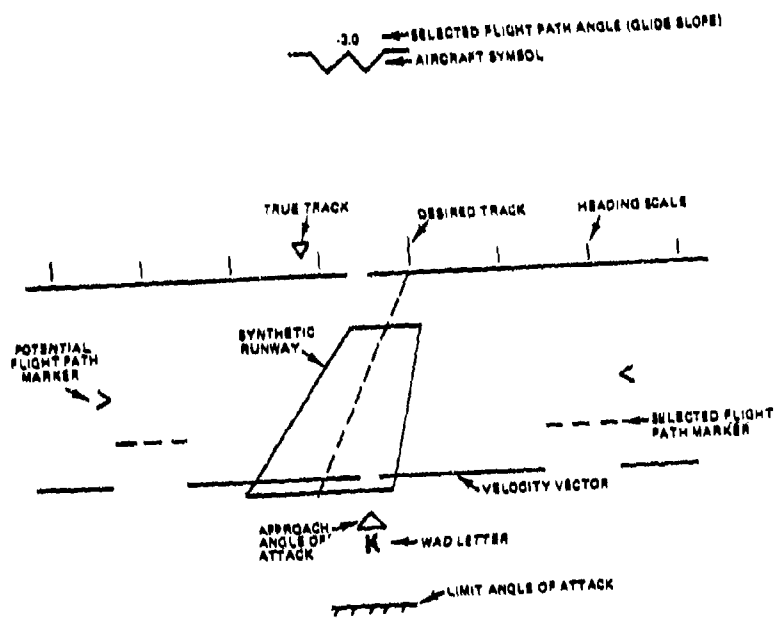
M-SET SIZE (NO. OF LETTERS)
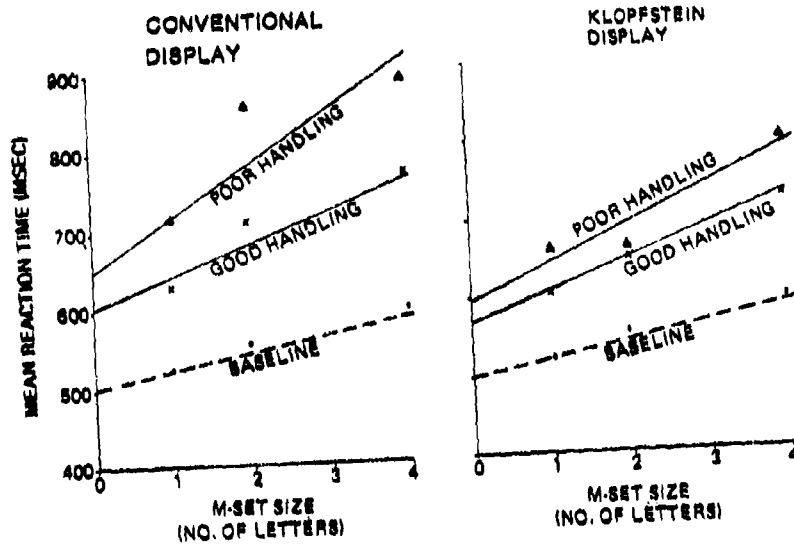
Figure 4 - Linear Regression Lines for Evaluation Pilot 1



CONVENTIONAL DISPLAY

KLOPFSTEIN DISPLAY

MEAN REACTION TIME (MSEC)

POOR HANDLING

GOOD HANDLING

BASELINE

M-SET SIZE (NO. OF LETTERS)

Figure 5  Linear Regression Lines for Evaluation Pilot 2

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Figure 6  Mean Percent Secondary Task Error for
Memory Set Size (Number of Letters) by
Display Format and Handling Quality

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TASK

   The Workload Assessment Device (WAD) presents to the subject an item recognition task
that requires him/her to respond to aural or visual stimuli that are composed of alpha-
betic characters or symbols.  After a stimulus has been presented, the subject responds
by pressing one of two switches to indicate the stimulus is (1) part of a pre-memorized
set of letters, or (2) is not part of the set (1).  The data collected are the reaction
times, in milliseconds, from the onset of a stimulus presentation to the physical
response of pressing a button.

   When a trial is completed, the subject is given another set of letters to memorize
and the sequence is then repeated.  Usually four trials are included in a given session
with the memory size ranging from one to four letters.  Data analysis consists of deter-
mining mean reaction time to a number of presentations, and the standard deviation of the
response reaction times.

SYSTEM CONFIGURATION

   Given the above task, its complexity, number of possible deviations, and timing
considerations, a microprocessor was chosen for the main controller.  Peripheral devices
are manipulated using software located in programmable memory, (RAM).  All data collected
are temporarily stored in memory and subsequently recorded on a digital cassette tape.
When the mission is completed, the tape is retrieved from the real-time controller and
taken to a ground-based data analysis computer.  Prior to each mission, certain
parameters are entered into the ground-based computer and written, along with the opera-
ting software, to the cassette tape.  These parameters are used by the main controller in
order to present variations of the task described.

   The system configuration is shown in Figure A-1 and consists of a real-time controller
and data collection device, software, and a ground-based data analysis package.

   In order to provide for portability, a chassis was constructed to fit into a specific
location in the nose of the NT-33A aircraft.  The chassis is small enough to fit into a
standard off-the-shelf enclosure and light enough to be hand portable.  The control panel
of the WAD has three connectors that provide all interface signals required for operation.
In the portable mode, these connectors provide I/O lines that can be interfaced to various
display devices and response keys such as used in many simulators and laboratory
environments.

HARDWARE

   The Workload Assessment Device (WAD) was designed around the IEEE 696.1/02 buss,
(S-100).  This buss configuration was chosen for the size of the printed circuit board,
availability, and cost.  Most S-100 devices manufactured today are reliable and well
constructed, and there exists a large base of different peripherals to choose from.
Since this system is experimental and cost a major concern, it was not required to meet
government/mil specifications for reliability, temperature, and vibration.

   The WAD mainframe contains 5 slots that are used for the various peripheral interfaces,
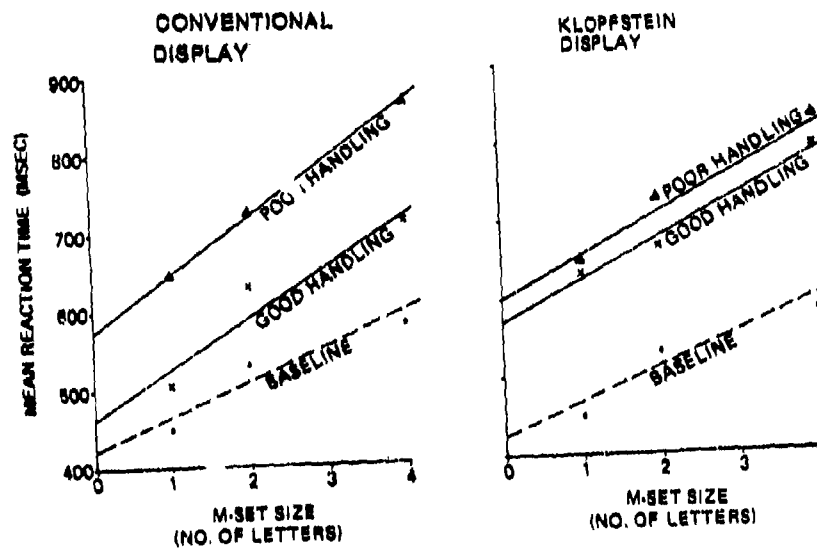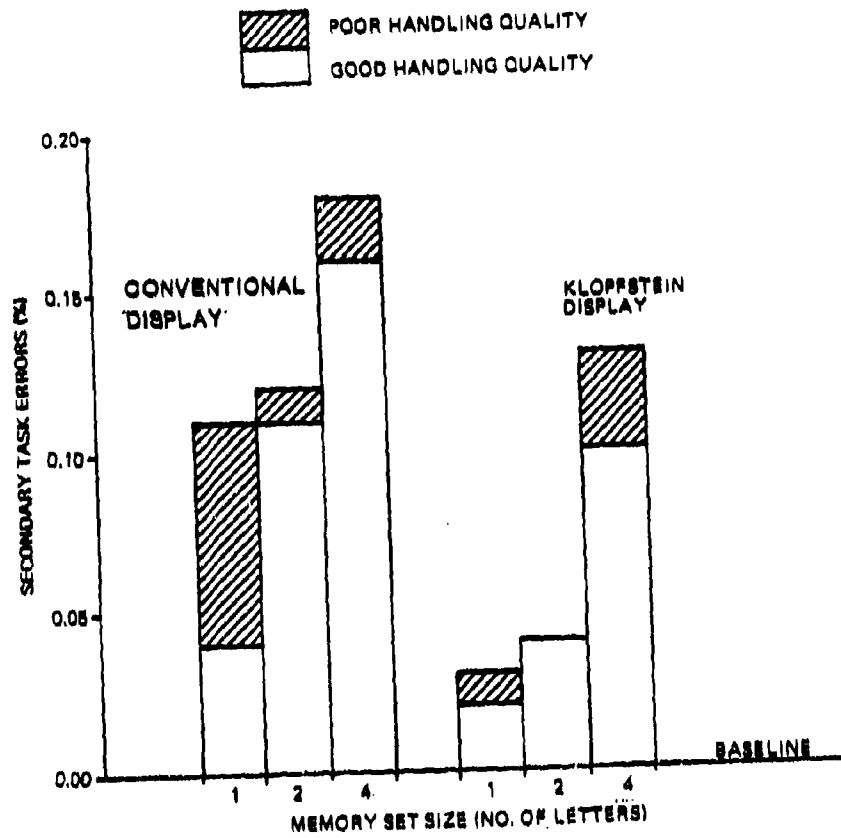memory, and CPU.  A single board computer manufactured by Cromemco, Inc., is used for the
main controller.  It contains a serial I/O port, several parallel I/O lines, real time
clock, Read Only Memory (ROM), Programmable Memory (RAM), and all necessary system timing
signals.  A 16K RAM board is used for program and data storage.  The next buss location
contains the digital cassette interface which is connected to the NFE Corporation digital
tape recorder located on the front panel of the WAD.  The fourth slot contains a 16
channel analog to digital (A/D) converter and interface.  This unit is connected through
cables to the aircraft's analog computer and can be used to monitor up to 6 different
control surfaces that will be used in a derivation of the described item recognition task.
The fifth position contains the speech synthesizer board.  This board contains the new
National Semiconductor speech processor IC along with its ROM vocabulary ICs.

SYSTEM OPERATION

   When power is applied to the system, a boot program located in ROM loads a file from
the cassette tape recorder.  This file contains a program that controls all operations of
the item recognition task.  After loading, the program gains control of the system and
waits for a command from the serial port.  The experimenter has several options at this
time.  Usually, he will enter a command for the system to load a specific parameter file
from the tape.  This file contains all the parameters used in this presentation of the
task, such as Inter-stimulus Interval (ISI), Memory Set Size (MSZT), use of visual mode
versus auditory, etc.  After the experimenter enters his selection the subject is
presented the task.  During the task presentation, all the error scores, reaction times,
and other useful data are stored in files of the cassette tape containing all the col-
lected reaction times, error scores, and various other parameters.  The program then
recycles to the experimenter's console and waits for another command.  When the experi-
mental session is over, the cassette tape is retrieved for preliminary data reduction
and display.

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In order to create a cassette tape containing the operating program and stimulus parameters, a microcomputer is provided that contains 2 floppy disk drives, mainframe, CRT terminal, printer, digital tape recorder, and Disk Operating System (DOS). Located on disks are several user programs that allow the experimenter/scientist to create parameter files. Also located on the disk is a program that contains the operating software for the WAD along with a linker. When the experimenter wants to create a parameter tape he links together the previously created parameter files to be used with the task and the WAD operating software. This newly created link file is then written out to the cassette tape.

During data reduction or analysis, the cassette tape containing the newly recorded data is placed in the tape transport and a loading program is run. This program creates files on the disk containing all the experimental data collected. The experimenter is then able to display the data on the CRT, print it out on the line printer, or submit the data to several data reduction or analysis programs.

## SOFTWARE

The WAD software consists of several programs mentioned above. Most of the hardware drivers and controlling software are written in assembly language, but some of the complex data handling routines are written using Pascal. All of the data analysis software runs under the CP/M disk operating system (DOS). This DOS was chosen because many applications software packages and high level languages are designed to use CP/M for their I/O and file structures.

## EXPANDABILITY

Since the main controlling software for the WAD is located at the beginning of each parameter tape and the source is on the floppy disks, it is very easy to modify. The experimenter simply makes his changes using the text editor and recompiles the program. When he makes a parameter tape the new controlling software will be included provided the file name was not changed. This provides the experimenter/scientist with a very versatile system that can be modified for custom applications and has the capability of adding new tasks. Since the peripherals provided are under software control, any sequence of operation can be programmed, thus allowing many different tasks to be included in the data base.

In addition, 16 channels of analog to digital (A/D) converters with interface are being installed. This will enhance the system by allowing it to sample up to six primary control surfaces from the NT-33A, or any other system/simulator. By arranging the data under software control, many derivations of the item-recognition task can be constructed.
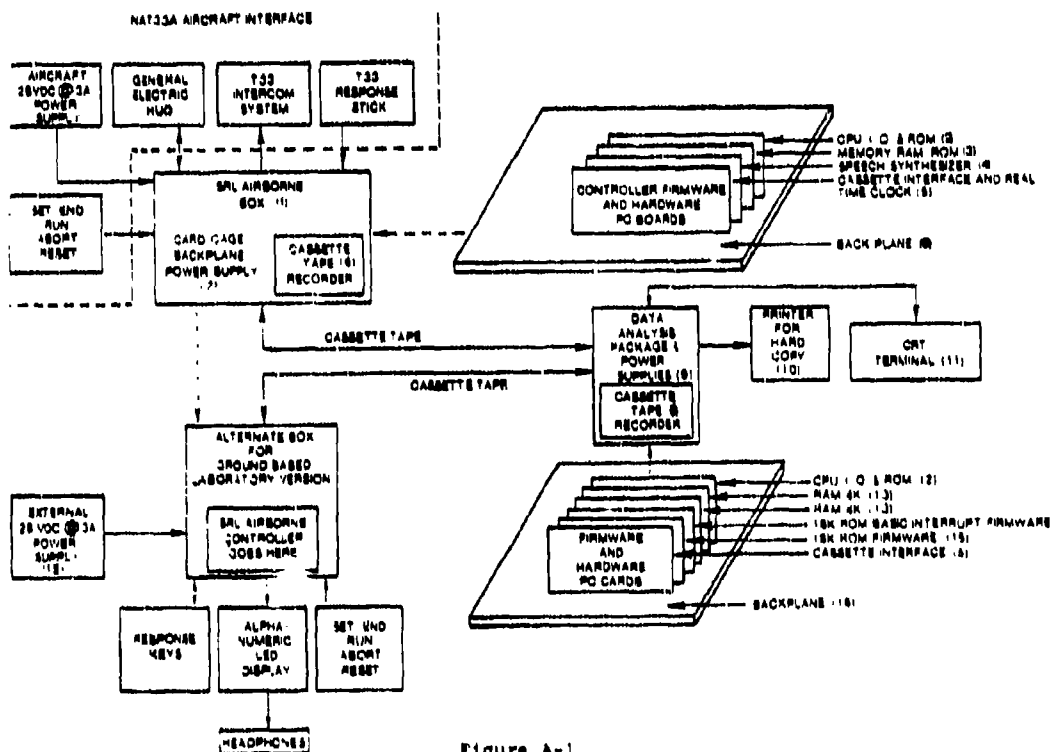


Figure A-1

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INFORMATION REQUIREMENTS FOR PILOT SUPERVISION
OF AUTOMATIC LANDING IN LOW VISIBILITY CONDITIONS

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By George Terhune and J. L. DeCelles
for the
All Weather Flying Committee
Air Line Pilots Association


Presented by J. L. DeCelles
at the 5th Annual Symposium
on Advanced Flight Instrumentation
U.S. Naval Air Test Center
Patuxent River, Maryland
September 15-16, 1981

Good morning, ladies and gentlemen. Speaking for the Air Line Pilots Association, I wish to express our appreciation for the opportunity to address this distinguished assembly on a subject that is very close to our hearts, a subject of the greatest importance to airline pilots, namely, the information required for supervising and assessing the quality of automatic landing operations.

I won't be describing exotic hardware. Instead, I want to talk about some fundamental concepts, because, in ALPA's view, the industry is losing touch with some very basic principles concerning the responsibilities and the functions of the pilot during approach and landing in low visibility. This tendency is apparent across the whole spectrum of approaches, from quasi-visual approaches through nonprecision ILS and full ILS approaches, right down to those with the lowest authorized or contemplated minima. But today I want to zero in on a relatively narrow aspect of that total problem.

Automatic landing systems have been introduced for use in very low visibility without adequate information for pilot supervision and assessment of the performance of the approach and landing. The pilot does not have adequate means for ensuring that the airplane can continue safely to an automatic landing, he cannot adequately determine when the automatic system must be disconnected, and he cannot be sure that he will be able to implement the optimal backup maneuver after disconnect.

Automatic landing systems incorporate elaborate annunciator and warning systems. In fact, the absence of an alarm or warning is the means by which the pilot is most often expected to deduce that the airplane will land safely. In ALPA's view, warning systems can be very useful adjuncts to the information system, but they can never be the principal means for assessing either the performance of the approach and landing or the status of the automatic landing system. Alarms tend to come too late, and they give too little information on the reason for the problem or the rate and direction of departure from the desired flight situation. Furthermore, some types of failure do not trigger the alarm system.

Well then, what information is required for supervising the conduct of an automatic landing in low visibility? In the opinion of the Air Line Pilots Association, the required information is that which is needed for assessing the position and direction of movement (i.e., the velocity vector) of the aircraft in both the lateral plane and the vertical plane.

Let's take a look at conventional instrumentation to see whether it satisfies this requirement. May we see the first view-graph, please? (See attached reproductions.)

This is an Attitude Director Indicator (ADI). The ADI includes the artificial horizon, the flight director, the ILS glideslope, the expanded-scale ILS localizer, a fast-slow indicator of airspeed error, and a "rising runway" indicator of radio altitude (below 200 ft.). Despite all this information, the ADI is not an adequate instrument for supervising the conduct of an automatic landing. Why? For a number of reasons:

o   The ADI is dominated by the flight director. The flight director gives attitude commands which, if they are correct and if they are obeyed, will

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cause the aircraft to follow the desired flight path.  But the flight
director gives no information which can inform the pilot of the existence,
size or direction of any deviation from the localizer or glideslope path.
Moreover, as a means for monitoring and assessing the path of the aircraft
during automatic approach and landing, the flight director is poorly
qualified because its logic and processes are too similar to those of the
automatic flight control system.  In fact, in some systems the flight
director commands are simply another output of the same computer that
drives the autopilot.

o    ILS situation information is given in the ADI (and elsewhere on the
     conventional instrument panel) but is not given in a manner suitable for
     effective use during the final stages of approach and landing.  The
     situation information is incomplete (no flare guidance) and is presented in
     a format that is not properly integrated for sufficiently timely
     assimilation.  Even though the various indicators are located in close
     proximity, they are still separate indications with different scale factors
     and different sensitivities; they are not connected by any common frame of
     reference; and their information must be picked off by a scanning process.
     Moreover, as a practical fact (demonstrated by NASA testing with
     oculometers), attention to situation information tends to be severely
     inhibited by attention to flight director commands.

o    Finally, the information presented on the ADI isn't adequate for the
     supervisory and assessment process because it doesn't display the velocity
     vector (the direction of movement) of the aircraft.  From experience on the
     line and in simulator exercises at Ames Research Center and in France, we
     have found that on very short final approach, position information becomes
     increasingly less urgent, while knowledge of the velocity vector becomes
     increasingly more urgent.  The ADI, with respect to aircraft movement in
     the lateral plane, provides only roll data; it includes no display of
     either heading or track.  The information it provides regarding direction
     of movement in the vertical plane is, to say the least, chaotic.  There is
     pitch, pitch command, airspeed error, and glideslope deviation informa-
     tion.  Elsewhere on the panel, rate of descent information is given.
     Nowhere on the panel is there a direct indication of the vertical vector,
     the _angle_ of descent.  Given plenty of time and stable flight conditions,
     the pilot could mentally integrate the scattered bits of vertical data that
     are presented and could _estimate_ the angle of descent; but in actual
     conditions on very short final he simply doesn't have time - nor would the
     resulting estimate be accurate enough to be useful.

In sharp contrast to the conventional ADI, we have flown simulations and
research aircraft with well-integrated electronic vertical situation displays
based on "airplane" symbols representing direction of flight (velocity vector)
instead of boresight.  These displays contain all elements of the airplane's
position, direction of flight, and aerodynamic status, in a format whose use
requires no special mental process.  One aspect of this type of display which
is particularly important for assessment of an automatic landing is that
inappropriate control inputs and destabilizing atmospheric effects show up very
quickly in the "airplane" symbol, which is a sensitive indicator of the
airplane's direction of flight.

At this point I would like to show you a series of 35-mm slides which we believe dramatically illustrate the crucial importance of velocity vector information - particularly with respect to flight path assessment in the vertical plane. These photographs were made in the now-defunct Fog Chamber at the University of California in Berkeley. They were made by positioning a camera in various attitudes at intervals along the final approach course corresponding with data taken at one-second intervals from the flight recorder of a turbojet airliner. The incident from which these data were taken occurred during a late night Category II approach with the RVR reported at 1200 ft. The aircraft struck approach light stanchions 1800 ft. short of the runway and succeeded in landing with no other damage than ruptured tires. This first slide shows the profile of the flight starting at a point where the aircraft was on the glideslope 225 ft. above TDZ elevation and ending at the point of initial impact 1800 ft. short of the runway. The following twelve slides represent what should have been visible to the crew at one-second intervals along that profile.

This next slide is a picture of the approach light structure which was contacted.

The final twelve slides show the same external scenes, but this time some very rudimentary "head-up display" symbology has been added. The single green line with a gap at its center shows the position of the horizon. The two parallel green lines represent the ILS glideslope. The green circle is fixed three degrees below the horizon. When the circle is centered on the glideslope symbol, the aircraft is on glideslope. When the glideslope symbol is above the circle, the aircraft is below glideslope. The two red wedges together represent the velocity vector of the aircraft. When they superimpose the circle, the aircraft is descending at a three-degree angle. When they are superimposed upon the horizon, the aircraft is maintaining a constant altitude. You will note that the first and most dramatic indication of trouble is provided by the velocity vector wedges.

Now may we see the other view-graph? This is a partial illustration of symbology used in the PERSEPOLIS program in France. The two "poles" standing on the horizon line mark the heading of the runway. The "synthetic runway" symbol is generated from ILS data. The rectangular window is centered on the ILS centerline at a point approximately 1/4 of the distance between the aircraft and the runway. The relation between the "runway" symbol and the ILS "window" constitutes an expanded scale indication of deviation from the centerline of the ILS localizer and glideslope. The winged circle symbol represents the velocity vector of the aircraft. If the vector symbol is in the ILS window, the aircraft is doing what needs to be done for the purpose of staying on or returning to the centerline of the ILS. When the aircraft reaches the height at which flare should be initiated, the vertical dimension of the "window" decreases to the size of the vector circle. At touchdown, the window narrows laterally, extends vertically and becomes a rollout guide. The most immediate indication of improper performance by the automatic flight control system during any phase of the approach and landing occurs when the vector circle moves out of the ILS window.

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Our purpose here is not to advocate or recommend a particular set of symbology. This is just one example of the kind of display which can transmit to the pilot the information required for assessing the conduct of automatic landings and for exercising emergency manual backup control. What are the essential characteristics of such displays?

o    First, they are well-integrated displays. Some flight information is
     inherently related to "earth," some to "airplane," and some is simply
     scalar. But all the information required for approach and landing is
     displayed in a coherent scheme geometrically related to the pilot's real-
     world view in the windshield or at least fully compatible with that view.

o    Second, the displays are based primarily on situation, not command,
     information. They enable the pilot to be in command of the situation
     rather than being a servo for the flight director.

o    A third characteristic has already been mentioned but is so important that
     it bears repeating:  these displays are centered on an "airplane" symbol
     that represents direction of flight (velocity vector) rather than aircraft
     attitude.

Let me expand that last idea just a bit. The velocity vector has two components, lateral and vertical. The lateral component can be represented by heading, though track - if drift angle is available - is preferable. The vertical component is flight path angle - angle of climb or descent - and can be referenced to the air mass (e.g., pitch angle minus angle of attack), or can be inertial (e.g., slope = vertical speed divided by groundspeed), or can be a hybrid approximation of inertial (e.g., slope = vertical speed divided by true airspeed).

In our experience, either the inertial or hybrid inertial form gives the best display, with only minor differences easily handled by the pilot. To make the airplane (velocity vector) symbol flyable, the symbol needs to include some kinds of anticipation cue which will give immediate and somewhat predictive response to control inputs. Such anticipation is easily provided by pitch rate and/or a vertical accelerometer mounted somewhat forward of the airplane's center of gravity.

A direct, sensitive, flyable indicator of direction of flight is particularly important in assessing the performance of an automatic landing system. Any inappropriate movement of that symbol can be the first indication that the autopilot is going bad. Also, it provides the central element of the information the pilot needs either to make a correction or to initiate a safe go-around.

Finally, and of very great importance in our list of essential display characteristics, the display should be available head-up. The advantages of head-up display in see-to-land approaches are well-known, so I won't dwell on that aspect of the matter. What is less obvious is the need to have the display head-up for very low visibility operations that are defined as not-see-to-land, so let's examine that question.

As noted earlier, some manufacturers and some airlines have proposed nonvisual landing operations with no provision for pilot assessment of the final critical phases of the approach and landing. When pushed very hard, some of the people representing these proposals will admit that some form of monitoring is required, but they contend that adequate monitoring can be accomplished by some combination of:

(a) automatic warning systems,

(b) reference to conventional instruments (primarily ILS localizer and glideslope deviation), and

(c) in those cases where some degree of visual reference is required, by split crew functions, wherein one pilot is head-down on conventional instruments while the other pilot is head-up on the external visual cues.

When pushed very, very hard, some of these people will agree that (a) automatic warning systems can not be the primary basis of the information system, (b) that conventional instruments are not fully adequate, and (c) that split-crew procedures for handling flight-critical information are a significant compromise of the principles upon which redundant instrumentation and crew duties were founded.

At that point we reach the ultimate fall-back position of the anti-HUD forces: they may be willing to provide (eventually, not now) an improved advanced electronic display, perhaps based on flight path, but head-down, not head-up. Since Cat IIIb is defined not to require external visual reference until the end of rollout, they ask, What is wrong with having all the information head-down?

What is wrong is that Cat III approaches will be conducted in the real world, not on paper or in a simulator. In the real world, the average pilot will seldom if ever see a truly nonvisual landing. It is well established that there is almost always "something" to see, and that "something", no matter how dimly seen, has the overwhelming advantage of being real, so there is an irresistable temptation for the pilot to look up and establish some kind of visual contact before landing.

Furthermore, applicable experience in line operations will be obtained in visibility which is very much better than the minimum for nonvisual landings. In these better conditions, it is not only irresistible to look up, it is required by regulation. Unless the display for the so-called nonvisual landing is also fully adequate for visual and quasi-visual landing, the pilot skills required for effective use of the display will not be developed.

Now one final point regarding advanced head-down displays. ALPA is certainly not opposed to having the best possible electronic flight instrument display presented head-down. Our point is only that it cannot substitute for a good head-up display. Ultimately we must have proper instrument information displayed head-up, and at that time it will almost certainly be found necessary

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to have the same information displayed head-down as well.  If that is the case,
then it seems obvious that the head-up and the head-down displays should be
perfectly compatible -- in fact it appears to us that they should be virtually
identical.  By that line of reasoning we arrive at the following position
regarding advanced head-down displays:  An advanced head-down display should be
a good head-up display presented head-down.  This is because there are certain
constraints on the design of a head-up display which do not necessarily apply
to a display that is intended solely for use head-down.  HUD must be fully
compatible with patterns of geometry and lighting that occur in the windshield
view.  HUD must be scaled to match real-world geometry.  HUD must have dynamics
which match the apparent movement of real objects in the windshield view as the
airplane is maneuvered.  These constraints would not necessarily occur to the
designer of a purely head-down display, but they must be allowed for right at
the beginning if we are to obtain compatible displays head-up and head-down.
Therefore, we say that any interim improvement in head-down displays should
take full account of head-up design principles.

In closing, let me recap the main points:

1.   The pilot-in-command is fully and solely responsible for supervising
     the approach and ensuring that the airplane will land safely in the
     touchdown zone, no matter what the visibility, and no matter whether
     control is manual or through an autopilot.

2.   Absence of an alarm is not sufficient information upon which to base
     any essential part of this assessment or decision.

3.   Situation information, not a flight director, should be the primary
     content of the display, and it must be delivered in a fully integrated
     format, head-up.

4.   Even if in theory nonvisual landings are permitted, considerations of
     pilot psychology, practical experience, and training require the
     display to be available head-up.

Thank you for your courteous attention.
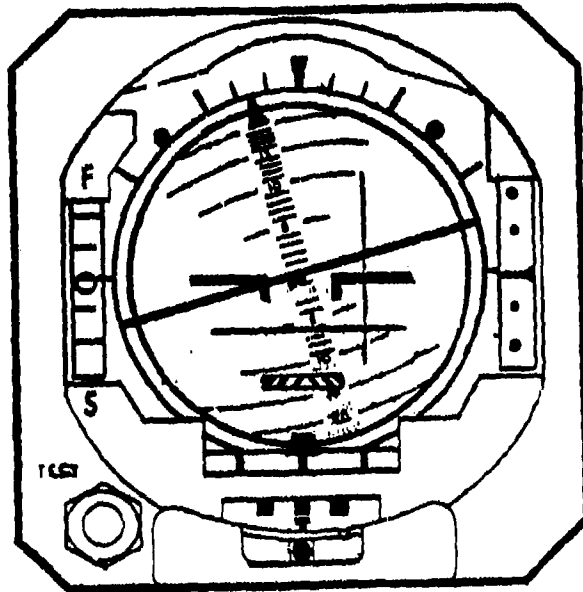
**CONVENTIONAL ADI**
**Two Needle Flight Director**

Expanded Localizer at bottom ⟶

Turn Needle also at bottom ⟶

Glideslope at right

Speed error at left
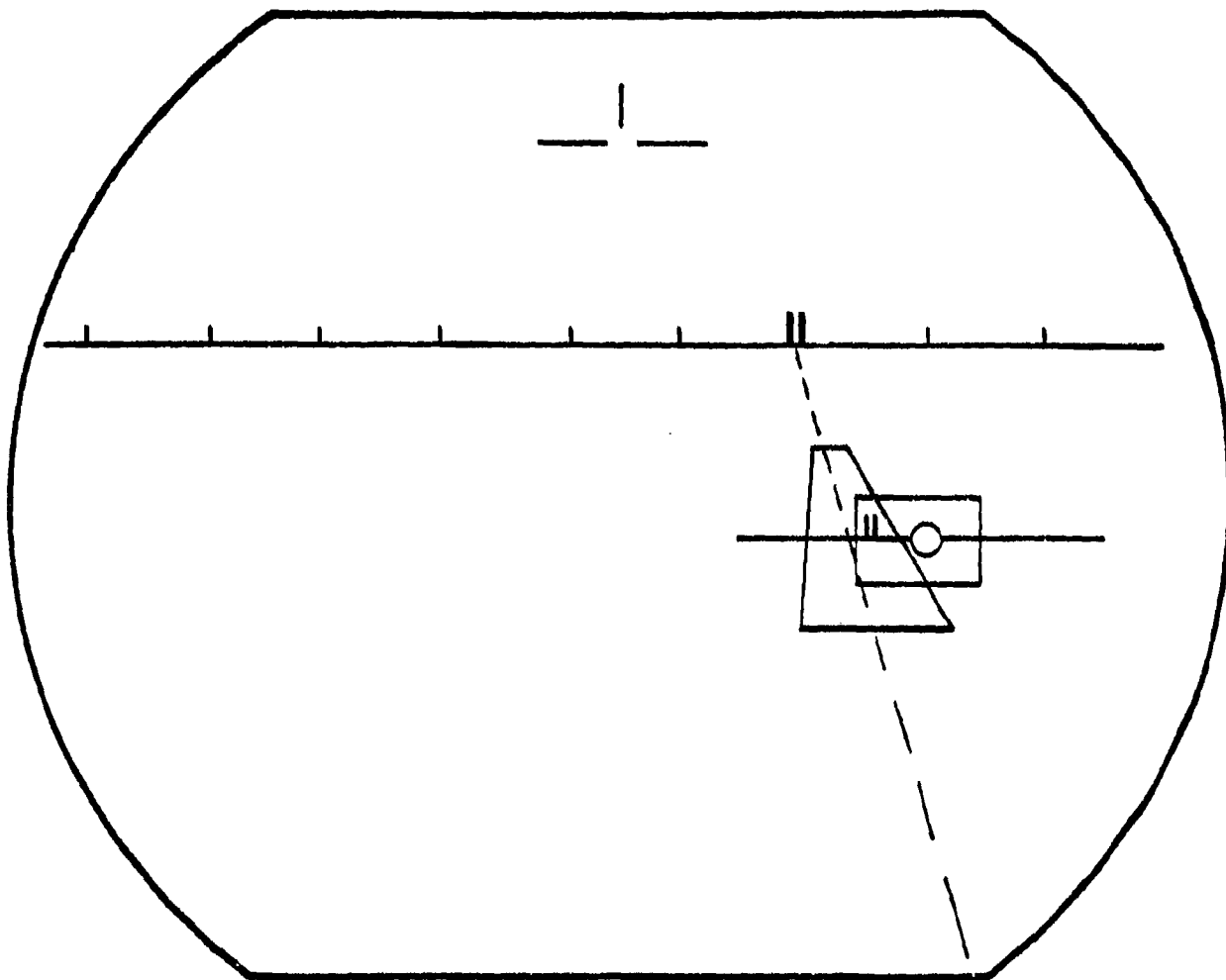
Simplified "situation" symbology.

"Persepolis" type, but with speed worm, and

without "potential flight path".

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AD P000670

# THE MANEUVERING FLIGHT PATH DISPLAY - AN UPDATE

BY

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W. B. LOGAN

NORTHROP CORPORATION, AIRCRAFT DIVISION

## ABSTRACT

The subject of flight trajectory displays has claimed the attention
of a considerable body of engineers and engineering psychologists over the
years, and a number of imaginative concepts have resulted from their efforts.
Only within the last few years, however, did the computer technology advance
to the state that some of these concepts could be implemented. One such
concept is the Maneuvering Flight Path Display (MFPD),which was first
advanced in the early 1950's. The MFPD provides to the pilot an anticipatory,
real-time presentation of the command flight path. The presentation depicts
the "solution" of the desired trajectory, thus telling the pilot "what to do"
and "how to do it". This information is displayed without resorting to the
traditional dials, scales, pointers or alphanumeric readouts.

An earth-stabilized, perspectively transformed, command flight path,
8,000 feet in length and 60 feet wide, is generated on the basis of flight
plan inputs. The flight path is then portrayed graphically in real-time
as an "inside-out" presentation on a head-up display or a head-down vertical
situation display. The elements comprising the flight path are analogous to
tarstrips on a highway, and move on the display in a corresponding manner.
The continuum of "tarstrips" depict the projected command attitudes, alti-
tudes and directions of the aircraft. Command speeds are provided by a
miniature lead aircraft, located 20 feet above and immediately to the left of
the flight path, which is programmed to fly at command speed.

The pilot, by controlling his aircraft to fly just above the flight path
in a loose cruise formation with the miniature lead aircraft, is assured
of precise 4-D (i.e., x, y, z, and time) trajectory control.

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The concept formulation, the development to date, the various operational features, and contemplated future refinements of the MFPD are described.

## INTRODUCTION

This paper discusses the results of IR&D and contract work performed at the Aircraft Division of the Northrop Corporation on the Maneuvering Flight Display (MFPD). The contract work was done under the direction of Messrs. W. G. Mulley and S. M. Filarsky of the Naval Air Development Center. Mr. G. W. Hoover served as a consultant on the project during part of the effort.

The concept of the flight path display was first formulated and defined under the Army-Navy Instrumentation Program (ANIP) in the 1952-1963 period. The ANIP was organized and, until his retirement in 1959, directed by CDR George W. Hoover of the Office of Naval Research. The objective of the program was to define and develop needed improvements in the man-machine interfaces for both conventional and V/STOL aircraft. The flight path display was one element of a comprehensive, integrated, display system designed by ANIP to satisfy all of the identified pilot information requirements so as to achieve greater aircraft weapon system performance, increased flight safety, and decreased pilot training. The then-prevailing limitations in computer technology frustrated development of the flight path display at that time.

In early 1975, Northrop initiated action under its independent research and development (IR&D) program to extend the earlier work on the flight path display and, in January 1977, was awarded a contract by the Naval Air Development Center to demonstrate the feasibility of the Northrop approach. This was accomplished on the Northrop Large Amplitude Simulator (Figure 1) using a six-degree-of-freedom F-5E aircraft dynamics program. The results of the feasibility demonstration are described in Reference 1.

The feasibility demonstration contract was extended to cover the study of the transition path, the velocity index, the texture of the flight path elements, and the MFPD field of view requirements. Reference 2 describes the studies involved in the extended effort and presents the related findings, conclusions and recommendations.

Since receiving the first MFPD contract award in January 1977, Northrop has also maintained an active IR&D project on the display concept. The IR&D

FIGURE 1. THE NORTHROP LARGE AMPLITUDE SIMULATOR

SKY-EARTH PROJECTOR

TARGET PROJECTOR

PROJECTION SCREEN

COCKPIT

COCKPIT GIMBAL STRUCT.

BASE STRUCTURE

PEDESTAL STRUCTURE

BEAM GIMBAL ASSEMBLY

BEAM ASSEMBLY

COCKPIT MOTION SYSTEM ASSEMBLY

VISUAL DISPLAY SYSTEM
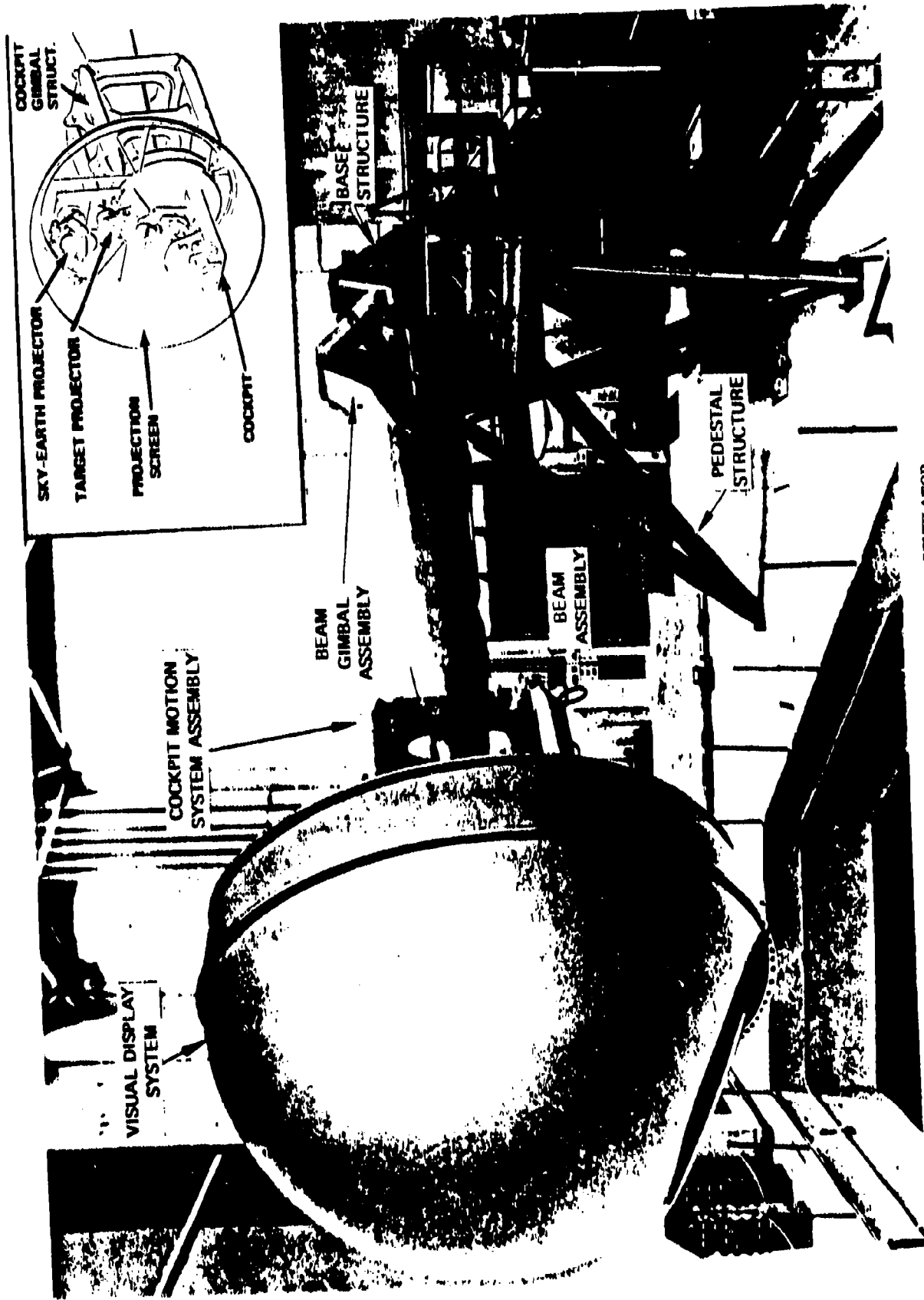
effort has been concerned with the fundamental issues of 4-D (i.e., x, y, z, and time) trajectory generation and display, whereas the contract work has been devoted to specific applications of those fundamentals to implement the current version of the MFPD.

References 3 through 6 constitute the principal technical papers presented on the MFPD since the start of the flight path development activity at Northrop. These papers served as progressive reports to the technical and operational communities on both the independent research and development effort and the contract work involved. Additionally, briefings on the project and demonstrations of the MFPD in a functional laboratory cockpit, primarily to government personnel, were provided by Northrop as the engineering of the concept proceeded and the design evolved. The functional cockpit is located in the Northrop Avionics Integration Laboratory (Figure 2).

The MFPD was developed with the intention that, eventually, the display would be presented simultaneously with a high fidelity contact analogue display. The complete, integrated presentation would be provided at all times on the head-down vertical situation display (VSD) and horizontal situation display (HSD) and, during periods of reduced visibility, on the head-up display (HUD) as well. This combined presentation is shown in Figure 3. Normally, only the MFPD and the horizon line would be presented on the HUD. In other words, the MFPD fulfills the critical need for real-time director information and fits very compatibly into the complex scheme of an advanced, integrated display system.

## THE PILOT WORKLOAD PROBLEM

The tactical aircraft pilot is faced with two major concerns in the course of flying his missions - controlling precisely the trajectory of his vehicle, and operating effectively the various elements of his system so as to execute the required mission functions. The pilot's principal problem arises from the necessity of dealing with these two concerns simultaneously and, often, under highly dynamic and hostile circumstances. Simply stated, the pilot has too much to do and too little time in which to do it.

In the interest of gaining some insight into the crew workload problem, let us consider for a moment the nature of crew tasks in general. Grossly, these tasks iteratively involve the perception of conditions of interest, the determination of the specific crew action required, the execution of that

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FIGURE 2. THE NORTHROP AVIONICS INTEGRATION LABORATORY
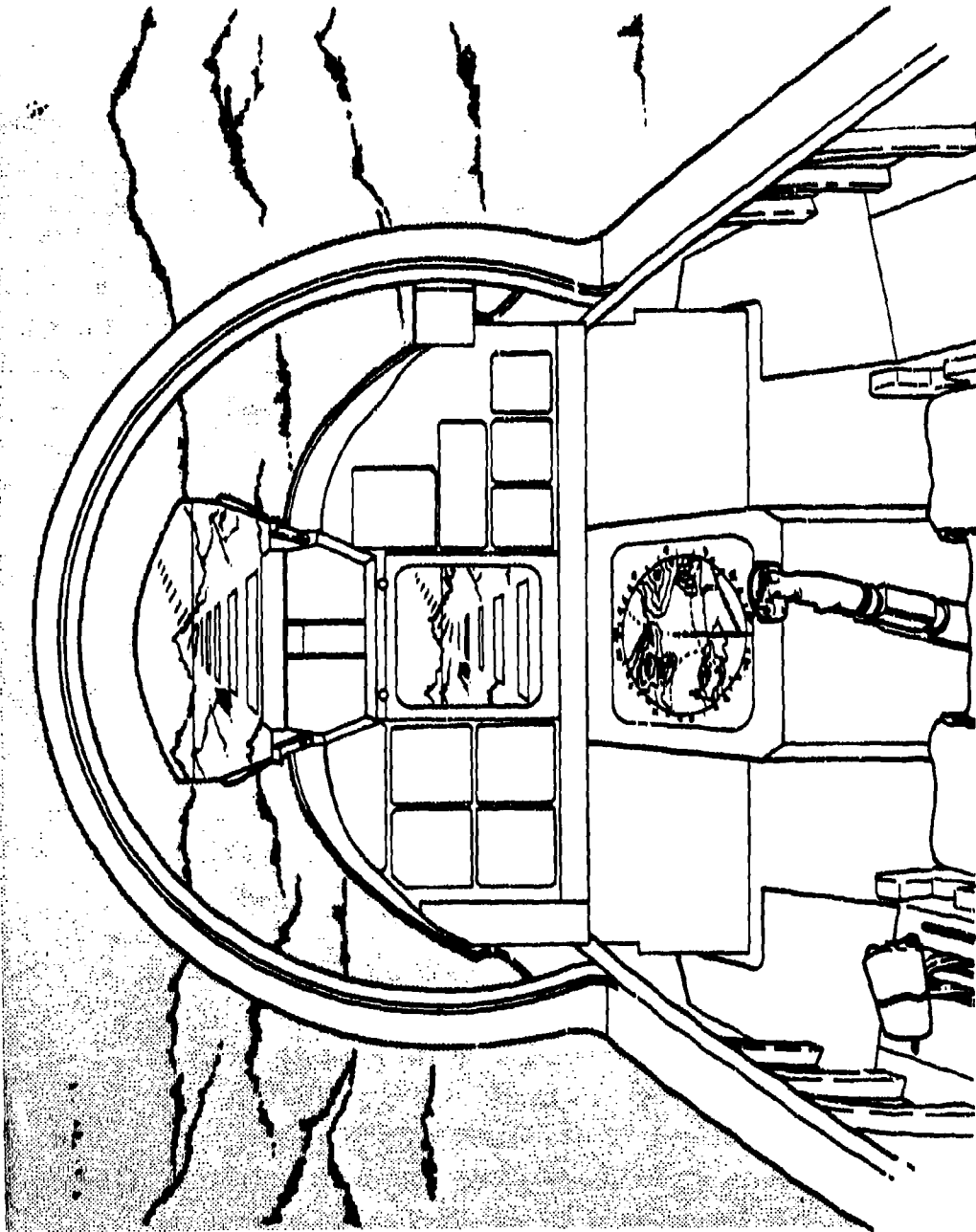
FIGURE 3. COMBINED PRESENTATION ON HUD, VSD AND HSD

action, and the observation of the effects of the action. In short, all
crew tasks require that information be provided to enable the crew member
to determine what is happening, what should be done, and how the required
task should be done. Further, it is necessary to keep the pilot apprised
of how he is doing as he does it.

In the case of present tactical aircraft, the pilot is called upon to
contribute significantly to the effectiveness of the total system. Systems
of the future are expected to impose even greater demands in this regard, despite
the increased use of automation which is anticipated. This expectation poses
particularly serious problems to the crew station designer, since the pilot is
already operating at or very close to his performance limits.

The operational environment need not include an overt threat by the enemy
in order to create a pilot overload condition. As reported in Aerospace Safety,
August 1979, "Approximately half of the aircraft that collide with the ground
do so on low level navigation/tactics missions which do not involve bombing,
cargo dropping, or aerial combat but simply navigation from point to point with
minimum exposure".

The practice of supplying the pilot with dedicated, single-function, con-
trols and displays started in the early days of aviation and, in some cases,
has persisted to this day. As each new capability was added to the system,
the new capability was usually accompanied by its own unique display and control
provisions. This practice served to increase the complexity and clutter of the
cockpit and, correspondingly, the workloads. Concurrently, vehicle performance
capabilities were increased, further compounding the problem of the crew. For
example, an increase in vehicle speed decreases the time span within which the
pilot must act, thereby adding internal stress to an already critical situation.

Given a high threat environment, the pilot tasks associated with the
operation of a modern aircraft weapon system become even more numerous and
complex and, almost without exception, the associated crew workloads become
unacceptably high.

The related need for improvement changes in the man-machine interface
has become generally recognized and, in recent years, significant efforts
toward that end have been launched by the entire aerospace community. For
instance, Air Force programs currently under way include an Integrated Flight/
Trajectory Control project which seeks to implement a four dimensional
(i.e., x, y, z, and time) navigation system for on-board flight trajectory

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control. Other related Air Force programs, also underway, include Integrated
Flight/Fire Control and Integrated Flight/Weapons Control.

Northrop's present effort is based on the assumption that the man-
machine interface can be improved to facilitate pilot decision-making and
control in the cockpit. The Maneuvering Flight Path Display (MFPD) develop-
ment activity is an important part of that effort and addresses directly
the more important of the two major pilot concerns previously mentioned -
trajectory control.

## BASIS OF THE CONCEPT

Combat aircraft capability has been expressed traitionally in terms of
such air vehicle performance characteristics as speed, altitude, maneuver-
ability, range and payload. In the continual race to produce tactically
superior aircraft, it is of course essential to concentrate on increasing
air vehicle performance. As observed above, there is one technologically
neglected area - the man-machine interface - which could, if properly ex-
ploited, augment air vehicle performance significantly. In fact, a properly
designed man-machine interface is capable of independently providing a
significant tactical edge in either the air-to-air or the air-to-ground en-
vironment.

Reviewing the man-machine interface of a typical single-seat combat
aircraft with a view toward providing a tactical edge, several observations
may be made. First, the pilot's primary interface with the world outside
his cockpit in all tactical phases of flight is visual, and the chief visual
display device involved is the head-up display (HUD). Second, the pilot
must scan continuously the world outside the cockpit and, except for limited
periods, cannot concentrate exclusively on the HUD presentations. Third,
in any engagement, two first-order considerations are paramount - position
and energy - and, together, they determine uniquely the vehicle's trajectory
requirements, both in terms of what to do and how to do it. Fourth, the
best means of ensuring success in any engagement is to be capable of operating
within the adversary's reaction time lag - in other words, to be able to
react more quickly than the enemy. Translating these observations into a
single, specific, man-machine interface requirement, it is clear that an
easy-to-understand HUD trajectory control presentation which may be flown
effectively with peripheral vision is required.

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Looking first at the matter of trajectory control, Figure 4 shows the complex array of parametric flight data which is typically presented to the pilot on a head-up display. F... this collection of symbols and numbers, the pilot must determine his dynamic flight status and then relate that status to the desired flight trajectory. But the parameters being displayed are not independent. A slight change in aircraft pitch will affect not only the pitch ladder but the altitude, the vertical velocity, the angle of attack, and the airspeed as well. Simultaneously, the pilot must maintain a high state of vigilance outside the cockpit. In this situation, the audition of any complications such as a system malfunction can result in unacceptable, and possibly fatal, deviations from the desired trajectory.

The problem then is to provide a better means of presenting trajectory information to the pilot. For example, the presentation must be capable of telling the pilot what to do and how to do it and also be capable of providing sufficient anticipation to ensure that it is done at the proper time. The MFPD satisfies this requirement. Recalling the specific elements of the over-all requirement, the corresponding capabilities of the MFPD may be stated as follows:

   o  The MFPD provides a visual presentation which is perceptually
      compatible with the real world (that is, it is earth-referenced)
      and electronically compatible with the HUD.
   o  The MFPD presentation is a graphical analogue of a real world
      entity (a highway) for which human response is well known and
      with which peripheral vision in particular is used successfully.
   o  The MFPD portrays the vehicle's command trajectory in terms of
      its attitude, altitude, direction and speed; therefore, the
      prevailing position and energy requirements are satisfied
      implicitly along with the "what" and "how" of the maneuvers involved.
      However, the pilot is free to accept, postpone, or reject the
      solution being presented as his judgment dictates.


## THE MFPD CONCEPT

The MFPD is an electronically generated, flight director presentation which provides the pilot with a dynamic, graphical representation of the trajectory to be flown. Thus, the MFPD obviates the traditional need for the pilot to visualize his flight trajectory, correlate a number of indi-

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TYPICAL HEAD-UP DISPLAY SYMBOLOGY

NAVIGATION MODE - LANDING GEAR UP

PITCH LADDER

COMMAND STEERING

HEADING

BAROMETRIC ALTITUDE

RADAR ALTITUDE

10

34

32

10

330

1050 B

850 R

VERTICAL VELOCITY

500 vv

100

0

-100

FLIGHT PATH MARKER

5

5

C 129

AIRCRAFT SYMBOL

CALIBRATED AIRSPEED

S

F

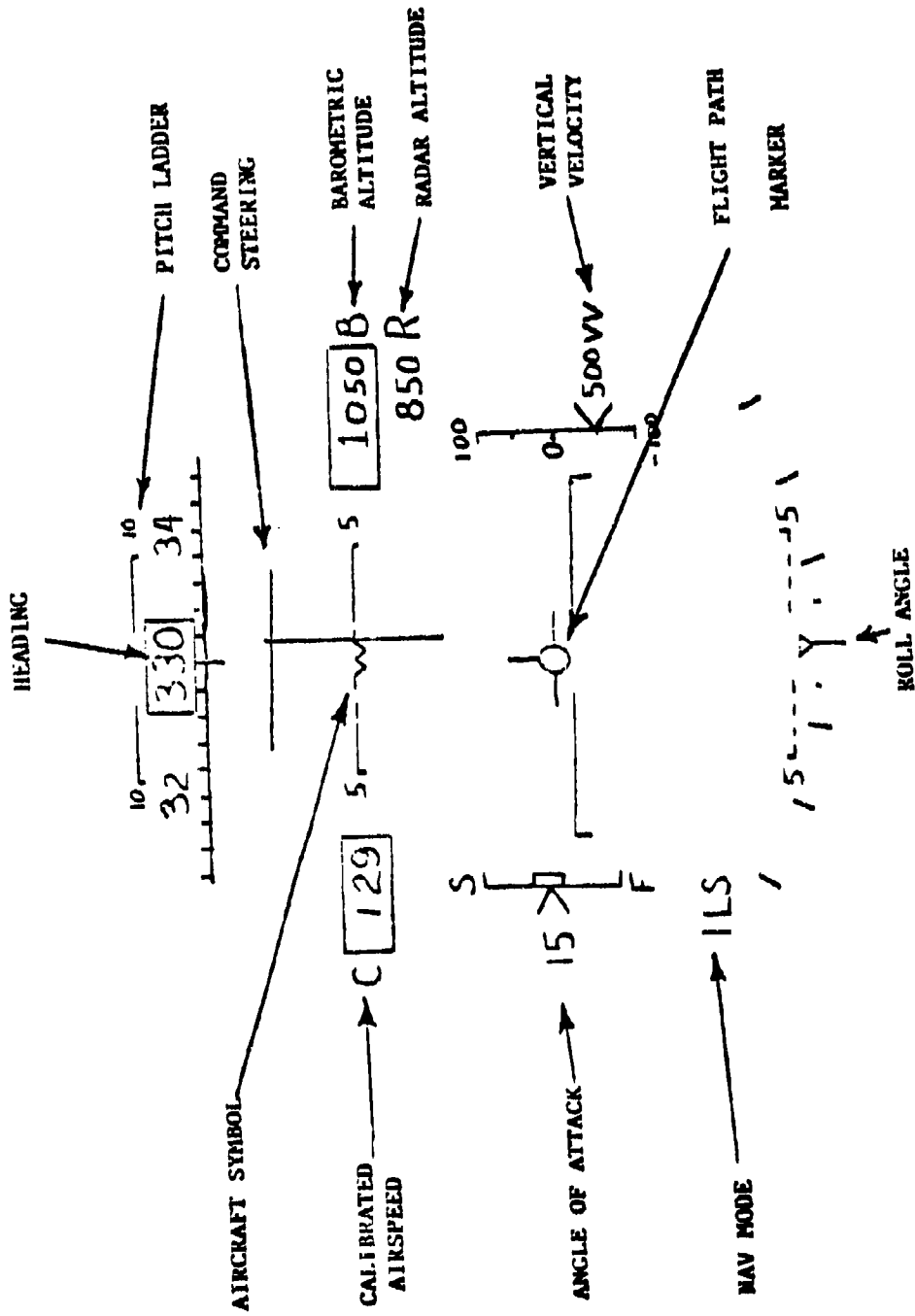15

ANGLE OF ATTACK

ILS

NAV MODE

5

5

ROLL ANGLE

FIGURE 4.

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vidual flight parameters to his mental image of the trajectory, and execute the trajectory by controlling his vehicle to the desired value of each of the individual flight parameters. Indeed, the MFPD eliminates the entire visualization and correlation process, and simplifies the execution process by computing and perspectively transforming the pilot's flight plan and then displaying the flight plan to him as if it were a visible "highway in the sky". The pilot responds to the display presentation in much the same manner as, when driving his car, he responds to the highway scene as viewed through the windshield.

Only two unique display elements are used in the MFPD presentation to provide the pilot with all of the guidance and control information needed for trajectory control of the vehicle: the flight path elements which define the aircraft's attitude, altitude and direction; and the velocity index through which the vehicle speed is controlled. A horizon line is always provided with the MFPD to preserve the pilot's real world orientation, but that feature is not regarded as part of the MFPD.

The flight path elements are analogous to "tarstrips" on a highway and in their aggregation from a discernible, perspectively correct continuum which is perceived by the pilot as the delineation of his flight path. When the aircraft is "on path", the flight path appears to extend out in front of the aircraft like a highway and the flight path elements appear to move under the vehicle at a speed equal to the vehicle's ground speed. The flight path elements properly depict, out in front of the vehicle, the aircraft pitch and bank commands required to achieve the altitude and course changes necessary to conform to the flight plan. Hence the pilot is provided with the anticipatory information he needs to "stay ahead" of his aircraft. Since the MFPD is earth-stabilized, these pitch and bank commands remain fixed geographically while the aircraft approaches them. In other words, the aircraft closes with a turn in the MFPD exactly as an automobile closes with a turn in the highway.

The velocity index appears to the pilot as a miniature airplane which is flying just to the left of, and about 20 feet above, the flight path. The pilot controls his vehicle's speed by flying a loose, non-taxing formation on the right wing of the miniature airplane (i.e., when the aircraft is "on speed", it appears to the pilot that he is holding position on and is about 700 feet behind the miniature plane). Thus, when the miniature airplane moves away from him, it denotes that he is too slow; and, when the little

plane moves toward him, it indicates that he is too fast. The velocity index also serves to enhance both attitude and altitude control. The miniature airplane flies in a plane parallel to that of the flight path. Thus, if the pilot is flying at a proper speed (and, therefore, 700 feet behind the little plane), he can obtain valuable, additional, anticipatory attitude cues by observing the maneuvers of the miniature craft as well as the flight path. Further, if the pilot takes an altitude about midway between that of the miniature airplane and that of the flight path (say, stepped down 10 feet below the little airplane), he then enjoys both upper and lower altitude references and will be "on altitude" and able to maintain that altitude with precision and relative ease.

The pictorial nature of the MFPD and the inherent redundancy of visual cues it affords (such as attitude and altitude information from the velocity index) enable the pilot to fly the display with his peripheral vision. This by-product provides another significant benefit to the tactical aircraft pilot - the ability to stay "head-up" throughout most of the mission. Thus the pilot, when he flies his mission, can look around with the same safety and confidence as the car driver proceeding down a highway. Figure 5 shows the MFPD as it appears when commanding a straight climb.

The MFPD computer program provides real-time presentations in both horizontal situation display (HSD) and vertical situation display (VSD) formats simultaneously (see Figures 6 and 7). The entire flight plan may be programmed or reprogrammed in flight. The flight plan, or an appropriately scaled segment of the flight plan, appears on the HSD as a plan view of the command course. This command course would normally overlay a map of the geographic area involved. As the flight proceeds, the flight path in the VSD presentation is generated automatically to display the eight thousand feet of command trajectory immediately in front of the aircraft.

To ensure that vital velocity (V) and normal acceleration (N) information is always displayed and that, during deviations from the flight plan, the most effective means of returning to the original flight path is presented, a feature known as the transition path is provided in the MFPD. In the present mechanization, a transition flight path is generated as soon as (actually, with some small intervening delay) the last flight path element has disappeared from the VSD and the aircraft is approximately in level flight. Figures 8 and 9 depict the process of "losing" the flight path.
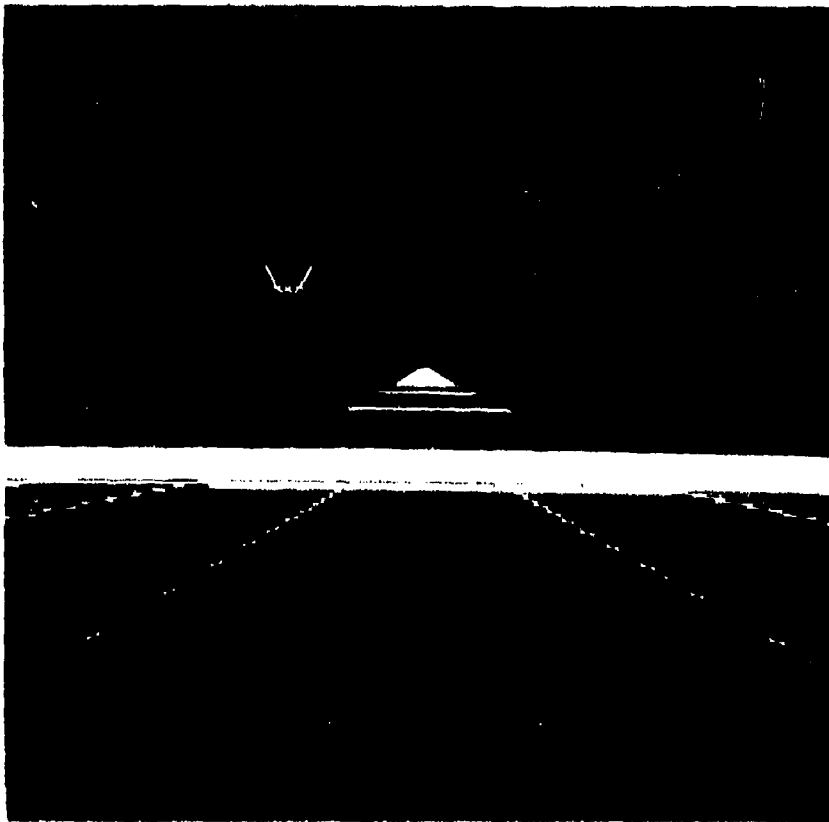
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FIGURE 5. THE MANEUVERING FLIGHT
PATH DISPLAY DEPICTING A
STRAIGHT CLIMB
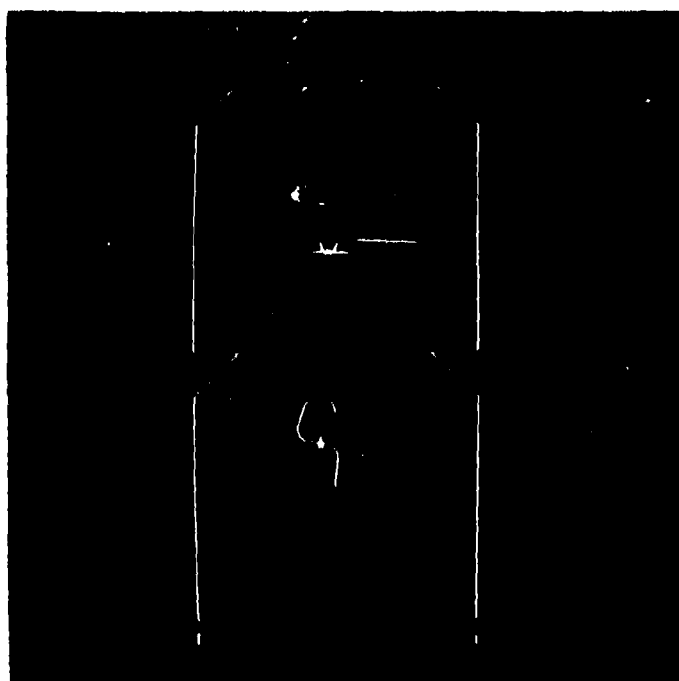
FIGURE 6. VSD VIEW OF THE FLIGHT PATH



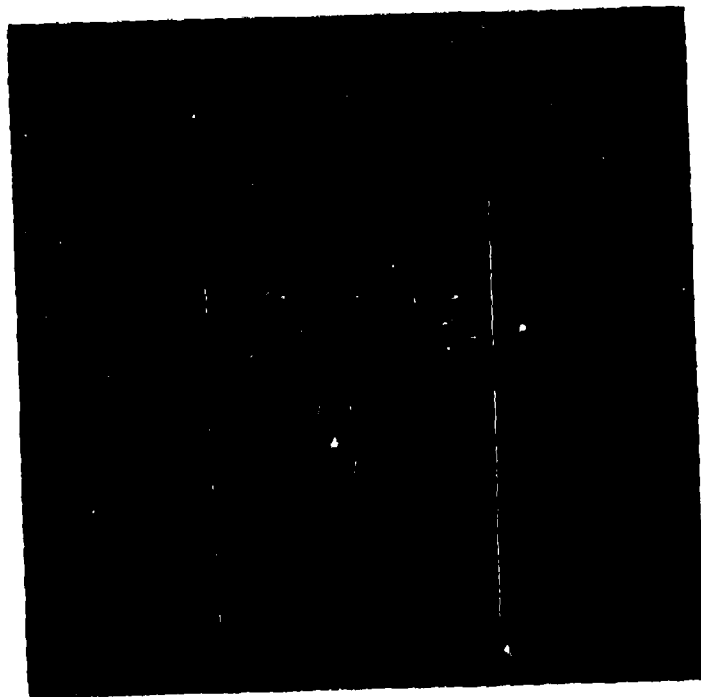FIGURE 7. SIMULTANEOUS VSD AND HSD VIEWS
OF THE FLIGHT PATH

FIGURE 8. LOSING THE PATH
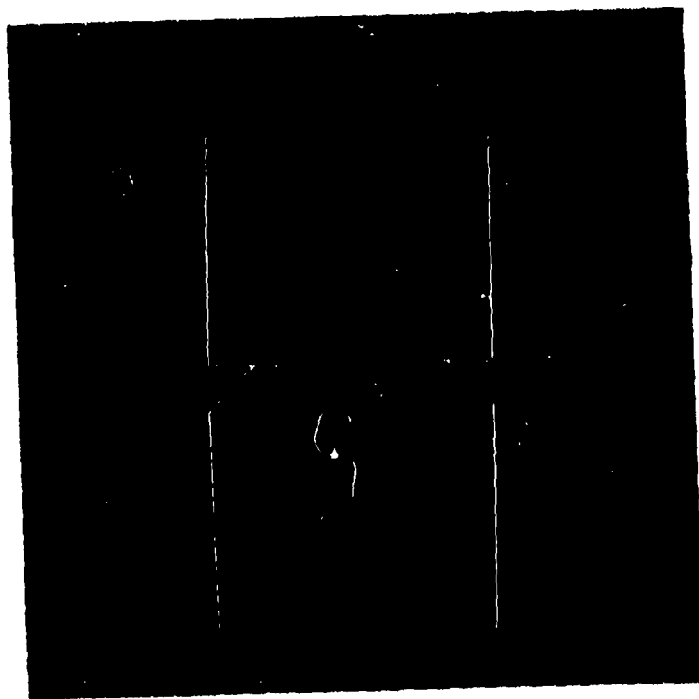


FIGURE 9. OFF THE PATH

Figure 10 shows the VSD and HSD aspects of the transition path immediately after its generation. The VSD presentation shows only the transition path. The HSD presentation shows the original programmed path as well as a second offshoot segment which is the transition path.

Figure 11 shows the two aspects of a second transition path. As the pilot continues to loose each path from the VSD, the program generates a new transition path to guide him back to the original flight path. When the pilot turns away from the programmed direction of flight by more than 180 degrees, the direction of the transition flight path will be reversed automatically to depict the "shorter return path". Throughout this process, only the active transition path is displayed in the VSD presentation. In the HSD presentation, only one transition path appears at any one time but the original flight path is always displayed. In this way, pilot orientation in the real world is maintained.

The present implementation of the transition path with the built-in time delays was chosen purely in the interest of demonstrating the concept. In an operational mechanization, a transition path would be generated as soon as the aircraft violates some predetermined "window of maximum acceptable deviation" about the flight path being flown. Such a window would not be displayed, but the corresponding limits would be included in the MFPD computer program. In effect, the window would be located about the flight path to denote those deviation limits beyond which the V-N information being portrayed by the MFPD presentation no longer would be valid.

The present version of the MFPD computer program is the evolutionary descendant of the computer program which was first unveiled in the feasibility demonstration effort. As such, the program incorporates all of the improvements implemented in that and subsequent contract efforts. In brief, this latest version of the basic MFPD computer program may be described as including the following features:

a. inflight programmable and reprogrammable,

b. automatically generated as the flight plan is flown,

c. capable of accepting present position inputs in either x, y coordinates or latitude and longitude,

d. partially textured surface (first three flight path elements),

e. miniature airplane velocity index which flies in a plane parallel to the flight path plane,

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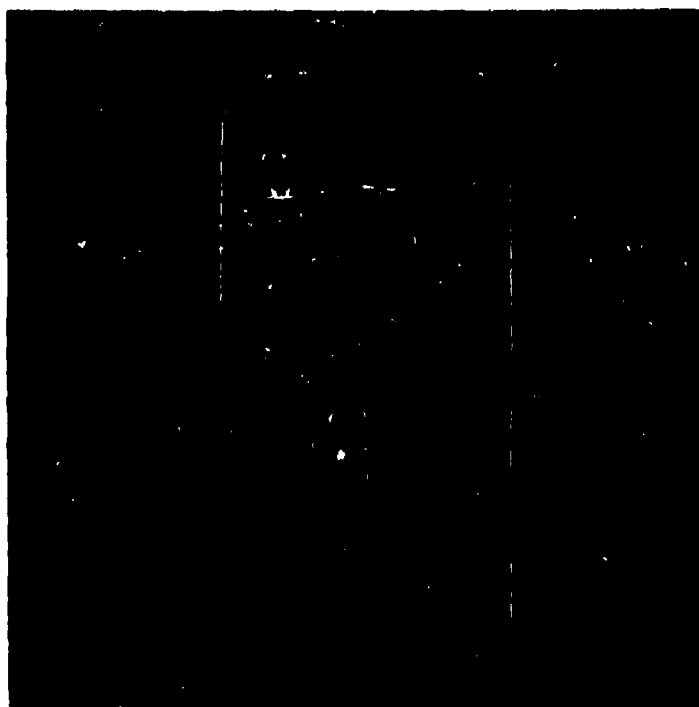
FIGURE 10. FIRST TRANSITION PATH
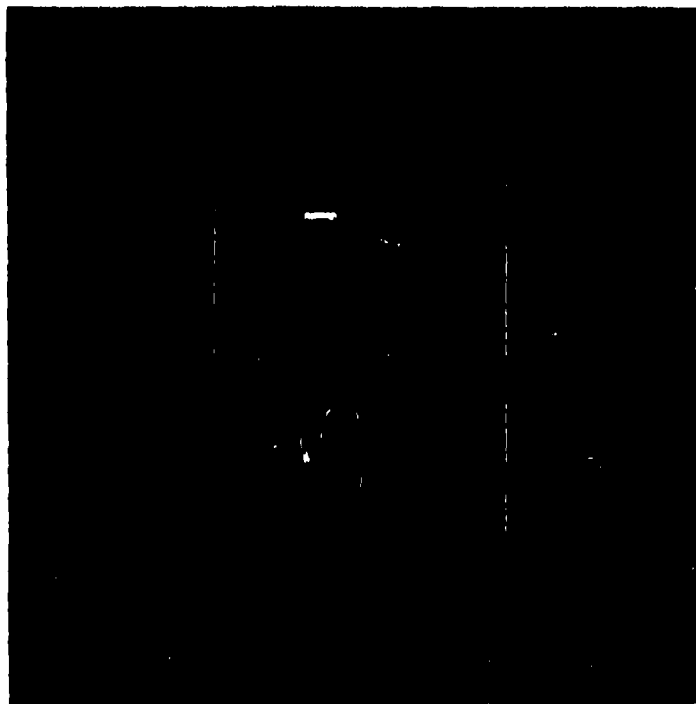


FIGURE 11. SECOND TRANSITION PATH

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f. upper altitude limit depicted by the velocity index,

g. simultaneous VSD and HSD presentations,

h. transition path back to flight plan trajectory automatically
   generated when flight path is lost from display field of view,
   and

i. position fixing capability.


## THE PILOT INTERFACE

The MFPD may be programmed for any flight plan. Once programmed, it
will generate automatically the command flight path presentation appropriate
for the particular flight plan segment then being flown. Alterations of the
programmed plan will of course result immediately in corresponding changes in
the MFPD. Such alterations can be input to the computer program in exactly
the same manner as the flight plan was programmed initially.

Mode select switches covering every phase of flight will be required to
assure that the presentation of the MFPD being displayed at any time is
appropriate for the phase of flight being flown at that time. Thus, for ex-
ample, pilot selection of TAKEOFF would produce a takeoff MFPD, and so on.
In the cruise mode, for those aircraft having an energy management capability,
the MFPD would command an altitude and a speed that will yield maximum range
unless one or both of those parameters have been fixed by the prevailing
mission requirements. Similarly, selection by the pilot of HOLD (or LOITER)
would result in commanding maximum endurance conditions on the MFPD, and
selection of a combat mode would cause the MFPD to be configured for minimum
time, energy conservative flight.

It is believed that the general operability of the cockpit can be im-
proved even more, and the effectiveness of the MFPD enhanced simultaneously,
by the judicious integration of all related control and switching functions.
For example, any pilot settings of flight-path-affecting cockpit controls such
as the HSI, TACAN, VOR, ILS, ADF, and INS should result in appropriate changes
in the MFPD. It may also be advantageous to effect radio frequency changes
automatically as the flight modes are selected, or vice versa. In short,
the MFPD may well prove to be the long-awaited catalyst for much needed
improvements in cockpit switchology as well as symbology.

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## CONTEMPLATED IMPROVEMENTS AND EXTENSIONS

As is the case with any concept undergoing development, areas of the
MFPD implementation in need of further improvement have been identified.
The more prominent of those areas are the basic flight path generation
algorithms and the behavior of the velocity index.

The basic flight path generation algorithms require further develop-
ment to increase their efficiency. These algorithms transform the flight
plan inputs of present position, way point locations, destination coordi-
nates, and enroute altitudes and speeds into the earth-referenced command
trajectory which is subsequently used by the taretrip generation algorithms
as the basis for producing the MFPD presentation. The development of the
flight path generation algorithms has continued under the Northrop IR&D
program and is resulting in the desired refinements to the MFPD computer
program.

The present implementation of the miniature airplane velocity index
is still in a preliminary state of development and is earmarked for further
study in the very near future to assure its complete perceptual compatibility
with the flight path presentation. In particular, the movement of the
velocity index will be programmed to be more consistent with the prevailing
mode of flight, less distracting in its motion, and more discernible in
conveying information to the pilot. First, the velocity index in the
TAKEOFF flight mode should start from rest and lead the pilot through the
takeoff and initial climb. The velocity index should be similarly appro-
priate for every other mode of flight. Second, the motion of the velocity
index and the method used to recycle it should be smoothed, clipped and
otherwise altered to provide a more natural and perceptually acceptable
portrayal of speed differentials. In other words, the little airplane should
not fly back to a given point along the flight path and start its motion over
again. Finally, the location of the velocity index should be varied to
assure that it is always clearly visible to the pilot. For instance, the
present velocity index is clearly visible in a right turn but masked in a
left turn as shown in Figures 12 and 13. To avoid such masking, the little
airplane should always be on the high side of the turn. One possible means
of mechanizing this scheme is to allow the little airplane to fly on either
side of the flight path during wings-level flight, and to execute a cross-
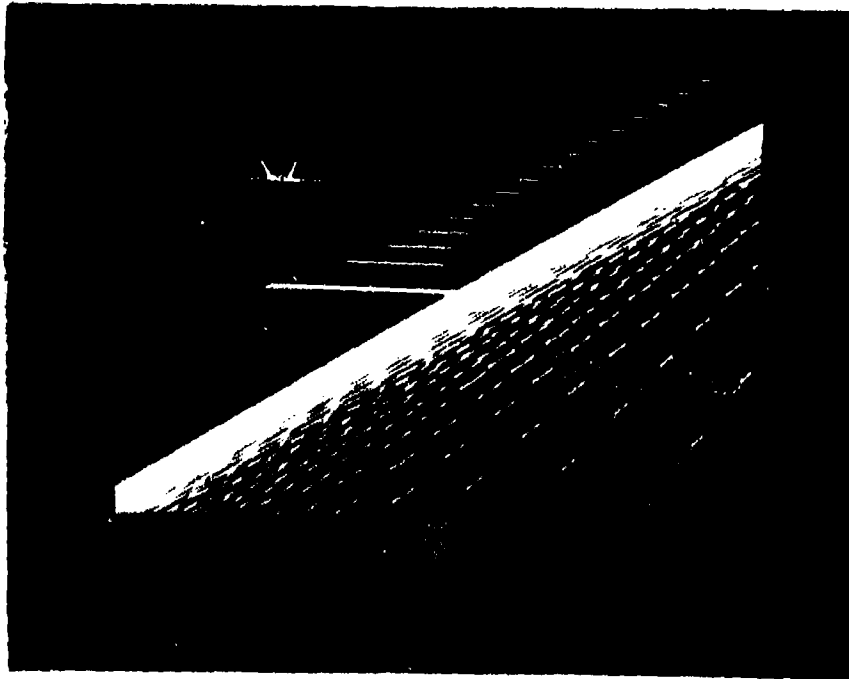over if required just prior to the turn. After the turn, the little airplane

FIGURE 12. VELOCITY INDEX (VI) APPEARANCE IN A RIGHT TURN
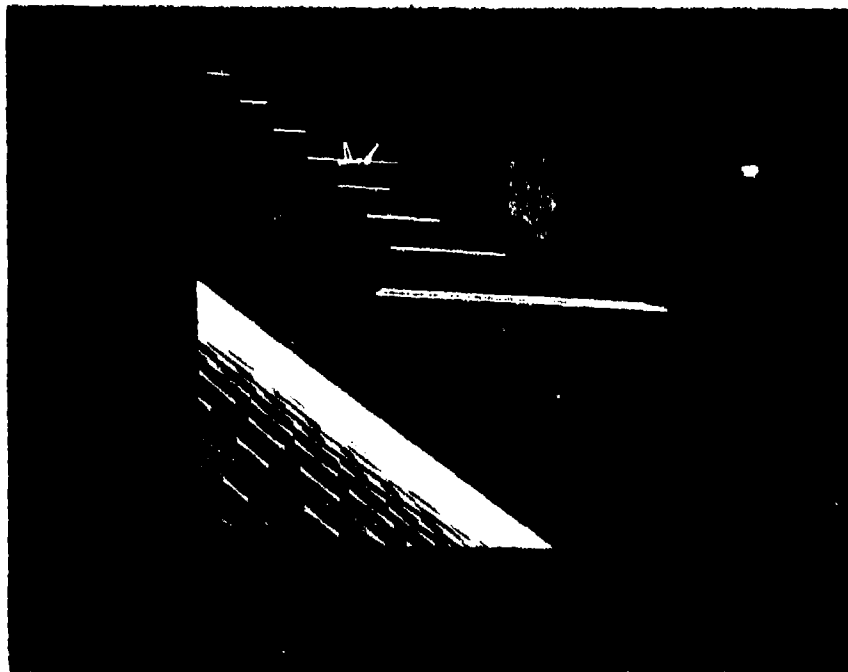


FIGURE 13. VI MASKED IN A LEFT TURN

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would remain on that side of the flight path until required again to execute a crossover in preparation for a turn in the opposite direction.

The MFPD is truly a total system integration vehicle in that, eventually, it will embody in its formulation almost every aspect of the mission. The inclusion of flight trajectory related MFPD constraints dictated by considerations of vehicle performance, optimal control, navigation, the tactical situation, energy maneuverability, survivability, fire control and weapon delivery, and emergencies can be foreseen readily. But what about information that is usually urgent but not trajectory related, such as engine fire, landing gear status, unsafe stores? It is believed that much, if not all, of this status information can be incorporated in the basic MFPD presentation. For example, the miniature airplane velocity index can be used to depict engine status (including fire), landing gear status, unsafe stores, and probably all first notice vehicle status data. Since the velocity index is a prominent element in the pilot's scan, it affords an excellent means of providing additional information. By adding specific pictorial cues (like, for example, the landing gear) and augmenting those cues with color and intensity and flash coding, it should be possible to elicit the proper pilot response quickly and consistently.

These possible extensions of the MFPD are mentioned more in the interest of expressing the vast potential of the display concept than in advocating their early implementation. In fact, there may be many other features that, from the standpoint of priority, should be added to the MFPD before those mentioned. Nevertheless, the Northrop approach has been planned to ultimately extract from the MFPD the full measure of its information presentation effectiveness.

Any contemplation of extensions to the MFPD should recognize that the display provides director information primarily and should be augmented with appropriate orientation information. The principal element of this orientation information is the ground plane, or contact analogue. The laboratory implementation of the MFPD at Northrop includes a simple ground plane consisting of two orthogonal line sets. The subjective enhancement of the MFPD afforded by the ground plane is significant. The Northrop approach also includes plans to, first, augment the MFPD with a simple, flat, ground plane and, eventually, implement a full capability VSD presentation including a ground plane with topographical information.

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One of the critical tasks a tactical aircraft pilot must perform is energy management. Specifically, the pilot is required to fly his aircraft to the point of engagement in such a way that he enters the engagement with as much fuel aboard as possible. Then, in the course of the engagement, he must maneuver the aircraft in the most energy-efficient manner consistent with a successful engagement, monitor his fuel consumption, and break off the engagement with sufficient fuel remaining to return to base. Finally, he must attempt to reach his base in the most fuel-efficient manner.

In order to satisfy these requirements, the pilot must be able to achieve a "maximum range" condition of speed and altitude when flying enroute to and from the engagement, a "maximum endurance" condition during any intervening loiter or holding periods, and a "minimum time/energy conservative" condition during the engagement.

The Maneuvering Flight Path Display (MFPD) is inherently capable of providing energy information in that it provides for complete vehicle trajectory control, including the vehicle's potential and kinetic energies. Therefore, the MFPD would serve as the primary energy management display. Specifically, the "command" and "actual" altitudes (potential energy) and speeds (kinetic energy) are implicit in the MFPD presentation. Once the energy management computations are performed and the appropriate (e.g., for "maximum range" or "maximum endurance") "command" altitude and speed are established, those "command" values will be reflected in the MFPD presentation. Proper response to the MFPD will thus assure the desired energy management.

## CONCLUDING REMARKS

The success of the MFPD development to date and the consequent maturation of the concept has stimulated a widespread interest in advancing the program to flight demonstration as quickly as possible. In light of this situation, a few observations appear to be in order.

The complete development of the MFPD will require that the laboratory development activity be continued, that both simulator and flight demonstrations be carried out progressively to sustain the development, and that operational applications of the concept be made available when they become feasible - even as the development proceeds. The complete development of the MFPD, because of budgetary limitations, may extend over a protracted period of time. Yet even the relatively simple present version of the MFPD, if it were available to the operating commands, could increase substantially the opera-

tional safety and effectiveness of the users involved. Therefore, the MFPD should be made available operationally as soon as possible after its flight validation, and more capable versions should be released progressively thereafter.

Simulator demonstrations of the MFPD are particularly desirable because the concept is novel with no operational precedents and it, conceivably, could induce some adverse coupling effects in the pilot control loop. When abstract symbology is used in an aircraft display presentation, it is customary to harmonize the display with the aircraft involved so that the presentation can be flown with relative ease. This harmonization is effected by adjusting the response of the display symbols to movements of the aircraft so as to achieve symbol motions that are perceptually compatible with the handling qualities of the aircraft.

In a display presentation such as the MFPD, which features and relies on one-to-one correlation with the real world, this procedure for achieving control-display compatibility cannot be used. Any such adjustment of the MFPD display presentation would destroy che required real world relationship. Therefore, any compensation added to the system for purposes of harmonization must be incorporated in the control augmentation system of the aircraft. In other words, if the pilot cannot fly his aircraft on the MFPD without experiencing pilot induced oscillations (or even undue difficulty for that matter), the handling qualities of the aircraft must be adjusted, not the display. It is clear from this requirement of the MFPD that man-in-loop simulations, in which the aircraft dynamics involved are represented in a relatively accurate manner, should precede all but the most elementary implementations of the MFPD in an aircraft.

Reflecting for a moment on the future development requirements of the MFPD, it becomes clear that the MFPD development must be complemented in the near future with similar work on compatible display concepts. Otherwise, the full operational effectiveness of the MFPD itself may never be realized. For example, the MFPD provides guidance and control "director" information only. This information is presented in a "solution" format to facilitate pilot response and is not intended to replace pilot judgment. In fact, the effective application of the MFPD will rely on the active participation of that judgment. Thus, the director information of the MFPD must be supported with all available "situation" or "orientation" information which is also in a compatible

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"solution" presentation format. This supporting information will enable the pilot to maintain his orientation in the real world, to be apprised continuously of the prevailing tactical situation, and to be aware at all times of the state and condition of his weapon system. Enriched with such information, the pilot can then critically monitor the situation, actively update his flight plan, and intelligently execute the required actions. Specifically, in the case of the MFPD, he can knowledgeably accept, postpone, or reject the solution information being offered.

This need for a "system" approach to cockpit design can be appreciated if one does not regard the crew station as a separate subsystem but rather takes the approach that the cockpit is simply the most visible part of the total system. In other words, the total system can be likened to an iceberg and the crew station to the visible tip of that iceberg. Accordingly, the cockpit is perhaps the most sensitive index of the sophistication and integrity of the system involved. Weapon systems of the future will require crew stations which are significantly more advanced than those flying today. If the MFPD is indeed a step in the right direction, it must be remembered that it is only one of many steps which will be necessary in the very near future.

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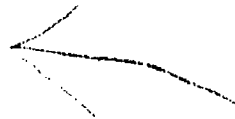
# THE APPLICATION OF DIFFRACTION OPTICS TO
# THE LANTIRN HEAD-UP DISPLAY

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## ABSTRACT

Head-Up Displays(HUDs) using diffraction optics(often called
"holographic HUDs") have been in development for nearly a decade,
seeking to exploit the potential of diffraction optics for improved
field of view, brightness, and see-through efficiency. But no
operational HUD has ever been built using diffraction optics, partly
because of limitations in head motion box, overlapping binocular field
of view, and producibility; partly because past mission requirements could
be met with simpler, cheaper, and proven conventional optics. The Low
Altitude Navigation and Targeting Infrared for Night(LANTIRN) program,
however, requires a field of view too large to be achievable using
conventional optics, necessitating the use of diffraction optics in
production quantities for the first time. The LANTIRN HUD will use new
approaches in optical design and fabrication techniques to meet the
LANTIRN requirements and overcome the previous limitations of diffraction
optics. This paper describes these advances in the application of
diffraction optics to HUD technology.

## DIFFRACTION OPTICS IN HUDS

The term "Diffraction Optics" as used here refers to any optical
element that uses the principle of diffraction in its workings. Such an
element will have a fringe pattern that takes an incoming wavefront and
recreates a new wavefront heading in a different direction. This
recreated wavefront may be either an exact reproduction of the original
(in which case the element is acting as a plane reflector) or a modified
version altered by optical power. Diffractive optical elements are
somewhat similar to holograms(often even called holograms) both in their
operation and manufacturing methods, but diffractive optical elements store
optical properties where holograms store image information.

Designers of HUDs have been looking to diffraction optics for
improvements in major performance characteristics with good reason. For
diffraction optics have a very large potential for such improvements as
the result of two properties(Figure 1): (1) an angle of incidence
selectivity; (2) a wavelength selectivity. The angle of incidence
selectivity dictates that only those rays arriving from a narrow range of
directions will be reflected, while those arriving from all other
directions will be transmitted, both with very high efficiency. Similarly,
only those incident rays that fall within a narrow band of wavelengths will
be reflected, while those of all other wavelengths will be transmitted.
These two effects are interrelated, so that from a different direction a
different wavelength would be reflected. There are two other properties
of diffraction optics that are significant to HUD design: (1) the ability
to carry optical power; (2) the presence of aberrations which become
increasingly larger as the angle of reflection is increased(especially

when optical power is present).

In a conventional HUD design(Figure 2), which uses a plate glass with partial silvering on one surface as the combiner mechanism integrating the display with the outside world scene, there is a fundamental tradeoff between the efficiencies of transmission of the display versus the outside world scene which extends over the entire visible spectrum. Typically, about 70% of outside world light and 20% of display light incident on the combiner reaches the pilot's eyes. A look at the properties of diffraction optics reveals a great opportunity for improvement here. For the cathode ray tubes(CRTs) used to generate HUD displays use only a small portion of the spectrum, providing a use for the wavelength selectivity property. A diffractive element designed to reflect a wavelength band matching that of the CRT phosphor can be used as the combiner, replacing the silvered surface. Now the display versus outside world scene tradeoff has been reduced from the entire visible spectrum to the spectral bandwidth of the CRT phosphor. This is especially effective if a nearly monochromatic phosphor like P43 is used. In such a case, taking nearly all of the light in that band out of the outside world scene has a negligible effect (a slight coloration change), so that the tradeoff can be resolved heavily in favor of the display efficiency. The net result is that both efficiencies are increased simultaneously by the use of a diffractive element.

Conventional HUDs also have field of view limitations which exist because cockpit space limitations impose upper limits on the size of each optical element. In cockpits such as the A-10 and the F-16, the element imposing the most severe limitation on the instantaneous field of view is the collimating lens, which is there to cause the display to appear to be focused at infinity rather than on the combiner glass. To get rid of this limitation, this lens must be removed from the system, but this can be done only if the collimation function is relocated to the combiner. This means a combiner with optical power is needed. A diffractive element for a combiner can provide this, both by the ability to carry intrinsic optical power and the facilitating of the use of curved reflecting elements, where the curvature provides optical power. In this way, the past limitations on instantaneous field of view of about 20$^\circ$ can be increased to 30$^\circ$ or more within the same space limitations.

Experimental HUDs and separate combiners have been built during the 1970s which substantiate that such improvements in major HUD performance parameters can be achieved using diffraction optics. The most active organizations have been the Hughes Aircraft Company, the Environmental Research Institute of Michigan(ERIM), and Marconi Avionics Limited. Hughes built the only HUD using diffraction optics to be flight tested to date. All of these have been in a configuration similar to that of Figure 3, which differs from the conventional HUD only in the removal of the collimating lens and the introduction of the diffractive element into the combiner, which has taken on curvature. Despite these successes, no production HUD has ever used diffraction optics. Why not?

For one thing, conventional optics have been able to meet all of the firm requirements imposed on HUDs despite the limitations previously noted. The larger field of view was certainly desired by pilots, but a firm mission requirement for it was never demonstrated. The brightness of the display was always sufficient for mission requirements, even if it was achieved by driving CRTs so hard as to account in large measure for the notoriously poor reliability of HUDs. Outside world scene visibility was

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always good enough to get by with. So there was no good reason to take on the higher cost and risk of diffraction optics. Also, certain limitations associated with diffraction optics in HUDs were discovered.

The angular selectivity property of diffraction optics results in a limitation on the range of positions from which the display is visible. The total volume of positions from which the display is visible is called the head motion box. It can become significantly smaller than that for a conventional HUD unless a sufficiently large range of angles is reflected by the diffractive element. This range, a sort of angular bandwidth, can be controlled by the design process.

Also from angular selectivity comes a limitation on the overlapping binocular instantaneous field of view(OBIFOV), that portion of the instantaneous field of view(IFOV) that is visible by both eyes at once. In the Precision Attack Enhancement(PAE) program, the small OBIFOV was found to be enough of a problem to require corrective action. Again, sufficient angular bandwidth is needed. A OBIFOV requirement was included in the specifications for the LANTIRN HUD as a result of the PAE problem.

The aberrations associated with diffraction optics have turned out to be large enough to require corrective action if accuracy and display quality requirements are to be met. The large angle of reflection at the diffractive element is the principal reason for this. The usual approach is compensation by additional elements in the relay lens. These have been effective, but they have added greatly to the complexity of the relay lens, often demanding elements that are aspheric, anamorphic, tilted, or off-center. More recent efforts have involved compensation of the diffractive element itself by aberrating the wavefronts of the beams of the exposure process during manufacturing. The Air Force Avionics Laboratory is sponsoring a program at ERIM in which holograms are used for such aberration.

The manufacturing process in general is considerably more complicated for diffraction optics, and still undergoing refinement. The design requires the use of specialized ray-tracing computer programs. Fabrication requires preparation of a photosensitive dichromated gelatin, coating it onto a glass substrate, exposure with overlapping coherent light beams, photochemical processing, baking, and finally sealing into a glass sandwich. Facilities requirements include stabilized optical benches, clean rooms, and lasers. Cost is much higher and yield rates lower than for conventional optics. Specific performance problems have been traced to the manufacturing process, most notably secondary images caused by stray holograms in the diffractive element. A Manufacturing Technology program conducted by Hughes for the Air Force Materials Laboratory has resulted in advances in the manufacturing process.

So both lack of requirements and technology problems have hindered the use of diffraction optics in operational HUDs. By 1980, solutions to the technology problems had progressed to the point that the technical risk was reduced to acceptable levels. All that remained was a requirement that conventional optics could not meet. The LANTIRN program provided such a requirement.

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## LANTIRN REQUIREMENTS

LANTIRN is a navigation and fire control system designed primarily to enhance weapon delivery in battlefield interdiction and close air support missions. It is subdivided into two parts: (1) a Fire Control System(FCS), contained in two pods, including two Forward Looking Infrared(FLIR) sensors, terrain following/avoidance capability, automatic target recognition and tracking, and laser designation and ranging; (2) an improved HUD. The LANTIRN system will be installed on F-16 and A-10 aircraft, some of which will get only the HUD.

The LANTIRN mission requires from the HUD all of the capabilities of the HUDs currently used on these aircraft plus two additional ones: (1) display of FLIR imagery simultaneously with the present symbology display; (2) field of view of at least 25° in the horizontal direction. The field of view requirement is the hard driver, as it is well in excess of the 20° limitation previously noted for conventional optics given A-10 and F-16 cockpit constraints. The need for diffraction optics has arrived.

An RFP for the LANTIRN HUD was released in February 1980. A design using diffraction optics was expected based on the field of view requirement, but was not mandated by the specifications. The specifications did include specific requirements to avoid past problems with diffraction optics, such as head motion box and OBIFOV. The RFP called for a full scale development program plus production options for several hundred units in both F-16 and A-10 configurations(which are necessarily different because of cockpit constraints).

After a competitive source selection, the contract was awarded to Marconi Avionics. The winning design involved diffraction optics, as expected. But it did not follow the configuration of Figure 3.

## LANTIRN HUD DESIGN

The LANTIRN HUD optical configuration as devised by Marconi Avionics is shown in Figure 4. The large, highly curved single piece combiner has been replaced by an assembly of three combiner elements, all of which use diffraction optics. All three have flat glass surfaces, and the two labelled "upper" and "rear" have flat diffractive elements as well. Only in the "forward" combiner is the diffractive element curved, and even here the curvature is considerably reduced from that of the single combiner designs. The physical size of each is significantly smaller than single-piece combiners in the same situation.

Following a display ray trace through this combiner assembly is an instructive exercise. It first is reflected from the upper combiner, being properly matched to its diffractive element in angle of incidence and wavelength. It next reaches the forward combiner where it is transmitted, not reflected. The reason is that the angle of incidence is not matched to the diffractive element's designed angle of incidence. It next reaches the rear combiner, where conditions are right for a reflection, and arrives at the forward combiner a second time. This time, the angle of incidence is right for a reflection. The ray returns to the rear combiner at a different angle of incidence and is transmitted to the pilot's eye. The angle of incidence selectivity has enabled the display

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ray to experience both transmission and reflection at the forward and rear combiners.

In this design, the angles of reflection at the diffractive elements are much smaller than they are for the single combiner configuration. This means reduced aberrations in accordance with the basic aberration property of diffraction optics. The benefit of this to the HUD design is the elimination of the need for highly complex elements in the relay lens. Only simple lens elements are needed for the LANTIRN HUD relay lens, despite stringent accuracy and display quality specifications.

The collimation function is contained entirely in the forward combiner. In the configuration of this combiner there are available three sources of optical power: (1) the curvature of the diffractive element; (2) the optical power that can be built into the diffractive element; (3) the lens action of the rear half of the combiner. The lens action, which occurs only during the reflection passage of the display rays(and not at all for outside world rays), is a unique feature of this design, and is practical only because of the small degree of curvature of the diffractive element. Higher curvature would necessitate an excessive amount of glass for such a construction. The lens effect together with the curvature of the diffractive element provides all the power needed for the collimation, so that the diffractive element itself has no optical power, a feature that also tends to reduce aberrations.

A significant result of all this is that the system has three elements that are much easier to produce than the single element of previous designs. The total flatness of two elements, the slight curvature of the third(and even for that one its external surfaces are flat), and the absence of optical power in the diffractive elements provide producibility benefits in many stages of manufacturing(e.g. glass grinding, element exposure).

The price paid for these gains is surprisingly small. Aside from the need to manufacture and assemble the three pieces(instead of one), the only penalties are losses in the display and outside world transmission efficiencies caused by the additional optical interactions.

PRODUCTION METHODS

Marconi has introduced several improvements into the manufacturing process, not all of which can be discussed here. One of the most notable is in the exposure of the diffraction elements. It is required to have overlapping coherent beams in the element as depicted conceptually in Figure 5a. This arrangement is not a practical one, and early procedures used an arrangement similar to Figure 5b to achieve the same result. This arrangement has deficiencies, including severe stabilization requirements, so that Marconi has switched to the back reflection method depicted in Figure 5c, where the overlapping beam is generated immediately adjacent to the element. The need to maintain the two separate beams stabilized with respect to each other over a large area has vanished. This eliminates some optical elements in addition, reducing the risk of exposure flaws.

Additional improvements involve the exposure, gelatin coating, and sealing processes. Benefits from these improvements will include better performance, lower cost, increased yield rates, and greater service life.

PERFORMANCE

This analysis deals with predicted performance, as the first LANTIRN HUDs are still being manufactured.

In the important area of field of view(FOV), the expected results are as follows:

|  | F-16 Version | A-10 Version |
|---|---|---|
| Total FOV | 30°H, 20°V | 30°H, 20.25°V |
| IFOV | 30°H, 18°V | 30°H, 19°V |
| OBIFOV | 20°H, 18°V | 20°H, 19°V |

They meet all of the specification requirements for field of view and exceed some of them. The existing HUDs on the A-10 and F-16 aircraft do not come close to matching them.

The outside world scene transmission efficiency will be about 78%. The contrast ratio of the symbology against a 10,000 foot-lambert background will be 1.38:1, significantly exceeding the specification requirement of 1.2:1. These are also improvements over the performance of existing HUDs. Their achievement demonstrates that the small losses in efficiency compared to the single-piece combiner design will be no hindrance to mission performance.

The HUD will also meet a detailed set of positional accuracy requirements ranging from 1 to 7 milliradians as well as tight specifications on positional and dimensional stability, display quality, and symbol-to-raster registration. This is a relatively easier achievement for the LANTIRN HUD because of the reduced aberrations in the three-piece combiner design.

Design problems do exist, but solutions are well within reach for all of them. Considerable attention has been given to solar and environmental effects, both well known problem areas for HUDs with diffraction optics. Solar effects can cause either background washout or bright spots in the field of view in the manners shown in Figure 6. Design refinements have reduced their level to the point that they are not expected to pose a significant threat to mission performance or safety. Efforts at further improvements are continuing.

Diffractive elements can be vulnerable to moisture, heat, and ultraviolet radiation. The effects are changes in optical characteristics. Marconi is introducing several refinements into the manufacturing process to minimize these effects. Testing on current samples shows only negligible effects from the environments encountered

by the combiners. This will of course be further verified in qualification testing.

The use of the Cockpit Television Sensor(CTVS) with the LANTIRN HUD poses an interesting problem. The CTVS normally monitors the scene looking through the HUD, symbology and all. The video output is tape recorded for ground playback. This procedure will not work with the LANTIRN HUD; for if the CTVS camera is placed outside the head motion box, it will fail to see the symbology; while if it is placed inside the head motion box, it will interfere with the pilot. This forces the use of a composite video. The CTVS camera is place to view only the outside world scene. The symbology is then electronically inserted into the video by the HUD electronics. The tricky part is to get the symbology accurately registered with the video. An alignment procedure is being devised to do this.

STATUS

The design is nearly complete for both F-16 and A-10 versions of the LANTIRN HUD, and manufacturing of the developmental units for the F-16 is underway. The delivery of the first unit is expected in early 1982. Qualification and flight testing will be conducted in 1982 and 1983. Deliveries of production units could begin in early 1984, depending on the progress of the test program. As many as 608 F-16 and 255 A-10 HUDs could be delivered if all production options are exercised.

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(a) **ANGLE OF INCIDENCE SELECTIVITY**

TRANSMITTED RAYS

INCIDENT RAYS

ELEMENT

REFLECTED RAY

(b) **WAVELENGTH SELECTIVITY**

OTHER WAVELENGTH TRANSMITTED

INCIDENT WHITE RAY

ELEMENT
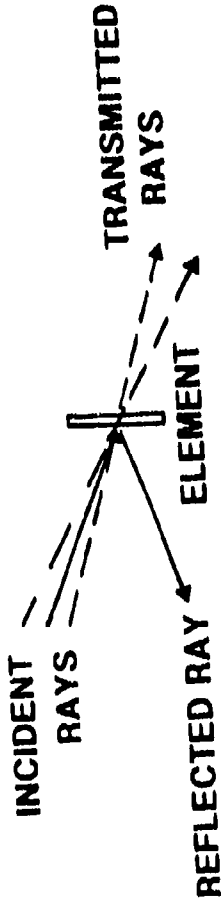
SELECTED WAVELENGTH REFLECTED
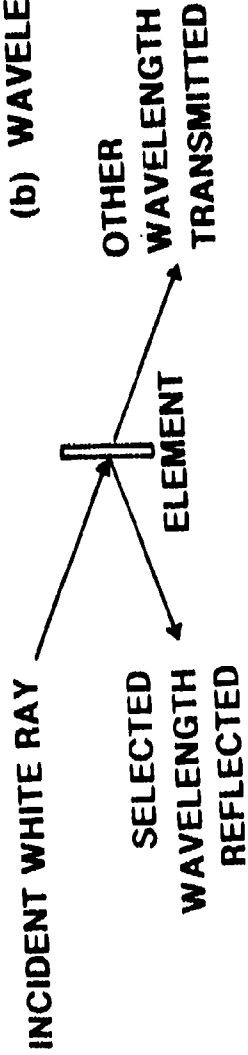
(c) **ABERRATIONS AND REFLECTED ANGLE**

ELEMENT

LOW ABERRATIONS

ELEMENT

HIGH ABERRATIONS
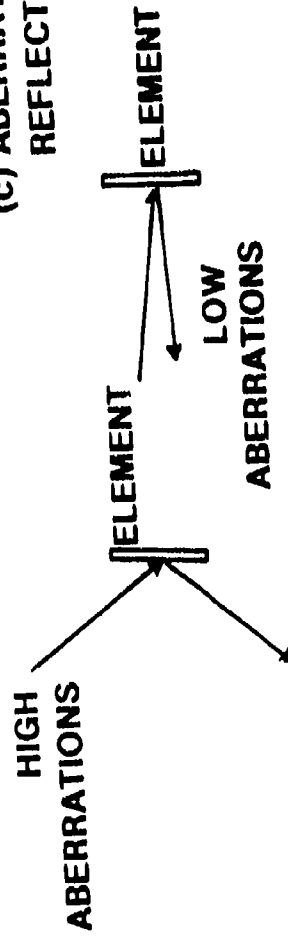
Figure 1 - Properties of Diffraction Optics

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EYE

PARTIALLY SILVERED SURFACE

LIMITING ANGLE FOR INSTANTANEOUS FOV

COLLIMATING LENS (LIMITS IFOV)

FOLD MIRROR

CANOPY

COMBINER

DISPLAY GENERATED

RELAY LENS

CRT
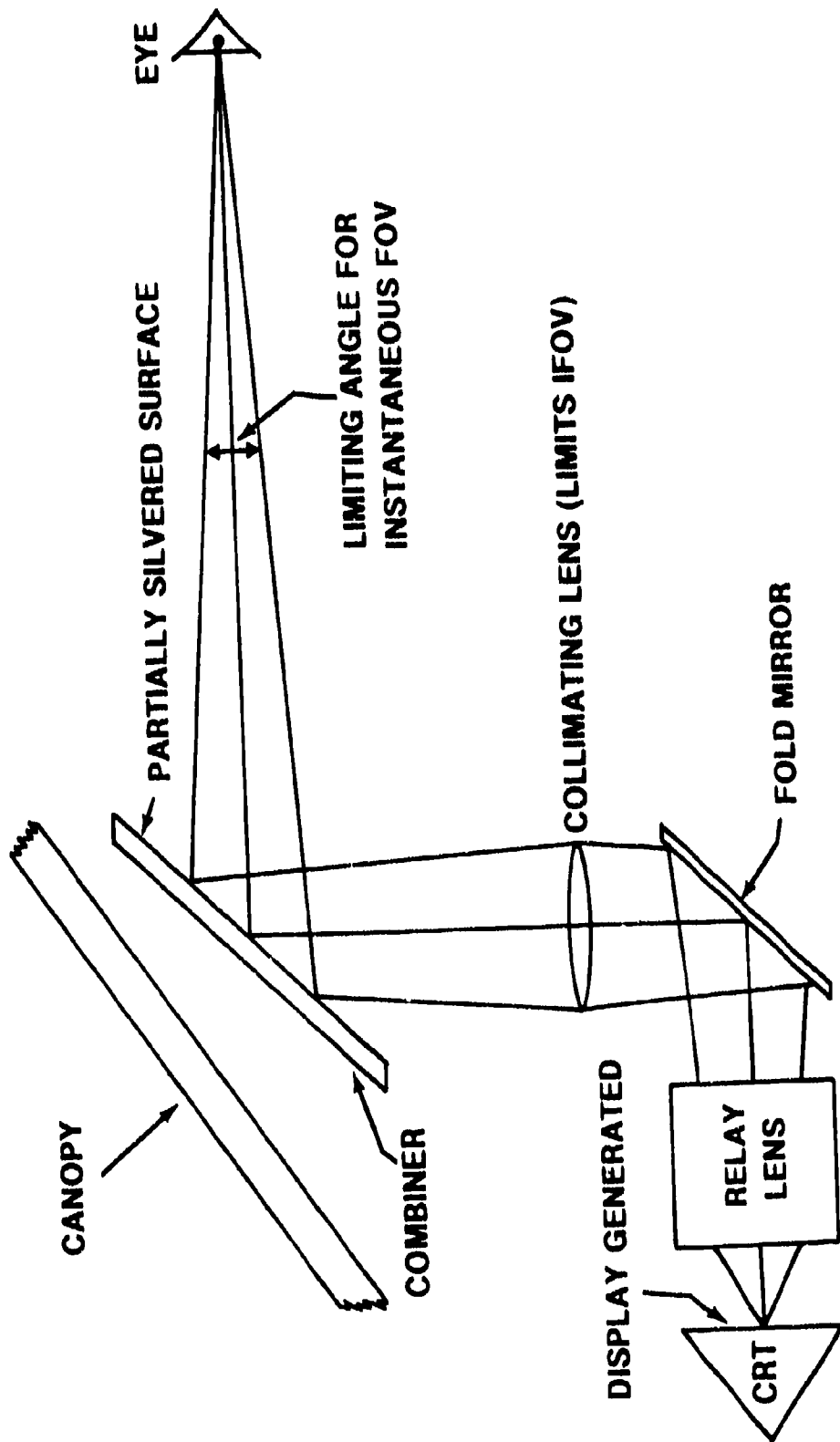
Figure 2 - Conventional HUD Layout

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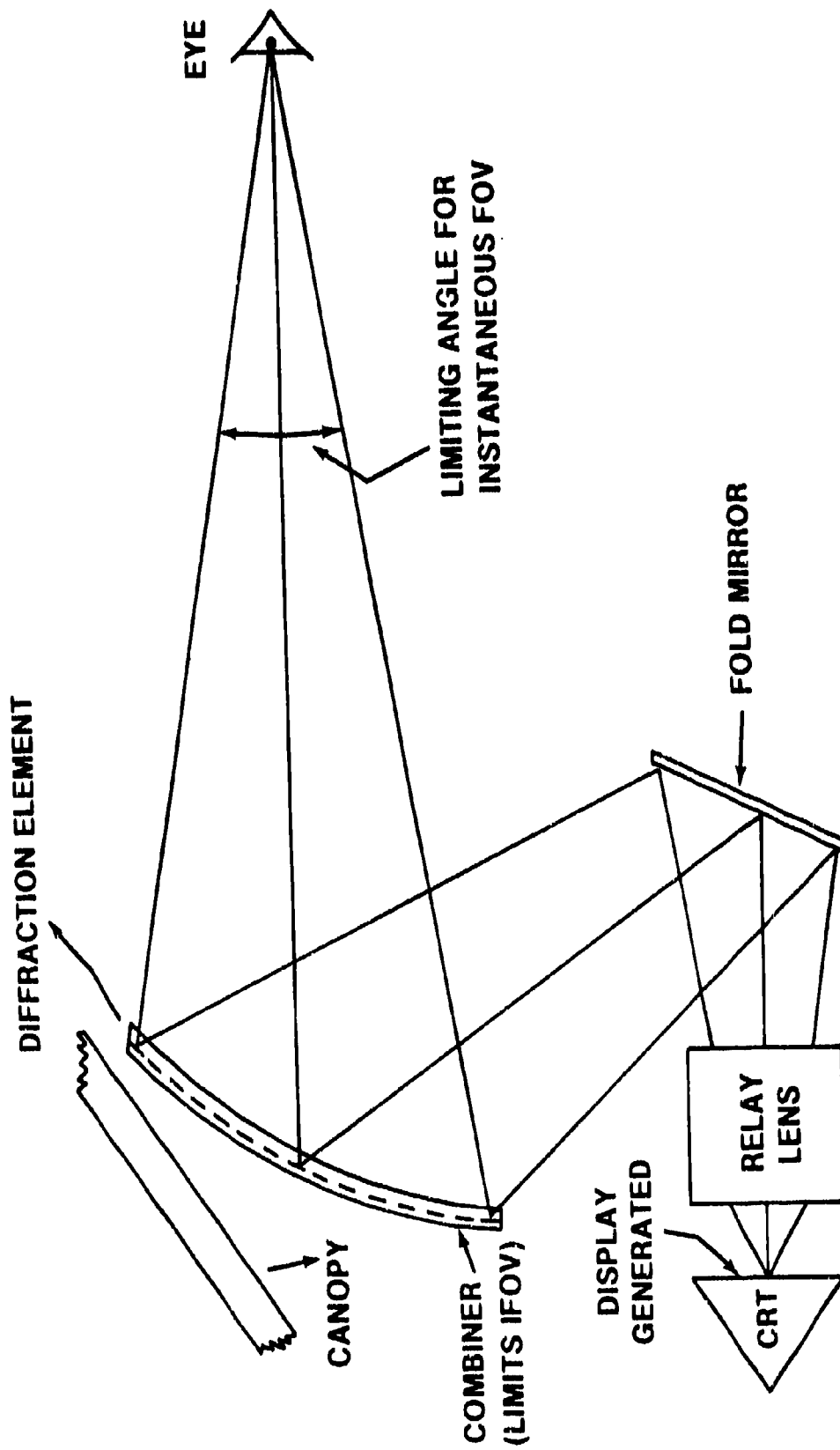
Figure 3 - HUD with Diffraction Optics

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CANOPY

FORWARD COMBINER ELEMENT

REAR COMBINER ELEMENT

EYE

FOLD MIRROR

UPPER COMBINER
ELEMENT

DISPLAY
GENERATED

RELAY
LENS

CRT
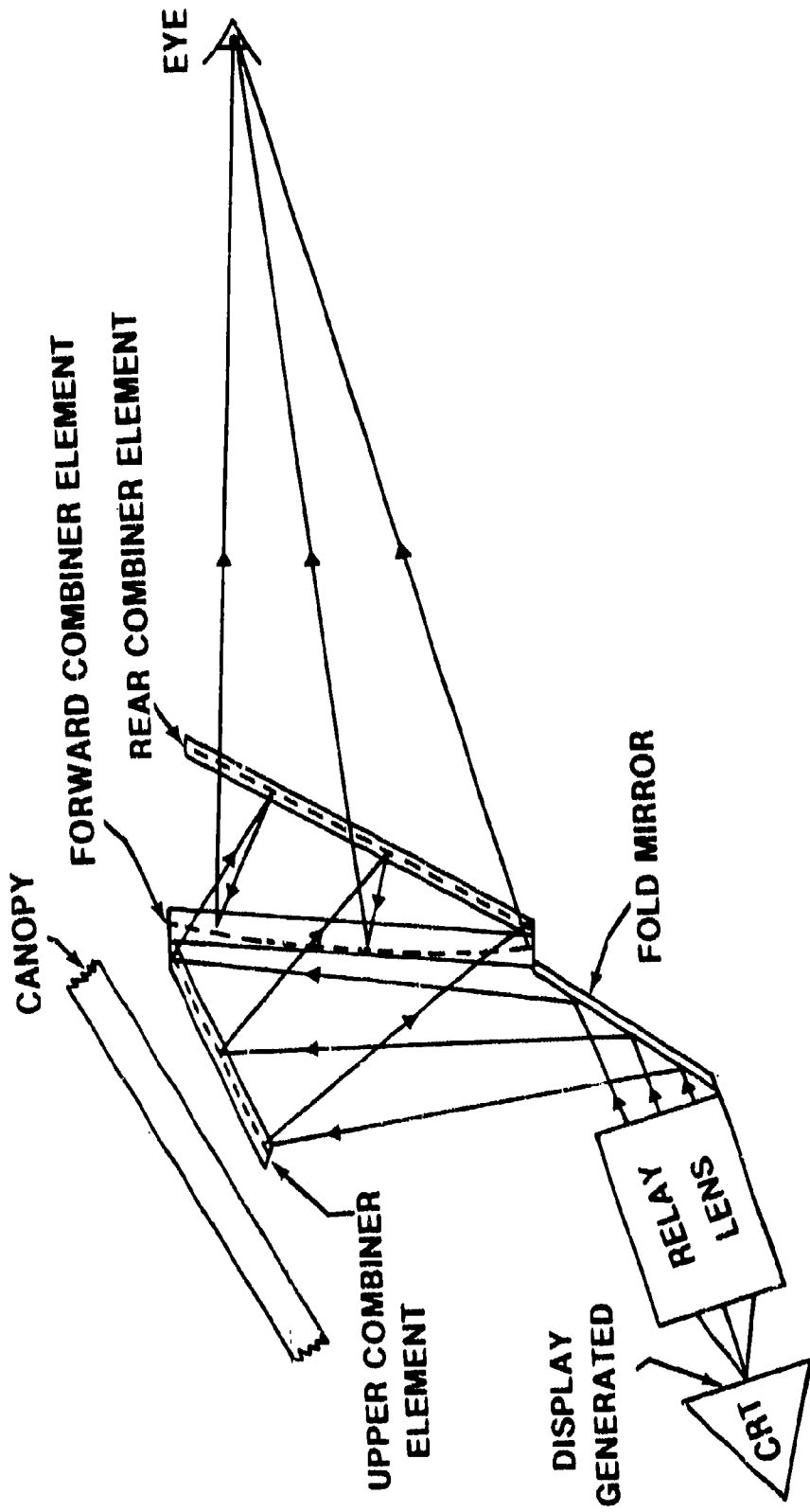
Figure 4 - LANTIRN HUD Configuration

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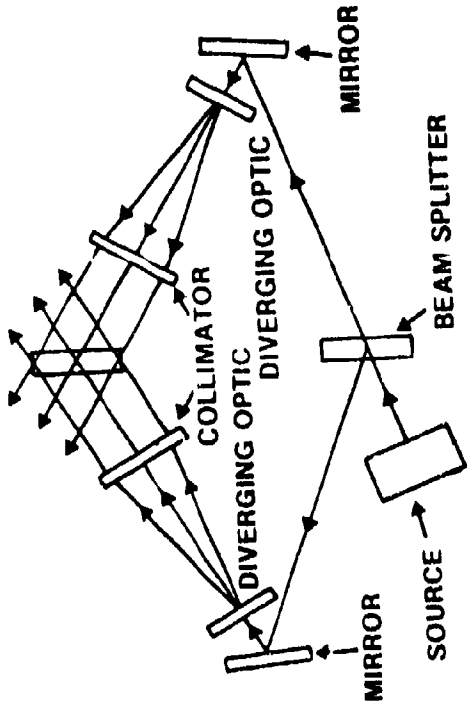
(a) DUAL SOURCE

(b) SINGLE SOURCE
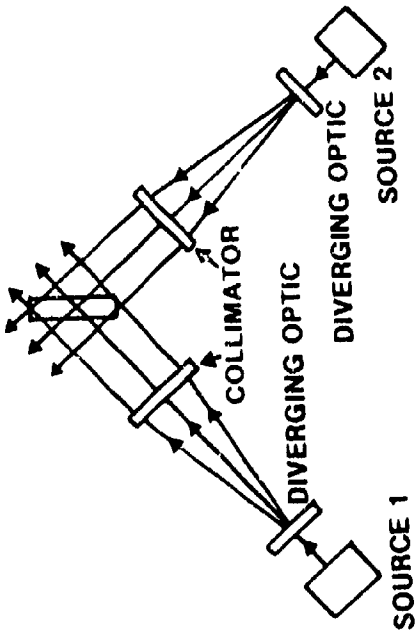
(c) BACK REFLECTION
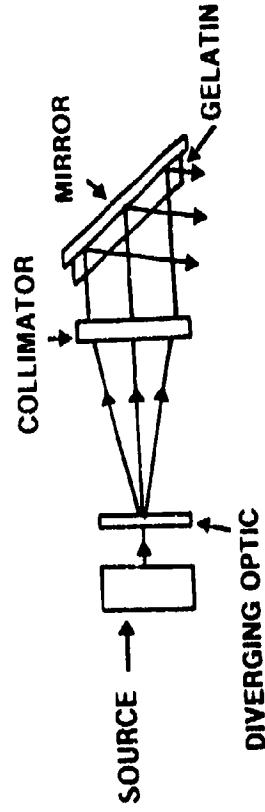
Figure 5 – Exposure Techniques

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EFFECT 1:
SUN POSITION

EFFECT 1: EYE SEES GREEN
PORTION OF BACKGROUND.

EFFECT 2: REAL
SUN IMAGE (GREEN)

EFFECT 2: ONLY REMAINING
GREEN BEYOND THIS POINT

EFFECT 2:
SUN POSITION

BOTH EFFECTS:
MOST OF GREEN REFLECTED
AWAY BY UPPER ELEMENT

EFFECT 1: BKGND.
ILLUMINATION
ON CRT FACE
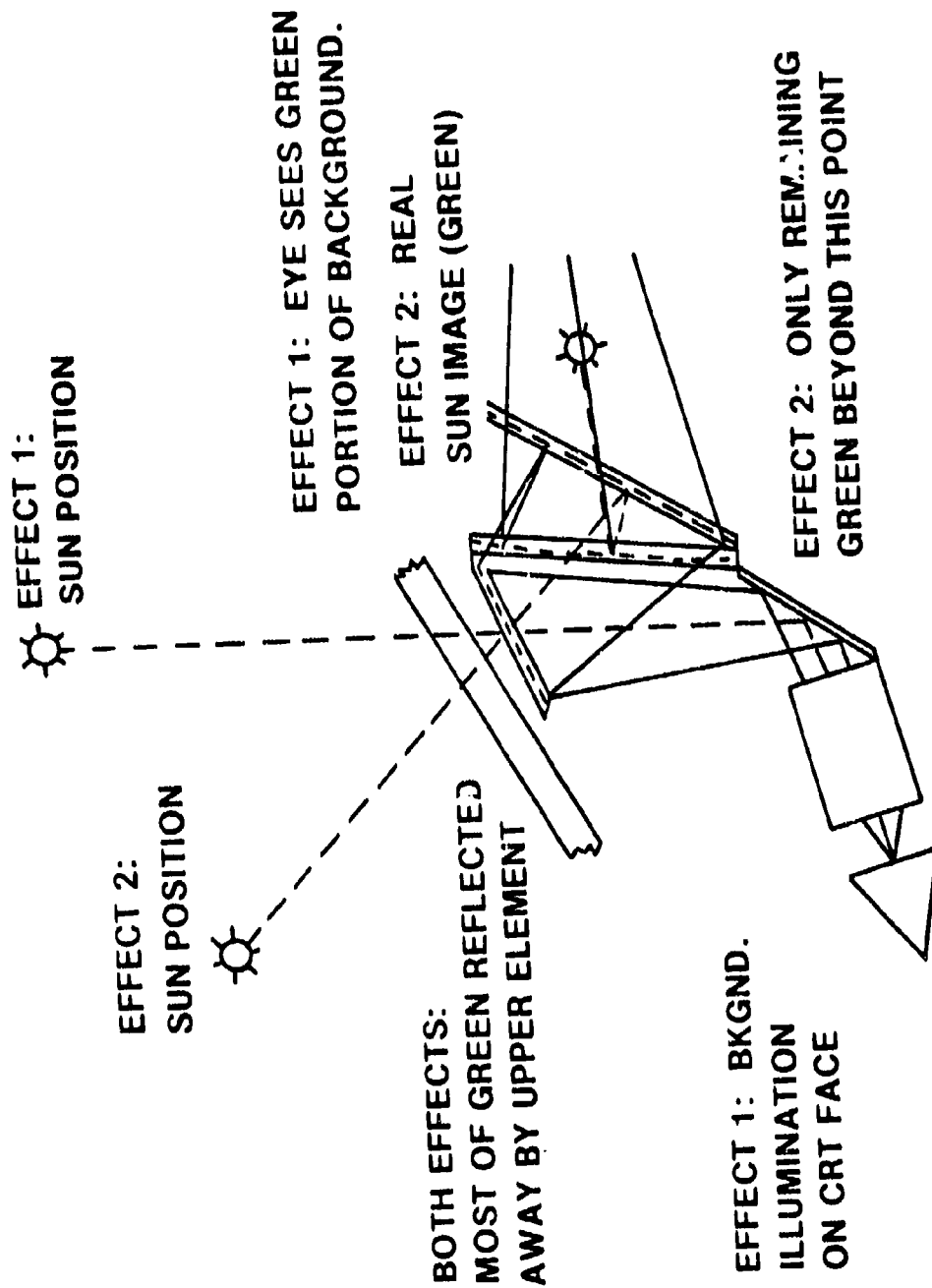
Figure 6 – Solar Effects

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Advanced Fighter Technology Integrator
(AFTI) F-16
Display Mechanization

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# 1.   I N T R O D U C T I O N

The AFTI/F-16 program is divided into two major phases:
Digital Flight Control System (DFCS) and Automatic Maneuvering
Attack System (AMAS). The first phase culminates with the
flight test of Digital Flight Control System (DFCS) technology
and the second phase culminates with the flight test of Inte-
grated Flight and Fire Control (IFFC) technology. Pilot-vehicle
interface advancements will be in conjunction with the major
program technologies.

In the development of an effective pilot-vehicle interface
(PVI), a variety of configurations must be evaluated in an oper-
ational context. General Dynamics is performing this iterative
process with the aid of the Research and Engineering Simulator.
Initial in-house evaluations were conducted to establish an
acceptable configuration for the cockpit and its multipurpose
display set. The in-house evaluations resulted in two display
mechanization concepts for the multipurpose displays which were
evaluated by the AFTI/F-16 program pilots in the simulator.

The primary objective of the multipurpose display (MPD)
evaluation was to assess the effectiveness of two alternative
display mechanizations. A secondary objective of this test was
to conduct a preliminary evaluation of the individual display
formats. Data obtained during the evaluation was used to assess
pilot acceptance of the AFTI/F-16 cockpit and to develop display
formats and mechanization concepts that improve operational
utility.
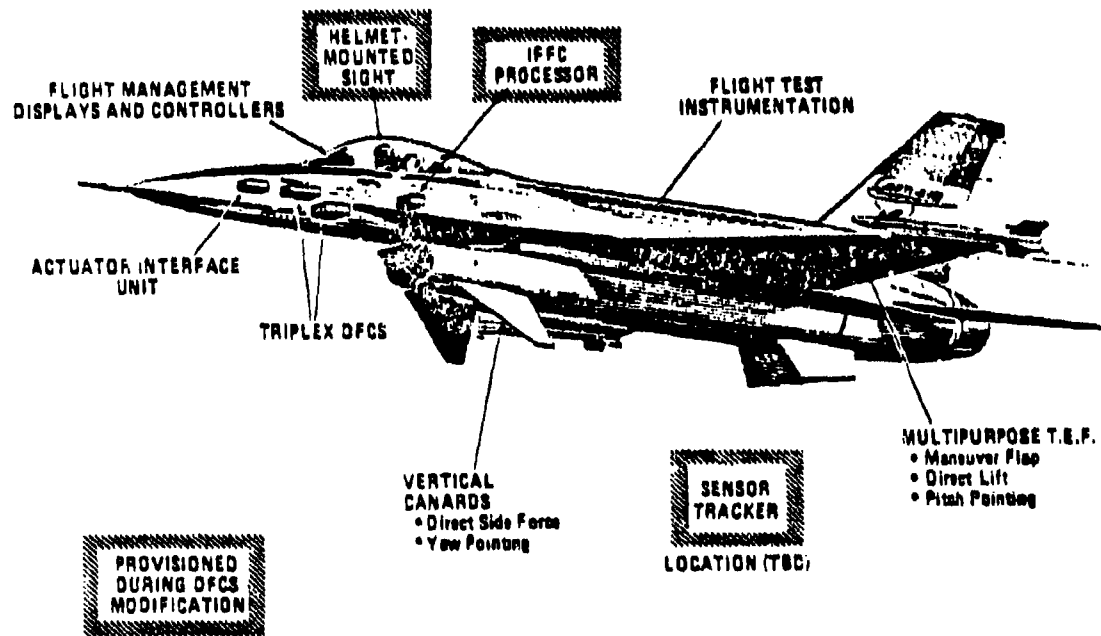
Figure 2-1    The AFTI/F-16 aircraft incorporates a number of

advance features.

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# 2. WEAPON SYSTEM CONCEPT OVERVIEW

The basic air vehicle of the AFTI/F-16 demonstrator is the Full Scale Development (FSD) F-16 single-seat aircraft. This aircraft has undergone Class II modifications to accomplish the changes required by the AFTI/F-16 contract. These changes primarily involve electronics and controls, although significant structural revision was necessary for installation of auxiliary flight control surfaces, CHIN, canards, and dorsal fairing for avionic equipment. A list of equipment and systems to be installed on the AFTI/F-16, Figure 2-1, aircraft is presented in Table 2-1.

## 2.1 COCKPIT CONTROL CRITERIA

The AFTI/F-16 control configuration is defined by the AFTI studies, a review of the F-16 control system, and the AFTI/F-16 peculiar requirements. A one-button mode selection of all systems was a primary requirement while providing the pilot the information and choices appropriate for the selected mode of operation.

The AFTI/F-16 control criteria incorporates the following features:

1. One-button (mission-phase switches) selection of all systems to provide the appropriate information and choices for the selected mode of operation.

   o Normal

   o Air-to-Air Guns

   o Air-to-Air Missile

   o Air-to-Surface Guns

   o Air-to-Surface

2. Compatibility with the F-16 single-switch operations

3. A means to effect control in event of failures

4. Capability to reconfigure text overlay and video underlay

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## Table 2-1  AFTI/F-16 EQUIPMENT AND SYSTEMS

### DIGITAL FLIGHT CONTROL SYSTEM PHASE

1. DUAL MPDs

   a. Radar
   b. Threat Warning
   c. SMS
   d. FCS Control
   e. Weapon Video

2. HUD (WIDE FOV)

3. RADAR

4. RADAR WARNING SYSTEM

5. BASIC FLIGHT INSTRUMENTS

6. INERTIAL NAVIGATION UNIT

7. FIRE CONTROL COMPUTER

   - Direct
   - Dive Toss
   - Continuously Computed Impact Point
   - Lead Computing Optical Site
   - Snapshoot
   - Missiles

8. 20 MM GUN

9. AIM - 9

10. ECM POD (as required)

11. VOICE COMMAND

### AUTOMATED MANEUVERING ATTACK SYSTEM

All DFCS Systems

   Plus

1. Helmet-Mounted Sight

2. Sensor/Tracker (FLIR)

3. IFFC - Air-to-Air Guns

        - Air-to-Surface Guns

        - Air-to-Surface Bombs

5. Control of sensors at the display

6. Declutter of display presentations

7. Capability for data-entry

8. Consistent operation in all modes.

This philosophy accommodates flight control and control of weapons, avionics, and sensors. Implementation of this philosophy makes use of the mission-phase switches and the MPD displays.

## 2.2 MULTIPURPOSE DISPLAYS

There are two Multipurpose Displays (MPD), Figure 2.2-1, in the AFTI/F-16 cockpit. Each MPD consists of a CRT surrounded by twenty switches; option select switches (OSS). On each CRT any combination alphanumeric characters, moveable symbology, and external video can be displayed. Alphanumeric characters can be displayed in a 30-column by 20-row matrix. The alphanumeric characters consist of two types, normal or highlighted. The moveable symbology set consists of symbols such as steering bars, cursors, a horizon line, etc. The external video options consist of radar, FLIR, sensor/tracker, threat warning, and weapon displays.

### 2.2.1 Interactive MPD Control Operation

The twenty switches on the face of the MPD allow interactive operation. The function of each switch is determined by an alphnumeric label displayed on the CRT adjacent to the switch. The alphanumeric labels may vary depending on the display being presented.

There are three levels of system options selectable on the MPD (Figure 2.2-1). Level 1 system options appear at the bottom of the MPD. The following system options are available:

o FCR - Radar

o SMS - Stores Management Set

o FCS - Flight Control Systems

o EOP - Electro-Optical Pod (Sensor/Tracker)

o TW - Threat Warning System

o WPN - Electro-Optical Weapon (selectable when an EO weapon is loaded)

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# AFTI/F-16 COCKPIT ARRANGEMENT



Figure 22-1

1-4

MASTER PAGES

LEVEL 2 OPTIONS

LEVEL 3 OPTIONS



LEVEL 1 OPTIONS
SYSTEM ACCESS
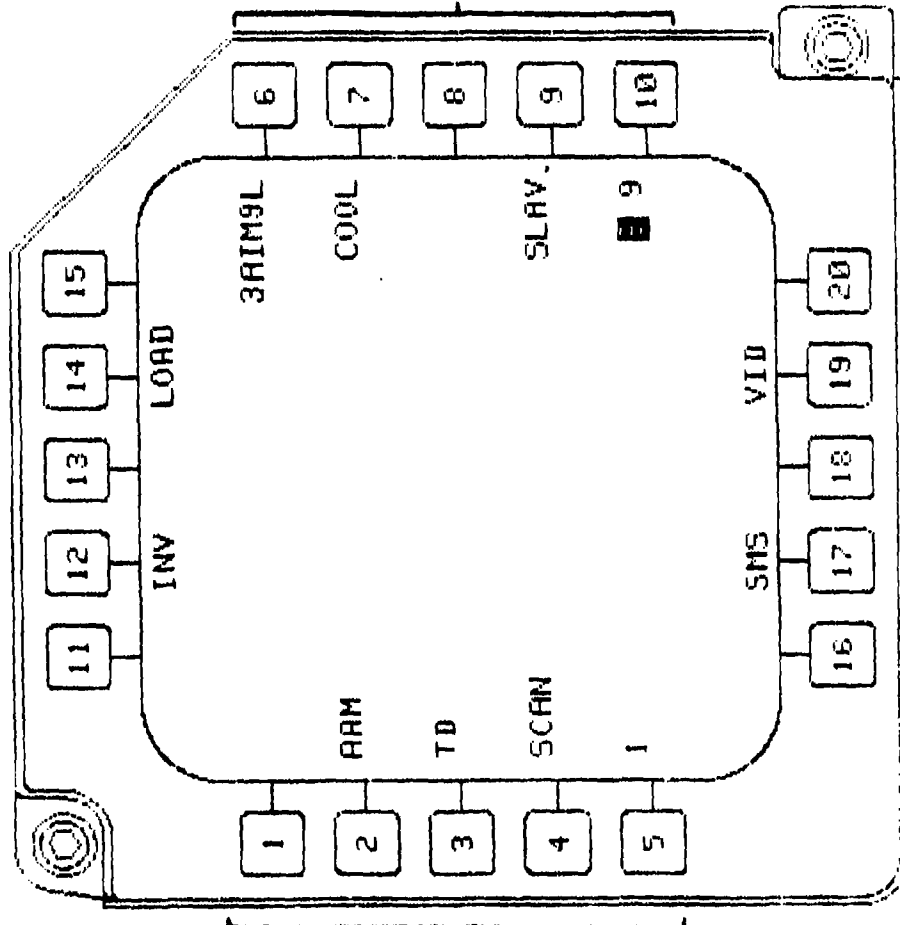
LEVEL 3 OPTIONS
SYSTEM
OPTIONS

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When one of these system options is selected, Level 2 options are automatically displayed at the top of the MPD. The Level 2 options provide control of the system operation display modes (Level 3 options). Level 3 options appear along sides of the MPDS.

In addition to the Level 1 through 3 options, a keyboard display may appear on MPDs, Figure 2.2-2. The keyboard display is used to enter data for the Level 3 options.

## 2.2.2  Display Techniques

Various techniques are used to indicate special conditions, available options, selected options, or to provide feedback. These techniques consist of the following:

o  Flash - Whenever an option select switch (OSS is depressed, a momentary flash appears by the switch whether a label is displayed or not. This provides feedback that the switch action was sensed.

o  Rotary - A rotary is a series of options associated with an OSS. Successive depressions of the OSS will step through the series of options. When the last option of the series is displayed, the next OSS activation will call the first option.

o  Menu - A menu is a list of selections that appear when there are too many selections to make a rotary usable. The selected option will appear highlighted along with the other options. To select an option, the pilot should depress the OSS adjacent to desired selection.

o  X - X's appear as place holders in the appropriate location when numeric data is selectable.

o  Highlight - Highlighting is used to indicate the option or system currently selected. It is also used in the keyboard display to indicate the location of the datum to be entered.

## 2.2.3  Display Mechanization

The two alternative display mechanizations that were evaluated are described below.

Mechanization A.  An initial text and video selection for each display results whenever a mission-phase switch is selected.  The Level 1 options allow independent selection of text and video.  The test OSS (option select switch) is a 2- or 3-position rotary and the video OSS is a 4-position rotary.  The four video switch positions are VID (video), FCR (fire control radar), EOP (electro-optical pod), and TW (threat warning).  The text rotary positions are FCS (flight control system) and SMS (stores management set) when VID overlay is selected and FCS, SMS, and SEN (sensor) when VID is not selected.  Whenever the VID (video) selection switch is depressed, the text rotary is positioned to SEN.

The keyboard display appears when an OSS next to selectable data is depressed.  The current data is then displayed in a central window along with the data label.  Upon successful entry of new data, the keyboard display is automatically replaced by the parent display incorporating the new data.

Mechanization B.  An initial primary and secondary Level 1 selection for each display results whenever a mission-phase switch is selected.  The initial selections may be reprogrammed by the pilot, if desired.  The Level 1 options are selected from a menu that appears when the OSS is depressed for the currently displayed (highlighted) option.  The menu selection allows only paired text and video selections (e.g., radar text with radar video).  Selection of a secondary Level 1 option reconfigures the display to that presentation.  An alternate means to reconfigure the display is the display option switch (DOS) on the side-stick controller.  Successive actuation of the DOS changes the presentation between the primary and secondary Level 1 options.

The keyboard display appears when an OSS next to selectable data is depressed.  The current data is then displayed in a central window along with the data label.  Upon successful entry of new data and depression of the ENTER button, the keyboard display is replaced by the parent display, incorporating the new data.

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# 3. METHODOLOGY

The procedures employed in the AFTI/F-16 multipurpose display evaluation were designed to extract the maximum amount of relevant data concerning

1. Selection of options from a menu.

2. Selection of options from a rotary.

3. Mixing nonrelated text and video.

4. Sequential selection between two sets of paired text and video.

5. Speed of display reconfiguration.

6. Preselection of displays and display options by mission phase.

7. Manual and automatic data entry from a keyboard.

8. Individual display formats.

## 3.1 PROCEDURES

The following section contains the specific procedures and experimental design used for this evaluation. A total of six F-16 qualified pilots served as subjects in this experiment. In addition to their F-16 experience, the pilots had participated in previous AFTI/F-16 simulation evaluations.

### 3.1.1 Training

After a preflight briefing, the pilot received hands-on training with the display mechanization, MPD formats, and mission specific procedures. The pilot then flew a mission profile representative of the one used for data collection. When the flying task was mastered, the display task was combined with the flying task and was continued until proficiency was reached. The two flying tasks are described below:

o  Scenario 1 - Daytime VFR Fighter Sweep at Medium to
   High Altitude
   The pilot completed the tasks on a preflight checklist.
   The pilot maintained a tactical spread formation line
   abreast of lead and about 700 feet out.  Flight leader
   was at 20,000 feet and 500 kts.  Lead detected a long-
   range target which may be hostile.  Pilot adjusted his
   radar range as the target closed, turned his AIM-9L's
   to COOL, and began to search for FLIR acquisition in
   hope of positive ID.  After adjusting FLIR controls, he
   noticed a Master Caution list and associated FLCC
   warning light.  Pilot checked the flight control fault
   page, acknowledged the fault, and continued with FLIR
   search.  The Missile Launch light illuminated and the
   pilot called up his threat warning display.

o  Scenario 2 - Low-Altitude Night Attack Mission
   The pilot completed the tasks on a preflight checklist.
   The pilot navigated with the INS to steerpoints at 1,000
   feet MSL (the simulator's visual scene will be turned off)
   to simulate the night low-altitude workload.  In the
   approach, the pilot used his radar in the ground-map
   mode with moving target indicator for target acquisition.
   FLIR was used to identify radar targets and for final
   attack tracking.  Pilot detected a possible radar tar-
   get and adjusted radar range as target closed.  As the
   target closed to maximum FLIR range, the pilot began
   monitoring the FLIR for targets.  After finding a
   target the pilot switched the FLIR to B-W.  He then
   selected the WPN display to replace the radar display.
   The AGM-65 was switched to B-W.  Missile Launch light
   illuminated and the pilot called up his threat warning
   display.

## 3.1.2  Data Runs/Experimental Design

A single data run was flown for each test condition.  A thirty-
second pre-event period of baseline flying performance was recorded
before each task instruction was given.  The experimenter followed
a written script to insure that each pilot received the same in-
structions for a particular task and mission.  All the experimenter's
instructions to the pilot were given over the headset except for

those on the preflight checklist. If an error was made, the pilot was required to repeat that task or subtask. If the pilot was incapable of completing the task, the flight was terminated for additional training. The flight resumed with the task that aborted the mission.

The planned schedule for the performance of the specific tasks is presented in Table 3.1-1. The task order for pilots one through four is a balanced Latin square design. The task order for pilots five and six uses a different scheme with the display mechanization comparisons confounded with the effects of the scenario and time. This construction allowed conclusions to be drawn about the display mechanizations, scenarios, and the ability of pre-test training to null the carry-over effects.

### 3.1.3  Post-Flight Briefing

A questionnaire designed for the test period was completed by the pilot at the end of each flight. A general questionnaire was administered following the completion of all data flights. A meeting was convened in the Simulator Operations Room after the pilot completed the general questionnaire. The purpose of this meeting was to discuss the conclusions reached by the pilot during the simulation.

TABLE 3.1-1

SPECIFIC TASK SCHEDULE

| | | | | |
|---|---|---|---|---|
| Pilot 1 | A-1 | A-2 | B-1 | B-2 |
| Pilot 2 | A-2 | A-1 | B-2 | B-1 |
| Pilot 3 | B-1 | B-2 | A-1 | A-2 |
| Pilot 4 | B-2 | B-1 | A-2 | A-1 |
| Pilot 5 | A-1 | B-1 | A-2 | B-2 |
| Pilot 6 | B-2 | A-2 | B-1 | A-1 |

Note: The letter designates the Display Mechanization and the number designates the scenario (e.g. A-1, Display Mechanization A and Scenario 1)

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# 4.    R E S U L T S

The data taken from the experiment were divided into three areas of analysis.  The video tapes were used to determine the times required to do each part-task.  The results of this analysis is presented in Table 4-1.  The strip charts permitted calculation of the number of excursions from predetermined criteria, Table 4-2.  The results of this analysis are presented in Table 4-3. The qualitative data, questionnaires, and debriefing notes were analyzed collectively.

The times and deviations of times in the part-tasks across pilots was statistically analyzed by use of a two-way analysis of variance, in which the null hypothesis, Mechanization A equals Mechanization B, was tested.

The number of excursions outside the fixed boundary set was first normalized across pilots by acquiring the percentage of time each pilot was within the boundary set.  These results were then statistically analyzed by use of chi-square (two-tailed) analysis, in which the null hypothesis, Mechanization A equals Mechanization B, was tested.

In each of these two statistical analyses, the test was shown to be inconclusive.  We believe this was due in part to two factors. The first being the small sample size of our subjects (5), and therefore, the small number of degrees of freedom in the statistical analysis.  The small number of pilots did not allow the intersubject variability, which in our case was very large due to the difference in background (NASA, AFFTC, and NAVY pilots) and experience, to wash out.  The second reason for inconclusive quantitative results was the small amount of time (15 seconds) allowed each subject between each part-task. A close analysis of the data showed that after each part-task there were substantial amounts of carry-over effects, and by not allowing enough time between part-tasks, these effects in-terfered with the next part-task in both the flying and task performance parameters.  This carry-over effect was only ob-served in the part-task that involved multiple pilot actions.

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Table 4-1   AVERAGE TASK TIMES (in seconds)

| Tasks | Mechanization A | | Mechanization B | |
|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| 1. Preflight Checklist | 78 | 94 | 222 | 229 |
| 2. CCV engagement and verification | 15 | 18 | 26 | 19 |
| 3. Keyboard Entry (Impact Separation/Roll Rate selection) | 21 | 33 | 16 | 17 |
| 4. Radar - EO Display Selection | 54 | 49 | 45 | 45 |
| 5. Threat Warning Display Selection | 5 | 8 | 6 | 3 |

Table 4-2   CRITERION FOR EACH SCENARIO

|  | Criteria |
|---|---|
| **Scenario #1** | |
| Airspeed (from 500 kts) | $\pm$ 10 kts |
| Heading (from 360$^o$) | $\pm$ 5 Deg |
| Altitude (from lead aircraft) | $\pm$ 100 ft |
| **Scenario #2** | |
| Airspeed (from 500 kts) | $\pm$ 20 kts |
| Altitude (from 1000 feet) | $\pm$ 200 ft |
| Ground Track (from 0$^o$ long) | $\pm$ 2 k-ft |

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Table 4-3    TOTAL NUMBER OF TIMES EACH PILOT EXCEED CRITERIA

| Scenario 1 | Mech A | Mech B |
|---|---|---|
| Pilot 1 | 14 | 11 |
| Pilot 2 | 14 | 8 |
| Pilot 3 | 4 | 2 |
| Pilot 4 | 5 | 12 |
| Pilot 5 | 7 | 16 |
| Pilot 6 | 19 | 19 |

| Scenario 2 | | |
|---|---|---|
| Pilot 1 | 12 | 14 |
| Pilot 2 | 6 | 1 |
| Pilot 3 | 0 | 0 |
| Pilot 4 | 5 | 12 |
| Pilot 5 | 1 | 1 |
| Pilot 6 | 12 | 14 |

# 5. CONCLUSIONS

Due to the inconclusive results of the quantitative data, conclusions were drawin on the basis of the qualitative results. The following conclusions were derived from both the questionnaires and each of the pilot debriefings.

1. Menu selection was preferred over rotary selection because all options are displayed at once. A rotary was judged useful when the number of options was limited to three or less.

2. Sequential selection between primary and secondary text and video displays is preferable to mixing unrelated text and video displays. This was concluded because an unrelated text display may mask or clutter a video display and sensor control may be lost during this time. It may be possible to mix an unrelated text display with a video display if sensor control is present.

3. When access to more than two video presentations on two MPDs is desired, Mechanization B was preferred. This conclusion would have to be reconsidered pending the addition of different types of video displays (i.e., terrain following).

4. Preselection of displays and display options by mission phase was desired. This was due to the reduction of pilot workload during high-stress periods. The procedure for preselection of displays (primary and secondary options were selected separately) was confusing and should be redesigned. The preflight task times for Mechanization B appear to support this conclusion.

5. The consensus was that manual entry using a keyboard display was preferred to automatic entry due to verification of the final digit to be entered; however, automatic entry in a high-stress situation was considered to have merit.

6. The display option switch (DOS) on the side-stick controller was considered very desirable due to its hands-on-the-controls capability. There was some concern with the DOS in that the switch operation was not intuitively obvious.

7. Display of the CCV (decoupled) engagement status by changing the schedules in the FCS base page windows was not easily interpreted and was determined to be inadequate.

8. Preselection of the FCS decoupled options and authorities was identified as needing improvement.

9. Pilot performance and comments during training indicated that the nomenclature used to describe the aircraft's capabilities needs to be standardized across all systems. The most confusion existed when AAM and NAV mission phases were selected.

> When the AAM mission-phase switch is depressed, the flight control system does not have a specified AAM mode so, therefore, AAG mode is shown.

> When the NAV mission phase switch is depressed the flight control system does not have a NAV mode but uses NORM, and the SMS uses STBY.

The conclusions from this experiment were reviewed, and it was decided that Mechanization B with alterations should be used. The alterations included making use of manual entry for all keyboard tasks. A menu selection will be used at all times except when the options available are three or less; then a rotary selection will be used. Another capability added to this mechanization was the use of a "swap" feature. This is a Level 1 option that when depressed on one MPD would replace both the primary and secondary Level 1 options from that MPD with the primary and secondary options from the other MPD. This effectively gives access through one MPD, four Level 1 options with one button selection.

Even with a superior MPD mechanization, effective control of the avionics also places demands upon the single-seat fighter pilot's hands and eyes. In the AFTI/F-16 program an attempt is being made to alleviate the situation by the use of a voice command system as an alternate method of achieving ntrol interaction between the pilot and the weapon system.

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To validate this concept, three fundamental questions are addressed: (1) Is the use of voice command a viable alternative to the more traditional methods? (2) Assuming that voice command is viable, which functions best lend themselves to this approach and offer the highest payoff in terms of overall weapon system performance? (3) Can the voice recognition technology base be extended sufficiently to provide reliable operation in the stringent combat aircraft environment? These questions are now being systematically answered through laboratory testing, man-in-the-loop simulation testing, and ultimately flight testing. For phase one (DFCS) flight testing, the voice control system is mechanized to provide complete voice command control of the MPDs by assigning a voice command word for each switch on the MPD. This allows control of the SMS, FCS, and video selection. The four mission-phase buttons will also be mechanized with the voice control system.

In recent years, advancements in technology have made it possible to perform more functions in an ever decreasing cockpit space. Increases in system complexity have created a high-workload situation for the single-seat multi-role fighter pilot. With the use of an advanced MPD mechanization, (four system displays within one-button selection), mission-phase buttons that can be task tailored to each individual pilot and situation, and a fully integrated voice-control system that compliments the previous two mechanizations, the AFTI/F-16 pilots will have an environment of decreased workload and a greater situation awareness.

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# AIRBORNE ELECTRONIC COLOUR DISPLAYS

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## INTRODUCTION

Monochrome electronic displays already form an essential part of the equipment installation of many types of military aircraft. Colour weather radar displays are now widely available for commercial use, and flight and systems information displays using colour cathode ray tubes (CRTs) are under development for several new transport aircraft. It is probable that displays of this type will form the basis of both military and civil airborne displays systems.

Although much effort is being devoted to the development of various types of flat-panel displays, primarily for use in domestic television receivers, it is likely to be many years before any such display device is developed to a stage where it can compete with the colour CRT in brightness, contrast, resolution, colour capability, and ease of addressing. Consequently, this paper will be confined to a discussion of CRT displays, although it is likely that for certain limited applications, where only alpha-numeric characters have to be displayed, matrix displays may come into use, particularly if there is no requirement for colour.

Until recently, CRTs capable of meeting the environmental requirements for airborne display devices were only able to produce monochrome displays, or by the use of the penetration phosphor technique, a limited range of colour. In the case of monochrome tubes a number of methods of generating displays have been used, from the various types of raster used for radar to the cursive (or stroke-written) generation used for head-up displays (HUDs). The former gave a display which was frequently too dim to see in bright daylight conditions without the use of a mask to exclude ambient light. The use of cursive generation enables very bright displays to be produced; these are obviously necessary for HUD applications, to ensure that the display can be seen against bright outside world backgrounds. Penetration tubes have generally used cursive generation, in the interests of minimising EHT switching complexity and of producing the brightest possible display; the maximum brightness which can be produced by this type of CRT is generally less than that obtainable with a monochrome tube.

During the last few years rapid developments in CRT technology have occurred, and these have led to the development of high brightness mono-chrome tubes capable of meeting military environmental requirements fully. Rugged shadow mask tubes have also been developed which are robust enough to meet at least the requirements for transport aircraft, and are likely to prove capable of use in combat aircraft; such tubes provide a full range of colour.

Although the possibility of using monochrome CRTs for flight information displays has been discussed for many years in the context of transport aircraft operations, and much experimental work has been done in this area, the advent of colour displays has brought about a rapid swing in pilot opinion to the view that a full colour capability is essential when CRT displays are proposed as a replacement for conventional instruments. Among pilots who have become thoroughly familiar with what the new technology can offer, the view is already being expressed that, except in the standby role, conventional flight and navigation instruments are obsolescent, as far as large transport aircraft are concerned.

## CURRENT ELECTRONIC COLOUR DISPLAY ACTIVITIES

Three types of commercial transport aircraft being built at present will go into service in the next few years with a significant amount of flight, navigation, systems, and warning information provided by colour CRT displays. There are two main reasons for the move away from conventional instruments; firstly, the cost of procuring and maintaining electronic equipment is decreasing relative to that involved in the case of complex electro-mechanical devices, because of the high level of labour with specialised skills which these require; secondly, the use of electronic displays for navigational information makes it possible to provide the crew with moving map displays on which can be superimposed the weather radar information, and this has operational advantages as well as possibly obviating the need for a dedicated weather radar display.

The electronic displays now being used for flight and navigational information form substitutes for the conventional attitude director indicators (ADIs) and horizontal situation indicators (HSIs); air data and other flight information are being displayed conventionally.  The sizes adopted for the electronic ADI (EADI) and HSI (EHSI) are such that the conventional lay-out of the transport aircraft panel (with the ADI situated above the HSI) can be retained.  Figure 1 shows the layout of a typical panel using this configuration.

It is interesting to note that in one of the current aircraft programmes, the primary display of airspeed and Mach number has already found its way into the EADI, because of the various advantages offered by the flexibility of the CRT.  In this aircraft, a conventional airspeed indicator is retained in its usual position in the panel, but is used only as a standby instrument.

In the areas of systems and warning information the current aircraft projects use CRT display in slightly differing ways, but in general, one display is used in conjunction with a number of conventional indicators, to present the information required for control and monitoring of engines and aircraft systems such as electrical supply, hydraulics, pressurisation, etc. whilst the other CRT displays cautions and alerting messages.  This second electronic display is backed up by conventional warning lights and audio signals.

It is clear that these display systems still use conventional instrumentation for a considerable proportion of the total information, and considering the problems in gaining certification and pilot acceptance which might have arisen if an attempt had been made to proceed directly to a full electronic display system, it is not surprising that developments have occurred in this way.

However, on an experimental basis, work started nearly ten years ago on a programme aimed at investigating the feasibility and desirability of replacing virtually all the conventional instruments on the flight deck of a transport aircraft with CRT displays, retaining only the instruments required for standby purposes.  This work was carried out at the British Aerospace plant at Weybridge, England, and led to the construction of a flight deck simulator[2] which was equipped with seven monochrome CRTs, providing raster-generated displays.  Of these, two displays in front of each pilot provided primary flight and navigational information, and three units in the centre panel supplied engine, systems, and warning information.  Because of the size of the displays (approximately

8 in x 6 in) it was necessary to install the primary flight display
(PFD - attitude, air data and heading scale) and navigation display
(ND - compass display or electronic map and radar) side-by-side, instead
of in the conventional positions with the PFD above the ND. Pilot
acceptance of this configuration, with its consequent modification to
the normal scan pattern, was one of the aspects of the display system
subjected to a particularly close scrutiny during the trials in the
simulator.

As a result of providing a full range of CRT displays, with their inherent
flexibility of information content, it proved possible to configure the
simulated flight deck so that all controls and displays were within the
reach of the two pilots, and the Flight Engineer's station was eliminated.
The resulting workload on the pilots was another subject of close scrutiny.

The result of extensive trials in the simulator was that there was general
agreement that the basic concept of this type of display system and flight
deck lay-out was sound (though it was generally felt that only two systems
displays (SDs) were required), that the side-by-side positioning of the
PFD and ND posed no particular problems to the pilots, and that the
technical feasibility of operating a large transport aircraft with a
two-man crew was established.

The next stage of the development of the Advanced Flight Deck was to confirm
the results of the simulator experiments with flight trials, and it was
agreed that a BAe 1-11 aircraft operated by the United Kingdom Ministry
of Defence at the Royal Aircraft Establishment, Bedford, England, should
be used for this purpose. It was originally proposed that the displays
should be raster-generated on monochrome CRTs, giving close similarity with
those used in the simulator, but during the early stages of the development
of the flight trials hardware, rugged shadow-mask colour CRTs became
available, and it was decided that the final installation must incorporate
tubes of that type. The monochrome displays were completed, and used
for checking out the aircraft installation and for initial flying, but the
system was designed so that display units could be changed, and so that
minimum modifications to symbol generators would be necessary, as soon
as colour display hardware was available.

Consideration of the possibility of reducing the number of CRTs in a
complete system to six (two PFDs, two NDs, and two SDs) led to the
proposal for a panel lay-out of the form shown in Figure 2, enabling the
display unit size to be increased to 8 in x 8 in. For the first stage
of the flight trials programme, only the PFD and ND at the Captain's
position are installed, the existing instrumentation being retained at
the First Officer's position and in the centre panel.

Figure 3 shows a block diagram of the experimental installation in the
BAE 1-11. Being a relatively old aircraft, it is equipped with a very
varied collection of sensors which supply data in a wide variety of
formats, and a separate interface unit has been provided, to accept all
the sensor signals and convert them to the serial digital format
(ARINC 429) required for the input to the symbol generators; this unit
would not be required in a modern aircraft, in which the interfacing would
be accommodated within the symbol generators. One symbol generator drives
the PFD and the other drives the ND, but each symbol generator has the
ability to drive both displays, if necessary, and the full display
capability is retained even if one generator fails.

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An external core-store and a paper tape reader are provided so that changes in display formats can be made during the flight trials, without removing the equipment from the aircraft. Interfacing with a general purpose computer in the aircraft is provided to enable the display system to be used in conjunction with an area navigation system being used in concurrent flight trials.

Operation of the aircraft with monochrome display units started in 1980, and the colour displays will be in use in the Summer of 1981.

## DISPLAY SYSTEM CONFIGURATION

An advanced flight deck display system can be configured in a number of different ways, depending on the performance capability of the individual units of the system and on the scale of redundancy required. A typical architecture for the flight and navigation information subsystem in a transport aircraft is shown in Figure 4. This is based on Symbol Generator Units (SGUs) capable of accepting multiple data inputs from the aircraft sensors and able to generate two separate display formats (PFD and ND) simultaneously. The display units are each capable of accepting inputs from either of two SGUs. Discrete signals from the pilots' control panels (P1 CP and P2 CP) select the data source to be used by each SGU, and the SGU to provide the display data for each display unit.

This system configuration provides maintenance of full display facilities after the failure of a SGU or of a data source, and leaves each pilot with access to all display data, by time sharing, after a CRT failure.

Figure 5 shows a possible configuration for the systems and warning displays, in which each SGU normally drives one display unit but is capable of driving both in the event of failure of the other SGU. The arrangement of the inputs to the SGUs depends very much on the particular form of warning system adopted for the aircraft, but is likely to involve warning computers which provide outputs to both SGUs. Engine and systems information is likely to come via data converters which change the large number of separate sensor signals to a common serial digital data format.

It is clear that the systems configurations depicted in Figures 4 and 5 are only appropriate to aircraft with twin, near-identical display systems, such as are normally used in transport aircraft. In a military combat aircraft, similar display system integrity would be achieved by the provision of multiple symbol generators, and by the facility to transfer data from one display to another in the event of failure of a CRT or its associated circuits.

## UNITS OF ELECTRONIC DISPLAY SYSTEM

### General

Display system hardware currently being proposed for military transport aircraft applications is generally designed to conform to the civil requirements defined by ARINC Characteristic 725. This lays down interface and equipment form-factor requirements based on the current state-of-the-art, and it may require amendment in the light of future developments. At present, it leads to a useful degree of standardisation of equipment without inhibiting developments required for specifically military applications.

## Display Unit

For the flight trials in the BAe 1-11 aircraft described above, display
units designated Form Factor 'D' in ARINC 725 are used.  These units
have overall dimensions of 8 in x 8 in x 14 in, and incorporate a CRT
which provides an active display area of 6.5 in x 6.5 in.  For installations
requiring smaller display units, other sizes, such as ARINC Form Factor 'C'
6.25 in x 6.25 in x 14 in, giving an active display area of 5 in x 5 in
are available.

The rugged shadow-mask tube used in these display units typically have
a resolution of approximately 76 colour triads per inch (about three
times the resolution of the tube in a domestic television receiver), each
colour dot being approximately 0.004 inch in diameter.  The interstices
of the screen are normally matt black, giving a low reflectivity to
ambient light, and therefore improving the contrast of the display.  Further
contrast enhancement may be provided by an externally-mounted filter.  Both
delta and in-line electron gun configurations have been used for these CRTs;
the in-line arrangement is generally accepted as enabling simpler methods
of convergence correction to be used, and giving better spot definition.

Figure 6 shows a block diagram of a typical display unit.  It has provision
for dual deflection, video and chrominance inputs, to allow for connection
to two separate SGUs, and selection between the two is by means of a
discrete from the PCP.  The deflection signals are shaped to provide the
necessary screen geometry correction, and are fed to the deflection
amplifiers.  When operating in raster mode (for radar display, for example)
an energy recovery circuit is switched into operation, providing fast fly-
back for the appropriate deflection signal with minimum power penalty.
Convergence correction is derived from the deflection signals via a matrix,
and operates on the convergence yoke of the CRT.  Writing speeds of
approximately 0.04 in/microsecond in stroke writing and 0.12 in/microsecond
in raster, are achieved.

Video and chrominance signals are fed to a microprocessor, together with
inputs from a display brightness control on the PCP and from ambient light
sensors fitted on the front of the display unit case.  The microprocessor
controls the operation of colour selection and video drive circuits.  A
phosphor protection system is provided, which blanks the display in the
event of faults such as failure of the deflection system, which would
otherwise be likely to result in burning of the screen.

All  the power supplies required in the display unit are derived from the
aircraft 115 V 400 Hz single phase supply.  The power dissipation is
typically in the region of 100 W, and provision is made for cooling by
means of air which is arranged to circulate round the CRT neck components
and the electronic circuit blocks grouped in that region.

## Symbol Generator Unit

Figure 7 shows a block diagram of a typical SGU.  For the civil market,
such a unit is contained in  a 6 MCU case as defined by ARINC 600, with
overall dimensions 7.5 in wide x 7.64 in high x 12.5 in long.  It has
provision for forced cooling, and dissipates approximately 110 W.  The
mass of the unit is less than 10 kg.  Alternative modes of packaging the
unit could be developed to meet the particular installation requirements
of combat aircraft.

Provision is made for dual inputs of data in each of three formats - serial digital (ARINC 429), discrete signals, and high speed digital data from weather radar equipment. Selection between the dual inputs is made by means of discrete signals from the PCP. The digital inputs are decoded and checked for transmission integrity and are then loaded into a buffer store; the processor extracts the information from the store and manipulates it into a form suitable to drive the vector generator. Deflection and bright-up signals, together with colour descriptions for the symbols in the cursive part of the displays, are produced by the vector generator, which also generates the outline of the sky/ground shading of the PFD and writes it into the flight display video memory.

The selected weather radar input is decoded and passed to a processor, where it is converted from the polar co-ordinate form in which it is transmitted to the cartesian form in which it is displayed, and is also scaled and combined with aircraft heading and groundspeed data, and stored in the navigation display video memory.

The digital outputs from the vector generator and the two video memories are time multiplexed to produce the flight and navigation displays. Two buffered outputs of each display format are provided, so that it is possible to drive four display units (in two pairs) from a single SGU.

The cursive symbology in the displays is refreshed at 80 Hz, and the 2 : 1 interlaced raster used for the sky/ground shading in the PFD and weather radar overlay in the ND is refreshed at 40/80 Hz. Cursive symbology can be called up in any one of fifteen colours, and raster areas of the displays in seven colours.

## Pilots' Control Panels

The form of control panel used in an electronic display system depends upon the particular system configuration which is used, but certain functions are necessary for all types of system. These include controls for overall display brightness, brightness balance between cursive and raster parts of display, map/compass rose, map scale and radar range, radar on/off, decision height selector, and test mode.

## DISPLAY FORMATS

### General

Much ground-based work to establish optimum display formats for transport aircraft operations has already been carried out in a variety of simulators, but there exists a relatively small amount of experience in the use of colour CRT displays actually in flight. It is to be expected that as flight experience builds up, some modifications to display content and to the shape and colour of symbols may be required. It is at the same time the great advantage of an electronic display system (to the operator) and the great disadvantage (to the hard-pressed engineer) that such changes can be effected late in the development of a system without disastrous costs for re-design and re-installation of hardware.

The total amount of information in each display clearly depends on the area available, and as has already been stated, the relatively small display shortly going into service in commercial aircraft have to be supported by a significant number of conventional instruments, whereas the large displays being evaluated in the BAe 1-11 aircraft require only a small number of stand-by instruments.

### Primary Flight Display

The format used in the 8 in x 8 in display in the BAe 1-11 is shown in Figure 8. This shows how the basic T-configuration familiar to all

transport aircraft pilots is provided, although the full navigation display
is located at the side of the PFD rather than below it.  The forms of the
individual parts of the display have deliberately been made to resemble
those of conventional instruments, to minimise the familiarisation period
for pilots transferring to the new display system.  At the same time, a
number of features are provided which are only possible because of the
flexibility of the CRT display.  These include a full  range, single scale,
single pointer airspeed indicator, with a sensitivity of 100 kt per revolution
of the pointer, limit speed data which are only in view during the appropriate
phase of the flight, and specific indication as to whether the datum setting
for the altimeter is QFE, QNH, or standard.

Colour is used, in addition to position and pattern, to differentiate
between the various types of information in the display.  Thus, at the
present state of development, white is used for elements indicating the
present performance of the aircraft (speed, height, etc), magenta is used
to indicate selections made by the pilot (selected speed, height, heading, etc),
green is used for fixed scales, and red for warning information.  Pictorial
parts of the display are presented in traditional colours; for example,
an amber aircraft symbol is used in the attitude display, together with
blue 'sky' and brown 'earth'.

Full information is given on the state of engagement of the autopilot/
flight director and auto-throttle systems, showing both armed and engaged
modes.   In  the case of an aircraft equipped for automatic landing,
the landing phase indicator would also be incorporated in the PFD.

Smaller sizes of display are generally similar, though with a restricted
information  content.   Figure 9 shows a typical 6 in x 5.5 in PFD.

## Navigation Display

Figure 10 shows the BAe 1-11 ND in the map mode.   The same conventions have
been adopted for the use of colour as in the PFD.   The weather radar return
can be overlaid on the map, giving an immediate indication of the position
of storm activity relative to the planned flight path.  The scale of the
map and the range setting of the radar are selected by a single control
on the PCP to ensure compatibility at all times.   In the electronic
display systems currently under development, the storage and processing
of the data required for the construction  of  the map display is carried
out in the flight management system rather than in the display system.

Full details of the operation of the radio/navigation system are given
in alpha-numeric form at the sides of the ND.   These include selected
frequencies, waypoint data, and time and groundspeed information.

In the compass rose mode, selected on the PCP, the centre part of the ND
provides heading and radio/navigational information in the same format
as in a conventional HSI.

## Systems Displays

Since the experimental display system installed in the BAe 1-11 aircraft
at present includes only the PFD and ND in the Captain's panel, less
detailed work has been carried out in the systems display area than in
the case of the other displays.   However, preliminary studies have

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generated various display formats, of which Figure 11 shows an example.
This is a display of primary engine information for a 2-engine aircraft, to
together with performance monitoring data for main aircraft systems.

It is perhaps in the systems area that the flexibility of the CRT display
becomes most useful, since it enables detailed information on the state
of any of the aircraft systems to be displayed on demand.   It is also
possible for the appropriate format to be displayed automatically in
the event of a malfunction, so that corrective action can be initiated
with minimum delay.

Caution and warning information (which will be displayed on  the second
Systems Display' is processed so that in the event of multiple warnings
(such as would occur in the event of an engine failure) the appropriate
priority order for corrective actions can be indicated in the display.

## HUMAN FACTORS

When CRTs were first considered as a possible means of displaying flight
information to pilots, doubts were expressed as to their acceptability
from the human factors point of view.   Although flight experience with
these displays is limited, there are no indications that any serious
problem exists.   Various studies of human factors aspects of airborne CRT
displays, have been made [3,4], and these have provided ground rules for
the design of the equipment for evaluation in the BAe 1-11 aircraft.

The rate at which a CRT display is refreshed must be considered carefully,
in order to avoid perceptible flicker, which is likely to be most apparent
in display units viewed peripherally.   The actual refresh rate that is
acceptable depends on the particular phosphors used in the CRT screen;
short persistence phosphors require a higher refresh rate than long
persistence types, to avoid flicker.   In the case of phosphors of the P22
type commonly used in colour CRTs for airborne displays, a 50 Hz refresh
rate is satisfactory for most observers, and the 80 Hz rate commonly used
provides a wide safety margin.   The higher frequency also reduces the
noticeability of the jump effect (which is in any case not perceived by
all observers); this is manifested as an apparent movement of the display
when the observer's point of fixation scans across it, and is due to the
interaction between the moving fixation point and the refresh pattern of
the display.   The effect is not peculiar to colour CRTs, and may be detected
by some observers in any periodically refreshed display.

It is frequently suggested that the use of a large number of CRT displays
in the flight deck may cause additional crew-fatigue problems; a number of
lengthy operations carried out in  the BAe simulator failed to produce
any evidence of this.

Much work has been carried out on the use of colour in CRT and other displays
and many of the associated perceptual problems have been studied in some
detail [5].   Typical of these is the apparent change in the perceived colour
of a display element with changing display luminance, ambient conditions,
and state of adaptation of the observer.   It will be impossible to say with
certainty that the solutions found to these problems are fully satisfactory
until equipment of this type has been in service for an appreciable period
of time.   One of the functions of the micro-processor in the display unit,

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described earlier, is to adjust the colour content of the display in such a way that the subjective brightness and colour contrast between different elements of the display remains balanced over the whole luminance range of the display.

Any light emitting display must have its brightness varied when the ambient illumination changes, if uniform display contrast is to be maintained, and in the case of airborne CRT displays this is done by an automatic system controlled by signals from sensors mounted on the front of the display units. In addition, to counteract the effect on the pilots' eyes of high light levels outside the aircraft (such as sunlight reflected off white clouds) an additional input to the automatic brightness control system can be provided from a forward-looking sensor.

Although the screens of the CRTs used for airborne displays normally use pigmented phosphors in a black matrix to minimise reflectance of ambient light, it is still necessary to provide some form of optical filtering to ensure adequate display visibility under all conditions. In single-seat cockpits directional mesh filters provide useful contrast enhancement, but the acceptance angle of this type of filter is inherently low, and makes it unsuitable for use in a transport aircraft, where cross-monitoring between Captain's and First officer's displays must be possible. The simplest form of filter for this application is a neutral density type, which provides twice as much attenuation of unwanted ambient light as it does of the light emitted by the CRT. An alternative approach, also suitable for wide-angle viewing, is to use an absorption filter with three pass bands arranged to match the wavelengths of the principal emissions of the three colour phosphors. Such filters provide a somewhat higher performance than the neutral density type, but currently at higher cost. Any filter which is used is required to be bonded on to the CRT face, and to have an anti-reflection coating on its outer surface, in order to minimise the effect of the additional, potentially reflecting surfaces.

Application of available technology has made it possible to design and manufacture colour CRT displays which should be capable of meeting all the requirements imposed by human performance capability. If extensive flight experience shows that modifications are desirable in such areas as the colour or shape of particular symbols, these can be effected, as has already been pointed out, without major hardware changes.

ADVANTAGES OF ELECTRONIC DISPLAYS

When considering the desirability of equipping a cockpit or flight deck with a fully comprehensive electronic display system, there are two major issues to be settled:

- what advantages and disadvantages does an electronic display system have compared with a conventional instrument fit?

- what advantages and disadvantages does a system based on colour CRTs have compared with a monochrome system?

Regarding the first question, there are both economic and operational advantages in equipping an aircraft with electronic displays.

From the economic point of view, an electronic display system already offers an advantage over conventional displays in cost of procurement; a recent study indicated a saving of more than 30% in the cost of a complete display installation for a large transport aircraft, and a corresponding advantage can be expected in the case of a combat aircraft.  A similar, or greater, saving in cost of ownership will be achieved, since electronic displays are amenable to a high degree of automatic testing, and require a relatively small amount of highly skilled labour for their maintenance.  In addition, application of the flexibility of electronic displays provides the possibility of configuring a transport flight deck for two-man operation, the economic advantages of which may be of more value in the military environment than in the civil, where there is strong opposition to the two-man crew concept from many pilots' unions.

This same flexibility provides the main operational advantage of the electronic display system: information in which the pilot is not currently interested can be suppressed from the displays.  Whereas in the past the pilot has been confronted with all the information all the time, and has had to filter out mentally the items in which he is interested, it is now possible to effect at least some of this filtering by suitable organisation of the programming of the display symbol generators, which has the effect of reducing the pilot workload.  There is also the advantage of being able to integrate information from various sources in a way which has not been possible previously.

A further advantage which arises from the flexibility of electronic displays is that all information is still available to the pilot, on a time sharing basis, after the failure of one display unit.  In a conventional display system, in the event of failure of an instrument, the information it provides can only be obtained from a standby source, or by deduction from the readings of still-serviceable instruments.  The two types of display system can be made comparable in their ability to withstand the effects of failures of data sources and processing devices with minimum inconvenience to the crew.

Thus both operational and economic considerations favour the introduction of electronic display systems, and the economic balance is likely to come down even more firmly in favour of the advanced displays in the future than it does at present.

Considering now the comparison between monochrome and colour display systems, it is generally accepted that there is a clear (though unquantifiable) operational advantage in using colour.  In a purely symbolic display, although sound design dictates that correct interpretation of the information provided should not depend absolutely on colour contrast between symbols, the appropriate use of colour reinforces shape and position coding of information, and makes interpretation of the display easier.  In the case of the display of sensor-derived images there will in some cases, such as low light television, be no use for colour, but in other cases, such as infra-red and radar, the use of colour generated during the processing of the sensor data can greatly ease the interpretation of the display. Similarly the ability to superimpose colour rather than monochrome symbology on a real-world image has great advantages operationally.

From the point of view of resolution a shadow-mask colour CRT inevitably compares unfavourably with a monochrome tube; although the high resolution type of colour tube already described provides entirely adequate cursively generated symbolic displays, it would not exploit fully the available resolution of an 875 line raster picture. This limitation would not apply in the case of a penetration phosphor type of colour CRT, although the problems make this type unsuitable for raster displays.

The brightness of the display produced by shadow mask CRTs is at present less than that available with some monochrome tubes, but with suitable contrast enhancement filtering, such as that provided by a narrow-angle directional filter, adequate visibility of the display can be ensured, even when raster generation is used.

The question of the relative complexity, and therefore reliability, of monochrome and colour display systems is being studied in some detail at present. It is anticipated that, although a decision to instal colour display equipment is likely to involve a marginal loss of overall reliability, this loss will be so small that it will be offset by the greatly improved operating characteristics of the colour system.

CONCLUSION

Aircraft instrumentation is on the point of taking what is probably the biggest single step forward that has happened in the whole history of flying. From the earliest days of flying until the present day, virtually all the primary information available in the cockpit has been presented by mechanical and electro-mechanical devices. Now, within the space of a few years, CRT displays will be appearing in ever-increasing numbers of aircraft, both military and civil. At present only a limited amount of information is being displayed electronically, but that amount will soon include much of the information that is vital to the safe and efficient operation of the aircraft.

It seems likely that before many more years have passed, all high performance aircraft will be equipped with all-electronic display systems, with conventional instruments retained only for standby purposes. This will realise to the full the operational and economic advantages which modern display technology can offer.

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    Interface: Human Factors Considerations'.  AGARDograph No. 255,
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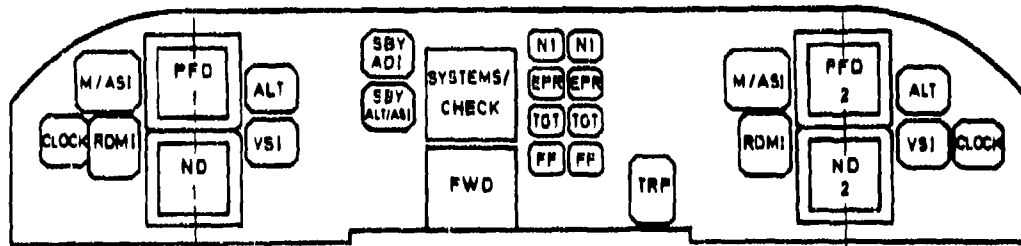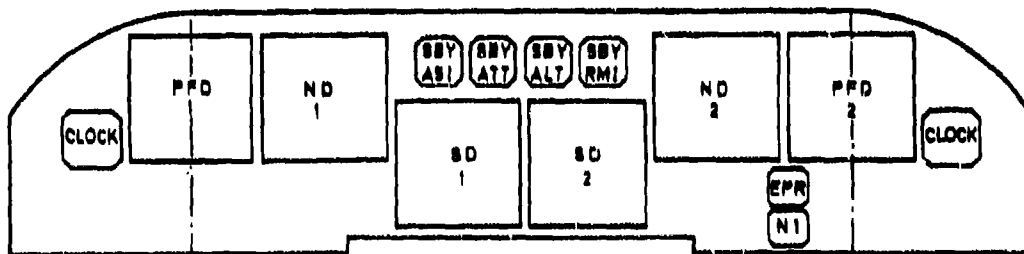FIG.1    INSTRUMENT PANEL WITH PARTIAL ELECTRONIC DISPLAY SYSTEM



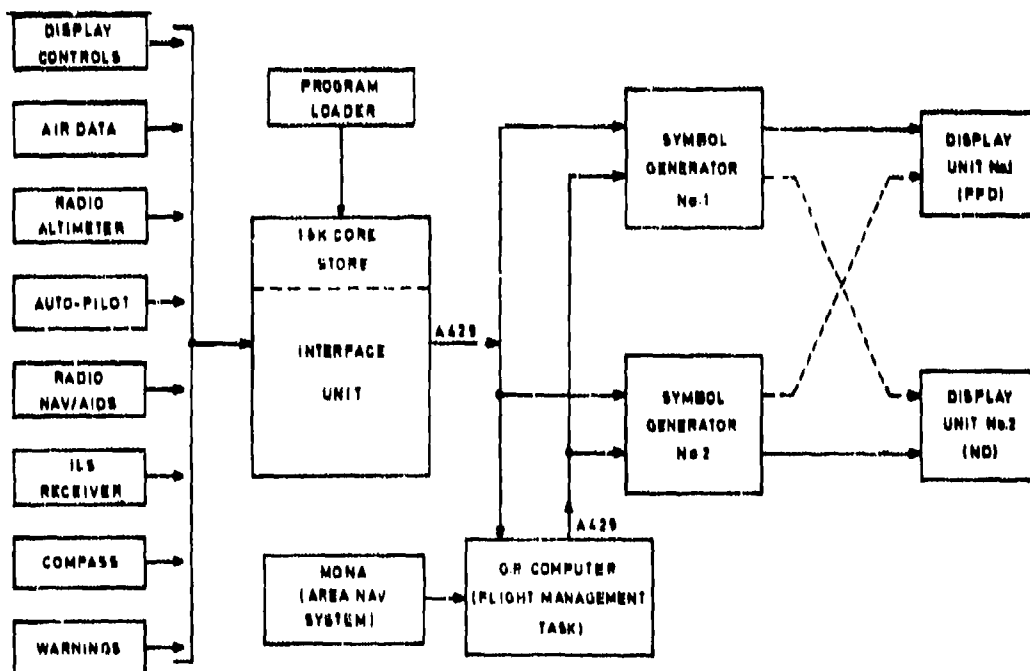FIG.2    INSTRUMENT PANEL WITH FULL ELECTRONIC DISPLAY SYSTEM



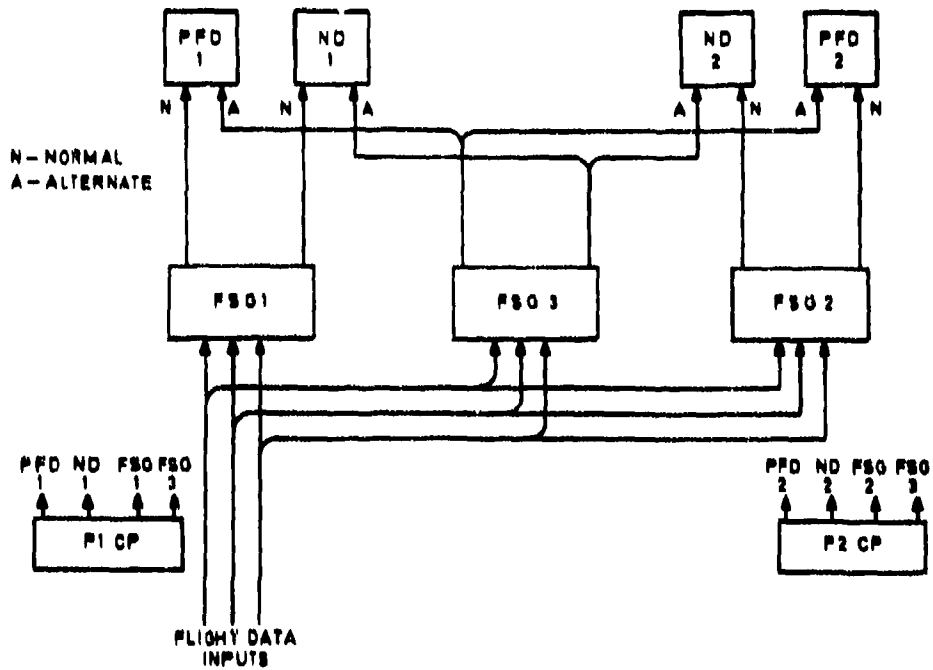FIG.3    EXPERIMENTAL ELECTRONIC DISPLAY SYSTEM IN BAs 1-11 AIRCRAFT

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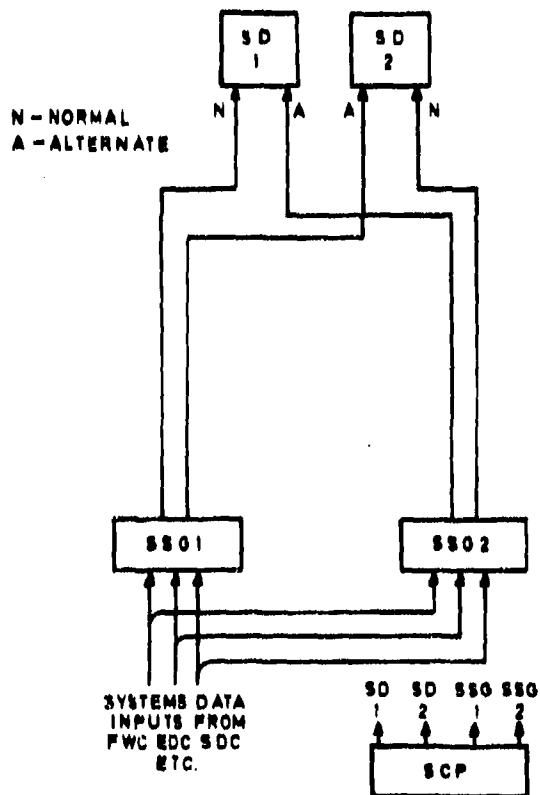FIG.4 FLIGHT AND NAVIGATION DISPLAY SYSTEM ARCHITECTURE



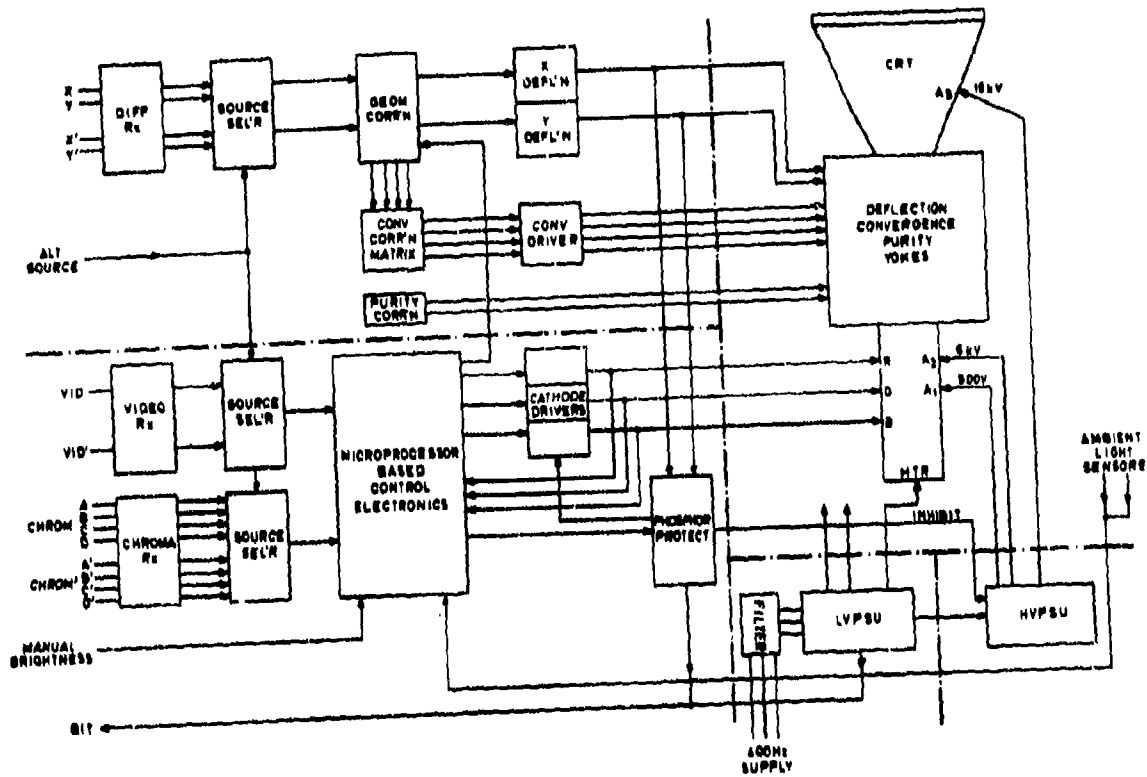FIG.5 SYSTEM AND WARNING DISPLAY SYSTEM ARCHITECTURE

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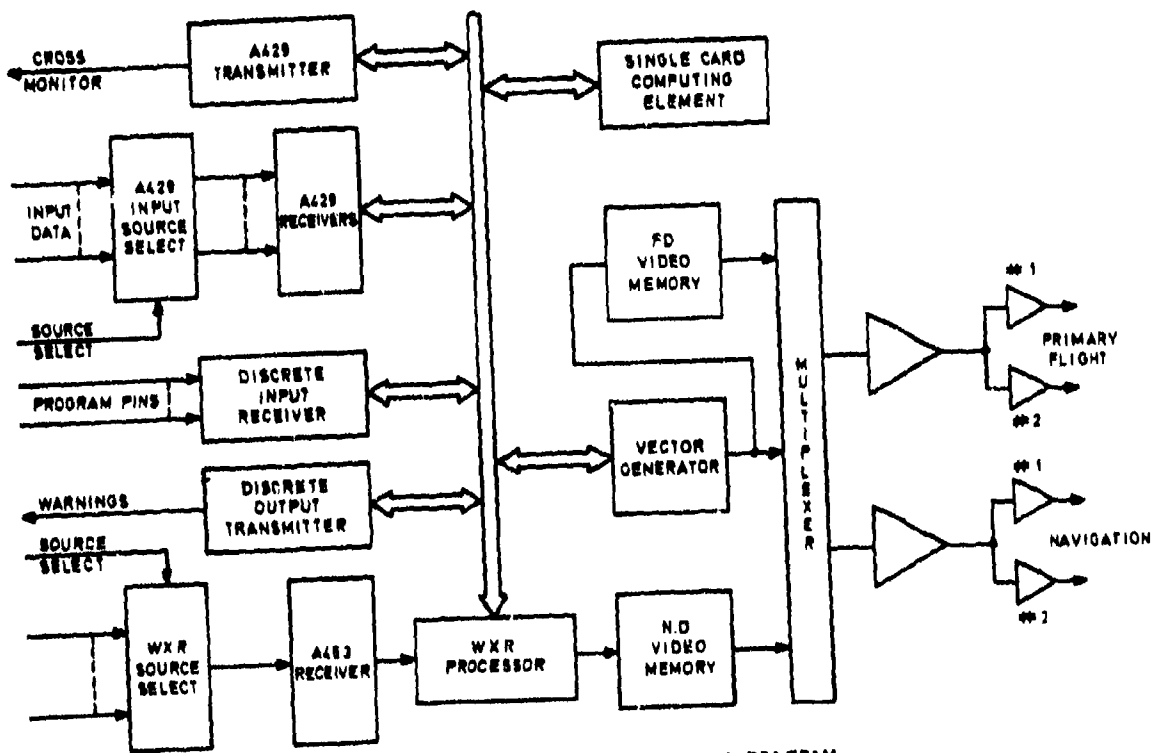
FIG.6   DISPLAY UNIT BLOCK DIAGRAM



FIG.7   SYMBOL GENERATOR BLOCK DIAGRAM
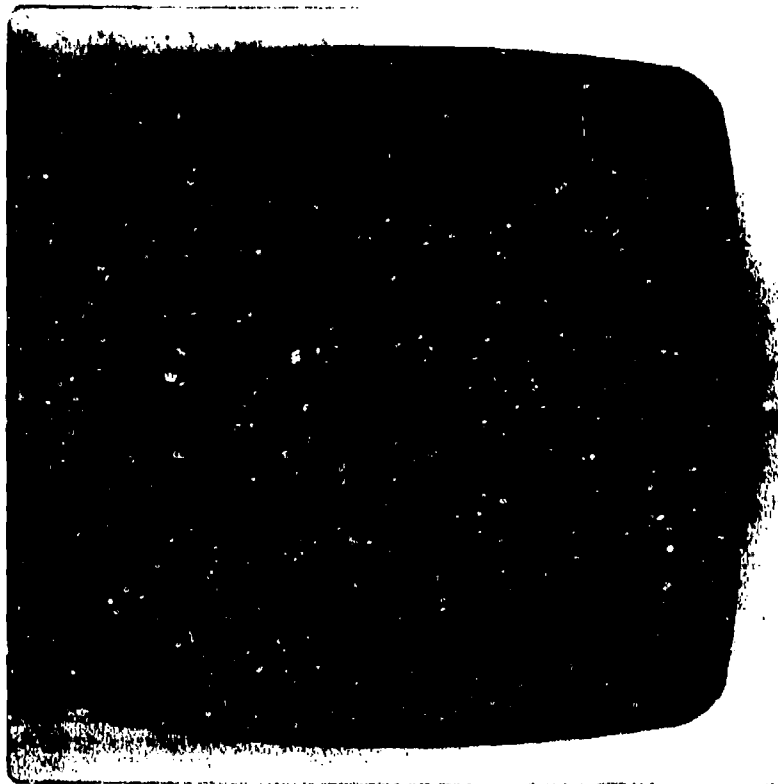
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FIG.8   PRIMARY FLIGHT DISPLAY IN 200 MM X 200 MM CASE
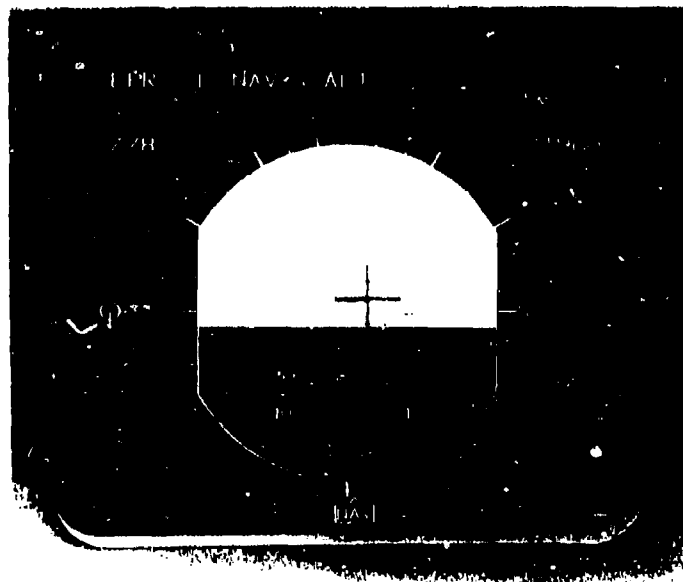


FIG.9   PRIMARY FLIGHT DISPLAY IN 180 MM X 150 MM CASE
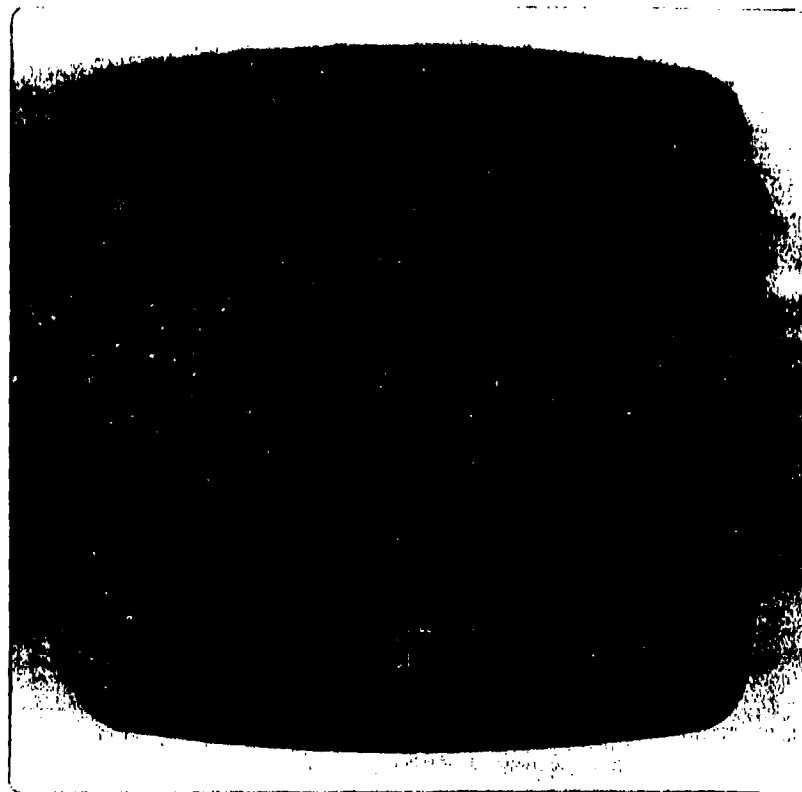
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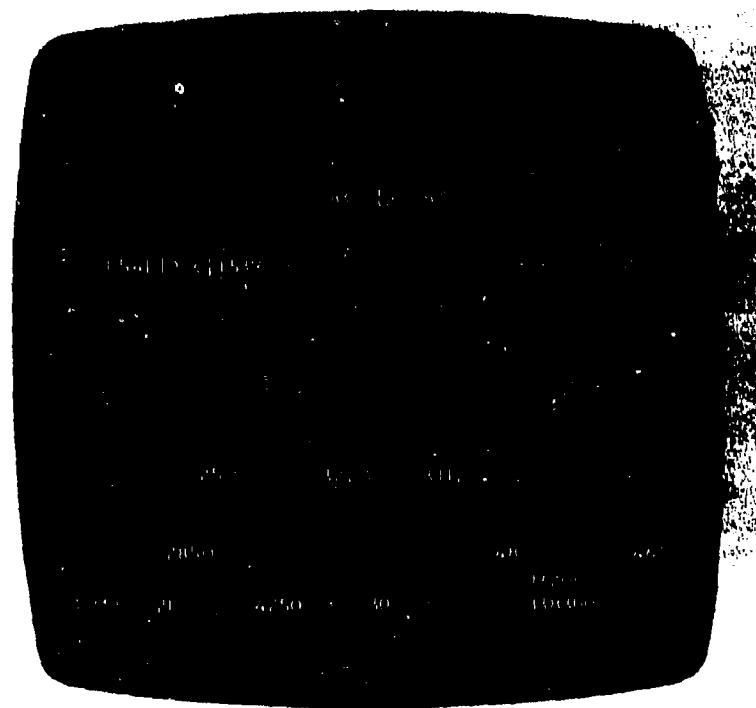FIG.10   NAVIGATION DISPLAY IN 200 MM X 200 MM CASE



FIG.11   SYSTEMS DISPLAY IN 200 MM X 200 MM CASE

AD P000674

# HELMET MOUNTED DISPLAY SYMBOLOGY FOR HELICOPTER LANDING ON SMALL SHIPS

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## SUMMARY

Helmet Mounted Display symbology has been designed to aid in landing a specific helicopter, the SH-2F, on small ships, utilizing the NAVTOLAND Precision Landing Guidance System. A "maximal" display for single-pilot operation and a "minimal" display for two-pilot operation have been developed, both without head tracking. The "maximal" display provides all the necessary flight information in three modes for localizer acquisition, approach, and hover. Novel symbology is introduced for aiding the pilot in localizer acquisition under high wind conditions and for glide slope and localizer tracking during approach. The "minimal" display symbology relies on active participation by the co-pilot via verbal communication. In this display the presentation of the positioning information is based on the doppler Direction Velocity Indicator panel instrument format throughout approach and hover.

## INTRODUCTION

The Navy has undertaken an integrated program for the development of V/STOL (rotary and fixed wing) hover and landing capability under adverse conditions. Criteria under consideration include operations in obscure ceiling/700-foot visibility and through sea state 5, on both aviation and non-aviation ships (Figure 1).

The Navy Vertical Takeoff and Landing (NAVTOLAND) program is addressing all elements of the V/STOL shipboard landing problem, including the Precision Landing Guidance System (PLGS), aircraft flight controls and cockpit displays, Visual Landing Aids (VLA) and piloting techniques. For manual approach and landing in adverse weather, effective integration of cockpit displays with aircraft control characteristics is required. Status information must be matched to the piloting task, and command information must account for the aircraft flying qualities as augmented by the electronic flight control system.

Display media must also be appropriate for the task and compatible for installation in a particular airframe. The Head-Up Display (HUD) and head down Multi-Purpose Display (MPD) in fixed wing V/STOL (AV-8B) provide adequate display media for Instrument Meteorological Condition (IMC) approach, and to some degree for final hover and landing as well. Representative reviews on this subject are References [1] through [11].

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The head-down instruments found in helicopters, however, require strict crew coordination procedures for IMC approach and pose problems for effective transition to head-up flight after breakout, especially with reduced weather minima. Head-up displays are typically found only in attack helicopters and provide a limited field-of-view.

In recent years, the helicopter community has effectively pursued use of Helmet Mounted Displays (HMD) for target designation and for enhanced low visibility, low altitude operations. Visual augmentation using infrared (IR) or low light level sensors combined with artificial symbology has been investigated (References [12] through [16]).

It is appropriate then to consider the potential of an HMD for the ship-board IMC approach and landing task. In this role, the HMD is envisioned as a medium to display symbology only, since unaided visual contact with the ship is possible during the final phase of the approach even in the weather conditions under consideration. Furthermore, utilization of an HMD without head position tracking would simplify aircraft installation.

There are undoubtedly numerous human factor questions raised by such an implementation (e.g., disorientation). In order to begin addressing these questions, two candidate display formats for an HMD without head tracker have been developed for use in an SH-2F helicopter. Since the HMD is to be used only for the approach and landing task, the Helmet Display Unit (HDU) of the Honeywell Integrated Helmet and Display Sight System (IHADSS) has been selected as the baseline hardware set (Figure 2). The HDU clips onto the pilot's helmet and thus alleviates the need of carrying the extra HDU weight (12 oz) throughout the mission.

The goal of the Helmet Mounted Display symbology design presented here is to aid the pilot in performing landings on small non-aviation ships by means of utilizing the information available from the NAVTOLAND Precision Landing Guidance System and from other airborne sensors. The following constraints are significant:

(a) The specific helicopter to be considered is the SH-2F with its present Automatic Stability Equipment (ASE) and the instrument panel left unchanged

(b) No head tracker is to be used

(c) Extra training and proficiency flying required for the display is to be as little as possible.

Constraint (b) implies that the display should not be of the contact analog ("forward looking") type. The concept employed can be called a "helmet mounted instrument panel," enabling the pilot to avoid confusing overlapping of symbols and certain elements, like light sources, in the view of the ship. This combination of symbology and outside view is similar to helmet-fixed symbology superimposed on an IR display where the orientation of the swivelling IR sensor is governed by the pilot's head movements. Such a system is being flown successfully in the Surrogate Trainer for the U.S. Army Advanced Attack Helicopter.

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Constraints (c) and (a) dictate a design philosophy that strongly utilizes the present training and experience of SH-2F pilots with the existing flight control system and cockpit instruments.

Two solutions, different in format and in content, have been synthesized and are presented here. A "maximal" display, intended for single-pilot operation, has three different modes, from localizer acquisition to hover, utilizing a moving-map type horizontal format throughout and introducing novel vertical display symbology derived from visual and instrument information used today.

A "minimal" display is synthesized based on the assumption that the co-pilot actively participates in the approach by providing the pilot with monitoring information verbally. This display utilizes essentially a single format throughout the approach, using error and error rate symbology derived from the Direction Velocity Indicator (DVI) panel instrument, with true situation shown only near hover.

The following principles were formulated as guidelines for the detailed design:

1. The information displayed on the HMD should eliminate the need to look inside the cockpit, except in response to warning.

2. Motions of display elements should not be in conflict with any panel display of similar information, especially insofar as evoked control modes are concerned.

3. The symbology chosen for various display modes should be "natural" in order to minimize the time and effort needed for familiarization and training.

4. Digital display of information may be used for monitoring purposes but not for continuous control loop closures.

In the following, the proposed display symbology is described in detail, including the reasoning for the choices of its various elements and features. The availability of a stroke-writing symbol generator is assumed.


A "MAXIMAL" DISPLAY FOR SINGLE-PILOT OPERATION


The Basic Display Format

The format common to all display modes of the "maximal" display involves elements of flight information that are available on the basic instrument panel. The central area of the display is to be reserved for various modes conveying positioning information, from localizer acquisition to hover. Because no head tracker is to be used, any resemblance between symbol movements and relative movements of outside objects should generally be avoided.

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Display Principles 1., 2. and 4. govern the design of the basic display format. In order to minimize the difficulty of transitioning from cockpit instruments to the HMD symbology, as much information as possible is arranged resembling the instrument panel (Figure 3) so that the basic scanning pattern is not very different. Therefore, much of the important instrument information is arranged at the bottom of the display area. The center piece in this area is the sketch of the attitude gyro, with bank angle indicator, turn needle and side slip ball. Several of the instruments indicated in Figure 3 are not represented in the basic HMD format; some, because they convey information that is to be included in the appropriate display mode in the central area, others, because they are not considered primary information for the flight phases at hand. Automatic warnings must be flashed on the display when instruments not shown on the HMD indicate trouble (Figure 4).

In addition to the gyro display the following information is shown in the bottom area: radar altitude, barometric altitude, ground speed, air speed, percent rpm and percent torque. Given the use of the ASE, all of these indications are only to be monitored while positioning of the helicopter is to be performed based on the central-area information. For this reason it is proposed that these instrument readings be shown in digital form. The arrangement shown in Figure 4 resembles closely the relative locations of the respective instruments on the panel in relation to the gyro. Exceptions are that the rpm information is moved to the left of the air speed read-out so that it does not intrude into the central area, and that the ground speed is shown below the airspeed, in place of the bearing-distance-heading indicator. The moving heading scale is across the top of the display area. A rate-of-climb scale is shown on the left-hand side of the central area. An area on the right hand side is reserved for warning information.

In order to minimize the chances of disorientation, it is important that the pilot be aware of his head angle with respect to the airframe at all times. The fixed elements on the HMD provide a "frame" which can be related to cockpit features (e.g., instruments, windshield frame).

In the following sections, central-area display modes for localizer acquisition, approach and hover are described.


## Localizer Acquisition (LA)

In the sequence of flight phases during approach and landing, the purpose of the first display mode is to aid the pilot in localizer acquisition. In high sea states the mean wind velocity is likely to be high which complicates the prediction of the flight path in a turn. This is considered the dominant problem in this flight phase.

The display needed for enhancing localizer acquisition is essentially a navigation mode with nominal approach path information to be added. Only a horizontal display is needed in the central area because this maneuver is performed at an altitude which can be held adequately by the ASE, or by the pilot using the altimeter and rate of climb information available on the display.

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The scaling of the horizontal display in the LA mode is determined so that no scale change should be necessary during several minutes before localizer acquisition is completed. Assuming an air speed of 80 knots during this flight phase as the design point, a range of 3 miles allows seeing ahead for more than two minutes and gives adequate lateral range for a standard turn diameter.

The first significant element in this display mode is the presentation of the nominal approach path when the helicopter's relative location (range and azimuth) with respect to the ship and the nominal approach angle are known. In addition to the nominal approach line the following information is considered quite useful for the horizontal situation display: the orientation of the ship with respect to the approach path and its direction of travel, and the point on the approach path where tip-over should be performed assuming that the helicopter stays at the same altitude. The ship can be shown as a small symbol or as an arrow at the end of the approach line (Figure 5). If the ship itself is off scale then it should appear where the approach line terminates, with a gap between the line and the ship symbol; the gap is to disappear when the ship is within range and then the ship symbol appears attached to the end of the approach line.

In order to assist the pilot in planning his turn onto the approach path, two dotted antennae-like symbols emanate from the aircraft symbol. These lines represent the ground tracks for left and right nominal turning flight paths. In the simplest case, with no wind, these paths are half circles which are calculated based on the helicopter ground speed and the predetermined turn rate for a 2-minute 360° turn. For cross-checking purposes, and also in the case of inoperative automatic turn coordination, the needle-ball presentation at the bottom of the gyro can be used. Ideally, a turn should be flown in such a fashion that the nominal approach line becomes tangential to the nominal turn path when localizer acquisition is completed. Only constant-heading-rate turns are considered here.

Automatic turn coordination (zero side force) has been ranked among the highest priorities for feedback augmentation of helicopters and it is assumed available under the flight conditions considered here. The sketch in Figure 6 indicates that a horizontal force component perpendicular to the helicopter x-axis has components both perpendicular to and along the flight path. The former causes the flight path to curve while the latter represents an accelerating or decelerating force component depending upon the direction of the turn. The implication is that longitudinal control must be applied by the pilot or by the ASE in order to maintain the airspeed. Changes in ground speed occur during a turn unless a significant effort is made to maintain it constant, but no good reason can be seen to make this a requirement. The kinematics of turning helicopter flight is analyzed in Reference [17]; a simplified approximation for level turns with constant airspeed, based on a quasi-stationary analysis, results in very simple on-line calculations to obtain the dotted "antennae"; each consecutive dot represents a 15 deg absolute heading increment. Figure 7 illustrates the changing shape of the antennae as the wind direction changes in the course of a turn. The accuracy

of the predicted turn path can be monitored easily throughout the turn and
appropriate modifications of the turn rate can be made to compensate for
approximations and instrumentation errors, or for inadequate turn rate
tracking during part of the turn.

Two more features might be added to the LA display if unused computa-
tional capacity is available.  The first addresses the problem of timing the
turn initiation when the approach path is moving sideways because it is at an
angle with respect to the ship's line of travel.  If the ship's speed is
known, then a straightforward calculation can predict where the approach path
would be located when it came nearest a nominal turn initiated immediately
(see the double line segments in Figures 5 and 7).  Under ideal conditions the
turn should be initiated when the predictor path element becomes a tangent of
the turn path.  This element then remains tangential to the turn path through-
out the standard turn while its distance from the actual moving approach path
decreases to zero by the time localizer acquisition is completed.  In the
absence of such a predictor symbol the pilot must perform the prediction.

The second feature that might be added at significantly greater expense
in computational capacity would provide bank angle commands throughout the
turn.  At each point along the nominal path the bank angle needed to provide
the required flight path curvature can be calculated.  In view of the small
bank angles and the rather lax accuracy requirements in localizer acquisiton,
this feature is only mentioned but is not recommended.

The localizer acquisition takes place at an altitude and a distance from
the ship where head-down flying is quite acceptable.  Therefore, the informa-
tion and symbology devised here is not tied uniquely to an HMD but could be
shown instead on an available panel-mounted tactical or other CRT display.


## Approach and Deceleration to Hover (AP)

Localizer acquisition can be considered accomplished when the helicopter
is in approximately straight line flight, its flight path orientation is
within only a few degrees from the nominal path, the helicopter is within
localizer range, and the range to the ship is decreasing.  Switching to the
Approach Mode can be done by the pilot when he deems it appropriate, or
automatically based on the criteria above which have been formulated so that
mode switching does not occur during an excessive overshoot.

The various horizontal velocity components playing a role in approach
path tracking are shown in Figure 8.  The helicopter motion with respect to
the nominal approach reference line is affected by the airspeed, the inherent
side slip, the wind velocity and the ship velocity vectors.  In the case of a
stern approach the situation is simplified by the fact that the nominal approach
reference line does not translate orthogonally to its direction.

In order to enhance the pilot's tracking task a velocity vector must be
displayed.  There are two alternatives available.  The ground velocity vector
along the ground track, in general, must be at an angle with the nominal
approach line in order to stay on the nominal path.  This angle can be

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calculated as $\delta_{ha} = \sin^{-1}((V_s \sin \gamma_{sa})/V_{hg})$ where $V_s$ and $V_{hg}$ are the ship and helicopter velocities and $\gamma_{sa}$ is the angle between the ship velocity vector and the nominal approach line. The nominal end point of the helicopter ground velocity vector can be calculated and shown on the display.

The other alternative, using the same information, is to display the helicopter ground velocity component as referenced to the nominal approach line. This is the alternative proposed for the approach mode because tracking the nominal approach line is then essentially the same in the case of $\gamma_{sa} \neq 0$ as when $\gamma_{sa} = 0$ (Figure 9). From the pilot's viewpoint, the effect of a laterally translating approach line is the same as that of an additional wind component orthogonal to a non-translating nominal path.

As the approach speed is decreased, appropriate heading changes must be made. An experienced pilot is likely to anticipate most of the required change. Throughout, it is assumed that the pilot is using the ASE and is flying longitudinal trim while the automatic turn coordination keeps the ball centered even if there is no banking. It appears desirable to have the ASE in altitude-hold in this phase of the approach. For the present discussion it is assumed that the initial altitude before tip-over is such that after this maneuver there is adequate flying time available to establish glide slope tracking before the decelerating phase begins.

As long as the altitude is held constant or is not yet a crucial flight variable, the horizontal display provides sufficient information. When the explicitly marked tip-over point is approximately one-half minute flying time away, a horizontal scale change is in order and glide-slope referenced vertical information must be made available. A presentation of ILS needles might be used for this purpose; this alternative has been rejected because the cross hair panel instrument above the gyro, the Direction Velocity Indicator, represents a horizontal display and therefore evokes a different control response.

In the search for a solution the following line of thought evolved. The dominant reason for using an HMD or a HUD is that the pilot wants to make visual contact with the ship as soon as he can. Therefore, it is considered desirable that the pertinent information during approach be presented in the central display area in an uncluttered way. Today's pilot training and experience is based on visual approaches, with valuable cues provided by a Fresnel lens system ("meat ball") or other vertical guidance and the "hockey stick" appearance of approach and drop line lights. The closer the symbology resembles conditions flown routinely the less extra training and additional proficiency flying is necessary. The symbology for the vertical plane information proposed below combines and enhances the cues available from the hockey stick and the meat ball.

Figure 10 shows sketches of three different views of a landing platform and, below them, the symbology derived from these views. The vertical information (above/below nominal path) is derived from the fact that a shallower/steeper than nominal view of the platform changes the aspect ratio of its visual image. This is purposely exaggerated in the Figure in order to enhance

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the resolution along the vertical axis. The centers of the two circles represent the points where the drop line and the extended approach line intersect the deck surface. The reference line, not available in the outside world, is provided so that the top circle is halved when the helicopter is on the nominal glide slope. The circle radius represents an angular glide slope deviation and the nominal spacing of the two circles is such that they would coincide at zero degree. As the absolute glide path deviations indicated by the circles shrink with decreasing range, there is to be a change-over from the angular representation to a linear representation.

The upper half of this symbology is designed to make it resemble a Fresnel lens system. In other words, the reference lines can be thought of as stabilized datum lines for a meatball at the bottom of the extended center line. For vertical error rate information, an arrow is added to the upper circle, as indicated in the sketches in Figure 10. No special symbol for localizer error rate is added because that information is perceptible from the changing shape of the hockey stick and is shown explicitly by the approach velocity vector in the horizontal display.

The vertical plane symbology set is placed above the horizontal display area so that the ship symbol of the horizontal display and the vertical display symbology set move together at all times. This assures a rather natural relationship by seeing the vertical information "looking down" along the approach line. A composite sketch of a "snapshot" of the resulting approach display mode just before tip-over, with glideslope and localizer errors, is shown in Figure 11.

Throughout the approach mode a digital readout of the closing rate appears at the left of the stationary aircraft symbol where it is cross-checked easily with the airspeed (as long as that is reliable) and the ground-speed shown at the left of the gyro. When a sensor output is unreliable its read-out is to disappear. The digital read-out of the range to the ship is shown next to the ship symbol at all times.

The approach of the tip-over point is shown by a bug traveling along the nominal approach line, and it can also be perceived on the hockey stick display because the upper circle is moving more rapidly toward its reference lines as the helicopter approaches the nominal glide path. During and after tip-over, until deceleration begins, the primary information for approach path tracking can be obtained from the vertical plane symbology.

The next phase of the approach is the deceleration to hover, identified by some pilots as the most taxing part of the approach under adverse conditions at night. It must be assumed that under extreme conditions the ship is not yet visible when deceleration is to be initiated. Fortunately, with the NAVTOLAND PLGS, it is possible to give the pilot adequate position and error information if some simple kinematic relationships are utilized. The point along the approach path where deceleration is to be initiated can be determined easily based on the known initial closing rate if the nominal deceleration of the closing rate is assumed to be a straightforward function of range only. For the purpose of this paper, constant deceleration is used as reference.

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It is proposed that the pilot have the option of selecting a deceleration of -.1g or -.05g. Under adverse weather conditions pilots may well opt for the slower deceleration if they have appropriate information on their display to set up the deceleration and to stay within acceptable tracking errors even before they have a direct view of the ship. The display feature described below is designed to provide significant help to this effect.

The U.S. Army Avionics Research and Development Activity has developed and simulator-tested a nonlinear scaling of the velocity vector in the final approach phase (Reference [18]). The essence of this idea is that keeping the tip of the properly scaled velocity vector on the desired landing spot as displayed in a horizontal plane results in a prescribed deceleration time history depending on the scaling of the velocity vector. For example, linear scaling results in an exponential decay of approach speed. It can be shown easily that quadratic scaling, i.e., making the approach velocity vector proportional to the square of the closing rate, would yield constant deceleration under idealized conditions. Such a feature is incorporated in the proposed display.

Depending on the preselected value of deceleration an automatic scale change is to occur at a range of 1,000 ft or 2,000 ft and at the same time the ship symbol changes to a properly oriented landing pad. In this final approach mode the magnitude of the approach velocity vector at any given initial closing rate is equal to the easily pre-calculated distance of the ship symbol from the point where deceleration is to begin. The transitioning from constant airspeed to deceleration occurs when the ship symbol reaches the vector tip; from that time on the pilot must keep the vector tip on the ship symbol while making appropriate collective adjustments based on the glide slope error information. The described feature allows the pilot significant freedom to modulate the idealized procedure. He may choose the location where he wants to come to a hover and he may choose to apply larger or smaller decelerations over parts of the final approach. Making the appropriate corrections in case the initiation of the deceleration occurred somewhat late is also straightforward. In order to improve the tracking accuracy a final scale change in the approach mode should occur at 500 ft range.

In order to assure a smooth transition to hover the approach mode of the display is to be terminated at 100 ft from the nominal landing spot and the display should switch automatically to the hover mode described in the next section.

Hover Mode

By the time the switching to the hover mode occurs, detailed features of the ship are in sight. It is an unresolved question whether, from this point on, artificial symbology   the moving image of the ship would be used by pilots in actual flight although, at least in principle, the stabilized and well defined position information on a display may make hovering and maneuvering near hover easier than flying based on the moving ship reference. The goal of devising a hover display mode is to provide the pilot with the best possible information so that he may use the symbology as a significant source of information.

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The hover display symbology is shown in Figure 12. The stationary aircraft symbol is inscribed in a circle representing the rotor to scale in order to provide innate perception of the horizontal scaling factor. The ship landing area is represented by a rectangle, also to scale, shown at the proper bearing, with the proper orientation. The nominal touch-down point is marked by a circle. For a linear control law the velocity vector tip should be kept on the "target" as mentioned in the preceding section in connection with proportional vector scaling.

The scale on the left can be used both for vertical position error and for rate indication if the center reference point on the scale denotes the nominal hover height and zero rate of climb. The actual hover height is indicated by two symbols moving together on the two sides of the scale; they are shaped to suggest a pair of wheels.

For illustration, the bottom of the vertical scale in Figure 12 represents the deck if it were not moving at a nominal hover height of 50 ft. The small reference circle shown there together with the two associated reference lines can be moved to any desired nominal hover height. Significant realism can be added to the display if landing spot motion information is transmitted to the hovering helicopter. This information can be used to show deck displacements in heave and sway as well as the deck roll angle. This motion being confirmed continuously by the moving background outside may contribute significantly to the confidence in the information displayed via the symbology.

No matter how good and successful a hover display proves to be, a nagging question remains to be addressed: what if the display fails while hovering? Obviously the pilot must have the capability to land safely based on visual cues with the help of the Landing Signal Enlisted (LSE) personnel and VLA unless a divert option exists. This means that he must have the proficiency to perform such a landing. The implication is that if he uses the display regularly because it makes his task easier, he actually looses proficiency in hovering and landing visually. These last two phases have been singled out for the above question because the close vicinity of hard surfaces makes proficient and quick reaction mandatory while the preceding phases might be handled relatively easier by simply slowing down. The conclusion is that great emphasis should be placed on devising a satisfactory stabilized hover VLA and, if that can be accomplished, the pilot may prefer to fly the VLA, with the central display area vacant, after the 100-ft hover range has been reached.


A "MINIMAL" DISPLAY FOR TWO-PILOT OPERATION

The display modes described in the preceding sections have been intended for single-pilot operation so that all the needed information is shown including some redundancies for enhancement and crosschecking. It was considered essential to provide situation information at all times. A much reduced display can be devised if two-pilot operation is assumed.

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The design of a "minimal" display is based on the principle that most of the monitoring and slowly varying information can be communicated verbally to the pilot by the co-pilot. The elimination of such information from the pilot's display results in a reduced scan and therefore allows him to focus his visual attention entirely on the immediate flying task. All the instrument readings on the left hand side of the gyro, except for torque, can be eliminated from the basic display. The two altimeters on the right hand side are replaced by a single altitude read-out elsewhere on the display.

The minimal display does not address the localizer acquisition problem. It is assumed that, flying at a safe altitude, the pilot can arrive within localizer range flying on the cockpit instruments, using the available navigation aids and the tactical display. The tactical display, with some modification, could be augmented to provide most of the Localizer Acquisition mode described earlier. Consequently, most of the basic format can be reduced to a somewhat sketchy representation of the gyro, with turn needle and ball (Figure 13). Because only relatively small bank angles are used during the approach, only "wings level" references and ± 10° marks are shown at the two sides of the horizon line; these symbols move up and down with the pitch ladder. This modification is preferred to a pointer on top (as on the panel instrument) because with the elongated horizon line it provides improved resolution. The heading scale is eliminated entirely.

Percent torque is shown at the left of the gyro. A scale format has been chosen because no other numerical information has been retained near the gyro on the minimal display. Only absolute position information is shown in the form of digital read-outs: altitude on the left and range on top of the display area. Rate of descent and range rate can be perceived from the "ticking" of the corresponding absolute values. The closing rate can be shown explicitly below the range, if this is found necessary or highly desirable in the course of simulation experiments. For the pilot's assurance, the co-pilot should call out various flight information, like descent rate and airspeed, from time to time.

The minimal nature of the display is the result of eliminating monitoring information from the basic display and much of the situation information in the central area of the "maximal" display, and of having a single mode for localizer tracking, glide slope acquisition and tracking, deceleration and hover (Figure 13). This is accomplished by using the DVI format and augmenting it with error information. The symbology has been chosen so that control responses learned and exercised with the DVI instrument are maintained and utilized over the entire approach speed range, down to landing. Vertical, lateral and longitudinal display elements and control are discussed separately below.

The vertical symbology on the left is similar to that in the hover mode of the maximal display, but the meaning of the scale is modified in order to cover the entire approach. The center of the scale denotes a point on the nominal path, traveling along with the helicopter so that the pair of wheels show the altitude deviation from nominal. The scale itself is an altitude error scale and an altitude error rate scale at the same time with the ranges of ± 5°, changing to ± 50 ft near the ship, and ± 500 ft/sec, respectively.

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The symbols are made to behave in the following way as the approach progresses. While flying on localizer before glideslope acquisition the ASE altitude-hold mode should be on. Accordingly, both the altitude and altitude rate indications show deviations from level flight. There is a negative glideslope deviation not shown to the pilot until this error reduces to -1 deg which occurs, assuming a 3 deg nominal glideslope, at 1.5 times the range of the tip-over point for the given flying altitude. At this point automatic switch-over to glideslope error presentation occurs. Some flashing may be used to call the pilot's attention to this occurrence. From this time on the altitude deviation symbol indicates the glideslope error which is negative initially, while positive error rate indication shows that the negative error is being reduced in level flight. Before the error reduces to zero the altitude-hold mode must be turned off. The pilot's goal is to reduce error and error rate to zero at the same time, using the collective, while the airspeed is held constant. The vertical error scale, being in degrees, becomes more sensitive as the approach progresses; the sensitivity remains constant after the range has been reached where the one-degree error cone intersects the ten-foot radius error cylinder. The numerical values cited above are subject to modifications based on future simulator tests.

Figure 13 illustrates the case where the nominal glideslope terminates at a 50-ft hover height over the deck mean. Actual height-to-deck information is shown by a rising deck symbol which at hover should come to rest between the two reference lines slightly below the vertical scale. The gap between these reference lines and the bottom of the scale is such that in calm water the altitude "wheels" indicate touch-down when the helicopter wheels make contact with the deck. If ship information is available, the deck symbol can indicate the rolling and heaving of the landing area.

The horizontal display has been developed based on the pair of needles on the DVI which is essentially a velocity command display in helicopter axes. The same symbology is augmented with a position error symbol in such a fashion that keeping the needle on the stationary double circle results in a satisfactory control law for making a correction. The cross hair components are driven by positon error and error rate so that with zero error rate the cross hair is on the "target." This way the "fly to" nature of the DVI instrument is maintained. For simplicity, the minimal display employs constant gains for the rate components so that an exponential approach to the "target" is made if the cross hair is kept perfectly on the reference circle. It is recognized easily that the cross hair in effect leads the target motion with the speed being proportional to the distance between the cross hair and the target. This known relationship enables the pilot to deviate from the exponential law in a controlled fashion. He can lead the target anywhere he wishes and can stop the helicopter's relative motion with respect to the target by simply placing the cross hair on the target.

Lateral directional control throughout the approach and hover can be divided into two sections depending on the ASE control mode used: coordinated turn and heading hold. In both modes lateral stick motions control essentially the force component along the helicopter y-axis. As long as the airspeed is held by the ASE, longitudinal motion is not controlled by the pilot and the target box representing nominal position moves only laterally representing the

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localizer deviation proportional to the angle, changing to a linear scale as a one-degree error becomes less than a ten-foot error. When the airspeed is high enough to allow for turn coordination by the ASE, only lateral stick inputs are needed for localizer tracking. At such speeds the drift angle is not very large and localizer error correction can be made using very gentle turns controlling the rate of change of the error rate.

The time constant of a perfect correction, keeping the cross hair nulled at all times, is determined by the ratio of the error rate and error display gains. Ratios of three to five, corresponding to time constants of three to five seconds, have been found satisfactory in the past. A ratio of five means that, e.g., a symbol displacement for a 2 ft/sec error rate is the same as that for an error of 10 ft. In practice, the noisiness of the rate information is usually the limiting factor on the display gain.

After deceleration has been initiated the same control policy can be used as long as ASE turn coordination is effective and keeps the side force zero. As the airspeed is decreasing a continuous heading change is needed, except in the very simplest case when all the velocity vectors involved are aligned. At low speeds the controlled task becomes more difficult because the pilot must use the pedals to keep the ball approximately centered. In summary, localizer tracking throughout most of the approach, with the ASE on, can be accomplished in a straightforward manner keeping the cross hair "nulled" by means of bank angle corrections only.

For x-axis control the horizontal bar of the cross hair is used essentially as a velocity command symbol like the corresponding needle of the DVI. While the ASE holds airspeed this bar can be used to indicate deviations from the set value. Deceleration can be commanded by this bar as follows. As discussed in connection with the Approach Mode of the maximal display, given the range to the ship and the closing rate, the range at which deceleration is to be initiated and the velocity profile for a given deceleration can be predetermined in a straightforward manner. The bar would remain nulled throughout the deceleration if the varying closing rate were always controlled to the value pre-calculated for the decreasing range. This can hardly be done perfectly, considering the lag between an attitude change and the corresponding speed change. The deviations of the bar are to be proportional to the closing rate deviations from the pre-calculated nominal profile. This raw error information may have to be augmented by lead information in order to reduce the work load during deceleration. In order to minimize the transient effects at the initiation of the deceleration, warning of the upcoming maneuver may be provided by flashing of the horizontal bar and only a gradual increase in deceleration should be commanded. In addition, the pilot knows the pitch attitude change needed for a given deceleration.

During most of the deceleration a longitudinal position error is not really meaningful. In the minimal display true longitudinal situation is shown in the central area only near hover. If the approach is flown correctly, both the target box and the cross hair are near the null circles at all times. At a range of 100 ft from the nominal hover point the box reference switches to the nominal hover point. At the instant of switching, the box jumps from the vicinity of the null circles to the nominal hover point in

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helicopter axes, near the top of the display area, with the proper orientation, and enlarged to scale to indicate the size of the landing area. From this time on both cross hair components move with the same error and error rate gains, leading to an exponential final approach to the hover point if the cross hair remains centered. It should be noted that the ship is already in view well before the reference point switching to hover occurs so that the situation information can be verified instantly.

In summary, the minimal display for two-pilot operation described above employs symbology derived from the DVI panel instrument used as a hover aid. That symbology is augmented to provide localizer and glide slope errors throughout the approach and situation information in three dimensions near hover. The velocity command feature of the DVI format is used to command a predetermined deceleration profile.

A great deal of attention has been given to choose the arrangement, the various display modes and the symbols in such a way that any disorientation arising from the image of the moving ship behind the display be possibly eliminated. Nevertheless, exploratory simulator experiments may well lead to some modifications in both the "maximal" and the "minimal" displays, and final verification can come only from flight experiments because of the difficulty of duplicating in the simulator the details of actual ship lighting conditions.

An evaluation of the HMD is planned as part of a NAVTOLAND SH-2F simulation to be conducted at the NASA Ames Research Center in 1982. The moving base simulation facility to be used incorporates a wide field-of-view computer generated image system. Figure 14 shows the simulator and the actual field-of-view available from the right seat of an SH-2F. A calligraphic symbol generator will drive the Honeywell HMD. The existing SH-2F mechanical flight control and ASE will be simulated. The experimental task will be a decelerating IMC approach to breakout and subsequent landing aboard a DD-963 class destroyer.

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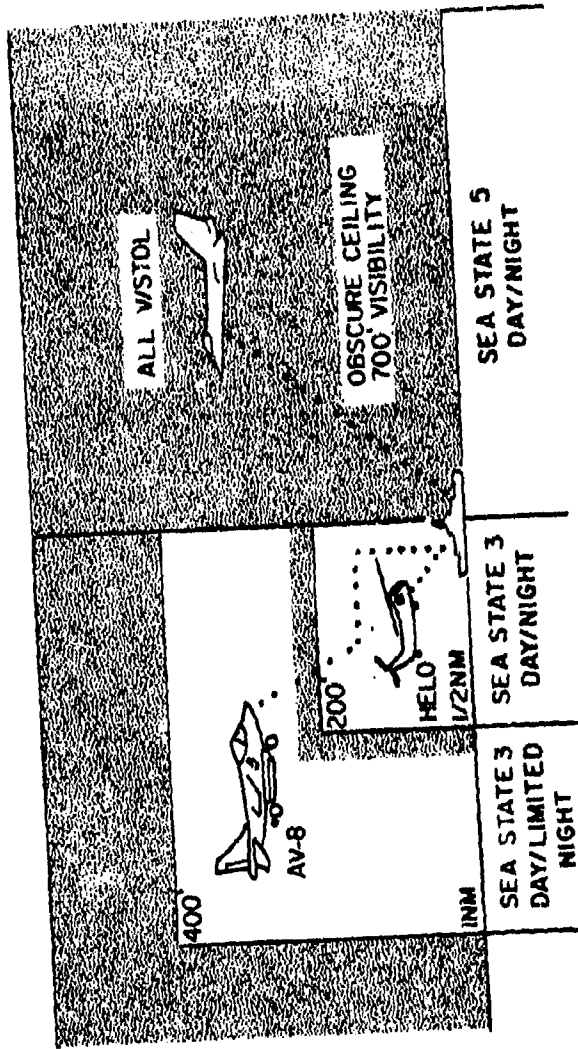Figure 1. NAVTOLAND Project Goal.

DISPLAY VISOR
HOUSING

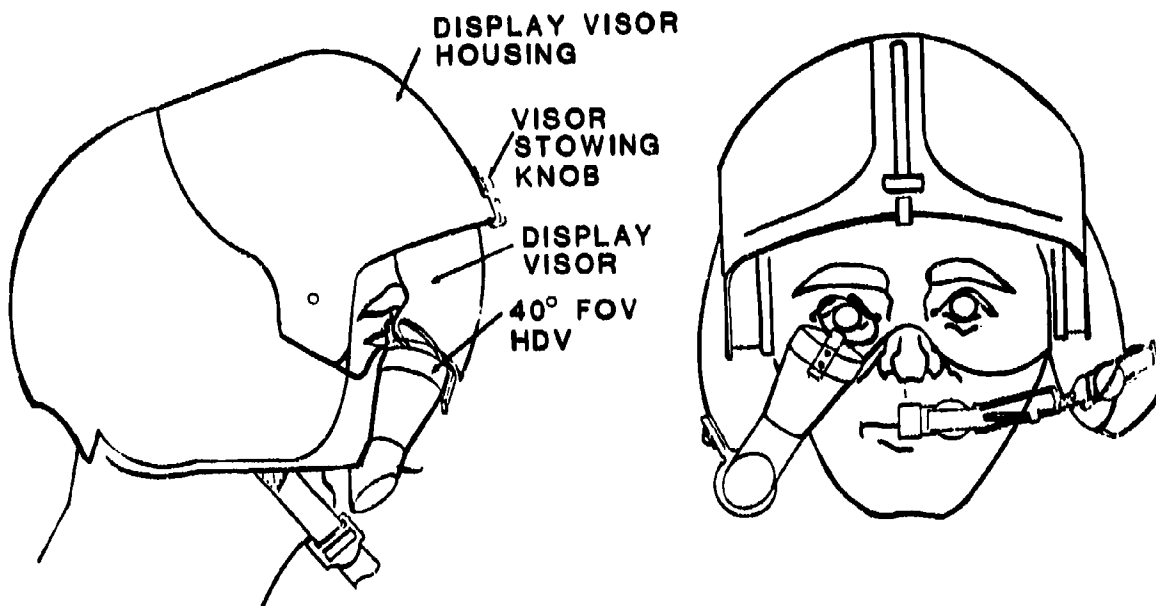VISOR
STOWING
KNOB

DISPLAY
VISOR

40° FOV
HDV

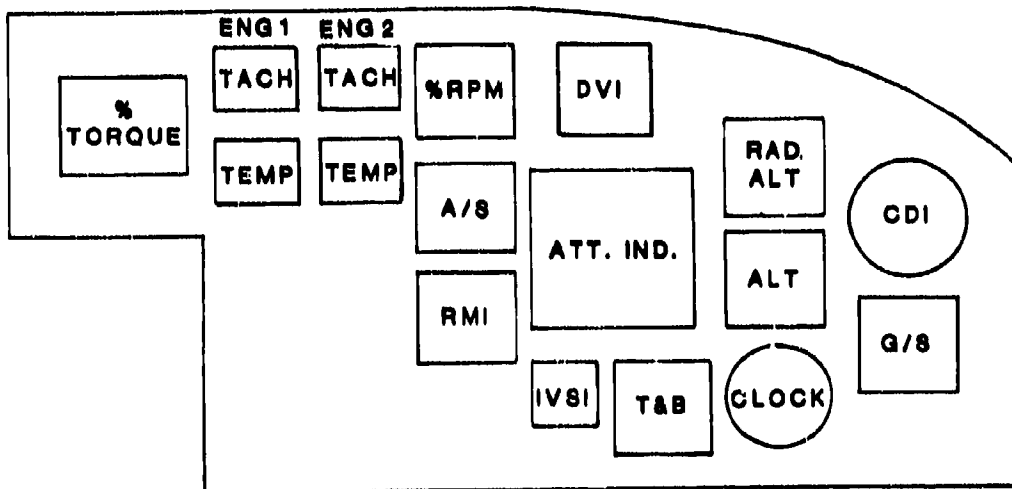Figure 2.   Honeywell Helmet Display Unit.

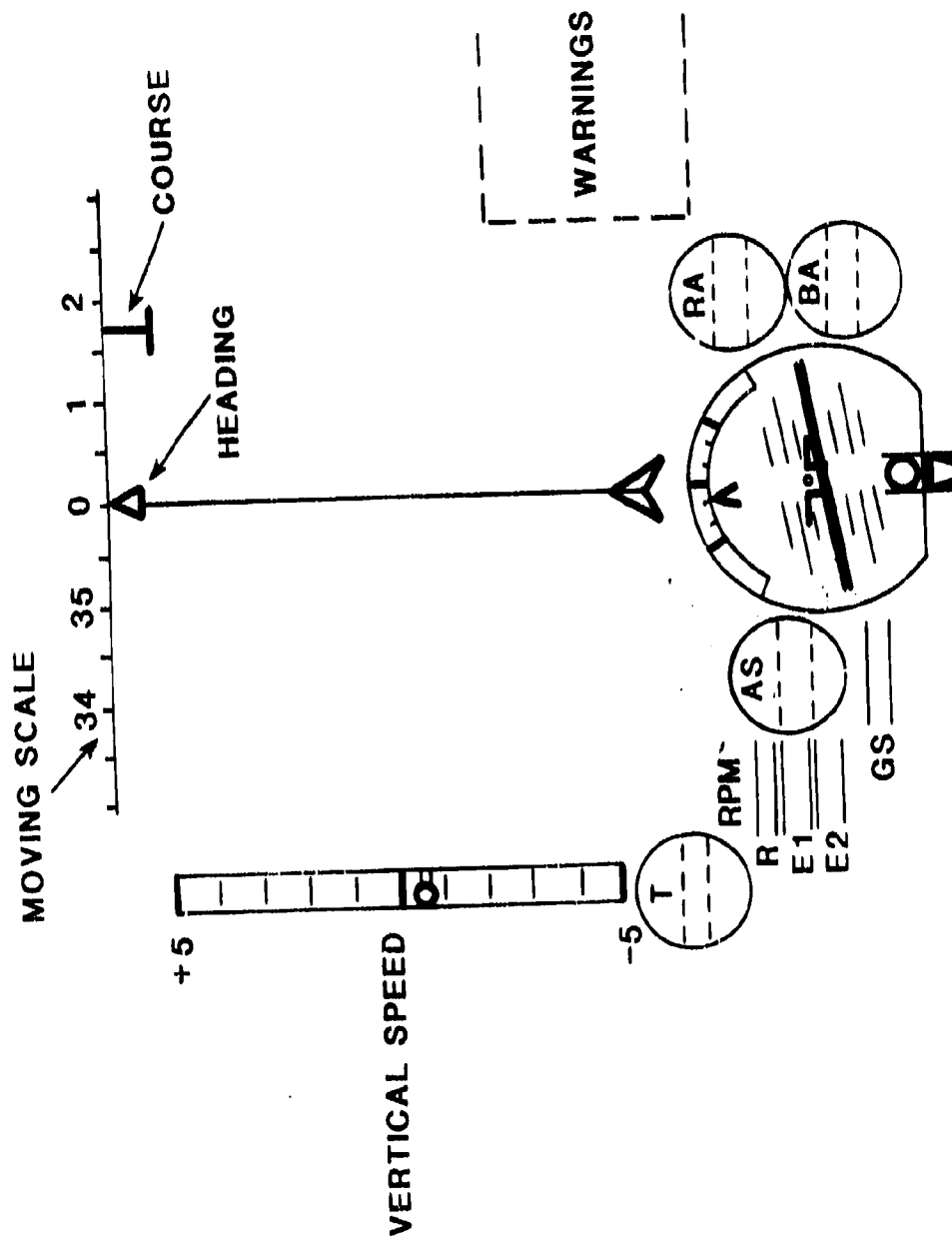

Figure 3.   SH-2F Instrument Panel.

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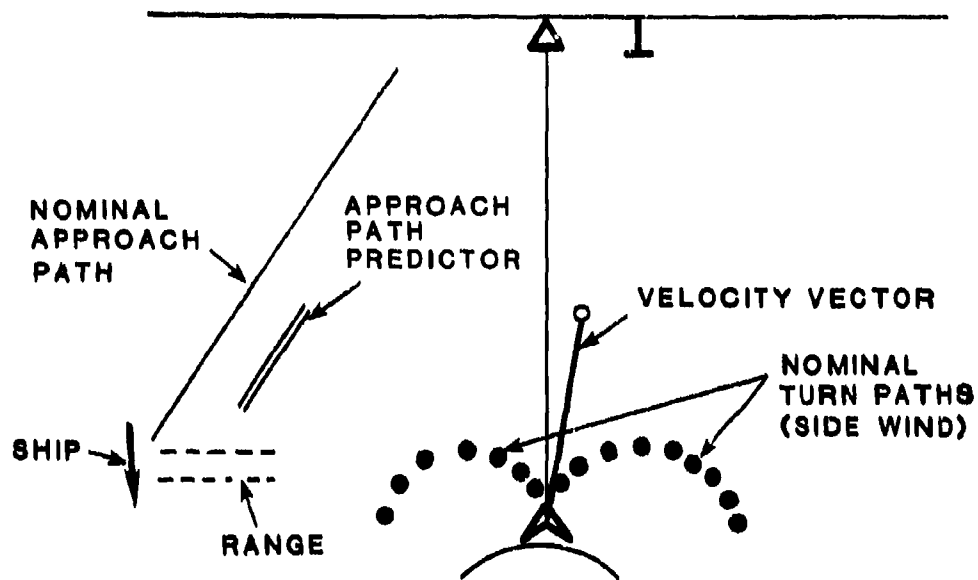Figure 4. Basic "Maximal" HMD Format.

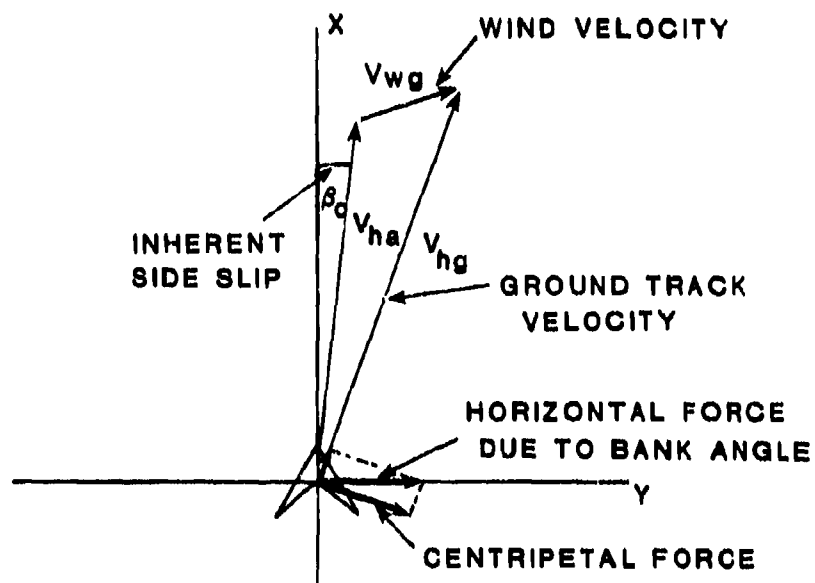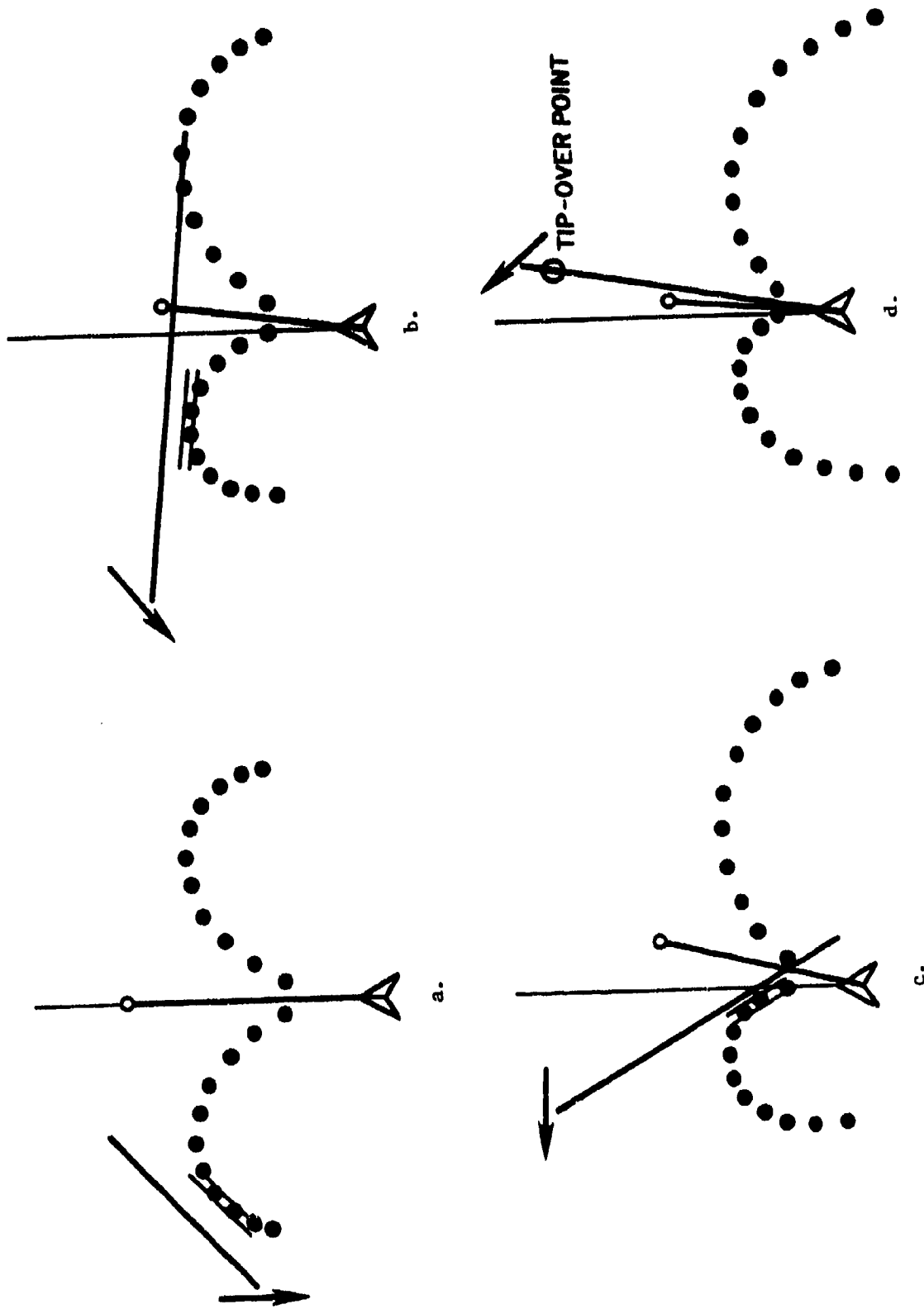Figure 5.   Localizer Acquisition Mode.



Figure 6.   Vectors in Level Turning Flight.

Figure 7. Left and Right Nominal Turn Ground Tracks Displayed While
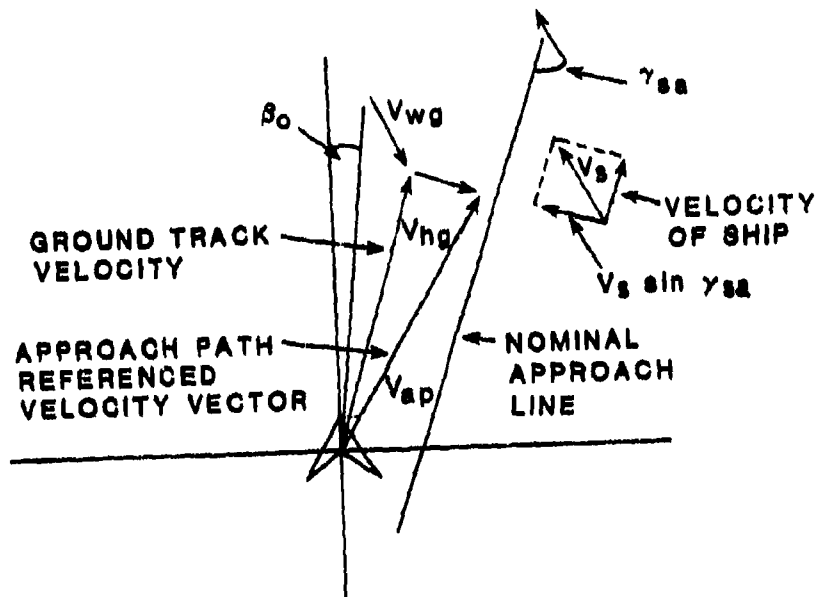Turning Onto Localizer Under High Wind Condition.

TIP-OVER POINT

a.

b.

c.

d.

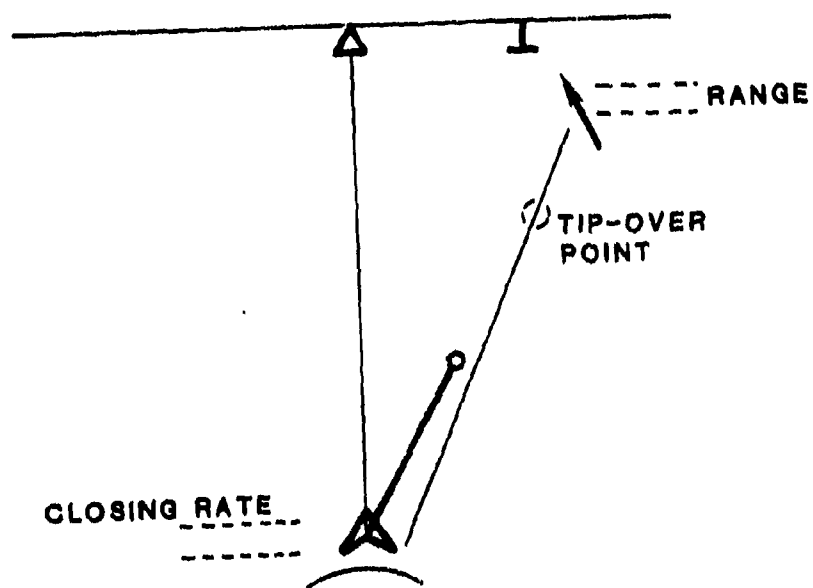Figure 8.  Velocity Vectors During Approach.
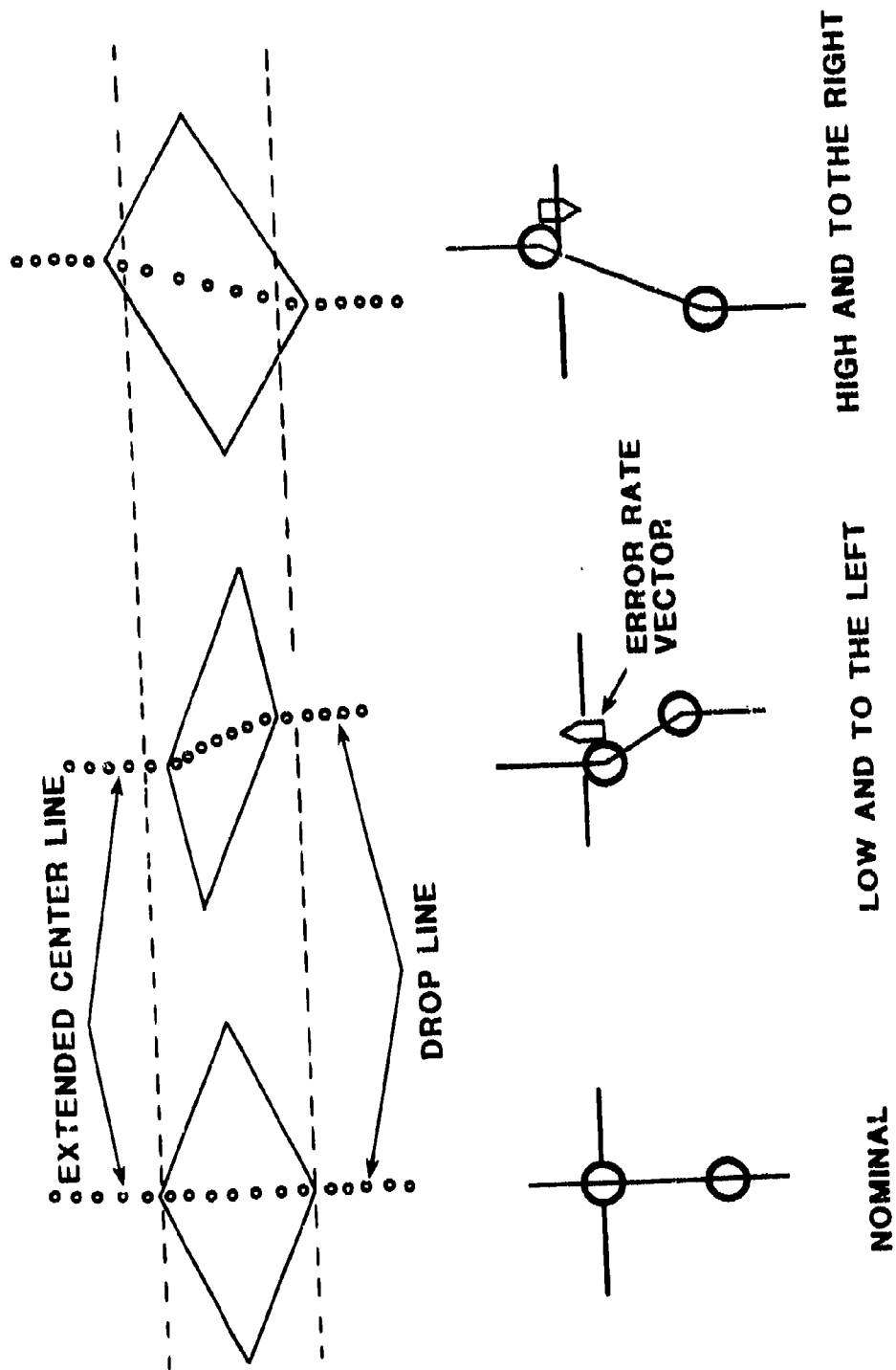


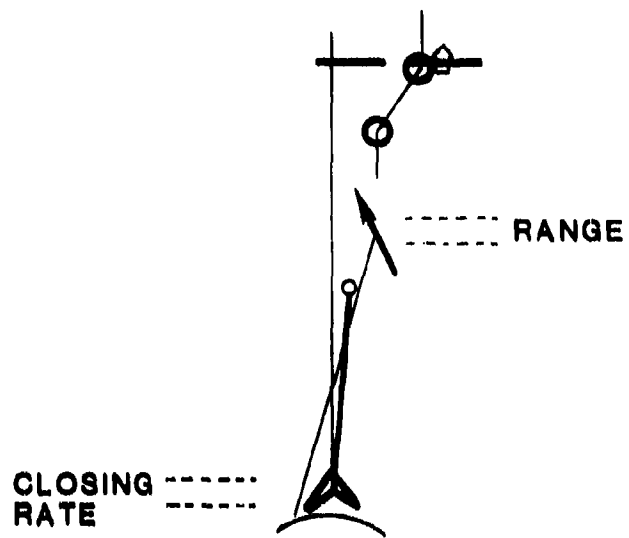Figure 9.  Approach Mode.

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Figure 10. Vertical Symbology.
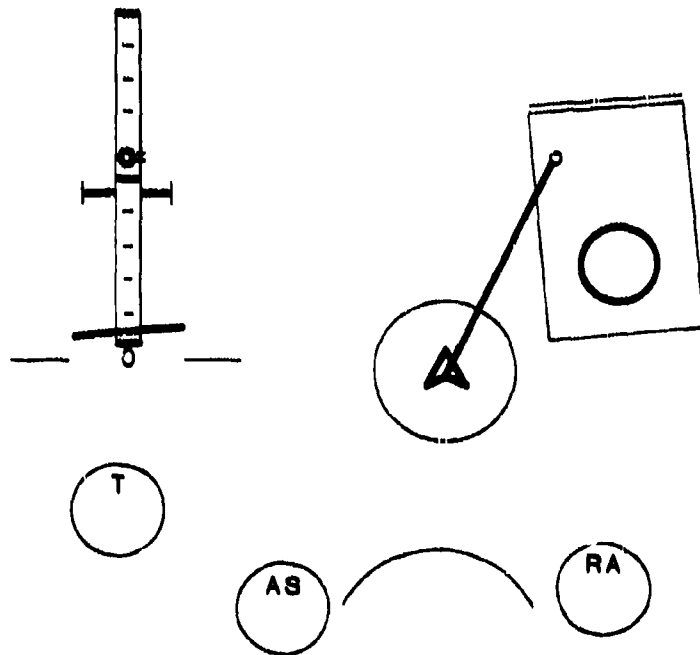
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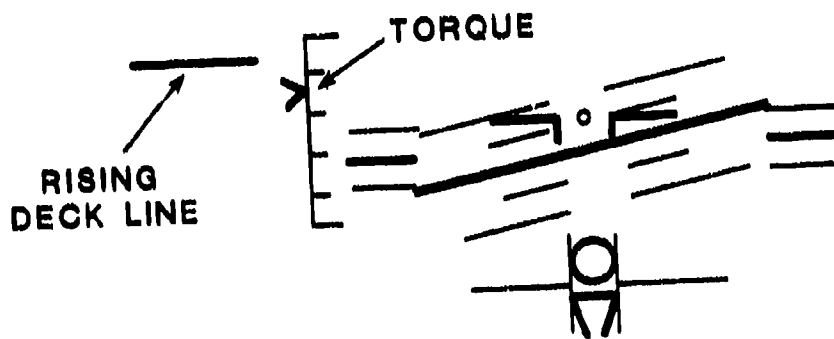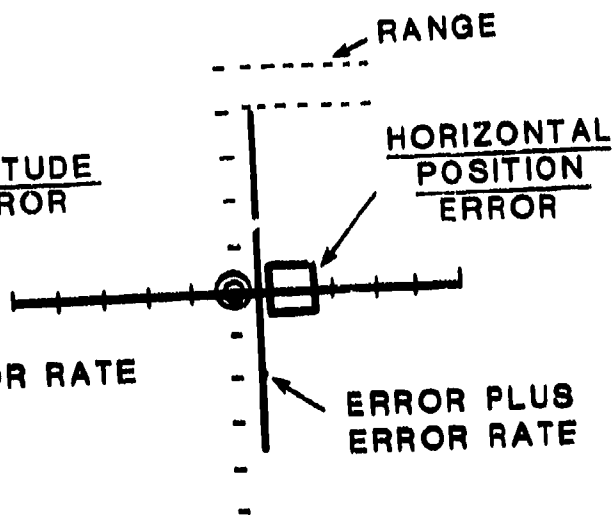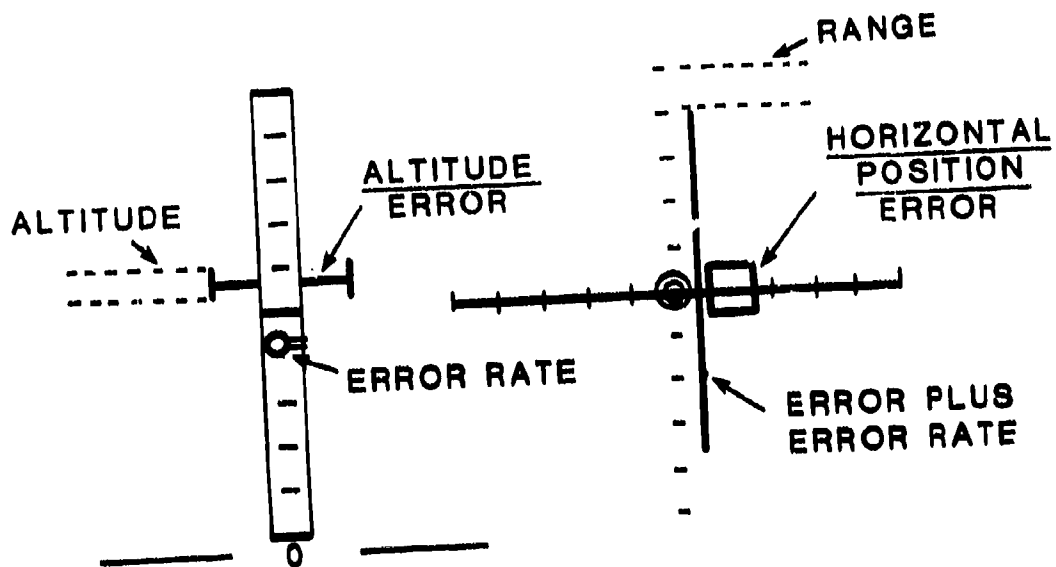Figure 11.   Approach Mode Near and After Tip-Over.



Figure 12.   Hover Mode.

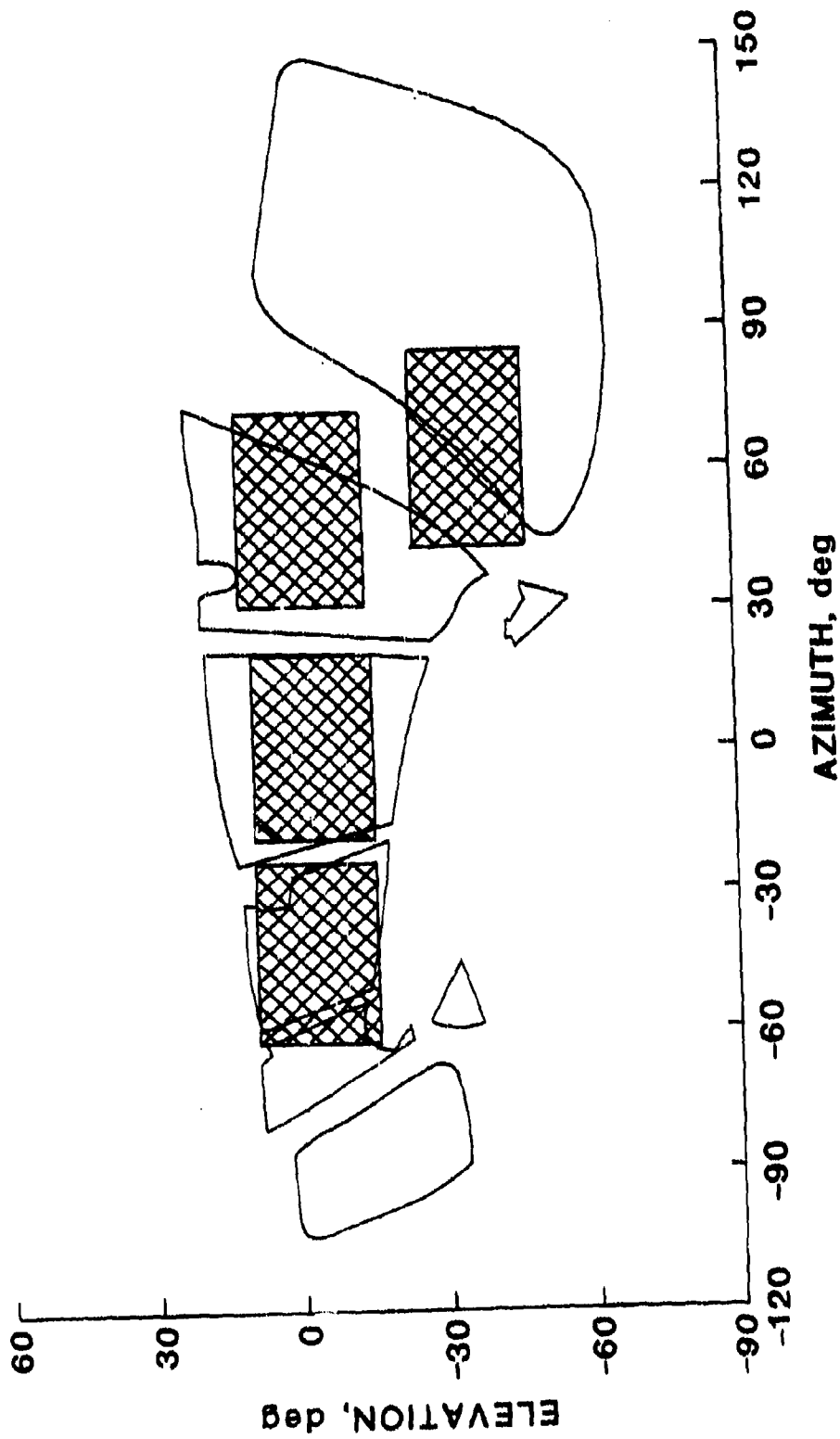Figure 13.  Minimal Display.

# BINOCULAR VIEW-NORMAL SEATING POSITION



Figure 14. Actual and Simulator Field-of-View From Right Seat of an SH-2F.

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# HEAD UP DISPLAY OPERATIONAL PROBLEMS

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## BACKGROUND

The head-up display (HUD) is an outgrowth of the reflecting gunsight of World War II. In such gunsights, the aiming symbol was generated as a beam of light, projected upwards from the top of the instrument panel, and reflected towards the pilot by a semitransparent mirror placed in his view through the windshield. If the design is correct, the pilot will see the symbol "floating" in his view of the outside scene. Several advantages arise from this type of gunsight: the aiming symbol can be moved to compensate for range, drift, or other factors; the image of the aiming symbol can be focused to form a virtual image overlying the target with no accommodation shift needed and eliminating parallax errors; and the brightness of the symbol can be easily adjusted to allow for variations in ambient light levels.

It takes no great amount of imagination to see the next step in the development of the HUD -- the addition of flight information to the virtual image. In fact, this can be our working definition of a head-up display: a cockpit display that presents flight data in the form of a virtual image in the pilot's view of the real world. The requirement for flight data disqualifies simple reflecting gunsights. The need for a virtual image eliminates such devices as angle-of-attack indexer lights or peripheral cues such as moving barber poles. As useful as these devices may be, they are to HUDs what iron sights are to lead-computing reflecting gunsights. Most such displays should be called peripheral cues, not head-up displays.

In the mid-to-late 1960s, the HUD was developed to the point where it could be included in the weapon delivery systems of military fighters. The first two significant US aircraft to use head-up displays were the A-7D/E (Corsair II) and the AV-8A (Harrier). Both of these aircraft are single-seat attack aircraft. In both cases, the driving

rationale for using a HUD was to upgrade the gun/bombsights used in previous attack airplanes.

The two HUDs differ from one another in their data presentations. The AV-8A HUD is a direct outgrowth of the early British approach to head-up displays which suggested that the symbology need not be conformal to the real world, but rather only an approximate overlaying of symbols and real world cues is desired (1). The primary symbol in the Harrier HUD is an "aircraft symbol" which indicates the pitch attitude of the airplane. The pitch and heading scales are compressed from the real world by a factor of 5:1.

The A-7D/E, on the other hand, derives its data from an inertial platform and the flight path data is scaled and presented so that it conforms to the real world cues. While the display references are conformal to the real world, this display can not be said to be a contact analog, but rather is a conformal, symbolic display. The primary flight symbol in the A-7 HUD is the velocity vector showing the aircraft's flight path.

In addition to other fighter/attack airplanes, certain C-130 and CH-3 helicopters have been equipped with HUDs as an aid in recovering parachute packages in mid air. These HUDs are electromechanical HUDs which conformal within the limits of the electromechanical display. They also include a director cue within the display designed to guide the pilot in flying a precise trajectory to a given point. The pilot superimposes the aiming symbol on the HUD with a target (a runway threshold or in this case a parachute) and flies the aircraft on a precise trajectory to the target.

The final HUD type, mentioned briefly above, is the contact analog. The major proponent of such a display is Klopfstein (2). In this display (a subtype of the conformal HUD), the display consists of realistic cues mimicking the real world cues -- such as an artificial runway. In the extreme, no quantitative data at all is presented, only the relationships between various angles gives the pilot his speed, altitude, and flight path cues. No operational aircraft, to our knowledge, uses this type of display.

Each of these HUD displays has proponents who can show by means of simulator and flight experiments that a particular design is superior for a given task. These experiments, particularly simulator experiments, do not adequately reproduce the operational environment. With this in mind, we set to use the very large store of HUD experience in the US military today as a means of examining the advantages and disadvantages of the various HUD designs presently in operational use.

This study was an outgrowth of an earlier survey by Barnette (3), who surveyed A-7D, F-15, and F-111 pilots. His conclusions were that there were problems with the instrument crosscheck between HUD and panel. This problem was made more acute by the lack of adequate HUD failure monitoring and the lack of required flight data. Barnette also reported that many pilots indicated an increased tendancy towards vertigo or disorientation while flying by reference to the HUD in instrument meteorological conditions. The flight procedures necessary to use the HUD as a primary flight reference were not adequately covered in the various publications and technical orders. Barnette concluded that "extensive research is required to determine if the HUD can be used as a primary flight reference system. In the absence of this research, the full potential of head-up display may never be realized."

A final factor influencing this paper was the long learning times noted in previous HUD flight experiments. In two particular evaluations, fairly long learning times had been noted for the pilots to reach steady state performance (4).

HUD SURVEY

The objective of the survey was to obtain from operational (as opposed to engieering) pilots their assessment of how well the head-up displays do their job of helping the pilot to fly the airplane. The survey was restricted to the so-called common modes of flight, not to tactical uses of the HUDs in weapons delivery. Over four hundred questionnaires were circulated to pilots flying HUD-equipped airplanes.

Because of the vast majority of HUDs today are in fighter or attack aircraft, most of the questionnaires were sent to pilots flying fighter or attack airplanes. A few were sent to pilots flying transports, such as the Lockheed Hercules (both military and civilian), the Boeing 737 and the Dassault Mercure. Some were also sent to pilots flying the HUD-equipped CH-3E (MARS) helicopters. The balance of this paper will concentrate on fighter/attack head-up displays.

The issues covered in these questionnaires included an estimate of the degree to which the responding pilot felt he used the HUD in various phases of flight and in various weather conditions. He was also asked to describe any

particular problems that he had encountered while using the HUD.

The remaining questions dealt with specific items of interest, his perception of HUD training, and his views of what data was required in a HUD to be used as a primary flight reference.

Additional follow-up questionaires and interviews were given to selected pilots during their first year of flying HUD-equipped aircraft. All of these pilots were Air National Guard pilots flying A-7D airplanes. This last effort was an attempt to determine if their HUD problems changed during their first two to three hundred hours as they became more experienced with HUDs.

Broadly speaking, the results can be divided into three general catagories: hardware-related, software-related, and procedural problems. The hardware-related problems most often reported by the pilots include an improper location of the design eye reference point (DERP) of the HUD and inadequate control of the brightness control, particularly at the minimum levels of brightness needed at night. Many pilots also commented that they would prefer a wider field of view.

The pilots complained that the location of the DERP was generally too low. It would appear that the location of the HUD exit pupil does not take into account the practice of fighter pilots sitting as high as possible in the cockpit to maximize their external field of view.

The brightness complaints generally are critical of the minimum useful levels of brightness. The intensity (at night) seems to go from "too bright" to "off." These hardware complaints appear for all of the HUDs in the survey and seem to be generic problems.

The software problems include complaints about the display dynamics, increased tendancy toward disorientation while flying with the HUD as the primary flight reference, and problems associated with flying the instrument landing system (ILS) approach using the HUD. Those problems will be amplified in the next section of the paper.

Procedural complaints include a lack of HUD checkout, the learning times necessary to reach steady-state performance, and a lack of procedures with which to fly the airplane by reference to the HUD. These too will be amplified later in the paper.

Details of the survey including the population sample, and the results are available (5).

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# HUD DYNAMICS

The response of the HUD symbols does not appear to be adequately controlled by the specifications. Typical descriptions by the pilots include expressions as "too sensitive" or "jitter." The present day HUD specifications do not address this issue, but simply describe the symbols as a "1:1 correspondence with the roll and pitch of the aircraft" (6). No mention is made of the dynamic response of the symbols. It must be emphasized that the description of any display cannot be of a static picture. The relative motion within the display in response to control inputs or disturbances must be shown as well.

According to the military standard for electronic and optical displays, the velocity vector is normally damped to make it usable, but the amount of damping is dependent on the system (7). This same document also states that the velocity vector should show the velocity vector of the aircraft center of gravity (cg). In tests reported by SAAB, the pilot's task is much easier if some display quickening is provided by having the symbol show the velocity vector some distance in front of the aircraft cg (8). In the case of the Viggin, a location eight feet in front of the aircraft cg was used. This, together with a pitch rate feedback, helped the pilot control the airplane much more accurately.

An additional complication is the lack of mechanical lags in electronic displays. Such lags are present in virtually all round dial instruments and their absence may explain the frequent comment of "too much jitter." This will also be a consideration as electronic head-down instrument displays become common.

The choice of a one-to-one scale for the primary symbol may not be optimum. The early British school suggested that some degree of pitch and roll compression provided for better tracking scores in simulator tests (9). In recent tests, reported by Monagan and Smith (10), indicates that the pitch scaling prefered by the pilots depends largely on the particular maneuvers being performed. One-to-one pitch scaling was preferred for the ILS task, while large amounts of pitch compression were chosen for large amplitude maneuvers.

In view of the lack of adequate control of the HUD dynamics by the specification, it is not surprising that

those HUDs which had the most complaints seemed to have some form of dissatisfaction with the response characteristics high on the list. It would appear that a better control of the display dynamics is required. Unfortunately, this is not possible at present without defining what is desired for which airplane and for which flight task.

Perhaps the most disturbing facet of this survey and Barnette's earlier survey (3) is the reported increased tendancy towards spatial disorientation. Approximately thirty percent of the responding pilots reported that the HUD tended to increase vertigo or disorientation. HUD-induced disorientation is reported to be common in a number of inflight situations. The most common of these is when flying the airplane in-and-out-of clouds. Another scenario involves confusing cues while flying the HUD on solid instruments in a strong crosswind. The lateral offset of the velocity vector was the cause in this situation. The other instances reported were the high susceptibility situations as night pull-ups, unusual attitude recoveries, formation flying, and air combat manuevering (ACM).

There may be several factors causing this potentially serious problem in the use of HUDs instrument flight. The primary cause of pilot disorientation is conflicting cues as to his orientation. A possible cause could be a subtle misalignment of the HUD cues with the real world cues. If the pilot has strong expectations that the HUD cue will overlie the real world, any misalignment may create a reduction in the perceived accuracy of either cue, possibly below the conscious level of perceiving the misalignment. If this is the case, then inertially driven HUDs could have a different degree of promoting disorientation. An inertial HUD should be much more accurate than an air mass HUD. However, if the inertial data doesn't satisfy the accuracy needs, then air mass data may induce less disorientation because the pilot may have lesser expectations and not have difficulty with misalignments. The question of pitch and roll compression should impact greatly on this issue.

Another factor is the reinforcement of the optokinetic stimulus by vestibular nystagmuc as a rapid roll is entered (11). This means that objects in the external field are clear while the instruments are blurred early in the roll. As the roll progresses, the opposite is true -- the external view is blurred and the instruments become clear. It is not clear what the effect of viewing a virtual image, part of which is attitude stabilized and part of which is not, during such a manuever.

Another factor that may be important in causing disorientation when flying by refernce to the HUD is the visual background, even if no alignment is possible. If a

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pilot flies through a cloud using the HUD, the background will be seen to be approaching rapidly. It is a well known illusion that if we remove a rapidly moving background, the remaining images will appear to move in the opposite direction. In our case, the HUD symbols would appear to recede from the pilot. A second factor was reported by Roscoe (12) who likened the problem to the moon illusion. While the HUD is focussed at infinity, the cloud may act as an "accommodation trap" making the pilot's eyes focus at a closer distance. This would make the HUD images appear to "bloom."

Other factors could influence the tendency toward spatial disorientation -- confusing backgrounds, the lack of a raster in a set of line images, lack of pilot confidence are amoung these. Again, further research is needed to quantify the problem and isolate the cause or causes.


## TRAINING ISSUES


It was apparent during the course of this study that very little attention is being directed to initial (or recurrent) HUD training for the military pilot. The overwhelming observation is that the problem is being ignored in both the airplane flight manuals and in instrument flight publications. The general apporach to HUD checkout in the airplane is to provide a brief description and a short cockpit orientation of the the switch locations. A significant problem with the use of HUDs may be the organizational attitudes of the particular units flying the airplanes.

Several particular HUD training problems were observed during this study -- the use of the velocity vector as a flight control parameter, the instrument procedures, and looking through the HUD.

HUDs have introduced a new dimension into flight control, the use of the velocity vector to replace or supplement aircraft pitch as a control parameter. This concept is a new one to most pilots and may not appear to be natural at first. This may create problems for those pilots trained in attitude flying. Unfortunately, many pilots do not realize that they don't understand the difference between flight patch and pitch reference. One pilot in our survey said "I know I'm nose high, but the velocity vector shows level flight." Several pilots who were followed during their first year of HUD flying appeared to change their control strategies with respect to the use of the

velocity vector as time went on. Some devloped problems with control strategies only after one or two hundred hours of HUD flying.

The second training problem involves just how to use the HUD. In some airplanes, the HUD is the primary flight reference, yet instrument procedures are taught using the conventional panel instruments. The instrument check flights may also be flown using round dials alone. Some pilots reported difficulties in switching quickly from flying a velocity vector and angle of attack strategy to a pitch attitude, vertical velocity, and airspeed strategy.

The use of the HUD has several facets that must be addressed during training. The student must be taught where and how to look at the specific cues of interest. He must also be shown how the HUD responds to control inputs and outside disturbances. It is instructive to compare the casual HUD training in the military with the careful instruction HUD vendors give during flight demonstrations and with the HUD training syllabus of Air Inter, the French airline using HUDs for category III operations (13).

The HUD would also be extremely useful during primary pilot training as a means of demonstrating the different concepts of pitch, angle of attack, flight path angle, and other control parameters. The pilots in our survey indicated that such a use of HUD would be quite beneficial. Although concern about the student pilot becoming overdependent on the display, there is some evidence that having been exposed to a HUD makes a more proficient pilot even after the HUD is taken away (14).

## CONCLUDING REMARKS

A number of operational problems associated with head-up displays have been identified. While we have identified problem areas, it must be remembered that the HUDs were generally so beneficial in helping the pilot fly better, that the pilots readily used the HUDs, problems and all. There is no question that many of the HUDs in use today, which were not designed for use as an instrument flight reference and which have certain deficiencies are better than many of our head-down instrument panels. The bottom line is that the pilots use HUDs because they work. Solving the few problems will make them work better.

Several areas are recommended for further research and development. A flight experiment is necessary to evaluate variations in the dynamic response of the display symbols in

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flight for various sets of flight manuevers and for various types of airplanes. The results of this experiment will enable us to write better specifications dealing with the dynamic response of HUD symbols. The same flight test could also evaluate the accuracy requirements (i. e. inertial versus air mass data) for HUDs. This experiment must be performed in flight since we can not fully model all of the dynamic cues in simulators. The DEFT NT-33 is an ideal vehicle for such a flight test (10).

At the same time, preferably in the same vehicle, we need to further determine what causes the increased tendency toward spatial disorientation. Again because of the many cues to be modeled, such a test must be conducted in flight.

The training to maximize the benefit of HUD use, both in terms of HUD checkout and in terms of primary pilot training should be examined. Procedures to maximize the ability of the pilot to fly using the HUD and still monitor his other instruments (and discrepancies in the real world) must be developed, evaluated and incorporated into our initial and recurrent training. The instrument flight publications must be updated to reflect these procedures.

In closing, we wish to emphasize that we were looking for problems. We found some. In spite of these problems, with the exception of certain head-up displays with obvious hardware deficiencies, the majority of the pilots surveyed used the HUDs because the HUD provided something they wanted. The bottom line is HUDs work and they work now. What we need to do is take a little time and make them work better.

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"LIGHT BAR" ATTITUDE INDICATOR


by Einar K. Enevoldson and Victor W. Horton

NASA Dryden Flight Research Center

For

"Fifth Advanced Aircrew Display Symposium"

At

Naval Air Test Center, Patuxent River, Maryland

# "LIGHT BAR" ATTITUDE INDICATOR

In November of 1979, the Wing Commander of the 9th Strategic
Reconnaissance Wing at Beale Air Force Base made an informal
request to the Dryden Flight Research Center for assistance in
easing the task of high altitude night flying.  The types of
aircraft being flown - the SR-71 and the U-2, are less tolerant
of attitude upsets than most.  In both aircraft, unusual attitudes
can develop rapidly while the pilot is coping with other dif-
ficulties.

The problem was discussed with the pilots at DFRC and Einar
Enevoldson recalled a Canadian magazine article describing
an installation in a helicopter for arctic night flying.  We
later discovered that this was a description of an instrument
developed by Dr. Richard Malcom.  To achieve the same result as
Dr. Malcom's instrument - the projection of an artificial
horizon across the instrument panel for pitch and roll information,
DFRC modified a standard four inch ADI.  A light bulb was put
in the center and a thin slit out on the horizon.  This resulted
in a thin horizontal sheet of light projected from the instru-
ment.  We had used a similar instrument in 1968 as an aid in
simulator flying (figures 1 and 2).

Because of a lack of priority, funds and official program status,
it was mid-February 1980 before we had an instrument installed
in the ground cockpit of a remotely piloted (RPV) Piper PA-30.
The instrument was mounted beside the pilot's head and projected
its light beam on the instrument panel.  This proved to be an
aid in flying the RPV.

About two weeks later, we heard of Dr. Malcom's work with the
Varian of Canada Corporation, through Lyle Schofield of the
Air Force Flight Test Center.  We then invited him to observe
a PA-30 flight using the instrument.  Varian, incidently has
the patent rights on the concept.  Subsequent to this, we
installed it in a Cessna T-37 jet trainer, attached to the canopy
between the two pilot's heads.  The first flight was made on the
night of April 9, 1980.

The intensity of the projected beam is such that it can only be
seen in a darkened room or at night.  Figures 3 through 7 show
the beam on the instrument panel of the T-37, depicting various
attitudes.  The aircraft's attitude indicator does not correspond
to the attitude shown by the light bar as the pictures were taken
on the ground.

We have since demonstrated the Light Bar A.I., as we call it, to approximately 50 pilots of varying backgrounds, SR-71, U-2, A-10, Test Pilot School instructors, Brooke's medical staff, Human Resources Lab staff at Williams AFB, the Navy Post Graduate School staff, and one Navy pilot. We have not had any adverse comments and most of them have been enthusiastic.

A summary of pilots' comments are:

(1) A 1/4 inch high beam with sharply defined edges is desirable.

(2) A dimmer for light beam intensity is required to accommodate ambient conditions.

(3) The center of rotation of the roll axis should be located in front of the pilot, otherwise roll appears as pitch.

(4) A means of slewing the beam vertically is required to position it on the desired location on the instrument panel or canopy bow when flying formation.

(5) It eases pilot workload generally and allows constant monitoring of the performance instruments.

(6) There is a need to investigate reduced gearing in the pitch axis in order to maintain the beam's position on the instrument panel.

Some possible uses for such an instrument to ease the pilot task are:

(1) High altitude flying, both night and day.

(2) Low level night or weather penetration.

(3) Night dive bombing under flare lighting (bright light into darkness on pull-out).

(4) Night carrier landings.

(5) Formation flying at night or in bright haze.

(6) Aerial refueling at night or in bright haze.

(7) General I.M.C. flying both "up and away" and on approaches.

Two potential problems exist in using the device:

(1)   Because of the ease in flying instruments with it,
      a pilot might become complacent.  It is our belief
      that the light bar should be used as a supplement to,
      and not a replacement for the "8-ball" and when an
      "off condition" is detected, an immediate transition
      should be made to the A.D.1., or basic instruments
      for recovery.

(2)   An upright-inverted ambiguity exists with our instru-
      ment  which we realized, and which resulted in one
      pilot recovering from an unusual attitude inverted.
      It is our opinion that traditional instruments,
      especially the "8-ball", offers the best upset
      recovery assistance.

DFRC wants to stress that our instrument is a conceptual dem-
onstrator only.  Although it has several shortcomings, it has
been sufficient to generate interest within the Air Force
so that several evaluations of the Varian instrument are being
conducted.

To adequately demonstrate that the system provides the expected
benefits:  eased piloting task, improved sense of vertical,
resistance to disorientation, is no doubt a formidable task.
However, our experiences lead us to believe that a thorough,
proper evaluation should be done.  The system tends to generate
enthusiasm which may be based on its novelty.

The Dryden program was to demonstrate the concept only, not
to develop an instrument, and we feel that this has been
accomplished.  We will continue to use the instrument as an
aid in the remotely piloted research aircraft ground cockpits
and fly it in the T-37 as necessary.

12.5 WATT BULB
(2 1/2 amp 5V)
Straight Element
Element aligned
with slit
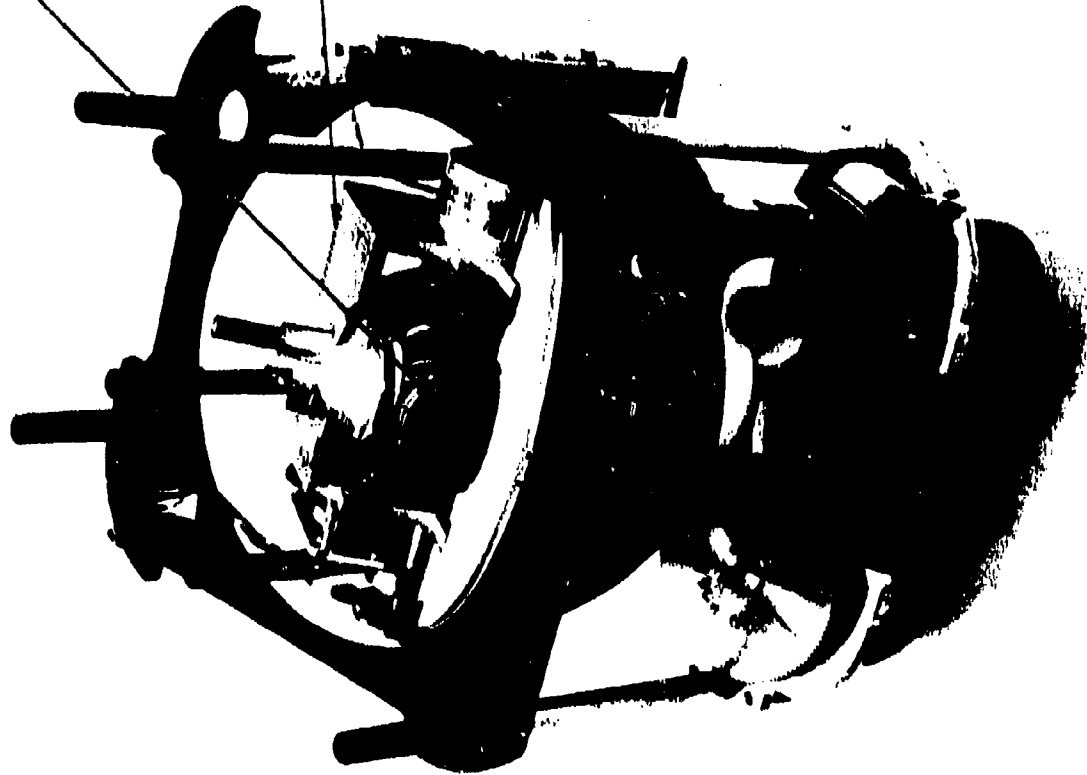
BALANCE WEIGHT
To counteract
azimuth removal



Figure 1

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Hugh L. Dryden Flight Research Center
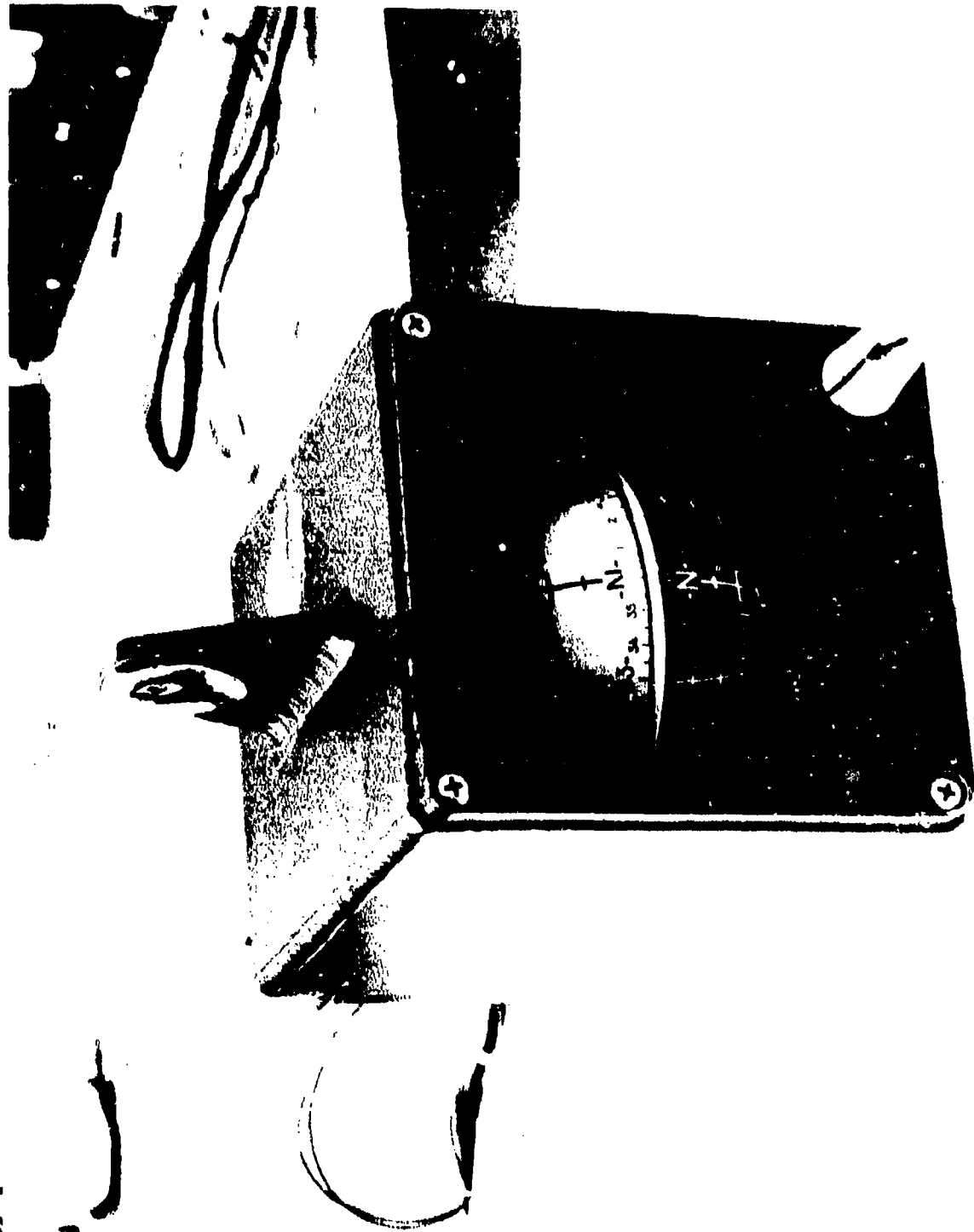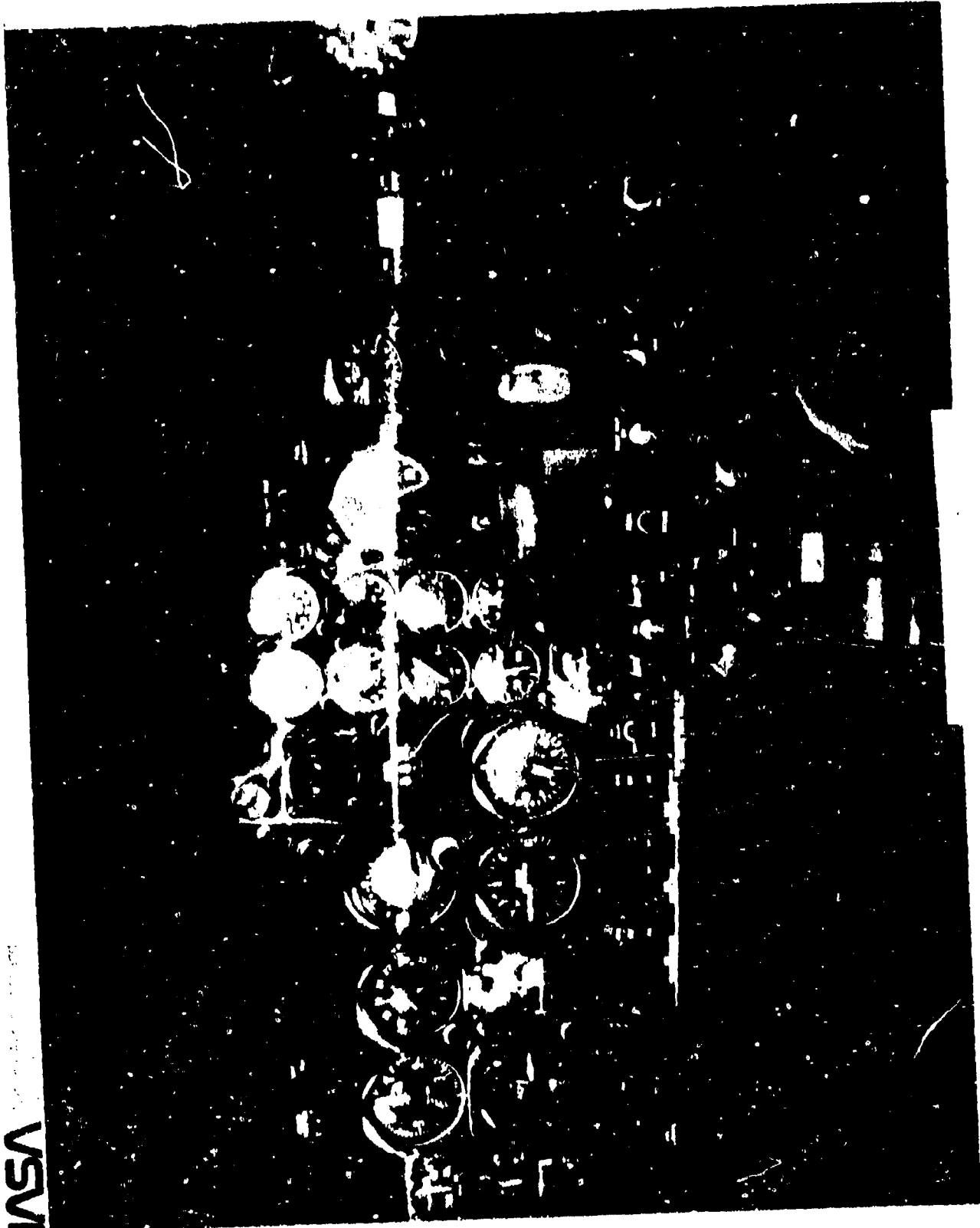
NASA

Figure 2
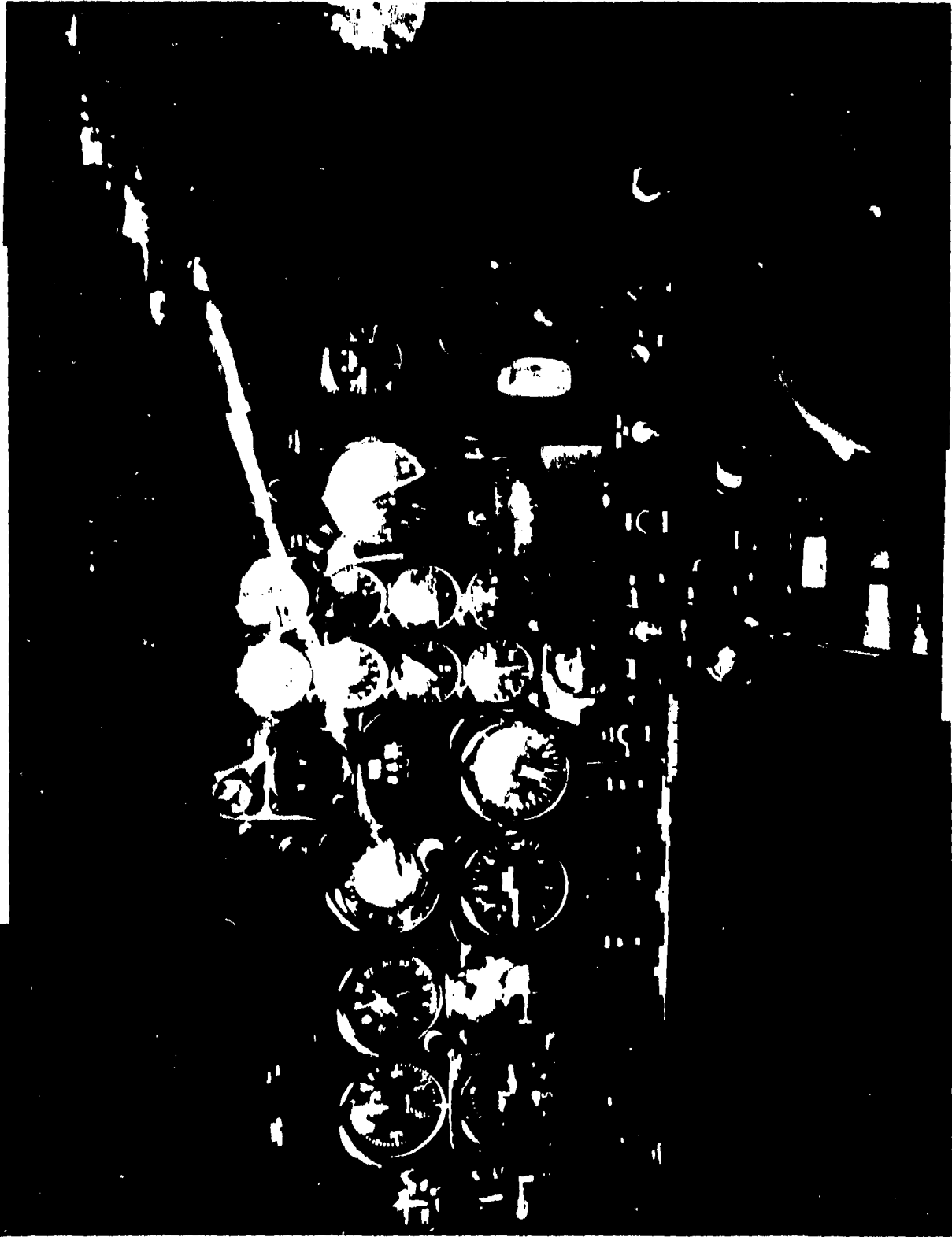
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