To the Graduate Council:

I am submitting herewith a thesis written by Michael Sean Murphy entitled "The Use of Analog and Digital Presentations of Altitude on the Head-Up Display of Tactical Jet Fighters." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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We have read this thesis and
recommend its acceptance:

Uwe Peter Solies

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

THE USE OF ANALOG AND DIGITAL PRESENTATIONS OF ALTITUDE ON THE HEAD-UP DISPLAYS OF TACTICAL JET FIGHTERS

A Thesis
Presented for the
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Degree
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Michael Sean Murphy

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Abstract

The pilot of a modern tactical jet fighter is responsible for monitoring a significant number of variables and displays throughout a flight, but among the most critical are basic flight conditions, including aircraft altitude. A generation ago, the means for communicating that altitude information to the pilot was fairly well standardized in the pressure altimeter. However, with the advent of computer-generated displays, especially the Head-Up Display (HUD), the format options have increased dramatically. Unfortunately, the process for selecting a format has differed substantially among the various aircraft, and the result is a wide range of displays in current use, even among aircraft with similar missions. While some display types can be shown to be more effective than others, the application of objective human factors findings to the display design process has sometimes been inadequate.

One of the basic decision points for HUD design involves the selection of a digital altitude display, an analog one, or some combination. In this study, previous laboratory research into the appropriateness of digital and analog display types for flight tasks was investigated. Operational studies and personal observation were also utilized. It was found that both theoretical research and practical experience call for the incorporation of rate-of-change information through an analog presentation as part of the altitude display given to the pilot. An existing military specification does in fact endorse this conclusion, yet it remains to be implemented in some current aircraft. A recommendation is made to standardize the altitude displays of tactical jet aircraft in a combined digital and analog format, sometimes called a "counter-pointer" display. Suggestions are also made for strengthening the method by which human factors and other scientific findings are assimilated into the military acquisition process.

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Chapter 1

Introduction

Flying tactical jet aircraft is an inherently dangerous occupation. Aside from the obvious risks of combat flying, routine training poses its own dangers. This is especially true during that training which replicates combat missions: examples include low-level terrain avoidance and steep angle dive bombing. While the challenge of navigating the aircraft safely in such scenarios is in itself significant, the pilot must simultaneously manage an ever-increasing number of sophisticated weapons and communications systems. This leads to further demands on the pilot's time for tasks not directly related to flying the aircraft, and to a greater need for making his piloting as efficient as possible.

As aircraft and weapons capabilities have grown, information management has become more and more critical: because of the amount of data which the pilot must monitor and process, the presentation of that data (especially safety of flight information) must be done in the most efficient and intuitive method available.

This need for maximizing the pilot's situational awareness is not new, just more urgent. Flight mishaps due to human error (of which pilot error is a major subset) continue to plague all of aviation, not just military organizations. Edwards (1995) baldly states that it is now "universally acknowledged" that human error is the primary cause of 70% of all aircraft accidents, that this has been true since the 1940s, and that not enough resources are being invested to improve that statistic.

Among flight parameters, altitude information is surely one of the most important. Indeed, a sizeable number of these mishaps, in both the military and non-military worlds, are classified as controlled flight into terrain (CFIT) incidents. Within the military services, there is a growing awareness of the seriousness of this particular issue. Over a recent eight-year period (October 1989 through September 1997), fully 15% of the major aircraft mishaps for U.S. Navy tactical aircraft were attributed to CFIT. Clearly, every effort should be made to optimize the pilot's altitude and vertical velocity awareness, as significant contributors to overall situational awareness.

The variety of different altitude presentations in the electronically-generated displays of fighter aircraft suggests that the best possible choice is not always being used. The purpose of this review is to determine the most desirable format for the presentation of altitude information on a Head-Up Display (HUD) to the pilot of a contemporary fighter aircraft, and to survey those display formats in use by current military aircraft.

Chapter 2

Historical Overview of Flight Data Display Methods

The pilot's determination of aircraft altitude as well as many other parameters can be done conceptually in a number of ways. Koonce, Gold, and Moroze (1986) describe a continuum of display methods, illustrated in Figure 1, which range from real-world visualization (most concrete) to a purely symbolic alphanumeric display (most abstract).

In the earliest days of flying, altitude and other flight variables were assessed simply by looking about—a very concrete, although not especially precise, method. As the need for greater precision arose, flight deck instrumentation appeared, and eventually cockpit altimeters attained a fairly uniform design. This analog pressure altimeter (illustrated in Figure 2) was, and still is, familiar to generations of pilots, although some of the particulars such as the number of pointers have varied from model to model.

Outside view	→	Pictorial representation	→	Analog display with similar motion	→	Symbolic display

Most concrete -- *Most abstract*

Figure 1. *Continuum of display methods for physical parameters, as described by Koonce, Gold, and Moroze (1986).*

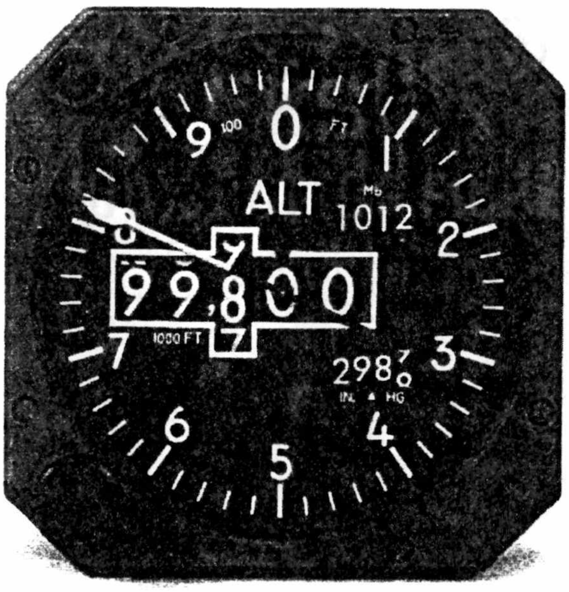

Figure 2. *Typical aircraft pressure altimeter.*

With the advent of electronic data processing and data transfer technologies, flight displays changed dramatically. The earliest HUDs appeared in the 1950s as Visual Flight Rules (VFR) landing aids for pilots of early tactical jet aircraft (Egan and Goodson, 1978). Their purpose was to overcome the difficulty of adjusting to this much more dynamic environment, and to assist the pilot by reducing the workload involved in combining instrument and outside-the-cockpit visual information. Once this premise was demonstrated, it quickly became evident that there were potential benefits in many other flight regimes (Instrument Flight Rules (IFR) to VFR transition, and weapons delivery, to name two). The underlying principle was that the more the pilot's outside-to-inside scan requirements could be minimized, the better his performance would be.

As computer and data transfer capabilities expanded, the numbers and kinds of information considered for presentation on the HUD likewise grew. Today we have such an abundance of data—aircraft performance, navigation, weapons employment, and external threats—available simultaneously that the management and integration of that information becomes the primary problem from the human factors design viewpoint. It has been pointed out (Lovesey, 1995) that while the amount of information available increases apparently without limit, the processing capacity of the human operator remains essentially constant. The chances of saturating the pilot increase.

Frequently that data has been presented abstractly, using alphanumerics and other conceptual symbols. Koonce et al. cite an earlier study (Leplat and Pailhous, 1971) which suggests that the more abstract the presentation, the more decoding of the information required by the operator, and the more time required to analyze and respond. The advent of computer processing in the information display process has pushed us farther to the right on the Koonce continuum (more abstract), increasing the workload. One contributing factor to this trend has been the technical limitations (memory space, processing speed, character generation capabilities) of earlier hardware and software. Simple symbolic displays were dictated by these limitations. On the other hand, the tremendous increases in processing capacity seen in recent years may now allow us to move somewhat back to the left by generating more pictorial and less abstract displays, thus reducing the interpretive burden placed on the pilot.

The following chapters examine the most common altitude displays presently seen in electronically-generated cockpit displays, and then attempt to assess their utility for the fighter mission.

Chapter 3

Discussion of Altitude Display Types

Overview

Formats for cockpit altitude display can be conveniently broken down into three main groups: digital, analog, and combination forms. The analog group includes a variety of rotating pointer, dial, and moving tape displays. Each of these types will be examined individually, with their advantages and disadvantages, and then their application and suitability for the fighter mission will be discussed.

In all cases, and by general agreement, the altitude presentation is placed on the right side of the HUD mirroring the placement of the airspeed display on the left side. Usually, but not always, the format chosen for the airspeed display will match that of the altitude. Figure 3 presents a typical HUD display, showing the orientation of the altitude presentation relative to the other display elements. Note the similarity between the airspeed and altitude display styles, and their symmetry about the center axis of the full display.

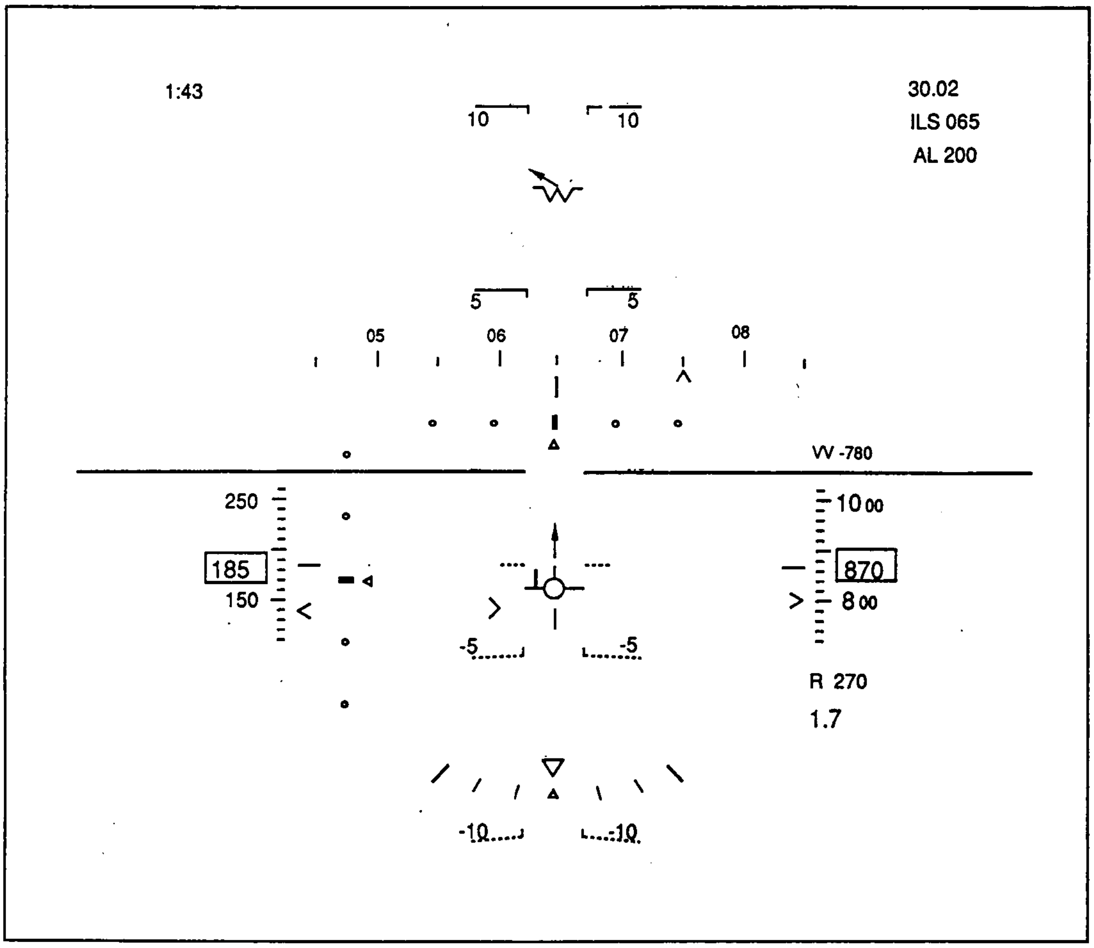

Figure 3. *Typical Head-Up Display arrangement. Altitude is shown to the pilot on the right side of the display.*

Digital Only Formats

The most straightforward means of displaying quantitative altitude information is simply to present it numerically. An example taken from a current fighter aircraft (the F/A-18) is illustrated in Figure 4. Here, the presentation resembles that of a mechanical counter (such as an automobile's odometer), but without the disadvantages associated with the mechanical rotation of the drums, such as an ambiguous display when one digit has partially advanced.

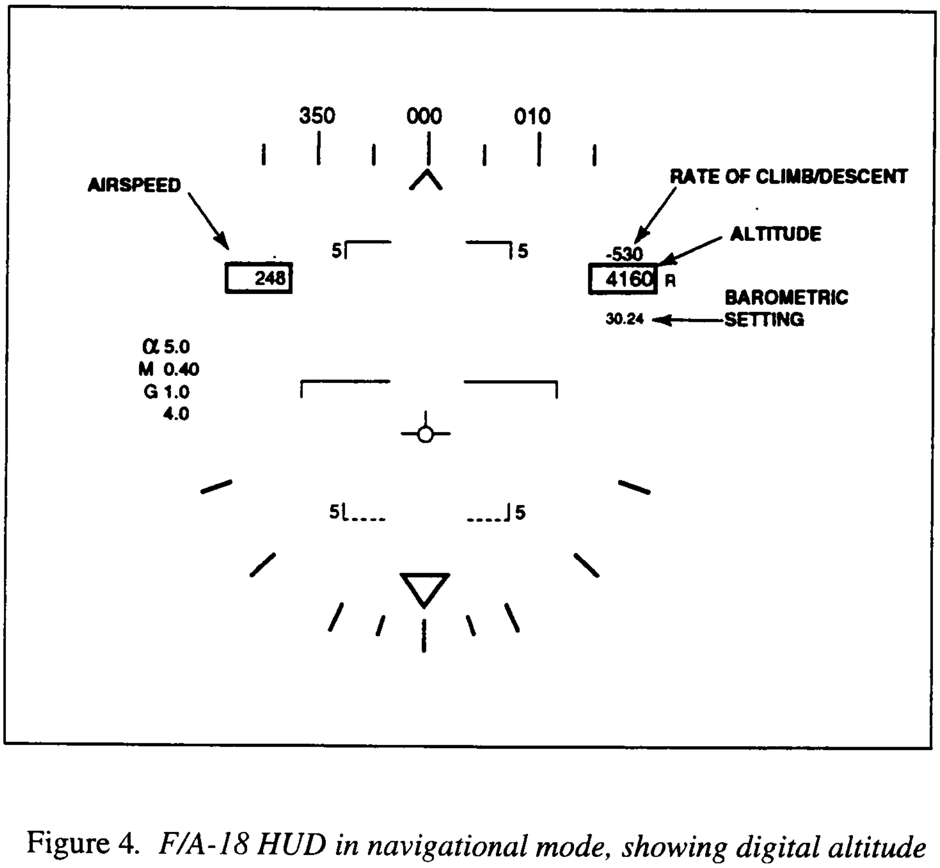

Figure 4. *F/A-18 HUD in navigational mode, showing digital altitude display.*

Because the display is electronically generated, it may be redrawn nearly instantaneously, and the update rate may be set to be as frequent as desired. The most common algorithm displays altitude to the nearest ten feet (the final digit is always zero), and has an upper bound on the update rate to avoid digits changing so rapidly that they become unreadable. Some applications have boxed the number in order to allow the pilot to locate and to focus upon it more rapidly; other applications omit this.

At least three advantages are apparent with the purely digital display. First, it can display data to whatever level of precision is desired. This may be of importance where very precise altitude measurement or control is required, such as in a precision approach to weather minimums, or while conducting flight testing. One must utilize caution here, however; it is possible that the precision with which altitude information is being displayed is greater than the precision of the measurement itself.

A second advantage is the reduced risk of ambiguous reading of the data. Assuming the font used for the digits has been carefully selected, there is little chance that, once read, this data will be misinterpreted. A technique used in some aircraft displays to enhance further this clarity is to emphasize by size the thousands (and ten-thousands) digits when above 1000 feet altitude. This is illustrated in Figure 5.

850	**8500**
(Altitude below 1000 feet)	*(Altitude above 1000 feet)*

Figure 5. *Altitude discrimination above 1000 feet in a digital presentation.*

This is intended to overcome a problem occasionally seen in certain analog displays, particularly those using a circular scale. A classic error has occurred in the reading of the standard circular dial pressure altimeter, where a casual reading by the pilot can result in a misreading by a multiple of one thousand feet.

Finally, the purely digital display has the advantage of greater display flexibility and ease of programming. No complicated graphics are required, and processing time and memory requirements are minimal.

There are notable disadvantages, however, to a purely digital altitude display. The most obvious to the pilot is the difficulty of determining rates of change and trend information. Kantowitz and Sorkin (1983) attribute this to the requirement to perform an abstract calculation (differentiation). They also point out that check reading—the determination of whether a parameter such as altitude is within predetermined limits—is much less successfully assigned to a digital display than to an analog dial. This has been quantitatively confirmed by Hanson, Payne, Shively, and Kantowitz (1981). Such a conclusion is easily understood when one considers that the more pictorial analog presentation can provide a visual reference to the acceptable limits of a variable, whereas the digital display demands the maintenance of a mental model and constant recalculation of the proximity of the current value to the limit value.

Analog Only Formats

A number of approaches have been taken to present altitude information in an analog format. Several of these are variations on the construction of the classic pressure altimeter. Others take a linear (usually vertical) approach; this includes the "thermometer" and "moving scale" types.

The most obvious design would simply replicate the features of the pressure altimeter in an electronically-generated format. This would allow the greatest transfer of learning from older, non-HUD equipped aircraft and trainers. Unfortunately, the size and complexity of such a display make it prohibitively expensive in terms of computational requirements, and defeat the general purpose of a HUD, which is to present essential information in as concise a display as possible. There are no production aircraft which have attempted this solution.

The next step, then, would be to "stylize" the display, retaining its essential features, but with a minimum of detail. One possible result is a presentation such as that shown in Figure 6. In this illustration, altitude is determined by the position of the pointer on the circle: each tick mark represents one hundred feet, and one complete revolution equates to one thousand feet, just as on the standard pressure altimeter. It should be noted that such a design has rarely, if ever, been presented alone as a purely

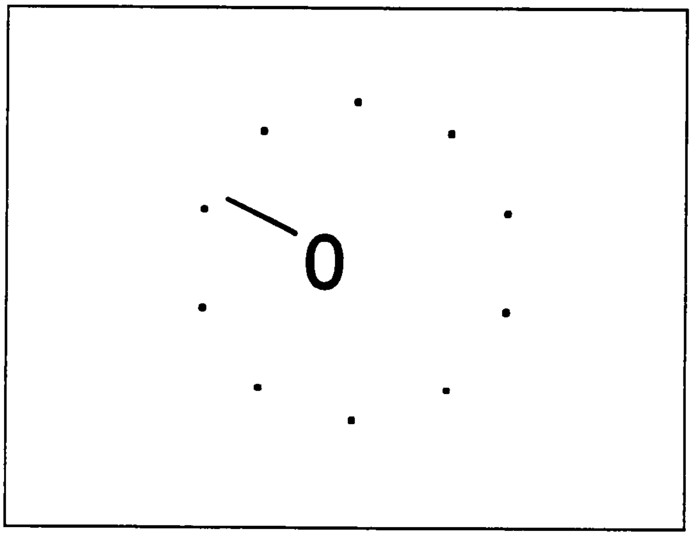

Figure 6. *Representative analog altitude presentation.*

analog display; invariably, a digital counter of some sort is presented within or nearby to allow unambiguous determination of the thousands and tens of thousands of feet.

A different approach for portraying analog altitude data is to convert from a circular to a linear scale. One popular implementation of this is illustrated in Figure 7, and is taken from the HUD display of the F-16C. Here, altitude is determined by reading the pointer against the moving scale, or tape. The tape is marked in 1000 foot increments (a smaller scale with 100 foot increments is used for the approach to landing configuration).

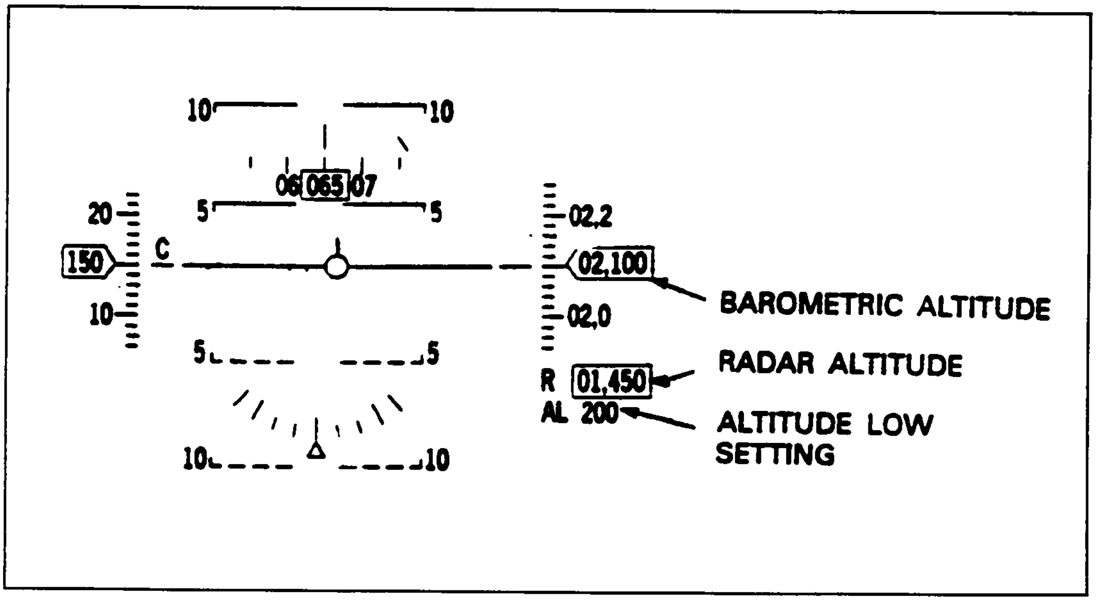

Figure 7. *Analog altitude display of the F-16C HUD.*

There are drawbacks to this approach: because only a portion of the scale is visible at any given time, there is no absolute reference with which to compare the current position of the pointer. Also, the fixed pointer, moving tape design was selected to accommodate the large range of possible values for altitude, but the moving tape itself can be difficult to read, especially when altitude is changing rapidly. One study (McBride, 1990) examining such a display for flying instrument approaches in the F-14D found that pilots rarely used the tapes to determine altitude, instead relying on the accompanying digital display. No assessment was made of the usefulness of the moving tapes in other flight regimes. Also noteworthy is the decision (McDonnell Aircraft Company, 1987) to eliminate such a display (used in earlier models of the F-15) in the F-15E, replacing it with a digital counter presentation similar to that of the F/A-18. The rationale given was "elimination of clutter."

A less recent implementation of an analog display is that of the A-7 (Figure 8). This design uses a thermometer display concept, where increasing altitude is represented by an ascending vertical bar. The total height of the scale represents a range of 1000 feet; the number of thousands and ten thousands is given digitally below the thermometer. The great disadvantage to this design is similar to that of the moving scales: there is no absolute reference to zero. Moreover, there is no graceful transition as the altitude ascends or descends through an even thousand of feet. The

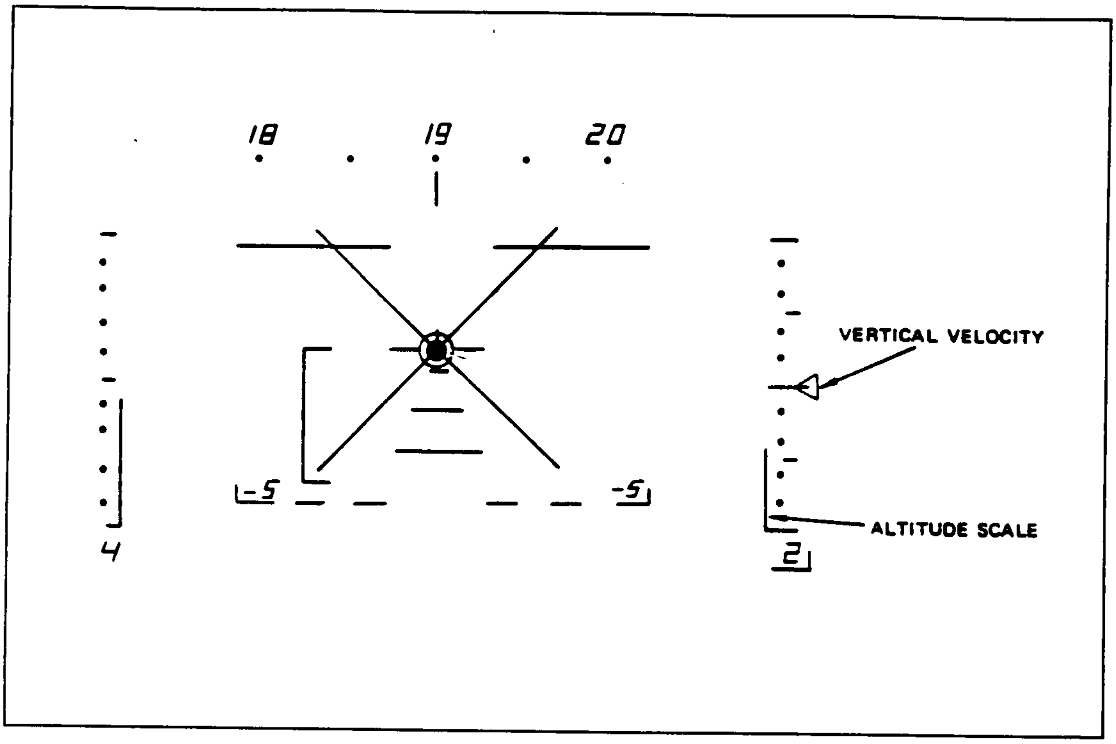

Figure 8. *Analog altitude display of the A-7E HUD.*

vertical line must leap from full scale to relative zero or vice versa, while the counter increments or decrements. Clearly, this is distracting when flying level at an exact multiple of 1000 feet, for the display must alternate constantly between full deflection and zero deflection as actual altitude varied randomly about the nominal value.

Other analog designs are possible as well. There are certain characteristics, however, that are common to all, including some important inherent advantages. First is the correlation of the display to the actual physical parameter which it is representing, i.e. height above the ground. For all types of analog displays, a given altitude has a corresponding physical "picture": position of a pointer on a dial, elevation of a bar in a thermometer, position of a moving scale. And as the aircraft's altitude changes, the picture changes as well: the pointer rotates, the thermometer rises or falls, the scales move. This places the presentation closer to the more pictorial, less abstract side of the spectrum described by Koonce et al. (see the discussion in Chapter 2). Their research, as well as that of others (e.g. Boles and Wickens, 1987), suggests that these displays can generate better performance than more abstract ones by requiring less interpretation on the part of the operator.

Secondly, all methods of analog presentation of altitude make trend information available to the pilot, without the need for abstract calculation. The rate at which the pilot's picture on the HUD changes is directly proportional to the rate at which the aircraft is ascending or descending. Depending upon the phase of flight, this trend information can be highly important: one example would be the final approach turn to landing flown by Navy carrier pilots, in which very precise control of altitude and rate of descent is demanded.

Finally, an analog display has been shown to enable faster response time by an operator conducting check-reading tasks (Kantowitz and Sorkin, 1983). Mital and Ramanan (1986) point out that such check reading tasks, by their nature, normally require that errors be detected as quickly and as accurately as possible, and that decades of research have demonstrated that an analog presentation (usually dial-and-pointer type) is best suited for such tasks. In a fighter aircraft, such a situation occurs frequently, as while maintaining an assigned cruise altitude or while maintaining a prescribed height above ground during tactical low-level navigation. In such environments, the pilot is frequently highly task-saturated, and any excess time spent in altitude check reading is time lost for other mission tasks.

Purely analog displays are not without their disadvantages, however. Most obvious is the lack of precision generally common to all. Because of the range of values for altitude which the display must accommodate (zero to tens of thousands of feet), it is not possible to show a reading to the precision which may be available from the aircraft sensors (ten feet or less), without making the display so large as to clutter the HUD. In addition, the variety of display options, shown in the illustrations above, creates an element of non-standardization and requires some amount of training and habituation to change from one aircraft to another.

Table I summarizes the strengths and weaknesses of digital and analog displays in general.

Combination Forms

Given the deficiencies inherent in both purely analog and purely digital altitude display formats, it seems only natural to attempt to combine the two in order to capture the benefits of each. And in fact, most analog displays, including the standard instrument panel pressure altimeter, incorporate already some amount of digitization for the sake of clarity. Figure 9 illustrates one possible design for a combined analog/digital display. (This is the format eventually chosen by the Navy for the HUD in the F-14D.)

Table I. Characteristics of Digital and Analog Displays

Type of Display	*Advantages*	*Disadvantages*
Digital	Greater precision Minimal ambiguity Ease of programming	Absence of trend data Difficulty in check reading
Analog	Match of sense to real world Intuitive trend information	Possible insufficient precision Non-standardization

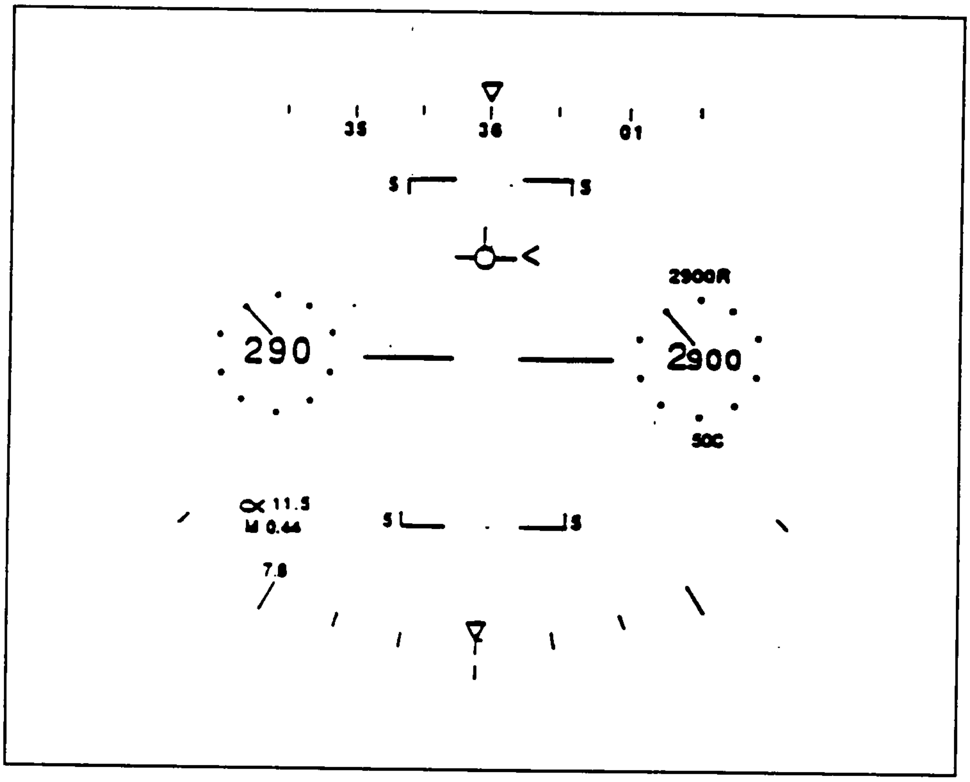

Figure 9. *Combined analog and digital altitude display.*

In this design, a digital counter is centered within a circular scale, with a pointer rotating within the scale to give an analog presentation of hundreds of feet. One complete revolution of the pointer corresponds to an altitude change of one thousand feet. As with other analog displays, rate of change is easily assessed by observing the rate of movement of an indicator within the display (in this case, the movement of the pointer); in addition, however, precise altitude data is always available when required by reading the counter. This would seem to offer the best of both worlds, and in fact

Oborne (1987, p. 118) cites an early study by Rolfe (1969) in which check reading performance was increased by 30 percent by using a combined display (counter-pointer) over a purely analog display.

Some concerns must be addressed in designing a combined display. One danger is the tendency to give the pilot too much information, or to clutter the HUD display to the point of distraction and decreased performance. (Scott (1995) describes this "kid in the candy store" approach, in which almost limitless options in systems functionality and displays are made available, as a real safety issue.) Also, research has shown (Legg and Williams, 1973) that combined displays in which the analog and digital portions are physically separated generate unfavorable reactions from those operating them, and that the advantage provided by the additional information is at least partially offset by the greater scan requirement. Noteworthy, too, is Oborne's finding (p. 118) that given a choice between an "open" analog display, such as a dial with a pointer on the outside, and a "closed" display, such as a dial with a pointer on the inside, the closed version is more effective. He believes this conforms with the "Gestalt principle of closure—that a solid boundary leads to more efficient perception because it gives the appearance of a 'whole.'"

Chapter 4

Assessment of Task Performance Using Analog and Digital Displays

Results of Previous Laboratory Research

It would appear from the discussion above that, while each type of altitude display has its advantages and disadvantages, a combined analog and digital format has the potential to be most effective to the fighter pilot. The theoretical research cited suggests that quicker accession of rate-of-change information and a more intuitive display should allow the pilot to respond more rapidly to an altitude or vertical velocity situation which requires correction. The drawbacks to an analog format (less precision, less commonality) are remedied relatively easily (incorporation of a digital counter in the center of the analog dial provides precision when required; standardization among the military services of a single display type for similar aircraft would solve the commonality problem).

The work of several researchers appears to substantiate this claim. Hanson et al. (1981) have confirmed the "vast superiority" of analog over purely digital displays for tasks requiring check reading or rate of change estimation. They also counter the argument that this apparent disadvantage of digital displays can be overcome through training, by demonstrating that an "additional transformational load" is placed on the operator in processing the digital data, a mental tasking which cannot be eliminated by any amount of exposure.

Equally emphatic are Payne and Gunther (1987) in their assessment of analog versus digital displays. They cite their own work as well as that of Hanson et al. and Koonce et al.: "Thus three separate studies provide converging evidence that analog displays are monitored more efficiently than are digital displays." The Payne and Gunther experiment involved subjects monitoring an indicator (digital or analog) and resetting it when a threshold was exceeded; reaction time was measured, as was the error rate (an error being defined as resetting when a threshold had not been breached). Interestingly, the researchers found not only a faster mean response time, but also a higher error rate, for the analog indicator. Their initial hypothesis was that this represented an operator trade-off between speed and accuracy, but further investigation showed that these errors appeared to come when the subject was "predicting" an impending threshold crossing. They conclude that this actually demonstrates better comprehension of the data by the subjects in the analog test, since they were able to analyze trend information as well as instantaneous data.

Finally, a recent study by Payne, Lang and Blackwell (1995) reinforces the assertion of analog preference. After combining their results with that of several previous investigators, they offer: "It is important to note that an analog superiority has been obtained using a number of different tasks (e.g. discrete trials vs. continuous monitoring) at different levels of task difficulty and with various subject populations…." Their conclusion is that in tasks demanding rapid response, analog displays are preferable to digital or verbal (textual) ones.

What remains is to analyze the utility of these types of displays in operating conditions which replicate the fighter mission as closely as possible, and to measure their effect on pilot performance.

Results of Operational Testing

The Leggs and Williams study (1973) was a pioneering effort in this area. Four different display types were presented in a flight simulator for British test pilots conducting a low-level terrain-following task. The four displays evaluated were digital counter only, counter-thermometer, counter-drum, and counter-pointer. These are illustrated (with the exception of the counter-drum, an illustration of which was unavailable) in Figure 10.

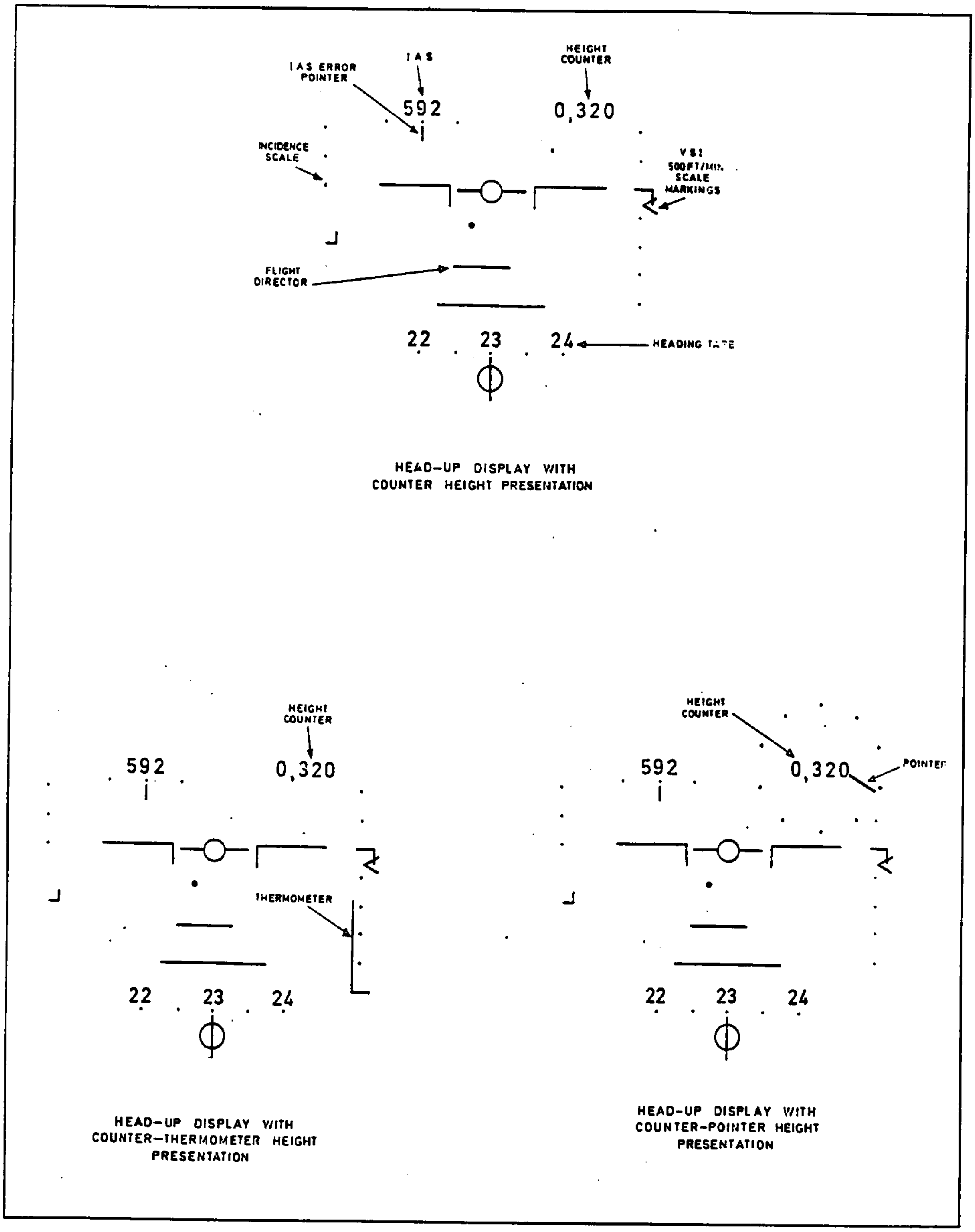

Figure 10. *Three altitude displays evaluated by Legg and Williams (1973).*

The evaluation was both qualitative (pilot opinions solicited through interviews) and quantitative (measurement of pilot response time to an out-of-tolerance altitude). The results were conclusive: the counter-pointer display was the preferred display for seven of the eight pilots tested, being judged far superior to the other two analog-digital displays and the digital-only display, these three being rated as approximately equal. The personal preferences were matched by the objective performance measurement. The counter-pointer presentation showed a pronounced improvement in response time over the other three. Of particular note, the mean response time for the counter-pointer was over 40% faster than for the digital counter alone (0.55 second versus 0.95 second). Reasons cited for the better performance with the counter-pointer included the following: it had good direct as well as peripheral readability; pointer, movement and direction could all be detected peripherally; the scan pattern was simple; clutter was minimal; the angular indication allowed the most rapid interpretation of rate-of-change data.

The other analog presentations in this test suffered because of scan and clutter problems: too much area of the display was covered, and the separation of the counter from the analog display essentially caused the pilot to have to scan two displays. The counter alone was disliked for the amount of concentration required to perform the task satisfactorily, for its unsuitability in check reading, and especially for its lack of trend information (a universal comment among the test subjects).

This study is significant for its thoroughness, for its application to a task which is common among fighter aircraft, and for the strong agreement on preferred display type among the test subjects.

Koonce et al. have examined whether experience level might have an effect on performance. Testing was likewise conducted in a flight simulator, with subjects flying basic instrument flight procedures with as much realism as practical (e.g. induced turbulence, audio tasking). Test profiles were flown multiple times, with both a purely digital display and an analog version. The result was better performance (flight profile matching) by both experienced and novice pilots when using the analog display. Use of a digital display was disadvantageous regardless of the level of pilot experience.

Data from an unpublished study by the Naval Air Systems Command (J. O'Hara, personal communication, October 1997) offer additional empirical evidence to support the use of analog presentations in displays for fighter aircraft. In developing the first electronically-generated flight reference for the T-45 jet trainer, the initial design included a digital counter display for altitude. This version was tested, using the tasks given in the current flight training instructions for fighter pilot training. In performing standard instrument maneuvers (including constant rate climbs and descents; combinations of timed climbing, descending, and turning flight; and simulated instrument approaches) the test pilots found it extremely difficult to capture and maintain target airspeeds and altitudes, due to the absence of trend information. As a result, the display was redesigned to include a counter-pointer type analog altitude display, which provided much more satisfactory results. This aircraft has now successfully completed developmental and operational testing and is in production; the display problem, which had been considered a safety of flight issue, is now considered corrected.

It is important to note that the maneuvers flown in this test are considered fundamental building blocks in the development of a fighter pilot's skills. The inability of experienced test pilots to perform them satisfactorily suggests a serious shortcoming in the transmission of essential data from digital-only flight instruments to the pilot.

Analysis and Mission Impact

Theoretical, laboratory, and operational research all point to a clear conclusion: for the electronically-generated display of altitude in the cockpit of a fighter aircraft, the optimal design should include an analog as well as a digital presentation. The most efficient display developed to date appears to be the counter-pointer with inside pointer, and with a digital readout centered in the display.

Again, the preference for analog presentations must be tempered by the requirements of the mission. An interesting counter-example is provided by R. Newman (personal correspondence, November 6, 1997). While conducting proof of concept testing on a HUD installed in a Grumman AA-5, in which analog presentations were selected for both altitude and airspeed, the airspeed display was determined to be a hindrance (due to clutter), rather than a help. The operational airspeed range for this airplane was 90-110 knots, a range so narrow that any changes could be easily perceived from a digital presentation and trend information was not especially needed. The HUD airspeed display was later simplified to a digital counter.

Analog displays are not the solution in every situation. But in the dynamic environment of the fighter aircraft, with its large and rapid altitude excursions and frequently high closure rates with the ground, an impressive amount of evidence leads to the conclusion that the inclusion of an analog altitude display is much preferred.

A number of mission scenarios can be envisioned in which the rate information provided by a counter-pointer altitude display would be beneficial. The author offers the following examples, based on firsthand experience flying with both digital and analog displays.

(1) Dive bombing. Altitude awareness in steep-angle dive bombing is critical for two reasons. The first is the attainment of proper release parameters, especially in a degraded mode where the pilot must put the aircraft at an exact position in the sky at a predetermined altitude, airspeed, and dive angle, in order for the bomb to hit the target. In this situation, the pilot normally establishes the dive angle, and allows the airspeed to build and the targeting reticle to "walk" up to the target while the altitude winds down, then releases the bomb as the reticle positioning, altitude, and airspeed parameters are simultaneously met. Because of the number of variables, all of which are changing as the solution point is approached, the pilot cannot afford to focus excessively on any on variable. Instead, a quick, disciplined scan is needed. To solve the altitude part of the problem, most

pilots establish a rhythm, using a mainly peripheral scan of the altimeter, counting revolutions of the pointer and anticipating the release altitude by gaging the speed at which it is rotating. If the analog altimeter is replaced with a digital counter, the pilot must focus on and read the counter directly instead of peripherally, thus reducing time available for monitoring the other variables and ultimately reducing his accuracy.

The second, and even more basic need for altitude awareness during dive bombing, is the avoidance of terrain and weapon fragmentation patterns. A minimum pullout altitude is always a critical briefing item for these missions, and must not be breached or the pilot's safety is jeopardized. Experienced pilots develop a feel for how fast the pointer on an altimeter should be moving, and can sense quickly from that motion how fast the minimum altitude is being approached. That feel is lost with a digital counter, where the dynamic cues are replaced by a stationary blur of digits, which imparts no particular sense of urgency.

(2) Approach to carrier landing. The nature of landing aboard the aircraft carrier demands extremely precise control of the aircraft's flight path. Naval aviators train extensively to master a landing pattern in which not

only altitude and airspeed, but also rate of descent must be adjusted to within very narrow tolerances. Pilots with significant experience in this environment develop a keen sense of their rate of descent throughout the approach turn by monitoring—again, usually peripherally—the position and rate of movement of the altimeter needle. A digital presentation requires the pilot either to read altitude over a period of time and mentally differentiate, or to read a digital vertical speed indicator and assess its meaning. In either case more mental effort is required, mental effort which could otherwise be expended on other flight tasks.

(3) Altitude capture during instrument flight. A task as simple as leveling off at an assigned altitude is demonstrably more difficult in the absence of trend information. Informal observation of pilots training on the Navy F/A-18, with its digital altitude display, has shown that level off altitudes are frequently overshot or undershot due to the uncertainty or lack of feel for the rate at which that altitude is being approached. Additionally, maintenance of that altitude, while not demanding, is more difficult. With an analog gage, the pilot can easily confirm through a peripheral glance that the pointer remains in the correct orientation and that the aircraft is therefore at the assigned altitude. A digital counter requires that the pilot

focus directly upon and read the display every time he cross checks altitude. During routine flight, this poses little problem; but during a high task-loading situation such as an in-flight emergency, that small but finite additional workload will cause precise altitude maintenance to drop from the pilot's scan, or will detract from the pilot's performance of other tasks.

These are just three of many situations which could be cited in support of giving the pilot altitude trend information. Frequently, the consequences of using less than optimal displays of critical flight information can only be extrapolated. But application of some of the findings reported above can be illuminating in this respect. As an example, an aircraft flying a tactical low-level navigation route at 480 knots and 200 feet above ground level, with an inadvertent nose-down input of just five degrees, will impact the ground in about three seconds. The Legg and Williams (1973) study suggests that the time required for the pilot to interpret the altitude trend data shown him might be close to one-half a second faster (i.e. one-sixth of the total reaction time available before impact) with the counter-pointer arrangement than with a digital counter. Such scenarios are only conjecture. But given the continuing high number of CFIT accidents, and recognizing the high task loading on the pilot of a high-performance aircraft, design teams should take every opportunity to provide the most direct, intuitive, and timely information concerning safety of flight parameters. An analog display of altitude must be considered for inclusion in the primary flight display of every tactical jet fighter.

Implementation

One might wonder at the variety of presentations of altitude displays on the HUDs of contemporary fighters, especially in light of the evidence supporting a combined analog/digital design. A review of the history of attempts to standardize formats in U.S. military aircraft is beneficial in this respect.

General military specifications for HUD design and elemental formats can be traced from as early as 1972 (MIL-D-81641(AS)). This first global specification was reviewed by Egan and Goodson (1978) and found wanting. In particular, the rather arbitrary selection of one set of symbology, without relating to the mission and without much human factors analysis, was considered short-sighted. (An egregious example is the mandated altitude display: a moving tape, similar to that shown in Figure 7, but with the orientation reversed such that higher altitudes are shown downward on the scale. This was done presumably to match the motion of the tape to the vertical motion of the nose of the aircraft when entering a climb or dive, but runs counter to the basic principle of human factors engineering that the sense of the display should match that of the environment it replicates.)

Egan and Goodson also suggest that this and other early specifications appear to have been released as they were, even though further research might have led to better-substantiated decisions, because some sort of standardization appeared to be needed. HUDs were becoming more and more accepted, and there was no formal guidance at all.

About a decade later, a review of existing HUDs was conducted (Lovering and Andes, 1984) and recommendations made to the Air Force for standardization. The altitude format proposed then was also a moving tape, but with the recommendation that it automatically be replaced with a digital counter when the pilot selected a weapons delivery mode that "implies good visibility." Thus the pilot would "have altitude trend information in segments that require reference to that kind of information, and digital altitude information in segments that require only occasional reference to altitude." The assumption seems to be that during target prosecution in visual meteorological conditions, rate information would not be required. This recommendation was never implemented, perhaps in part due to the difficulty in assessing ahead of time exactly which display truly is the most appropriate for any given flight regime. (In the author's opinion, such arbitrary distinctions made by the designer are inappropriate. No amount of requirements analysis can uncover all the possible scenarios in which an aircraft will be employed, and then determine the "correct" display for each. A much better alternative is to allow the pilot to decide, real time, what display is most suitable: a simple implementation might include a "declutter" switch which eliminates the analog portion of a combined analog/digital display at the pilot's discretion.)

Newman, in a comprehensive review for the Air Force in 1987, recommended a boxed digital counter for both airspeed and altitude, with an alternative display of an unboxed counter surrounded by a dial and pointer (i.e. the counter-pointer format illustrated in Figure 9).

The most recent military specification (MIL-SPEC-1787B, 1996) now requires a counter-pointer display for both altitude and airspeed; this replaces a previous requirement (MIL-SPEC-1787A, 1987) which called for moving tapes.

Taken as a whole, these documents reflect the evolution of a consensus toward the counter-pointer for altitude display. Yet some fighter aircraft continue to use other, less effective formats. Hughes (1991) offers some insight into possible reasons for this. He describes early analog displays as poorly implemented, with too much clutter and confusing, hard to read presentations such as moving tapes. As a result, pilots began looking for simplicity, and found it in the basic digital counter. Once implemented, it became accepted, with few operators seeing any need for change. Newman and Foxworth (1984) also sensed this complacency, particularly among the F/A-18 pilots of their survey. Discussions by the present author with a number of operational F/A-18 pilots have confirmed this reticence to change a familiar display. Much of this hesitation can be attributed to a lack of awareness of other options, and to the comfort level that invariably develops as one becomes accustomed to a particular format.

Chapter 5

Conclusion and Recommendations

The Optimum Altitude Display

Personal experience and observation, as well as laboratory and operational studies, lead to the conclusion that certain display types are more effective than others for presenting altitude on the HUD of a tactical military aircraft. Digital-only displays have been demonstrated to lack the rate-of-change and trend information critical to rapid and accurate assessment of the aircraft's dynamic state, and to making timely decisions to modify that state as required; and delayed or inappropriate decisions in a dynamic flight environment can mean loss of situational awareness, disorientation, and even a flight mishap.

In the past, the use of digital-only and other less-than-optimum designs might have been justified by technological limitations. However, advances in display and processor technology in recent years allow more sophisticated presentations without sacrificing HUD performance. The driving force for retention of these displays is no longer the state of the art, but the complacency which accompanies a system which has been in operation for years.

It is time, then, to recognize an opportunity for improvement. The most desirable altitude display on a tactical HUD should include an analog presentation, preferably with a digital readout embedded (a "counter-pointer" format). This recommendation is supported by the work of numerous researchers over a period of twenty-five years, and is indisputable. Such a display, which is recommended by the current military specification, MIL-SPEC-1787B, should be standardized among the services for all tactical military aircraft. This is an example of a relatively low cost improvement which has the potential to provide substantial dividends in flight safety. Aircraft in the design phase, or those existing aircraft with scheduled systems upgrades, should be required to comply with this standard.

The Acquisition Process

This paper has addressed one narrow topic within the broad field of human factors considerations in flight displays. But beyond the technical issues of altitude presentations lies a more fundamental question. For if such a rudimentary decision as how best to display a basic flight parameter cannot be reached and implemented, even after a generation of studies, how can we expect the design of whole systems to be optimized? One must recognize that, at best, the current acquisition process misses the most effective solution to some technical problems. At worst, however, this suggests a systemic problem, where the optimal design not only is not selected, but in some cases is not even considered. How this happens, and what can be done to improve it, is worth some reflection. The author offers the following thoughts in order to stimulate discussion on the subject.

In the current requirements generation process, inputs for new weapons systems or improvements to existing systems come from "front-line" operational units, sometimes even from an individual soldier or sailor, but more likely from a unit such as a squadron or a wing. These raw requirements are developed, sifted, and prioritized as they are endorsed up the chain of command, and eventually are formalized in the service headquarters staffs. Each validated requirement is assigned a sponsor within that staff, responsible for securing funding, tasking the appropriate materiel command with developing a program to satisfy that requirement, and then ensuring that the product they develop actually satisfies the user's needs.

There are at least two weak points in this process. First, while the end user should certainly be the driver of any weapons requirement (after all, he is the one who knows best what his mission entails), he does not necessarily have the most complete understanding of technical possibilities, both existing and future. The feeling of comfort with existing solutions to a given problem can blind users to significant opportunities for improvement.

The second difficulty with the current process is that while the normal method for validating, prioritizing, and funding requirements is well established, and allows for careful review by all stakeholders, the external budget environment varies rapidly. One consequence is that rapid decisions to reprogram the service's budget must frequently be made in response to tasking from outside the military department; these decisions can be equal in magnitude to those of the more deliberate process already enacted, and there is little or no time for inputs from many of those involved, including the unit-level operator. A carefully laid out program may be substantially undercut, and priorities dramatically altered, with little or no input from the program manager, much less the eventual users.

Unfortunately, this latter problem cannot be substantially improved without changing the annual congressional authorization and appropriation process. But there are concrete steps which can be taken to attack the first. One approach already in place is the formation of operational advisory groups, made up of current operators and designed to build consensus within that community on requirements issues. Existing groups represent particular weapons systems (e.g. F/A-18 aircraft), subject matter (e.g. electronic warfare), or technologies (e.g. flight displays). These working groups have already demonstrated their ability to streamline the requirements generation process and to better organize the discussion within the operational community of what the most pressing requirements really are. The technology-oriented groups in particular show promise in applying the results of commercial and government research to the solution of contemporary weapon design problems. The use of such groups must be encouraged: they must be chartered at a senior executive level and funded sufficiently to accomplish their objectives; they must be recognized formally as fundamental contributors to the requirements analysis portion of any related developmental programs; and their inputs should be required to be an essential part of the decision process at major program design points.

This approach can be carried one step further. Having attempted to introduce science and technology developments into the process at the user level, it is recommended that the lines of communication in the opposite direction be expanded as well. One helpful step would be the debriefing of the results of the operational advisory groups, described above, to those directly involved in systems development, especially engineers and design team leaders. Even when the outcomes of advisory group meetings do not bear directly on a particular program, awareness of how those operators see the world, how they assimilate new technology into their tactics, and how they come to a consensus on user priorities, is important. Such reports should provide the design team with insight into what may work and what may not, perhaps shortening the design cycle and making for a more efficient process.

These and similar enhancements to the military acquisition process have the potential to better and more systematically incorporate the findings of human factors and other basic research into system designs. In the past, it would seem that sporadic integration of such reasearch has caused many cost-effective, even life-saving advances to go unnoticed. It is hoped that improvements such as those outlined above can be implemented to ensure that the best possible weapons systems are provided to the warfighter.

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Vita

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