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Design and Integration of a Display for a Low Cost Laser Altimeter for General Aviation Applications

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To the Graduate Council:

I am submitting herewith a thesis written by Scott Edward Hutcheson entitled "Design and Integration of a Display for a Low Cost Laser Altimeter for General Aviation Applications." I have examined the final electronic 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.

Dr. William D. Lewis, Major Professor

We have read this thesis and recommend its acceptance:

Dr. U. Peter Solies, Dr. Ralph D. Kimberlin

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:

Dr. Anne Mayhew
Vice Provost and Dean of
Graduate Studies

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DESIGN AND INTEGRATION OF A DISPLAY FOR A LOW COST LASER ALTIMETER FOR GENERAL AVIATION APPLICATIONS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Scott Edward Hutcheson
August 2002

DEDICATION

This thesis is dedicated to my wife K. Lynn Hutcheson for all of her support throughout my career and my son Christopher James Hutcheson who endured my absence for a year to give me the opportunity to finish this degree. Additionally, I would like to dedicate this work, to my parents Ernest B. Hutcheson and Beverly A. Hutcheson who taught me the value of education.

ACKNOWLEDGEMENT

I am grateful to the many people who made my short time at the University of Tennessee Space Institute very rewarding. I am particularly grateful to the faculty and staff of the Department of Aviation Systems Research and Development and especially to my Thesis Committee, Dr. Bill Lewis, for his guidance and mentorship and to, Dr. Peter Solies and Dr. Ralph Kimberlin for their invaluable help in the preparation of this thesis. I would also like to acknowledge the input of Dr. Patrick Murphy and Mr. Matthew Johnson of Opti-logic Corporation. Additionally, I would like to thank Mike Heatherly for always dropping what he was doing to give me a hand in preparing the aircraft for launch and for his original and unprecedented use of a showerhead.

ABSTRACT

This project began when Opti-Logic, a local manufacturer of laser rangefinders for military and sporting applications, expressed a desire to design an altimeter for General Aviation application to measure absolute altitude based on the laser range finder as a sensor. The sensor they chose was the RS400, which was originally designed for security applications. The purpose of this thesis was to aid Opti-Logic by designing and flight-testing an intuitive display for the laser altimeter. A Systems Engineering approach was used throughout the design process. A basic assumption in the design of the system is that a suitable laser sensor was available and as such, the sensor was treated as a Non Developmental Item.

The development of an intuitive display was problematic in that the concept of intuition can have differing meanings from one individual to another. As a result, the topic of perception and cognition with respect to aviation was explored fully to gain better insight into how a pilot processes altitude information. Additionally, even though the sensor was fixed in the design process, basic laser theory is presented to give the reader an understanding of the problems associated with this type of system and to provide background in the analysis of the performance of the system overall.

A system engineering approach was adopted for the design of the display. The development of the altimeter display from requirements analysis to prototype validation was accomplished. These steps represent only the first iteration of the design process.

Qualitative evaluation of the symbology demonstrated that the display design reduces total pilot workload. This was accomplished by reducing the cognition required to process the information a pilot needs to execute control of altitude. Recommendations for future iterations include:

1. Testing the display using the caution, alert, and fault indication symbology sets to determine the effectiveness of color-coding as an alert strategy.

2. Continue evolving the software to incorporate a more effective filtering technique to eliminate lag errors without increasing the noise of the system.

3. Incorporate a method of recording altitude information for quantitative analysis to support qualitative evaluation.

4. Increase the maximum value or the VSI from ± 1000 fpm to ± 2000 fpm.

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LIST OF ABBREVIATIONS

A/D	Analog to Digital
AGATE	Advanced General Aviation Transport Experiment
AGL	Above Ground Level
AMLCD	Active Matrix Liquid Crystal Display
ATC	Air Traffic Control
CB	Circuit Breaker
COTS	Commercial Off The Self
CRT	Cathode Ray Tube
CW-FM	Continuous Wave – Frequency Modulated
DEP	Design Eye Position
DH	Decision Height
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FED	Field Emissive Display
FPD	Flat Panel Display
fpm	feet per minute
FTE	Flight Test Engineer
GA	General Aviation
GAATA	General Aviation and Air Taxi Activity
HGED	High Gain Emissive Display
HQR	Handling Qualities Rating
Hz	Hertz
IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
ITO	Instrument Takeoff
LADAR	Laser Detection and Ranging, in analogy to RADAR
LASER	Light Amplification by Stimulated Emission of Radiation
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LOS	Line of Sight
NASA	National Aeronautics and Space Administration
NDI	Non-Developmental Item
NTSB	National Transportation Safety Board
MDA	Minimum Descent Altitude
MIL-STD	Military Standards
MSL	Mean Sea Level
OGE	Out of Ground Effect
PDP	Plasma Display Panel

RADAR	Radio Detection and Ranging
RCS	Radar Cross Section
SE	Standard Error
SEP	System Engineering Process
SNR	Signal to Noise Ratio
STC	Supplemental Type Certification
TFT	Thin Film Transistor
TV	Television
USAF	United States Air Force
VAC	Volts Alternating Current
VASI	Visual Approach Slope Indicator
VDC	Volts Direct Current
VFD	Vacuum Fluorescent Displays
VMC	Visual Meteorological Conditions
VSI	Vertical Speed Indicator

I. Introduction

Background

The past decade has seen the proliferation of technology with regard to display and display presentation, which has kept pace with the advances in computer technology. The major benefactors of this technology have been the military and commercial aviation for obvious reasons, namely the cost. While the accident rate for the commercial airline, industry is far less than that of the GA community, the cost in terms of human lives and dollar amounts for a single commercial aviation accident far exceed that of GA. Additionally, the airline industry and US Government can more readily absorb expensive production and developmental cost incurred in the design of state of the art avionics. It is accepted that many GA pilots and aircraft owners are limited in funds they have available for aviation. This is readily apparent in the FAAs reluctance to impose requirements, which are expensive and restrict those requirements to what is necessary for safe operations. (Ritchie, 1988)

The spiraling cost of GA has been attributed to several factors. The decades of the 70's and 80's saw a large increase in GA aircraft sales. With the increase in GA operations also came an increase in the GA accident rate. This in turn drove up the cost of operating a private aircraft as families of accident victims sought grievance through litigation against the insurance companies and the aircraft manufacturers. During the same period oil price escalated. These factors combined, increasing the cost of the GA aircraft to the point where the average American could no longer afford to buy an airplane, much to the decrement of the GA industry. In 1978, at the height of the GA boon, the manufactures delivered 14,398 aircraft. By 1994, that number had decreased to just 444. (NASA, 1998)

NASA, along with the FAA and industry, has begun a program to develop the next generation of GA aircraft, in an attempt to revitalize the GA market. The program, Advance General Aviation Transport Experiment (AGATE), incorporated breakthrough technologies in structures, avionics and cockpit design, to develop a radically new aircraft. (NASA, 1998) This new aircraft will incorporate a sophisticated avionics package that will take advantage of advances in presentation and display technologies formerly unavailable to the GA pilot, to aid in situational awareness. Such systems while notably beneficial, are likely to remain cost prohibitive to most potential aircraft owners and still do not address the problems inherent in the more than 187,000 aging GA aircraft flying today.

A need exists to explore low cost alternatives that will take advantage of the technologies and research of the past decade. This project provides the research necessary to develop a low cost display to be integrated in an inexpensive laser altimeter system for use on GA aircraft. The purpose of the altimeter will be to display the aircrafts absolute altitude and aid in situational awareness.

Perception and Cognition

A pilot perceives his environment, orientation, and aircraft systems status using three of the five human senses: vision, hearing, kinesthetic (vestibular), and touch or proprioceptive. Using the information gained from the senses the aviator is able to make decisions and execute control inputs necessary for flight. This process is termed cognition. (Roscoe, 1994) While the modern cockpit is replete with displays to provide information to the pilot, it is not the quantity but the format in which this information is presented that has been the greatest obstacle to information processing and requires the most revision. (Ritchie, 1988) An understanding of the process of aviation cognition will help determine how human error in the cockpit occurs, thus leading to a more effective display format design.

Human Perception

Perception is defined as the assignment of meaning to a physical stimulus. The pilot’s primary sensing organ is the eye. The lens focuses the light entering the eye onto the back of the eye, which is called the retina. The act of focusing on an object is termed accommodation. The retina consists of nerve cells concentrated in the fovea and para-fovea. The nerve cells of the fovea are made up of two types of cells, rods and cones, named for the shape of the cells. The rods and cones are bundled together and connected to the optic nerve, which sends the signal to the optical lobe of the brain. The cones are used for vision in good lighting conditions and are sensitive to color. Cone cells are concentrated in the fovea centralis and become less dense the further from the center until rods gradually replace them. Rods are located in the para-fovea and become active during periods of low light levels. The optic nerve contains neither rods nor cones and is a source of a blind spot, which is overcome by the binocular nature of vision. (Hawkins, 1987) Figure 1 below illustrates the major components of the eye.

When the level of light entering the eye changes the process of adaptation occurs. Firstly, an adjustment in the diameter of the pupil takes place in an attempt to control the amount of light entering the eye. Secondly, as the light level within the eye changes the task of sensing is passed from the rods to the cones. The rods contain a chemical called rhodopsin, which is bleached, under high levels of light. As the intensity of light decreases, the level of rhodopsin increases in the nerve cells and they become more sensitive to the decreased levels of light. The cones located in the center of the fovea become ineffectual causing a “night blind spot” in the center of the visual field, which cannot be overcome by binocular vision. Additionally, the rods are not sensitive to color so objects, which are colorful during the day gradually, become various shades of gray at dusk. (Hawkins, 1987)

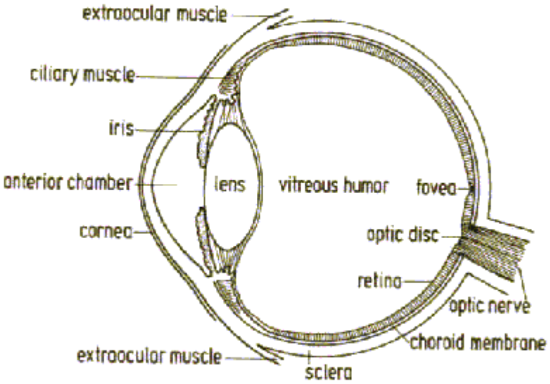

Figure 1. The Human Eye

While the eyes provide the pilot with a visual representation of the environment, it is the vestibular system, which provides the pilot with the orientation and sense of motion with respect to the earth's center. The vestibular system consists of the semicircular canals and the otolith organs, which measures angular and linear accelerations. Figure 2 shows the composition of the vestibular system.

The organ to sense angular accelerations consists of three canals situated at approximately right angle to each other and includes the anterior, the posterior, and the lateral canals. As the head experiences an angular acceleration in the plane of the canal, as in a turn, the fluid within the canal begins to move. The fluid bends the cupula, a structure located within the canal, which stimulates nerve cells at the base of the cupula. The nerve impulses are sent to the brain, which interprets the signal as a movement of the head. If the turn continues at a constant rate the fluid within the canal reaches, the same velocity as the canal itself and the hairs return to a resting position. When the turn is completed, the fluid within the canal is slow to stop and the hair cells are bent in the reverse direction giving the sensation of turning in the opposite direction. (Hawkins, 1987)

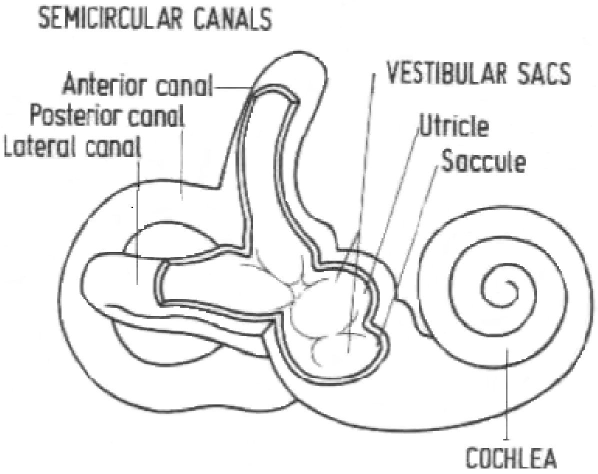

Figure 2. The Human Vestibular System

The second apparatus of the vestibular system, the vestibule proper, contains the otolith organs and senses linear accelerations. The vestibular sacs contain sensory hairs and otolith crystals suspended in a gelatinous fluid. When the head is upright, the hair cells transmit a resting frequency to the brain. As the head is tilted, the motion causes the otolith to bend the hair cells, which transmits a new frequency to the brain. The brain determines the position of the hair cells by the change in frequency. As the body accelerates, the otoliths resist the acceleration and move the hair cells to a new position. The body cannot distinguish between the inertial forces resulting from acceleration and those of gravity, which may lead to a form of vestibular illusion that will be discussed later. (Hawkins, 1987)

The proprioceptive sense, sometimes referred colloquially as “seat-of-the-pants,” is a result of pressure changes on the organs, muscles, and skin of the human body. As the pilot sits in the cockpit seat, the pressure of the seat on the skin due to the weight of the body causes sensations to be relayed to the brain. As the aircraft is maneuvered, the body experiences an increase or decrease in the sense of pressure on the skin and a slight shift in the position of internal organs, which the pilot interprets as accelerations.

Information Processing

Information processing is the method humans use to transform sensed stimuli into useful information and respond to that information. There have been numerous studies on the subject of information processing and just as many theories. Just as there are two types of nerve sensors in the eye, which contribute to vision, there are two functions or modes of processing visual images: object recognition and visual guidance. The type of visual function depends largely on the area of the brain used. The function of recognition requires attention from the observer while the function of guidance can be accomplished with little or no awareness by the observer. (Leibowitz, 1988)

The implications of the dual modality of the visual information processing became apparent shortly after the introduction of the Boeing 727 in 1968. Conrad Kraft, a human factors engineer with the Boeing Company noted similarities in the accidents of number of 727s. A number of the aircraft landed short of the runway at night with unrestricted visibility. Kraft noted that all the accidents shared a common characteristic; all of the approaches were made over dark areas of water or unilluminated terrain. Based on the circumstances of the accidents, Kraft surmised that the lack of visual reference caused the pilots to estimate their altitudes to be higher than they actually were causing them to land short of the runway. He tested his hypothesis by conducting several test in simulated conditions where he eliminated the altimeter from the cockpits, requiring the pilots to estimate their altitude visually during nighttime VMC approaches. The results indicated that even the most experienced aviators approximated their altitude to be higher than they actually were. Next, he asked the aviators to fly the approach in the 727 without reference to the altimeter. The results of Kraft's experiments are presented in Figure 3.

The approach to landing segment of flight is perhaps the busiest phase for a pilot. A pilot entering the terminal area must monitor the radios as well as scan visually for other traffic in order to maintain the principle of see and avoid, communicate with ATC, change the radio

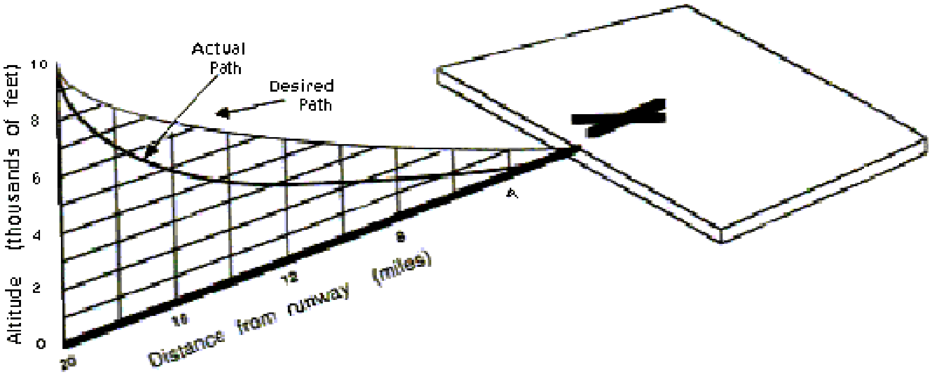

Figure 3. Kraft's Altitude Estimation Experiment Results

frequencies upon request, as well as maneuver the aircraft, and monitor aircraft systems. It's not difficult to see how a pilot could ignore the barometric altimeter; especially in light of the fact that the pilot believed, he was able to determine the altitude by visual estimation alone.

No one knows exactly which parts of the brain are responsible for cognition or even how this process occurs so much of the research is based on models. The human-computer analogy is the foundation for the study of aviation psychology, however other theories have provided insight the cognitive aspects of aviation. No matter which model is used to describe the process, the language remains essentially the same. Each model is based on the assumption that the mental process progresses in a series of stages from stimulus to response. Figure 4 illustrates a typical four stage cognitive model. Much of the current research is directed at identifying the characteristics of each of these stages. (Wickens, 1988)

The first stage is the sensory store. In the sensory store, physical energy such as light is transformed into neural energy through the sensory organ (in this example the rods and cones) and is stored as patterns. The storage of this pattern last less than one second and does not require attention resources. (Wickens, 1988)

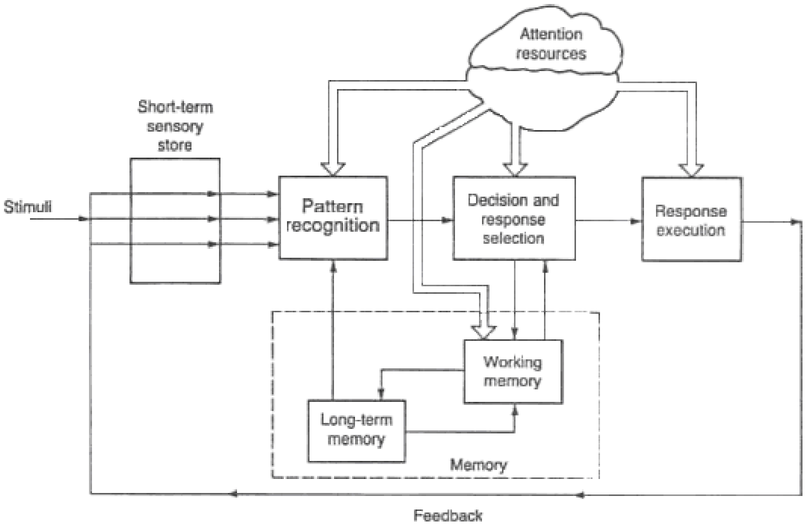

Figure 4. The Information Processing Model

The second stage is pattern recognition. This is also sometimes referred to as perception. This is perhaps the most important yet least understood of all the stages. It is at this stage where the physical stimulation is recognized as meaningful elements. This process involves comparing the pattern mapped in the sensory store to patterns mapped in long-term memory (experiences). A common example of this stage is the odor of cooking causing a childhood memory of a trip to grandmothers. At this level the shape and size of known objects are inferred to provide an indication of an aircrafts altitude. The process is complicated in that many sensory stimuli may lead to one memory. Conversely, a single sensory stimulus may lead to many memories. It is also the stage where confusion of stimuli occurs and the term sensory overload takes it's meaning. (Wickens, 1988)

In the third stage, decisions and responses are made and several choices are available; the recognized pattern can either be stored in memory for future use, combined with other information, or may cause a response. If the pilot chooses to respond then the final stage, response execution, is initiated. Once the decision is made to act, the response is translated into a series of motor commands to the muscles. The resulting response then becomes yet another input, via a feedback loop, to the sensory store and the process repeats. (Wickens, 1988)

As mentioned earlier perception is the process of comparing sensory input to memory to derive meaning from patterns. Several key issues to the investigation of perception include detection and selection. Classical detection involves four possible outcomes; a stimulus is present and it is sensed, the stimulus is present and it is missed, a stimulus, which is not present, is sensed, and a stimulus is correctly observed to not be present. The determination of outcomes is a function of sensitivity and response bias. The ability of a pilot to detect a signal is dependent on his ability to distinguish a signal (stimulus) from the background noise (all other stimuli). This is the principle of sensitivity. Response bias is the criterion a pilot uses to make those decisions. Response bias is a function of expectancy or likelihood of one of the four outcomes previously mentioned occurring. When a pilot is required to monitor a display for long periods, vigilance decrement may occur. Vigilance decrement is a decrease in probability of a pilot detecting a stimulus as a function of time increase and has been attributed to changes in sensitivity, fatigue, memory load, and changes in expectancy. (Wickens, 1988)

When the ability to process the quantity of information approaches saturation the pilot must chose what information to monitor. This is the concept of selection. Research on the subject suggests four conclusions. First, selection depends to an extent on statistical knowledge of the frequency of events occurring on a particular display as well as the correlation between certain displays. Displays, which have a perceived, higher frequency of change occurring, will be monitored more closely. Secondly, human memory is imperfect. If memory were perfect, the need to reference a display for changes would be less than shown in research. Third, referencing specific displays improves when the events most likely to occur in the future are reviewed to provide a “planning horizon.” Lastly, environments high in stress limit the cues that are perceived. (Wickens, 1988)

Spatial proximity determines whether visual stimuli are processed in parallel or individually, that is serially. Research indicates the optimum angle for placement of information to be processed in parallel is 1^{o}. This led to the general design guidelines that stimuli which needs to be processed together should be placed close together while information which should be considered separately should be placed farther apart. (Broadbent, 1982)

Visual Distance Estimation and Depth Perception

It is important to note that humans do not perceive the environment in a totally deterministic way. A pilot’s perception is based on sensual stimuli and governed by expectations. This can best be demonstrated by how a pilot estimates depth. (Green, 1996) Both distance estimation and depth perception are vital in determining closure rates and altitude estimation in flight. When the normal cues associated with depth perception are lost due to poor visibility condition such as those encountered in marginal IMC or during the hours of darkness, the pilot must compensate for this degraded performance.

Binocular vision depends on the differing perspective each eye maintains on an object. As the distance of the object increases the lines of perspective become parallel and the advantage is lost. For this reason binocular cues are only effective at relatively close distances. Additionally, binocular cues work on a subconscious level. When the advantages of binocular vision are gone, the pilot must use the clues to distance and depth perception offered by monocular vision.

The first of the monocular cues is termed geometric perspective. Objects such as runways tend to have a different shape when view from different distances and angles and is one of the first techniques a pilot learns when executing an approach to landing; the view of the runway during a correctly executed approach. Geometric perspective depends greatly on the concept of linear perspective, when two parallel lines tend to converge the farther in the field of vision they fall. Another concept pertinent to geometric perspective is apparent foreshortening. As objects are viewed from large distances they appear to be elliptical and its not until the pilot is close enough to distinguish detail that the true shape of the object is revealed. Additionally, the further an object is in distance the higher it will appear on the horizon. This is known as the vertical position in the field.

Many approaches to landing are made using VASI or some other visual aid such as know ground features. In approaches without the use of landing aids, the pilot must estimate his approach angle based on the image of the runway. This is an example of apparent foreshortening and vertical position in the field, which will be discussed in a later paragraph. In order to maintain a 3^o approach angle the pilot must place the intended impact point 3^o below the horizon and keep it there. The visual angle between the impact point and the horizon is constant and equal to the angle of approach. In order to accomplish this the pilot uses the visual texture flow. The image on the retina flows away from the intended point of touchdown. As long as the distance between the intended touchdown point (flow field) and the horizon remains constant the pilot is on glide slope. During conditions of low visibility or during night flight the pilot may not be able to see the horizon or even see enough detail to estimate the flow field, therefore an alternate method of estimation is required. Several techniques are available, but these techniques are only viable if the runway and surrounding terrain is level. Additionally, immediately before touchdown, if the pilot does not check his approach by flaring, the aircraft will touchdown short of the intended touchdown by a distance equal to the length from the pilots seat to the rear landing gear. To gauge his height above threshold the pilot may use clues to apparent rate such as the speed with which the ground texture is passing. This technique is only valid below approximately 50 feet.

The second monocular cue is that of the image focused on the retina. There are several factors, which aid in determining the distance of an object based on retinal image size. The nearer an object is the larger the image projected onto the retina. The brain learns to interpret the size of an object and correlate it to its distance. Additionally, the brain also learns that as the size of the image increases, the object must be approaching. Conversely, if it is getting smaller the object must be moving farther away. A pilot may also use terrestrial associations to determine distance. In using this cue, the pilot associates the known size of a familiar object such as an aircraft in a traffic pattern to one of unfamiliar size such as an airport to determine the distance.

The last, and perhaps most important, cue to depth perception is that of motion parallax. Motion parallax refers to the apparent movement of stationary objects from the pilot’s frame of reference. Object farther in the field of view appear stationary while nearer objects appear to move in a direction opposite to the aircraft. The closer to the aircraft the object is the faster the object appears to travel. It is motion parallax that allows a pilot to determine their intended landing point and keep it fixed on the horizon.

Visual and Vestibular Illusions

Sensory illusions arise when there is a breakdown in the pilot's ability to assign the correct meaning to sensory stimuli. There are numerous types of illusions, which plague human perception. In the interest of brevity, the discussion will be limited to those illusions, which have a direct or indirect influence on a pilot's perception of altitude.

Visual illusions occur when a pilot misinterprets what is visually perceived and are generally based on erroneous experience or expectation. Most visual illusions are easily corrected when the aviator crosschecks the orientation of the aircraft with the instruments. However, if the pilot is lax in visually referencing the aircraft instrument or if his attention is diverted during other tasks then the condition may go undetected with disastrous effects. During certain situation, pilots have confused naturally occurring linear formations for the horizon placing the aircraft in an attitude not conducive to straight and level flight. This often leads to loss in altitude. Examples include confusing a linear formation of ground lights for the lights of a distant city, or the confusion of a sloping cloudbank with the horizon. Fascination some times referred to as target fixation occurs when the pilot allows himself to become engrossed in a task or procedure at the exclusion of aircraft control. An example includes the aviator desperately searching for the proper tower frequency during final approach allowing the aircraft to build a descent rate, which puts him below optimum glide path. A total lack of visual references can lead to height perception illusion as discussed during Kraft's experiment. Height perception illusion misleads the pilot into believing the aircraft is higher than it actually is.

While visual illusions may be overcome by the proper use of aircraft instrumentation, vestibular illusion are so insidious that even cross checking the aircraft instruments may not be enough to allow the pilot to regain control of the aircraft. There are two types of vestibular illusions, somatogyral and somatogravic.

Somatogyral illusions are those, which affect the semicircular canals, the organ measuring angular acceleration. The leans are the most common of the vestibular illusions; and occur when the pilot fails to perceive an angular motion such as a slow turn. After detecting and correcting the roll condition, the semicircular canals are stimulated and produce the sensation of flying in a perpetual turn. To correct for this condition the pilot must fly the aircraft while leaning (hence the name), referring to the aircraft instruments, until the condition subsides. The graveyard spiral is an illusion, which occurs during an intentional or unintentional turn maneuver. If a turn is held for several seconds the fluid semicircular canal reaches equilibrium. As the pilot recovers from the turn, he is decelerated. The fluid within the canal continues turning due to inertial forces and the pilot perceives that the aircraft has entered into a turn in the opposite direction. This process may continue indefinitely as the pilot recovers from one turn to the next and may result in an uncontrollable spin. The coriolis illusion causes overwhelming disorientation and is the most dangerous of all the vestibular illusions. This illusion occurs during a climbing or descending turn when the pilot moves his head in a direction other than the turn. All three semicircular canal become stimulated and the pilot perceives the aircraft to be rolling, pitching, and yawing all at the same time.

The somatogravic illusions arise from changes in the linear acceleration or gravity and affect the otolith organs. There is three kinds of illusion associated with the otolith organ and include: oculogravic, elevator, and oculoagravic illusions. As the aircraft is accelerated forward, inertia causes the otolith organs to sense a nose high attitude. This illusion usually does not occur if adequate visual references are present, however if the pilot is flying at night or during low visibility conditions correcting for his perception without reference to the instruments a pilot would place the aircraft in a diving attitude. The elevator illusion occurs during upward accelerations, as might be experienced with an updraft. Because of the inertia, the body will try to maintain the visual fixation on the environment and cause the eyes to track downward. As the eyes move downward, the pilot perceives the nose of the aircraft rising and correct by placing the aircraft in a descending attitude. Oculoagravic illusion is the opposite of the elevator illusion in that the downward acceleration causes the pilot to perceive the aircrafts nose is falling and will place the aircraft in a climbing attitude.

Proprioceptive illusions are closely associated in vestibular and visuals systems and rarely occur alone. However, without the aid of visual references the pilot in a coordinated turn may perceive a climb or descent. As a coordinated turn is executed, centrifugal forces combine with gravity to press the pilot into the seat, which may give the pilot the false perception that the aircraft is climbing. Conversely, as a pilot recovers from the turn the forces combine to give the sensation of becoming lighter in the seat. The pilot then falsely interprets this as a descent.

Intuitiveness vs. Transference

Transference is a process in training were the skills, procedures, or experiences gained in one situation are applied to a different situation which maintains similarities to the situation in which the skill or experience where originally learned. It is this principle that allows flight training in simulators to be so beneficial, allowing an aviator to experience and learn dangerous emergency procedures without exposure to the risk of having to execute them while flying an actual aircraft. Transference also allows an experienced aviator to learn new skills more quickly than a student pilot by building on the base of previous learned knowledge. An example of this is an aviator who learns to operate an altimeter with a new style of display presentation. As long as the display presentation is similar to the altimeters he is familiar with, e.g., as long as the display is circular and the pointers move clockwise to indicate an increase in altitude, then the time to learn the presentation is short. A student pilot who must learn how to interpret the altimeter has no previous experience from which to draw.

Transference is for the most part beneficial except in those instances when it becomes an obstacle to learning a new task. This is termed interference. Many have often confused the concepts of transference and interference with the unrelated concept of intuition. Webster’s Dictionary defines intuition as “1.a. The act or faculty of knowing without the use of rational processes: immediate cognition. b. Knowledge acquired by the use of this faculty.” While transference and interference by definition are cognitive processes, it is easy to see how the concepts might be confused.

For the most part, humans, by nature, are resistant to change. A pilot who is familiar with the altimeter from the example above, and who has used that altimeter his entire flying career, has learned to process the information perceived from the display in the most efficient manner and is able to determine his altitude by merely glancing at the instrument face. While this may seem intuitive to the pilot, the process of determining the position of the needles and performing the requisite math has become so familiar that the pilot is no longer aware of it. As a result, the pilot has learned to process the information in such a manner that processing it any other way may seem counter-intuitive to him.

By contrast, the student pilot who is charged with learning to determine his altitude and combine it with other information to develop situational awareness has no other experiences, which may interfere with this process. For him, the measurement of what constitutes intuitiveness is how quickly he is able to learn to obtain information from one presentation format when compared the amount of time to learn to use another.

Current Altimeter Systems

When the Wright brothers conducted their historic first flight in December 1903, their aircraft instrumentation consisted of a piece of string to serve as a slip indicator. (Hawkins, 1987) The earliest aircraft were flown using the aviator's visual, vestibular, and proprioceptive senses and little else. The open cockpit designs left little area to mount instrumentation, even if it existed. As the complexity of aircraft design increased so did the rate of accidents and the need to develop instrumentation, which would describe the pilot's position relative to the earth as well as the operating state of his aircraft, arose. No one knows the exact order of development of the modern aircraft instrumentation however it is almost certain that the first instrument introduced into the cockpit was the magnetic compass. With the outbreak of World

War I instruments such as limited engine instruments, airspeed indicators, and the first barometric altimeter were introduced into military cockpits. (Pallett, 1981)

Current altimeter systems used on aircraft include: the barometric altimeter which measures pressure altitude relative to sea level standard pressure, and radar altimeters which measure absolute altitude above the ground. Other more exotic altimeter such as LADAR altimeters do exist however since there is no vendor available to the GA pilot the discussion will exclude these altimeters.

Barometric Altimeter

In order to fully understand how the barometric altimeter works it is first necessary to appreciate the structure of the atmosphere. The envelope of air surrounding the earth is divided into several indistinct layers. The layer closest to the earth is the troposphere, which extends from the surface to approximately 36,089 feet. Above the troposphere are the stratosphere, ozonosphere, ionosphere, and exosphere. The atmosphere is held in place by the gravitational attraction of the earth, which produces the effect of pressure.

Barometric altimeters measure the change in the standard atmospheric pressure as altitude increases or decreases, e.g., p = f(dh). The hydrostatic equation measures the change in atmospheric pressure as shown in Figure 5.

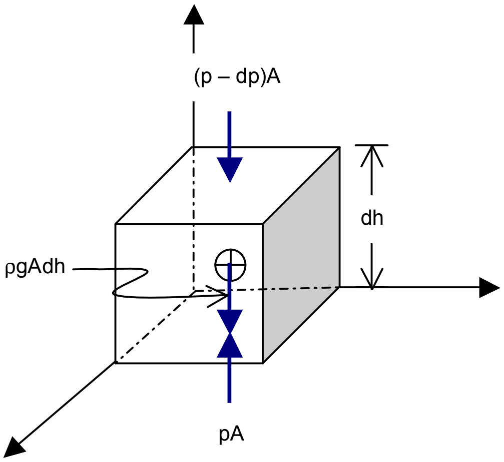

Figure 5. A Volume of Air in Static Equilibrium

$$\Sigma fy = 0$$

$$(p - pd)\,A + \rho gAdh - pA = 0$$

$$dpA + \rho gAdh = 0$$

$$dp = -\rho gdh \qquad (1)$$

The difference in pressure (dp) is a function of the density (ρ) of the air and the difference in altitude (dh). (Halliday, 2001)

The density of the air (ρ) expressed in the hydrostatic equation is expressed by the equation of state and is given by the function:

$$\rho = \frac{p}{RT} \qquad (2)$$

where p is pressure, ρ is the density, and T is the temperature. The specific gas constant is represented by R and is equivalent to 287 J/kg K in the metric system or 1716 ft-lb_f/sl ^{o}R in the English system. (Halliday, 2001)

By substituting equation (2) into (1), integrating and solving for h, pressure altitude, we get the following equation (good for altitudes below 36,089 ft) from which the common pressure altimeters are based:

$$h_p = \frac{T_o}{r}\left\{1 - \left[\frac{P}{P_o}\right]^{\frac{g_o r R}{g_c}}\right\} \qquad (3)$$

where p_o is the standard sea level pressure, T_o is the standard sea level temperature, g is the standard acceleration of gravity, R is the gas constant, and r is the standard atmospheric lapse rate. (ICAO, 1962)

Temperature also has an effect on the pressure of the atmosphere. As air is heated, its density decreases and it begins to rise. As the air rises, its pressure drops which decreases the temperature. The rate at which the temperature of the atmosphere decreases is termed the lapse rate. The relationship between pressure, temperature and density is given by the equation of state (assuming a perfect gas) and is illustrated in Figure 6 below.

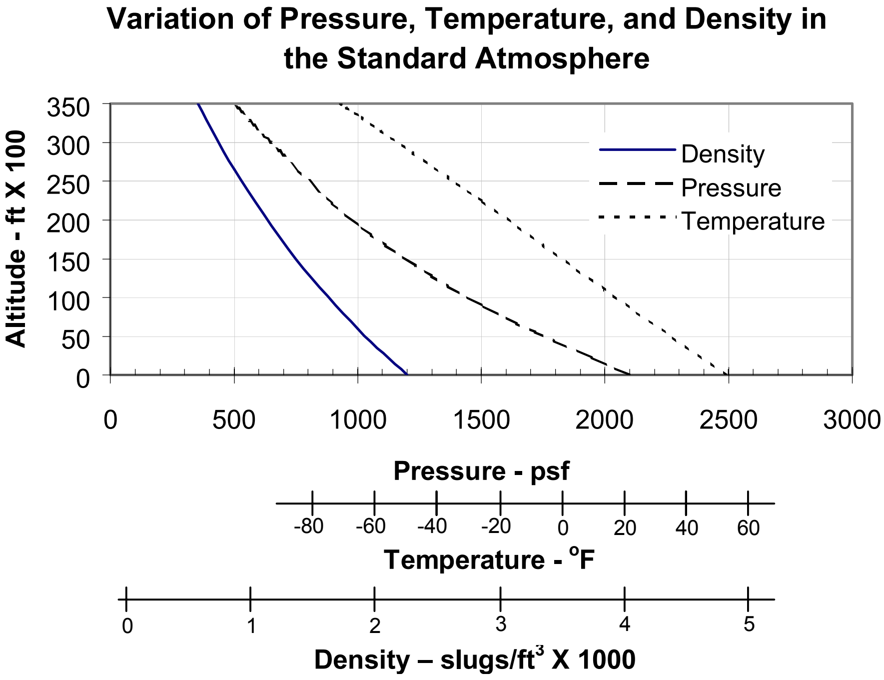

Figure 6. Variation of Pressure, Density, and Temperature in the Standard Atmosphere (ICAO, 1962)

Most aircraft employ a pitot-static system to measure the total pressure produced by the forward motion of the aircraft and the static pressure of the atmosphere as measured at the static port. Three primary flight instruments use the pitot-static system including the airspeed indicator vertical speed indicator and the instrument we are concerned with, the altimeter.

The earliest recorded use of an altimeter was in the 18th century when balloonists used barometers to gauge their altitude. Present-day altimeters although more complicated in design are in essence aneroid barometers utilizing an evacuated metal capsule as the pressure sensor. The metal capsule or “aneroid wafer” is sealed which maintains a constant pressure. As the instrument increases in altitude, the atmospheric pressure decreases and the capsule expands minutely. Conversely as the instrument decreases in altitude, the capsule contracts. The expansion and contraction of the capsule is transformed into rotary motion, which, in turn drives an indicator needle. (Pallett, 1981) An exploded view of a typical sensitive altimeter is shown below.

The barometric altimeter is a required instrument in the majority of aviation operations to include GA, however the barometric altimeter is prone to a variety of errors both in its mechanical operation and in the interpretation of its display presentation. Electromechanical errors can range from errors internal to the instrument, errors associated with flight into changing pressure gradients, and temperature errors. Errors dealing with the placement of the static port on the aircraft will not be discussed as the pilot has no control over this phenomena and it is corrected for in the calibration of the instrument. As noted earlier, the barometric altimeter measures the barometric pressure of the outside air and determines the changes in altitude based on changes in the pressure of the atmosphere. As the pressure falls, the altimeter will indicate a climb even if the altitude of the aircraft has not changed. Conversely, if the atmospheric pressure where to rise the altimeter would indicate a descent. Since pressure and temperature are proportional in the equation of state (assuming constant density), as temperature decreases the pressure decreases and the altimeter will report a higher altitude than the aircraft is flying. The pilot normally compensates for changes in atmospheric pressure and temperature by recalibrating the instrument using a Colesman window. However, the pilot can only compensate for pressure changes if he is aware of these changes. This requires the pilot to periodically request updated altimeter settings from an authorized source such as ATC or a pilot weather reporting station.

While most of the mechanical errors inherent in the altimeter can be compensated for and pose little danger to the pilot, if practical procedures are followed, the error produce by misreading the altimeter has caused many fatal accidents and been the focus of several major studies. Because of those studies the altimeter display has undergone several evolutions, however the basic format of the barometric altimeter has changed very little over the years. The triple pointer altimeter is the oldest of the altimeter presentations and the subject of the famous 1947 study of misreading vulnerabilities by Fitts, Jones, and Grether. Despite its susceptibility to misreading the 1,000 feet and 10,000 feet pointers, the three-point altimeters continue to be used. In 1980, NASA stated that despite the 1947 study, and others like it, it is unlikely that the triple pointer altimeter will be replaced in older operational aircraft. (Hawkins, 1987) While the three point display format is still used in current designs, the problem inherent in its predecessor have been accounted for in the more distinctive shape of the 1,000 feet and 10,000 feet pointers. (Pallett, 1981) It is likely that a three-point altimeter will be the present and contributing factor in future mishaps. Modern designs, especially those using LCD and CRT displays, utilize a combination of digital and analogue display formats, however they still resemble the electromechanical instruments.

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The earliest recorded use of an altimeter was in the 18th century when balloonists used barometers to gauge their altitude. Present-day altimeters although more complicated in design are in essence aneroid barometers utilizing an evacuated metal capsule as the pressure sensor. The pressure inside the capsule is approximately zero. A leaf spring, attached to the top of the capsule, tends to open outward and maintains a state of equilibrium at 14.7 lb_f/in^2. As the instrument increases in altitude, the atmospheric pressure decreases and the capsule expands minutely. Conversely as the instrument decreases in altitude, the capsule contracts. The expansion and contraction of the capsule is transformed into rotary motion, which, in turn drives an indicator needle. (Pallett, 1981)

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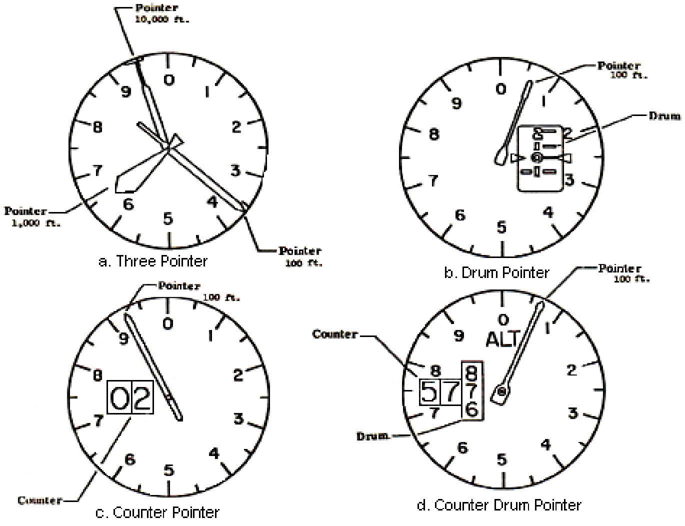

a. Three Pointer

b. Drum Pointer

c. Counter Pointer

d. Counter Drum Pointer

Figure 7. Basic Types of Barometric Altimeter Displays

Four major variations of the display face of the electromechanical altimeter have arisen. These include the three-point altimeter, counter pointer, drum pointer, and counter drum pointer. (Spady, 1980) Figure 7 shows the configuration of the four common types of altimeters. Barometric altimeters range in price from $100 to $500.

Radar Altimeter

Radar altimeters employ Radio Detection and Ranging (RADAR) to determine range to the earth and display that range as absolute altitude Above Ground Level (AGL). Range to a target is predicated on several factors, the least of which is the energy of the signal reflected by the target. The following expression is used to determine the amount of energy reflected from the target as perceived by the antenna and hence the range.

$$\text{Signal Energy} = K \frac{P_{avg} G \sigma A_e t_{ot}}{R^4}$$

Where K is the factor of proportionality and is given by $1 / 4\pi^2$, P_{avg} is the average transmitted power, G is the antenna gain, σ is the radar cross section of the target, Ae is the effective area of the antenna, t_{ot} is the signals time on target, and R is the range to the target.

Radar cross section, describes how much of target is seen by the radar, and is the product of the targets geometric cross section, targets reflectivity, and the directivity of the reflected signal. Geometric cross section is the area of the target, which is seen by the radar. Target reflectivity is the fraction of energy intercepted by the target, which is reradiated away. The majority of the energy, which reaches the target, is reflected away as scatter. Directivity is the ratio of the energy scattered back toward the radar to the amount of power that would have been back scattered if the radiation had been scattered isotropically, i.e., uniformly.

Currently there are two principle types of radar altimeters and are distinguishable by their technique employed in ranging the earth. The two types of radar altimeters include those employing the technique of Continuous Wave – Frequency Modulation (CW-FM) and those using pulsed radar. The large Radar Cross Section (RCS) of the earth and the relatively short-range permit the altimeter to use very low transmitting power and allows for low antenna gain. Figure 8 shows the functional block diagram of a generic pulsed radar altimeter.

In a pulsed system, the signal is generated by the transmitter and is sent to a coaxial switching module. The switching module applies a narrow pulse to the signal and radiates the signal via the antenna. As the signal is received, a time compensator processes the signal. The time compensator controls the gain of the receiver and compensates for any leakage from the transmitting antenna or any of the other components, which may create an error in the

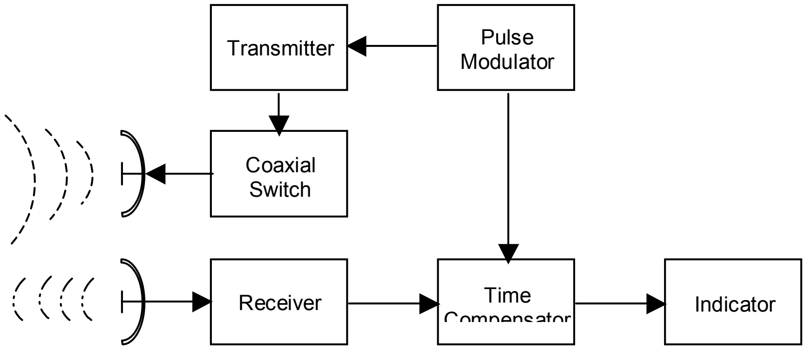

Figure 8. Pulsed Radar Altimeter Block Diagram

received signal. (Hovanessian, 1984) The time between the transmission of the signal and reception of the return pulse is measured and the altitude is calculated by the following equation:

$$R = \frac{c\tau_d}{2}$$

Where R is the altitude (range), τ_d is the time difference between the transmitted and received pulse, and c is the speed of light.

The technique of using FM – CW altitude ranging uses part of the transmitted signal to act as a reference signal (Figure 9). The reference signal is mixed with the received energy and the resultant frequency is termed the beat frequency. The frequency of the returning signal can then be compared to the beat frequency and an altitude calculated. Two methods are employed to calculate altitude. The first method is to fix the frequency excursion Δf and allow the beat frequency to vary. In this method the low frequency amplifier needs to be large enough to accommodate the wide range of frequencies over which the beat frequency may vary. Since the bandwidth of the amplifier is broader than needed in order to pass the wide range of frequencies, the Signal to Noise Ratio (SNR) and sensitivity are reduced. The second method employed is to fix the beat frequency and allow the Δf to vary. The advantage of this method is that the low frequency amplifier need only be as wide as the receiver signal frequency. This reduces the SNR without degrading sensitivity. The value of the frequency difference now becomes the measure to the altitude. (Hovanessian, 1984)

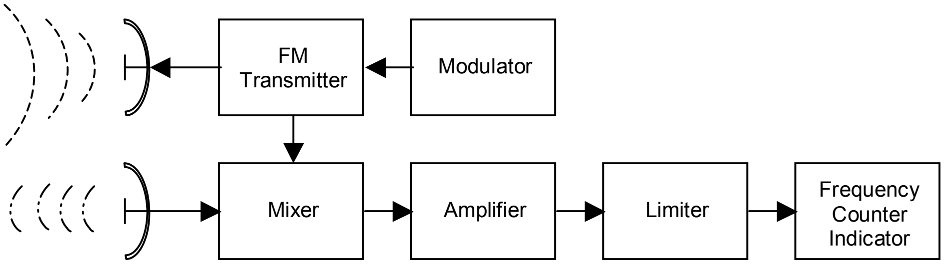

Figure 9. CW-FM Altimeter Block Diagram

Accuracy of the system is a function of the bandwidth of the transmitted signal and the SNR. Additionally, accuracy may also be limited by the inaccuracy of the frequency measuring device, multi-path errors, and frequency errors caused by the turn-around of the frequency modulation. Additionally, an error common to CW-FM altimeters is the fixed error or step error. The altitude of a CW–FM altimeter is found by the equation

$$R = \frac{cN}{4\Delta f}$$

Where R is the range, c is the speed of light, Δf is the frequency difference and N is the average number of cycles of the beat frequency. Since the output of the frequency counter is an integer, the range will be a multiple of c/(4Δf) and will cause a quantization error equal to

$$\Delta R\ (\mathrm{ft}) = \frac{246}{\Delta f\ (\mathrm{MHz})}$$

The step error is independent of the range and the carrier frequency and soley a function of the frequency difference. Large frequency differences are required if the error is to remain small. (Hovanessian, 1984)

Several critical assumptions were made in the design of the two radar altimeters described above are the same. The first critical assumption is that the antenna can be located at a sufficient distance apart to neglect the coupling or leakage between the two antennas. Since the CW-FM altimeter uses a portion of the transmitted signal, this system is rather insensitve to this assumption. (Hovanessian, 1984) Pulsed systems are relatively insensitive to coupling. Since the doppler shift is small (at normal angles), pulsed systems avoid the problem of interference by continuously shifting the transmitter's frequency. Additionally, the problem of coupling can be avoided by switching off the receiver while a signal is transmitted.

The second critical assumption is that the doppler frequency shift due to the relative motion between the aircraft and the ground is so small that it can be ignored. The doppler shift of the radar frequency is a function of the radar's vertical velocity. The velocity of the radar is a function of the sine of the angle of incidence θ. The magnitude of the sine of any angle changes most rapidly as it passes through 0^o so the largest change in amplitude of the doppler shifted frequency occurs about 0^o angle of incidence. The following is the equation for range corrected for the doppler shift and lookdown angle of the antenna:

$$R = \frac{2V_R}{\lambda} \sin \theta$$

The angle of incidence of a radar altimeter antenna is nearly normal to the surface of the earth ($\theta = 0$). At just 22^o angle of incident the magnitude of the doppler shift is approximately 40% of the maximum range value. (Stimson, 1998) Increasing the beamwidth of the transmitted signal will decrease the susceptability of the radar to roll and pitch errors, however the problem of multipath reflections increases. (Kayton, 1969)

Because the RCS of the earth is so large and at relatively small distances the radar altimeter is able to employ a small, low powered, broad beamed, CW or pulsed radar, using FM ranging to provide precise reading of absolute altitude. Radar altimeters designed for civil operations are CW while the military altimeters tend to be pulsed using a very low PRF and utilize pulse compression to spread the frequency of the radar over a wide band. (Stimson, 1998)

The altitude returns of most radar make them natural instruments to measure absolute altitude and in fact, the military and civil aviation have been using them since the mid 1960s. Figure 10 below shows a radar altimeter display used in many General and Civil Aviation aircraft. What keeps this technology out of most GA cockpits is the cost. The average price for a radar altimeter system designed for civil aviation is between \$3,000 and \$6,000.

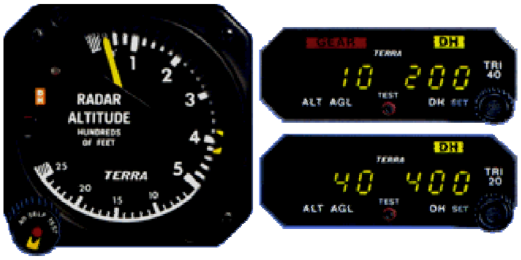

Figure 10. Typical Radar Altimeter Display

II. Review of Theory

Laser Propagation

The information contained in this chapter to include the diagrams, came from one source, *Lasers and Their Applications* written by Dr. Rami Arieli. Dr. Arieli is currently a Professor of Physics at the Weizmann Institute of Science in Israel.

Laser, or Light Amplification by Stimulated Emission of Radiation, involves exciting a chemical, called the amplifying medium or gain medium by adding energy to the chemical system. The amplifying medium can be a solid, a liquid, or a gas. Whatever its physical forms, the amplifying medium must contain a high proportion of atoms, molecules or ions that can readily store and release energy. As the atoms within the system absorb the energy, the electrons are raised to a higher energy level. As the electron drops to a lower energy level, the excess energy is shed in the form of photons. Since specific lasing materials absorb energy at a specific frequency, the coherent light is emitted at specific wavelengths. The color of light is determined by its frequency or wavelength. The wavelength of the emitted light is precisely related to the amount of energy released and is given by the equation:

$$E = h \times \nu$$

The energy, E, of a photon is determined by its frequency, ν, and Planck's constant, h. The wavelength, λ, of light is related to from the following equation:

$$\lambda = \frac{c}{\nu}$$

where c is the speed of light and approximates 300×10^6 m/s. The term coherent refers to the fact that the emitted light waves are in phase with one another and are so nearly parallel that they can travel for long distances without spreading. By contrast, light from an incandescent bulb emits light incoherently and diffuses in all directions. Coherence means that laser light can be focused with great precision.

The process of energizing the amplifying medium is termed pumping. There are several methods of pumping the medium. In the case of a solid, an intense burst of light is sufficient to excite the atoms within the medium at a specific frequency. This is called optical pumping. The optical pump may take the form of a Xenon-filled flashtube or may be another laser. Lasers, which are pumped in this fashion, are usually pulsed in nature.

Gaseous mediums require a container in order to enclose the gas. With this amplifying medium, an electric charge passed through the container, pumping the medium. The effectiveness of the laser pump is dependant on the medium being pumped. Often the ends of the container are inclined at an angle, which allow polarized light to pass freely. This angled window is called a Brewster window. Gaseous lasers, which are pumped in this fashion, produce a beam, which is polarized. Electrically pumped lasers can be either pulsed or continuous.

An amplifier is often used to increase the intensity of the laser. An amplifier usually consists of a mirror at one end, and a partial mirror at the other. As the coherent light contacts the partial mirror, part to the energy, from 20% to 98%, depending on the laser, is reflected back for further amplification and is referred to as positive feedback. A laser, which utilizes positive feedback, is known as an oscillator. The portion of the reflected light further excites the medium and as the light is reflected several times through the medium the intensity of the beam quickly builds. This process also ensures that the light becomes coherent. Only light that is in phase, i.e., traveling parallel to the axis of the cavity is reflected for multiple passes. Incoherent light is reflected at odd angles, eventually escape the cavity. This process also serves to improve the spectral purity of the laser. As the medium is excited, it produces a photon in a small band of frequencies. Only a specific frequency will undergo repeated passes in the cavity. Light which may still be amplified but of frequencies outside the specified frequency are quickly attenuated. This process of spectral purification is called the cavity mode and the light will only resonate at a given frequency. The product is beam of light, which is coherent, parallel and in phase.

Factors Affecting Laser Performance

Surface Reflectivity

A material can either reflect, absorb, transmit, or a combination thereof, the laser energy. The sum of energy transmitted, absorbed, and reflected will equal the amount of energy incident upon the surface. The term “specular” is used to describe a surface whose imperfections and surface variations are much smaller than the wavelength of incident radiation. When the surface imperfections are larger than the wavelength the surface is said to be diffuse.

A diffuse surface is a surface that will reflect the incident laser beam in all directions. The beam path is not maintained when the laser beam strikes a diffuse reflector. Whether a surface is a diffuse reflector or a specular reflector will depend upon the wavelength of the incident laser beam. The effect of various curvatures of diffuse reflectors makes little difference on the reflected beam. Figure 11 illustrates the geometry of the reflected energy as the beam is reflected or refracted. In reflection, the angle of incidence is equal to the angle of reflection. The angle of refraction, θ’, is dependent on the index of refraction n’ of the material the light passes through.

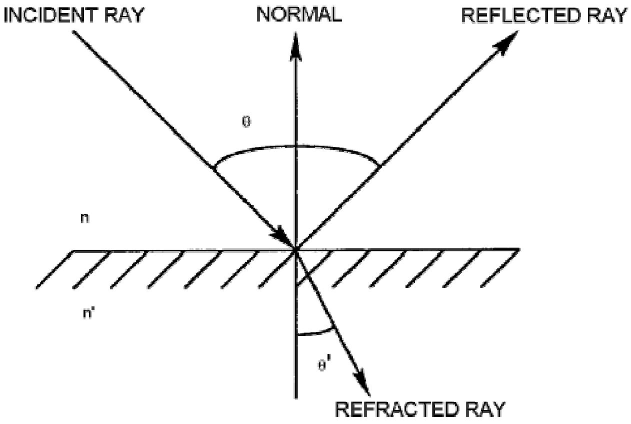

Figure 11. Reflection and Refraction

Beam Divergence

Although the beam of a laser is nearly parallel, there is still a small amount of divergence or increase of the diameter of the beam width with distance. The beam divergence of radiation emitted from a laser is described in Figure 12. A good approximation for the laser beam divergence is:

$$\theta = \frac{d_2 - d_1}{L_2 - L_1}$$

where θ is the beam divergence (in radians), $d_2 - d_1$ is the difference in the diameters of the beam at points 1 and 2, and $L_2 - L_1$ is the difference in the distances along the laser axis at points 1 and 2. Depending on the optical cavity type there is a point where the beam diameter is minimum. This point is termed the beam waist.

The equation for calculating the beam divergence is always correct at large distances from the laser. Thus, it is the "Far field" equation, and is not necessarily correct near the laser. The far field is defined as 100 times the beam diameter squared divided by the wavelength of the laser. Conversely, the near field is defined as any distance less than the far field boundary.

Pulse Repetition Frequency

A laser pulse can be described by plotting the laser power as a function of time. Most laser pulses have a short rise time, and a longer decay. As shown in Figure 13 below, the shape and area of the pulse can be approximated by using a triangle. There are several characteristics common to all pulses, which are helpful in describing the amount of energy

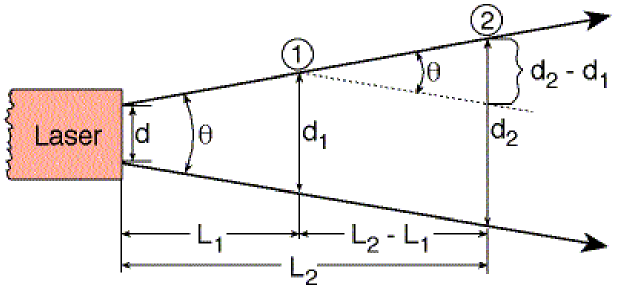

Figure 12. Geometry of Divergence

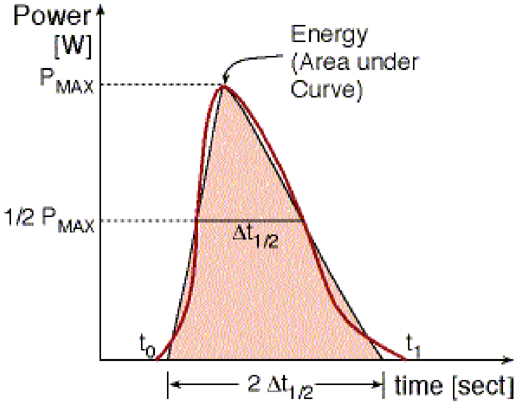

Figure 13. Single Pulse Geometry

carried by the pulse. The maximum emitted power is P_{max} and corresponds to the apex of the triangle. The pulse duration ($\Delta t_{1/2}$) is its width at half maximum (0.5 P_{max}). The pulse width is the time interval in which the pulse power is higher than half the maximum power: The area under the curve describe the amount of energy carried by the pulse and is half the length of the base ($\Delta t_{1/2}$) times the height (P_{max}), and is given by the following equation:

$$E_p = (\Delta t_{1/2}) X P_{max}$$

For typical pulsed lasers the energy of a single pulse is not particularly high, however, the peak power is extremely high, usually $X10^6$ W. Since the pulse duration is short, all the energy is concentrated during this short period.

So far we have discussed a single pulse. Pulsed lasers such as those used in a laser range finder send out multiple pulses and are periodic in nature; hence, it is possible to determine the period and frequency of the pulses. The period of any repetitive phenomena is the time interval between two equivalent points on adjacent pulses and is assigned the nomenclature of T. The frequency of the pulses us the number of pulses occurring in a second and given by f. The pulse frequency, f, and the frequency of the laser energy, ν, are mutually exclusive.

The relationship between the period and the pulse frequency is given by the equation:

$$T = 1/f$$

The duty cycle is the relative amount of time the laser is on, or pulsing. We can determine the duty cycle by dividing the pulse duration ($\Delta t_{1/2}$) by the period (T).

Since the output power of a pulsed laser is not continuous, a more useful description of the power output of a pulsed laser is required for some calculations. This is often accomplished by determination of the laser's average power. Average power (P_{avg}) describes the amount of energy transmitted by the laser in a second and is equivalent to the amount of power required for a continuous laser to transmit the same amount of energy per second as a pulsed laser. Average power is calculated by energy of a single pulse by the frequency of the pulses (f). The following equation describes this relationship:

$$P_{avg} = E_p \times f$$

Figure 14 illustrates the relationship between the maximum power and average power of a laser pulse.

Optical Signal to Noise Ratio

Sometimes noise can interfere with the transmission and reception of a signal. Common examples of the phenomena that cause noise include: the reflections of phased light from the active medium walls, the diffraction of the laser as it passes through an aperture, and the diffraction of the beam by small imperfections in the lasing medium such as dust particles and scratches.

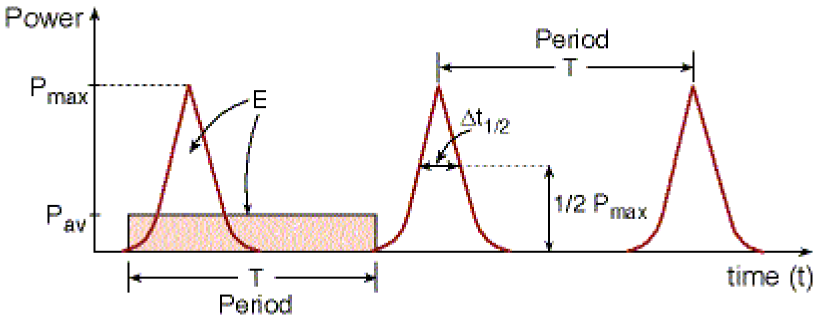

Figure 14. Periodic Nature of Pulsed Lasers

It is possible to visually observe the noise present in a laser. When the laser beam illuminates a far screen, the picture shows light and dark areas. These are caused by interference phenomena between different parts of the beam, which arrive at the screen through slightly different paths. Since the path difference between the main beam and the "noise" is small, only at the far field it is possible to see the interference pattern. Instead of being far away from the laser, it is possible to use a lens to create the far field of the beam at the focal point of the lens and thus measure the amount of noise present. The ratio between the strength of the signal and the strength of the noise is referred to as the SNR.

Calculating Range

Much like radar technology, one of the first applications for the military was as an instrument to determine range. Since the beam of a laser consists of light, its speed of propagation is a known constant. By measuring the time it takes the laser to strike a target and return it is an easy calculation to determine the distance to the target.

As the pulse of laser light is sent, an electronic trigger signal is send to a time counter. When the detector receives the reflected signal from the target, it stops the time counter. A computer calculates the distance to the target by multiplying half the time of the counter by the speed of light (c) (Since the laser beam travel the distance to the target and back). The laser beam is scattered by the target into all directions (diffuse reflectance). Thus, very little intensity from the reflected signal reaches the detector. In a simple detecting system, the reflected signal from the target is collected by the detector, amplified electronically, and the electronic signal is transferred to the computer for processing.

III. The Systems Engineering Design Process

The process utilized throughout the design of the display and display format was the systems engineering design process or SEP. The entire process is iterative and recursive in nature and consists of four major tasks. The tasks, which comprise the SEP, are shown in Figure 15 below.

The process input consists of specific requirements as designed by the consumer and can include: definition of the mission, the expected operating environment, and any constraints such as monetary or regulatory constraints. Additionally, since the process is recursive the system output from a previous iteration of the SEP may become the process input for the following iteration.

The first major task in the SEP is the requirements analysis, which defines what the system must do and how well the system must do it. The requirements analysis establishes quantifiable critical performance parameters from the process inputs. The product of this task is the design concept.

The second task is the functional analysis, which defines the functional architecture of the system. This task translates the general system requirements as defined in the requirements

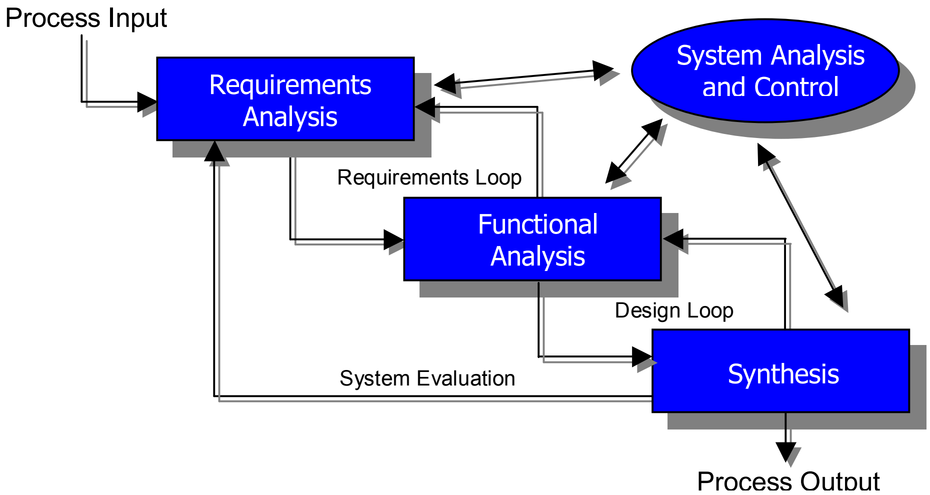

Figure 15. The Systems Engineering Process

analysis and translates them into specific systems requirements. Additionally, the functional analysis defines the hardware and software requirements of the design. The product of this task is the preliminary design, which provides a general description of the overall system. The requirements loop is closed when the functions of the system satisfy the requirements defined in the previous task.

The next step is the design synthesis. The design synthesis defines the physical architecture of the system by describing the subsystems required to perform the functions as described in the functional analysis. Alternatives for hardware and software requirements are analyzed and the preferred solution is selected. The output of this task is the detail design or description of the set of subcomponents, which comprise the system. The design loop is closed when the design solution meets the functional requirements.

The system analysis and control is a management function, which is applied to each of the tasks previously described. Subtasks which comprise the systems analysis and control function include: interface management which ensures proper form, fit, and function of the design elements, tracking of cost and scheduling, conflict resolution, and verifying the requirements have been met at the completion of each task in the SEP.

Prior to the completion of an iteration of the SEP and process output, the design solution must be verified or evaluated to ensure that the design meets the requirements as defined in the requirements analysis. If a conflict arises at this level or during the requirements loop or design loop then 2 options exist, either change the solution or modify the requirements. The SEP is applied throughout the lifecycle of the design.

IV. Operational Requirements Analysis

A Limited Market Survey

In designing the laser altimeter display, it was first necessary to establish the need. A limited market survey helped to determine the need and to define the design objectives of the display. By defining the critical design aircraft and for whom the display was being designed, a logical starting point was established. Since Opti-Logic expressed the desire to explore the GA market, the user was essentially defined. However, the definition of General Aviation is somewhat enigmatic, and can vary depending on whose definition is used. The FAA defines GA as "That portion of civil aviation which encompasses all facets of aviation except air carriers." (FAA, 1996) Since it was impractical to design a display suitable for all civil aviation, it became evident that, for this project, the definition of GA needed further refinement.

The Aircraft

To this end, the NASA published a report outlining the typical GA aircraft. The data for the report came from the FAAs 1996 General Aviation and Air Taxi Activity (GAATA) survey. For the purposes of the study, NASA defined GA as any fixed wing aircraft operating under FAR Part 91, 125, 135 (non-scheduled), or 137. This definition excluded experimental aircraft, gliders or any aircraft that is a known commuter or commercial air carrier aircraft. (NASA, 1999) Table 1 below shows the portion of the GA market excluded by the NASA definition (not highlighted) is relatively small at only 14.3%.

According to the GAATA survey, almost 85% of GA aircraft are single piston engine fixed wing aircraft with four seats and fixed tricycle landing gear. Additionally, the NASA report further defined the top six aircraft models based on popularity in sales using the above criteria. These aircraft models comprise 45.5% of the GA aircraft population and are presented in Table 2 below. (NASA, 1999)

Table 1. Composition of GA Market by Aircraft Type

Aircraft Type	Total	Corporate	Business	Personal	Instruction	Air Taxi	Other
Fixed-Wing	**160,577**	**8,227**	**26,963**	**93,174**	**13,248**	**3,194**	**15,699**
Piston	150,980	2,549	26,043	92,715	13,149	2,057	14,394
Turboprop	5,309	2,327	708	364	73	743	1,090
Turbojet	4,287	3,350	211	94	25	393	211
Rotorcraft	6,391	868	463	482	487	500	3,175
Other Aircraft	4,144	13	21	3,247	225	0	601
Gliders	1,882	0	8	1,469	176	0	226
Lighter-than-Air	2,261	13	13	1,777	79	0	373
Experimental	16,198	176	788	12,715	270	143	2,036
All Aircraft	187,312	9,286	28,236	109,619	14,261	3,838	37,805

Table 2. Top Six General Aviation Aircraft Models

Rank	Type of Aircraft	Nickname	# of Seats	# of Aircraft	% Total GA
1	Cessna 172	Skyhawk	4	19,754	13.30%
2	Piper PA28	Archer, Cadet, Cherokee, Arrow, Warrior, Dakota	4	17,947	11.18%
3	Cessna 150	Aerobat, Commuter	2	12,885	8.02%
4	Cessna 182	Skylane	6	11,573	7.21%
5	Beech 35	Bonanza	4-6	5,450	3.39%
6	Mooney M20	Ranger, Master, Chaparral, Executive, Statesman, Ovation, 201, Encore, Bravo, Eagle	4	5,423	3.38%

The Pilot

Just as the definition of the typical GA aircraft is useful in establishing the operational requirements of the display hardware; it was also necessary to identify characteristics, level of training, and income of the GA pilot to aid in the development of the display. This is extremely difficult in that variety is the word that best describes the GA pilot. It is important to recognize this variety when designing new technologies which target GA. (Hunter, 1995) While diversity seems to be the operative word, there are some characteristics common to all GA pilots, which provided a basis to begin formulating the requirements analysis.

In 1995, the FAA conducted a large-scale survey to gain a better understanding of the pilot population in the US. Almost 7,000 responses were received to 20,000 questionnaires mailed to pilots nationwide. Of the 7,000 responses, 2,548 were received from individuals who held a private pilots rating as there highest rating. Reduction of these responses yielded the following characteristics:

Demographically, the typical GA pilot is educated with 61% holding a four-year or equivalent degree and nearly 14% having completed the requirements for a PhD. Although this statistic is not surprising in that higher education often leads to increased disposable income, care must be taken not to draw the wrong conclusion with regard to problem solving skills. Research suggests that expertise gained in one domain does not necessarily transfer to another. In fact, the opposite may be true in that success in one may lead to overconfidence in the other. (Hunter, 1995)

Data from the survey, presented in Figure 16, clearly indicates the relative inexperience of the GA pilot processing a private pilots certificate with 58.7% attaining less than or equal to 500 hours experience. (Hunter, 1997) While several recent studies have shown little correlation between experience and expertise, it is an aviator's experience, whether real or vicarious, that provides the knowledge base a pilot draws on in any situation.

A recent FAA report, to determine the GA pilot's decision-making skills, concluded that "although GA pilots may demonstrate on paper that they have the knowledge and perspective for deciding upon and taking the safest course of action, there is no assurance that in real-time situations, under the pressures and motivations of the moment, that they will in fact apply this knowledge appropriately." (Driskill, 1998) Indeed, accident statistics suggest that they often do not make the correct decisions in these critical situations.

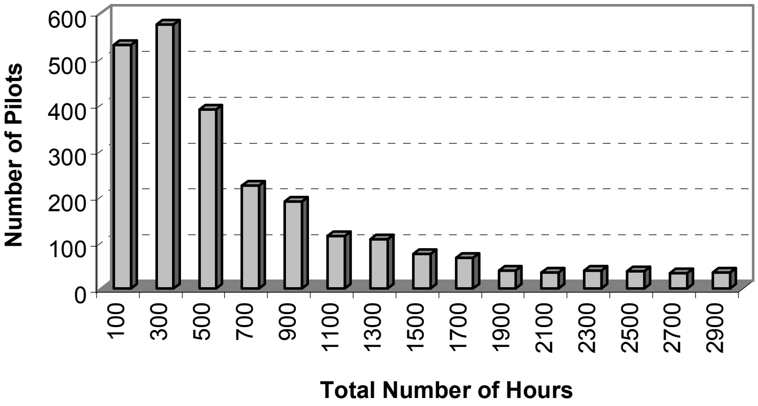

Figure 16. Total Flight Time Among Private Pilots

More important than total time, however is an aviator's recent experience. As shown in Table 3, nearly half of those who responded to the survey reported flying 30 hours a year, executing an average total of 16 approaches and landings. Additionally, the GA pilot conducted only 5 hours of night flying during the same annual period. This is not enough reoccurring experience to maintain a level of proficiency commensurate with the degree of difficulty in operating an aircraft safely. Lack of practice in flying and aviation decision-making can be detrimental to human performance. (Hunter, 1995)

While the above research determined the critical design aircraft and established the characteristics of the GA pilot, the question remained where to fix the cost of the system. A limited market survey was conducted during the 2001 Staggerwing Convention held at Tullahoma Airport, Tullahoma, Tennessee. The primary purpose of the survey was to determine the market price the average GA pilot was willing to spend for a device to display absolute altitude during an approach. Thirty responses were received to the forty survey questionnaires distributed. The average total flight time of the respondents was 4433.33 flight hours with over 63% holding a pilots certificate higher than private pilot. Half of the pilots responding to the survey had at least one "close call" with terrain or incident in which they had misjudged their altitude. When asked how much they were willing to spend on a laser altimeter, displaying absolute altitude, 14 respondents or 46.6% indicated they were willing to spend $1500 or less as shown in Table 4.

Table 3. Average Flight Experience Among Private Pilots

Mode of Flight	Mean	Median	Stand Dev
Day Time – Last 6 Months	24	11	152
Day Time – Last 12 Months	46	27	95
Day Time - Career	777	396	1664
Night Time – Last 6 Months	3	0	13
Night Time – Last 12 Months	5	0	18
Night Time - Career	108	22	644
Landings – Last 6 Months	61	40	109
Landings – Last 12 Months	29	16	43
Total Time – Last 6 Months	22	12	34
Total Time – Last 12 Months	50	30	68
Total Time - Career	819	445	1293

Note. Data from the 1995 FAA National Airman Research Questionnaire.

Table 4. Willingness to Pay Specific Price for Laser Altimeter

Price of Altimeter	f	%
$500	2	6.7
$1000	6	20.0
$1500	6	20.0
$2000	6	20.0
$2500 or More	2	6.7
No Response	8	26.6
Total	30	100.0

Note. Data from market survey conducted during the 2001 Staggerwing Convention, Tullahoma, TN.

The above survey is certainly not representative of the GA pilot population for two reasons. First, the sample size of survey was small with only 30 questionnaires received. Secondly, the cost of a Staggerwing aircraft far exceeds the cost of a typical GA aircraft, which could lead to the assumption that the owners of Staggerwing aircraft have more disposable income to allocate in outfitting their aircraft. A literary search of several popular aircraft accessory catalogs yielded a more reasonable figure in fixing the cost of the system. The average price advertised for add-on electronic equipment such as GPS and other radio navigation instruments was $1000.00

The Mission Defined

The next step was to determine the missions for which the system was to be used. Examination of the GA performance record should establish at what point in flight the system would provide the most benefit to the aviator. (O'Hare, 1999) Statistical analysis of accident data of the GA population for the years of 1995-1997, Figure 17 shows a disproportionate 35.9% of accidents occurred during approach and landing phase of operation, which represents only 2% of the average flight time. (NTSB, 2000) Due to the statistical data as well as the limited range of the laser sensor it was determined the best application for the altimeter would be to aid the aviator in the terminal approach and landing phases of flight operations. This would provide the pilot with the ability to use the instrument to transition from the enroute portion of his flight using the barometric altimeter, to the approach phase using the laser.

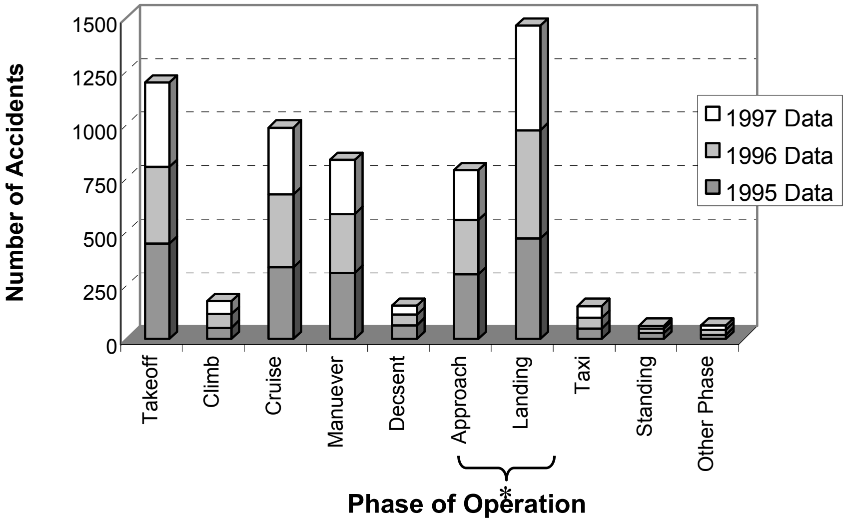

Figure 17. General Aviation Accidents by Phase of Operation – Calendar Years 1995-1997

General Requirements

Once it was determined for whom the system was being designed and for what purpose, the next step was to outline the operational requirements of the display. The fundamental requirements can be summed up as follows:

1. The system cost should be as low as possible.
2. The system should have as little impact on the aircraft as possible.
3. The display should be readable in all lighting conditions to include direct sunlight.
4. The system should display the altitude information as accurately as possible.
5. The system should be reliable and maintainable.

The display can further be broken down into the several subsystems, each with its own requirements. The display subsystems include the display-pilot interface or symbology presentation, and the aircraft-display interface or hardware to include the display mount.

Symbology Requirements

In order to decrease pilot workload and enhance safety the display symbology must be as intuitive to the operator as possible. The altimeter display needed to present qualitative and quantitative information to the pilot to ensure that the pilot received not only precision in reading altitude but also trend information in order to maintain situational awareness during the landing phase of flight. Additionally, the altimeter had to be able to present the information to the pilot in real time. Lastly, in order to be effective the symbology needed to incorporate an alert feature to warn the pilot of hazardous situations involving high rates of descent with insufficient altitude to correct.

General information requirements according to the Human Factors Design Guide Include:

1. The information displayed to a pilot shall be sufficient to allow him or her to maintain altitude to within desired limits.
2. Information shall be presented in feet without requiring the pilot to transpose or calculate his or her current absolute altitude. (Wagner, 1996)

Display Hardware Requirements.

To keep the cost as low as possible it was necessary to utilize COTS display systems to avoid expensive developmental cost associated with the design of a unique system display. In addition to meeting the general systems requirement listed above, specific performance and physical parameters exist. Since cockpit space is limited, the size of the display must be kept to a minimum while achieving satisfactory readability of the symbology. In addition, the weight of the hardware must also be minimal.

Visibility requirements are outlined in the FAAs Human Factors Design Guide and are as follows:

1. Displays shall be legible under all anticipated viewing conditions.
2. Information shall be updated at a rate that ensures the pilot has sufficient time to react to an undesirable condition.

3. Failure of a display or its circuit shall be immediately apparent to the pilot. (Wagner, 1996)

Display Mounting

Just as the display hardware is integral in the legibility of the symbology so is the location and system of mounting the display. The location of the display shall not require the pilot to assume an uncomfortable or awkward position in order to read the display. If possible the face of the display should be oriented perpendicular to the pilot's line of sight (LOS), however the maximum displacement will not exceed 45° from the pilot's LOS. Figure 18 graphically illustrates these requirements.

Additionally, the display symbology must be visible during the vibrations experienced during the normal flight envelope. The preferred viewing distance of the display as measured from the aircrafts DEP should be at least 20 inches with the absolute minimum viewing distance of 13 inches. (Wagner, 1996)

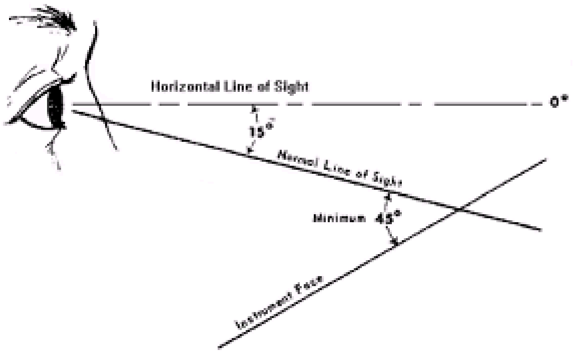

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Figure 18. Line of Sight Requirements

V. Display Functional Analysis

The second step in the systems engineering design process is the system functional analysis. Functional analysis consists of identifying specific functions the system must perform in order to achieve the design objectives. The purpose of the functional analysis is to identify: system and subsystem functions and the method and resources to accomplish those functions. (Blanchard, 1990)

The functional flow block diagram is a method of portraying system design requirements pictorially, illustrating parallel relationships, the hierarchy of system functions, and functional interfaces. Functional flow block diagrams are usually prepared down to the level adequate to describe the needs of the system. (Blanchard, 1990) Figure 19 is the top level and level 1 of the functional flow block diagram for the laser altimeter system.

The top level describes the overall flow from the initial laser return to the pilot's display. As previously mentioned, the sensor is a NDI and is considered fixed for the design process.

Once the processor senses the signal, the signal must be altered into information, which the pilot can use. Level 1 shows the breakdown of the function of processing the signal, block 3.0, from the reception of the signal to the generation of the symbology for presentation on the display. By analyzing the information presented on current barometric altimeters it was possible to determine the minimum required information needed to make the display effective in maintaining situational awareness.

From experience, a pilot requires both position and rate information to maintain altitude awareness during flight. The source of this information on current cockpit instrument panels is the barometric altimeter and the vertical speed indicator. Depending on the type of altimeter display, the pilot determines his exact altitude by either reading a digital drum display or by cognitively adding the position of the needles. Additionally, the pilot also derives trend information by the rate at which the pointers on the altimeters face move. The faster the

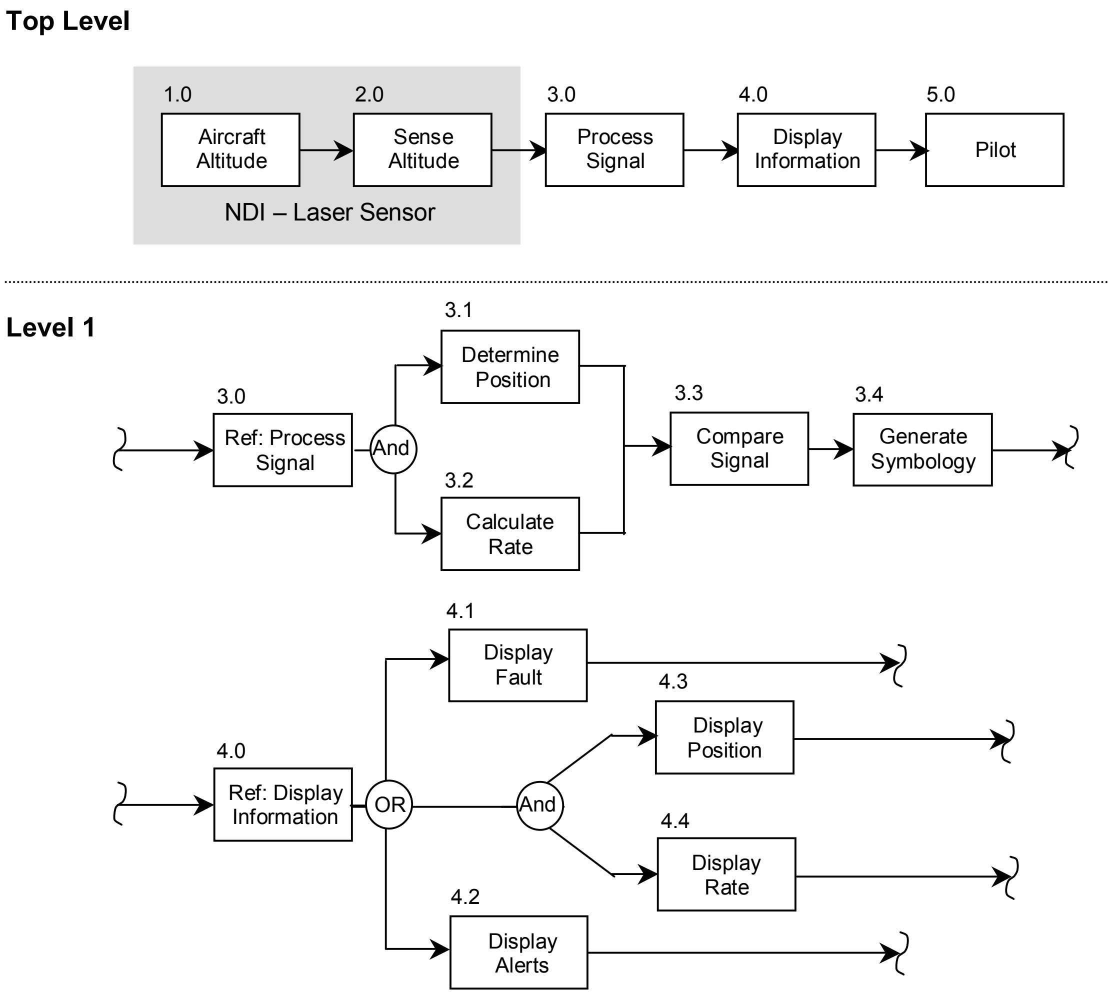

Figure 19. Top Level and Level 1 of the Functional Flow Diagram

needles move the faster the ascent or descent. Crosschecking the rate information with the VSI provides a quantitative value to the rate information.

The relative workload in determining this information depends largely on the design of the display, i.e., the way the information is presented. Altimeter designs such as the three-point altimeter shown in figure 5 require a higher workload to calculate the altitude. The pilot must determine which needle represents what increment of altitude (100, 1000, or 10,000 feet), assign a value to each needle then add the values. Even the simplest design, such as the drum and pointer requires some level of arithmetic to calculate the altitude. Qualitative rate information gained by the movement of the needles can be processed in parallel with the position information with little effort. However due to the circular design of the instrument this information is not presented as intuitively as possible.

A study conducted at NASA's Langley Research Center on how long a pilot looks at the altimeter during flight concluded that there is a characteristic difference in the dwells (the time the pilot spent looking at the altimeter face) between the right side and left side of the altimeter. The pilots in the study spent approximately 48% of the time reading the left side of the altimeter even when the needles were on the right side. The study concluded that the pilot is able to read the position and rate of the needle on the right of the display parafoveally while fixated on the left side of the display. (Spady, 1980) The study failed to discuss one factor of the circular design of an altimeter display. The movement of the needle on the left side of the display has a direct correlation to the movement of the aircraft, e.g., when the aircraft is climbing, the needle is moving up while it is on the left side of the display. When the needle is on the right side of the display, the relationship is reversed. As the aircraft continues its climb, the needle is descending on the face of the display. This can be very counter-intuitive to the pilot and explains the greater amount of time looking at the altimeters left side as shown in the study. The pilot is able to gain more intuitive rate information from the linear movement of the needles head or tail when it on the left side and hence has a direct correlation to the aircrafts movement, thereby reducing his workload.

If the pilot wishes to know the exact rate, the workload increases even further. The pilot upon referencing the VSI, must process this new information in serial with position information due to the relative distance from the altimeter.

Since it was determined that position and rate are the critical information requirements to determine altitude, the data processor must calculate this information from the range data supplied by the sensor. Once the signal is processed for rate and position, the information is then compared and displayed via symbols integrated into a single display set and presented with or without alerts.

A decision was required to formulate the parameters for the display of fault messages, cautions, and alerts. Level 2 of the functional flow block diagram shows the functional decomposition of block 3.3, Compare Symbology, to determine what parameters constituted cautionary display symbology and what parameters would require an alerting display symbology. As shown in Figure 20, a rate of greater than 1000 fpm rate of descent when combined with an altitude of 400 feet would cause the processor to display a cautionary symbol set while a rate greater than 1000 fpm at less than 200 feet would drive an alerting symbology set. The display of the caution would provide the pilot with 24 seconds to correct his rate of descent and hence altitude before contacting the ground while an alert would provide 12 seconds.

The altitude of 400 feet and 200 feet are significant in that they correspond to the MDA and DH altitudes of a typical instrument approach, however, these events, in and of themselves, do not warrant a caution or alert. (Kershner, 1998) Similarly, a 1000 fpm rate of descent alone is not cause for a caution or alert. These parameters were chosen to provide the pilot with ample time to recover from a potentially hazardous situations involving altitude with a higher than normal sink rate.

The decomposition of block 3.4 of the functional flow block diagram illustrates the generation of the specific display symbology sets for a given parameter. The first step in this sequence is to evaluate the systems operating state. To do this the processor determines

Level 2

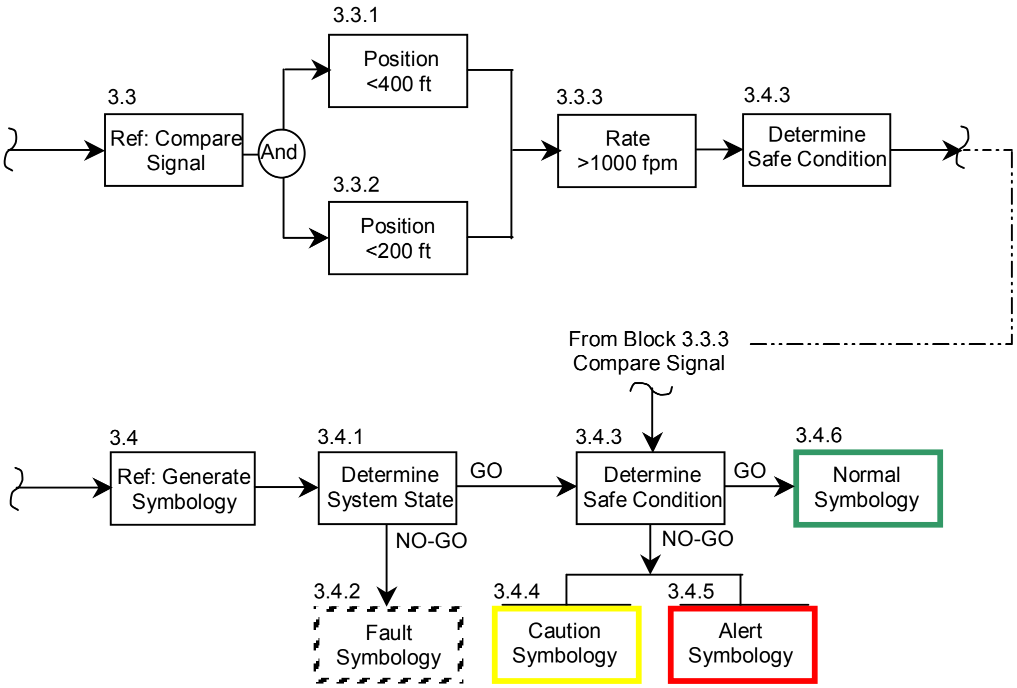

Figure 20. Level 2 Functional Flow Diagram

whether a viable signal is received from the sensor. If no signal is sensed the processor displays a fault symbology set to notify the pilot of the unreliability of the altimeter. If the processor is receiving a signal, then the next step is to determine if the signal falls within the safety parameters as defined by block 3.3, Compare Signal, to block 3.4.3, Determine Safe Condition, discussed in the previous paragraph. If the parameters fall outside of that determined for safe flight then the processor would display a caution or alert based on the relationship between the aircrafts altitude and rate of decent. If the parameters are within that required for safe flight then a normal symbology set would be displayed.

VI. Design Synthesis

Analysis of Alternatives

The next step in the design process was to select the physical components that would comprise the system. The top level of the functional flow block diagram outlines three systems components, the sensor, the data processor, and the display. Only the data processor and the display were considered using a weighted matrix. The matrix assigned a score of zero to performance parameters considered average. Components with better than average characteristics were awarded a value of + 1, while those with a performances less than average received a score of – 1. Once the performance characteristics were analyzed, the scores were tallied and the component with the higher score was selected.

Data Processor Hardware

The data processor receives the digital signal from the sensor and processes the signal for display. In addition to displaying the positional information from the sensor, the data processor must calculate rate information as well as determine the conditions requiring a display of a caution or warning. The systems considered are a custom built system, or an existing Windows© or Macintosh© based computer system. The advantage of a custom built system is that the system can be as small as needed. The disadvantage is the cost of development in terms of time and money. The advantage of a computer based system is that no developmental cost are involved. In addition, a Windows© or Macintosh© based system would be capable of running existing software to process the data. Disadvantages include the size of the computer. A laptop system would be the logical choice due to the size requirements. A weighted matrix, Table 5, was used to evaluate the merits of each system.

The weighted matrix evaluated each system based on the following characteristics: cost, size, and flexibility. Since there were only two choices to consider the scoring of the matrix

Table 5. Analysis of Alternative Data Processors

System	Cost	Size	Flexibility	Total
Custom	- 2	+ 1	0	- 1
Laptop	+ 1	0	+ 1	+ 2

deviated from that specified in the previous section. The parameters of each characteristic are as follows.

Cost was determined to be the primary consideration. In addition to the cost of purchasing the hardware, the cost of the development was also analyzed. A cost of $500 was considered average with a price below that awarded a score of + 1. Each $250 above the average was awarded a – 1.

The size of the data processor considered not only the physical dimensions but also the memory capacity of the processor itself. The smaller of the two choices considered was awarded a + 1 while the larger was given a score of 0.

Flexibility was rated by whether an existing program could be utilized or whether one needed to be developed. If the system required development, it was awarded a 0. If a program was designed to run on the operating system existed it was given a score of + 1.

Display Hardware

As shown in Figure 21, there are currently two broad categories of displays for use in avionics and include emissive and transmissive displays. Emissive displays include CRTs and FEDs, and operate on the principle of the electron gun projecting photons onto a luminous screen. Transmissive displays, by contrast, pass light through openings in a liquid crystal substrate. Transmissive displays can be further classified by the use of a switching element within the liquid crystal. Switching elements are used to control the amount of light transmitted through the pixel elements. Displays lacking any switching mechanism are said to be passive while those with an active switching element are termed active. The most common type of switch is the thin film transistor or TFT.

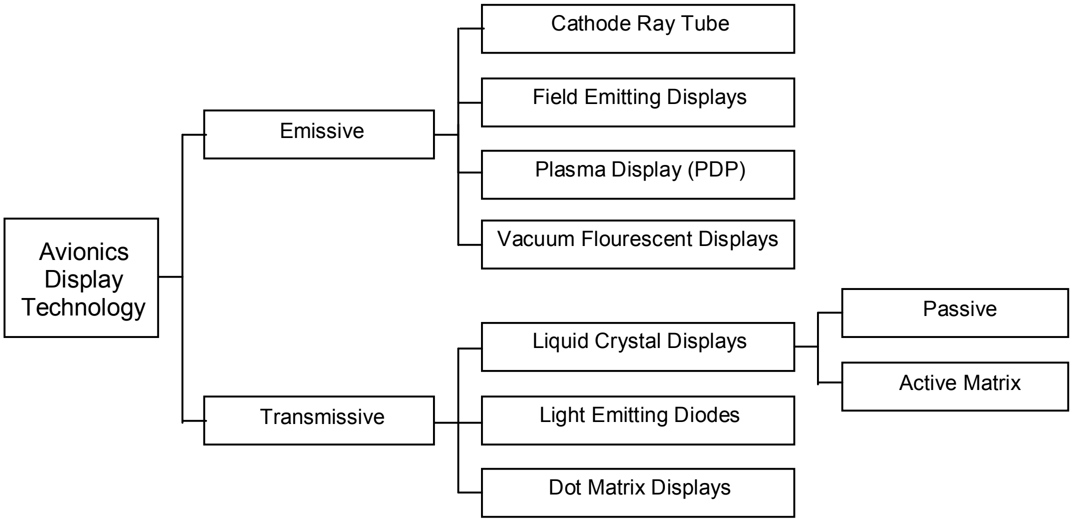

Figure 21. Comparison of Display Types by Category

Five display technologies were considered for the laser altimeter display. CRTs, which are the oldest display technology, are similar to TV and desktop computer monitors. The advantages of using a CRT are the cost and readability of the display. It's for these reasons that CRT technology has been the industry standard for avionics companies over the past two decades. The only disadvantage to CRT display is their bulk; they generally require large amounts of space. FEDs are flat panel displays utilizing the same principle as the CRT. However, where the CRT uses a single electron gun to paint the phosphorescent screen by bending the stream of electrons, the FED utilizes millions of miniature electron emitting tips called nanocones. Each nanocone paints a single pixel. The FED has all the advantages of the CRT in readability yet it is less intrusive to the instrument panel. The biggest disadvantage is the cost of the display. The FED on average cost three times that of the CRT. HGED, like the FED, utilizes microtip technology to project the electrons onto the phosphorescent screen, however due to the manufacturing techniques are comparable in price to the CRT. The disadvantage is a slight reduction in resolution and the availability of the technology.

The LCD is the most common representative of non-emissive displays. The Active Matrix LCD, descendant of the LCD, contains TFTs as switches in the pixels of a display. The use of TFTs has greatly improved the image quality of the display while significantly increasing the viewing angle and visibility of the screen in direct sunlight. Additionally, AMLCD have become so thin they are quickly becoming the display of choice for many avionics companies. The disadvantage of the AMLCD has been the cost of the display, however, manufacturing techniques are constantly improving and consequently the price of the displays have fallen significantly in the last few years. The last display technology considered was the gas plasma display or PDP. The PDP operates by sending an electrical charge through the pixel containing three gasses. By varying the voltage to each of these gases the brightness and color of the image is controlled. The image generated is comparable to FEDs and AMLCD. The disadvantage is the cost, nearly 5 times that of the CRT, and more importantly the size of the screen. The process of generating the image in the gas plasma displays make them extremely difficult to manufacture in sizes smaller than 36 inches.

Display technologies eliminated outright included LED, passive LCD, and dot matrix displays. Although these displays represent the least expensive alternative of the technologies presented, they were not considered due their poor resolution or readability in direct sunlight or at extreme viewing angles. Additionally, with the exception of the passive LCD, these technologies are not readily available in screen sizes suitable for this project and would require custom ordering.

Table 6 outlines the performance characteristics of each display technology evaluated while the weighted matrix for the display hardware is present in Table 7. The performance characteristics and criteria used to rate each are as follows.

The primary consideration of this project was to keep the system affordable. As a result, a decision was made to utilize a COTS displays. Evaluation of the cost of the displays was based on an average cost per square inch of display screen. Displays with a price of $1 - $10

Table 6. Characteristics of Alternative Display Hardware

Type of Display	Cost	Resolution	Brightness	Viewing Angle	Intrusive
CRT	$5	.35 mm	300	160°	N/A
FED	$15	.21 mm	170	170°	10 mm
AMLCD	$15	.35 mm	180	155°	10 mm
Gas Plasma	$25	.35 mm	200	160°	100 mm
VFD	$3	.35 mm	100	170°	90 mm

Table 7. Analysis of Alternative Display Hardware

Type of Display	Cost	Resolution	Brightness	Viewing Angle	Intrusive	Total
CRT	+ 1	+ 1	+ 1	0	Too Intrusive	N/A
FED	0	0	0	+ 1	+ 1	+ 2
AMLCD	0	+ 1	0	0	+ 1	+ 2
Gas Plasma	- 1	+ 1	0	0	Too Intrusive	N/A
VFD	+ 1	+ 1	- 1	+ 1	- 1	+ 1

per square inch received a score of + 1. Those displays priced from $11 to $20 received a score of 0 while those with a cost of $21 to $30 received a score of –1.

The resolution of a display evaluates image output capacity. Resolution is usually measured in dots per inch (dpi). A higher resolution means a greater the amount of detail that can be shown. Display type resolution was evaluated against the following rating scale. Resolution from 0.40 down to 0.31 dpi received a score of + 1. Displays with a rating of 0 had a resolution between 0.30 dpi to 0.21 dpi. Resolution of 0.20 and lower received a score of –1.

Each of the displays was evaluated for brightness. Brightness and resolution are the leading factors in determining the readability of a display. The scale used to evaluate brightness is as follows. Brightness levels of 300 to 201 nits received a score of + 1 while levels, which fell between 200 – 101 nits, received a score of 0. Any component, which failed to achieve 101 nits, received a score of – 1.

Viewing angle was evaluated using the total viewing angle from left to right; a scale of + 1 was awarded to displays with a viewing angle greater than 165°. A viewing angle of 155° to 165° received a 0. Any system with a viewing angle less than 155° received a score of –1.

Intrusiveness was rated by its impact on the cockpits instrument panel. Width of the display unit was chosen as the characteristic, which would best describe the need for an STC. Those units with a width less than 15 mm where given a score of + 1. Units with a width of 16 mm to 30 mm were given a score of 0. Those displays exceeding 31 mm received a score of – 1.

Both the field emitting display and the active matrix liquid crystal display scored the best with + 2 points each. The display hardware selected to test the presentation was an Optrex Corporation 6.4 inch TFT AMLCD flat panel display, part number T-51382D064J-FW-P-AA and is shown in Figure 22. In addition to the selection criteria established in functional analysis, analysis of alternatives, the panel was selected due to its size, weight, and connectivity to a personal laptop computer. The displays resolution is 640X480 pixels with 32-bit color depth (262,144 colors). The maximum display brightness was 300 nits. The size shape and weight allowed the display to be mounted on the console of the test aircraft in a number of ways.

Figure 22. Display for Test Aircraft

Designing the Symbology

The elements of the display were selected based on the information requirements needed to control the aircraft's altitude during a descent from enroute altitude on an approach to landing. To the extent as was possible, the display was designed to incorporate standard symbology. This ensured the training to use the system was kept to a minimum by alleviating the need to learn a new symbol set. An example is the use of the aircraft reference symbol in the VSI portion of the display. This symbol is described in the MIL-STD-1787B and is incorporated on many instruments used in both civilian and military aircraft. Figure 23 shows the conceptual design of the display symbology presentation.

The size of the display was set at 3 1/8 inches diagonally. Although there is no requirement regulating the size of the display, this size was selected to approximate the industry standard for aviation electromechanical instrumentation. This would allow the pilot to utilize existing cockpit instrument panel cutouts and increase the number of locations for mounting. The display size provided sufficient area to incorporate the fonts and symbols without cluttering the display.

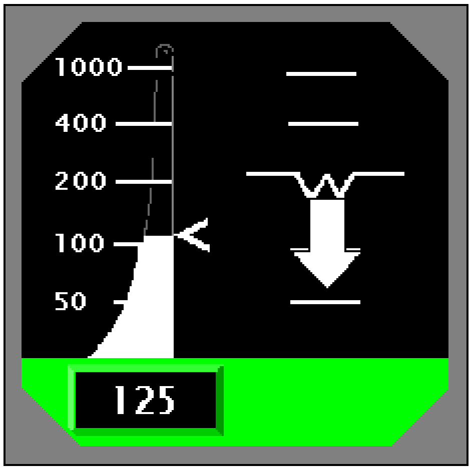

Figure 23. Laser Altimeter Display Symbology Design (Concept) – Actual Size

The symbology is divided into three sections, the analog altitude trend bar, the digital altitude presentation, and the vertical speed indicator. The design philosophy of the symbology presentation was to incorporate both position and rate or trend information into a single display.

A horizontal line extending from the 0 foot mark on the altitude trend bar to the right side of the display was incorporated into the symbology. The area below this line (with the exception of the digital altitude presentation readout) is displayed in the color green. This color was selected to simulate the earth and provide an intuitive graphical representation of the ground to the pilot. The color brown was considered in representing the ground however the color green provided greater contrast between the symbol and the dark background of the display.

The analog altitude trend bar scale extends from 0 to 1000 feet and allows the pilot to transition from the enroute portion of flight or traffic pattern using the barometric altimeter to utilization of the laser altimeter display prior to establishment on the descent. The scale is split and exponential with delineations at 50, 100, 200, 400, and 1000 feet. The scale was designed to be exponential to allow for greater accuracy in resolution below 400 feet absolute altitude. It is more important for the pilot to gauge his altitude closer to the terrain where errors in estimation are more hazardous than it is at altitude. Graduations were placed at 200 and 400 feet to notify the pilot to the altitudes corresponding to the standard precision approach decision height and non-precision approach minimum descent altitudes, respectively. (Kershner, 1998) A tapered trend slide was chosen to present an intuitive representation of proximity to the earth at lower altitudes. Additionally, the tapered slide would better illustrate the exponential nature of the scale to the pilot. Altitudes above 1000 feet will be displayed by illuminating a semicircular bulb at the top of the trend bar. A sliding chevron to the left of the trend bar aids in determining altitude by drawing the pilot’s eye to the top of the trend slide. An update rate of 30 Hz was selected. This rate corresponds a human’s ability to perceive change in information. (McCormick, 1982) Since determining precise information was not required from the trend bar, this allowed the information to be updated as rapidly as possible without decrementing the pilot's ability to perceive the information.

The trend bar was chosen based on USAF School of Aerospace Medicine research in display presentation of altitude versus basic performance. The Air Force study employed a subject base of 25 USAF aviators with an average time of 2,800 flying hours. The pilots were asked to fly a simulator utilizing a series of five display format presentations. The presentations included: a rotating pointer with dots, a rotating pointer without dots, a vertical tape, boxed digits, and boxed digits with a trend bar. As altitude and airspeed were intentionally varied, the pilots were asked to maintain level flight and their performance was evaluated. While the study concluded that the best performance in altitude control resulted from the trend bar and the rotating pointers, rotating pointers were probably more effective. Because of their position and movement, they were more easily detected in the parafoveal and peripheral vision. Additionally, the study disregarded the aviators experience with rotating pointer altitude displays as a possible cause for their relative success. The raw data form the Air Force study is presented in Table 8 and illustrates that the least deviation in altitude occurred with the column E. trend bars. (Ercoline, 1990)

The alphanumeric symbols to the left of the trend bar correspond to the absolute altitude in feet AGL. Selection of the characters was based on several qualities including stroke width, width to height ratio, font, and size. These qualities were considered in light of the fact that the characters would be based on stroke written fonts constructed by illuminated pixels.

Table 8. Pilot's Deviation in Altitude Using Different Symbology Sets

	ANOVA p<0.0001				
	A. Pointers w/Dots	B. Rotating Pointers	C. Vertical Tapes	D. Boxed Digits	E. Trend Bars
Altitude (ft)	124.98	130.78	192.91	207.24	117.92
Standard Error	8.89	12.99	14.28	18.26	19.03
Duncan's Multiple Range Test: A, B, E less C, D					

Based on numerous studies, several guidelines have be set forth. The optimal stroke width for a white character on a black background is between 1:8 and 1:10. In other words, the stroke of the character must be a 1/8 to 1/10 the characters height. The relationship between a characters width to its height should be a minimum of 3:5. (McCormick, 1982) Selection of the font is perhaps the most problematic in that with the increase in display resolution of newer computers the number of available fonts has also increased substantially. Military Standard MS 33558 specifies a character set with a stroke width of 1:8 and a width to height ratio of 70%. Although commercial fonts do not represent these characters, there are several Gothic styles, which approximate the standard to include: Futura, Sans Serif, Tempo, and Vogue.

The size of the character is a function of its viewing distance and can be determined using the following formula:

$$H \text{ (height of the character, in)} = 0.0022D + K_1 + K_2$$

Where D is the viewing distance measured in inches, K_1 is the correction factor for illumination and viewing distance and, K_2 is the correction for importance. The size of the characters, based on various viewing distances, is shown in Table 9. (McCormick, 1982)

The font chosen for the display was Lucida Sans Unicode due to its resemblance to the character set specified in the military standard MS 33558 (ASG). Font size for the trend bar scale was set at 14 points, which yields a character height of 0.15 inches as measured at the screen. The character height for this font at 14 points is below the guidelines set forth in the table below, however because of the limited space of the display and the fact that the primary function of the font is to provide reference marking (not to provide accurate altitude information) a smaller sized font was chosen. The digital altitude display is intended to relay accurate altitude information and is of greater importance than the reference markings of the trend bar so a larger font size was needed. The font size selected for the digital altitude display was 28 points, which yields a character height of 0.32 inches measured at the screen.

Table 9. Size of Characters Based on Viewing Distance and Illumination (inches)

Viewing Distance in	Value of 0.0022D	Non-Important Markings, K_2 = 0			Important Markings, K_2 = .075		
		K_1 = .06	K_1 = .16	K_2 = .26	K_1 = .06	K_1 = .16	K_2 = .26
14	0.0308	0.09	0.19	0.29	0.17	0.27	0.37
28	0.0616	0.12	0.22	0.32	0.20	0.30	0.40
35.5	**0.0781**	**0.14**	**0.24**	**0.34**	**0.22**	**0.32**	**0.42**
42	0.0926	0.15	0.25	0.35	0.23	0.33	0.43
56	0.1232	0.18	0.28	0.38	0.25	0.35	0.45

Applicability of K_1 Values:
K_1 = 0.06 (above 1.0 fc, favorable reading conditions)
K_1 = 0.16 (above 1.0 fc, unfavorable reading conditions)
K_1 = 0.16 (below 1.0 fc, favorable reading conditions)
K_1 = 0.26 (below 1.0 fc, unfavorable reading conditions)

In addition to the analog presentation, a digital display was added to the lower left quadrant of the display below the altitude trend scale. This location was chosen to capitalize on the principle of visual proximity and allow the pilot to process the analog trend information in parallel with the digital altitude display. The digital readout displays the aircrafts altitude from 0 to 1000 feet in 1-foot increments. Altitudes above 1000 feet will be displayed until the sensor has reached its maximum range. Above this range, a fault display symbology set will be displayed. The rate the value of the digital display is updated by the sensor was selected to be 1 Hz. This rate was selected on the principle that the maximum rate at which the pilot can accurately distinguish digital characters is 2 Hz. (McCormick, 1982)

Since the analog altitude scale is not linear, the rate information presented to the pilot is not easily derived visually. For example, at a 500 foot per minute rate of descent it takes 1 minute and 12 seconds to travel from the top graduation mark (at 1000 ft.) to the mark below (which represents 400 ft.). This equates to 600 feet of altitude. At the same rate of descent it takes 24 seconds to travel the same physical distance on the display, from the second mark (at 400 ft) to third graduation mark (at 200 ft.), yet the aircraft has only descended 200 feet. To ensure the pilot is presented with a linear rate cue, a VSI was incorporated to the right of the altitude trend bar. This positioning is consisted with the standard “T” convention used in most cockpits.

The VSI consists of an aircraft reference symbol overlaying a sliding arrow which indicates a climb or decent. An arrow was chosen to portray the up or down movement of the aircraft more intuitively. The aircraft reference symbol was needed to provide the pilot with visual reference of the aircraft and to further define the meaning of the arrows direction. A graduated scale of 500 and 1000 feet per minute was placed above and below the aircraft reference symbol to better quantify the rate of climb/descent. A decision was made not to incorporate markings on the VSI scale. This was done to keep the display symbology from becoming too cluttered with information. The scale represents the most commonly used rates of decent during an approach. (Kershner, 1998)

The display of warning and alerts was accomplished by the use of color-coding as shown in Figures 30 – 32 of Appendix B. As described in the functional analysis, a rate of greater than 1000 fpm rate of descent when combined with an altitude of 400 feet would cause the processor to display a cautionary symbol set while a rate greater than 1000 fpm at less than 200 feet would drive an alerting symbology set. The cautionary display symbology set is similar to the normal display set except that the sliding trend bar and VSI pointer change from white to the color yellow. Yellow was selected based on convention. Yellow is generally accepted as the color for caution. (Wagner, 1996)

As the display transitions from a cautionary display set to an alert, the sliding trend bar and VSI pointer change from yellow to the color red. Red was also selected base on convention. Additionally since the alert represents a condition more serious than a caution, the VSI is commanded to flash at 2 Hz. (McCormick, 1982) This is done to attract the pilot’s attention to the display.

In addition to the caution and alert symbology sets, the display incorporates a system fail symbol set, which alerts the pilot to the unreliable nature of the laser altimeter, should the data processor loose the signal from the sensor. In the event of a loss of signal, regardless of cause, a series of four XXXX will be displayed in place of the digital readout. Additionally the trend bar and VSI indicators will disappear and be replaced by the phrase “Altitude is

Unreliable” in white 20 point Swiss746 font. Below this is the phrase “Do Not Use Altimeter” in yellow 26 point Swiss746 font.

Because of the their unique abilities, helicopters are routinely employed in missions, which require the aircraft to operate at very low altitudes often in remote unimproved areas with no ground based approach aids. Additionally, many of the mission’s helicopters fly; require the pilot to hover at very precise altitudes. Where the fixed wing pilot may think in terms of tens of feet while on an approach, the rotary wing pilot may think in terms of individual feet while performing hovering operations or terrain flight.

Cockpit Evaluations

Since it was necessary to determine an appropriate location for mounting the display as well as the optimal size of the symbology elements, cockpit evaluations were conducted on four of the top GA aircraft as defined by the GAATA survey. The purpose of the evaluations were to measure the distance from the aircrafts design eye position to open areas on the instrument console, which were determined to be suitable to mount a display. Once the results of the evaluations were gathered, the data was reduced per MIL-STD-1787B Military Interface Standard, Aircraft Display Symbology. Since there is no criterion established which dictates the size of civilian display element the MIL-STD was used. The actual symbol size on a direct view display can be calculated using the following formula:

$$L = 2D \tan (a/2)$$

where L = size of the symbol at the display, D = design eye distance from the display, and a is the symbol subtense (in milliradians). Results of the evaluations are presented in Table 10:

Table 10. Distances from DEP to Possible Mount Location

Aircraft Type	Pilot’s Yoke	Position 1	Position 2
Cessna 172	27.00	**35.50**	N/A
Cessna 150	20.25	30.00	24.50
Mooney M20	21.25	32.50	N/A
Piper PA32	18.00	34.50	28.75

The design eye distance selected for the display was the largest distance measured during the cockpit evaluations, e.g., 35.50 inches (as measured in the Piper PA-32 Saratoga). This provided a basis to convert the symbology subtense as defined by the MIL-STD given in milliradians to an actual size in inches. Only three of the symbology sets were defined in the MIL-STD-1787B. These included the aircraft reference symbol, vertical deviation indicator (used for the VSI), and the aircraft directional reference symbol and are given in inches in Figure 24.

Software Development

The software chosen to drive the display symbology was National Instruments LabVIEW 6.0 ™. LabVIEW was chosen for its cost, availability, and its ability to communicate with hardware utilizing several different interfaces to include RS232. LabVIEW is graphical and uses GUI icons as an interface. The file created is called a virtual instrument or VI. Since there are no VI sets for aviation applications and specifically altimetry, one was created to interface with the laser altimeter.

Each VI consists of two main parts, the front panel and the block diagram. The front panel contains the user interface of the VI. The block diagram contains the graphical code for the

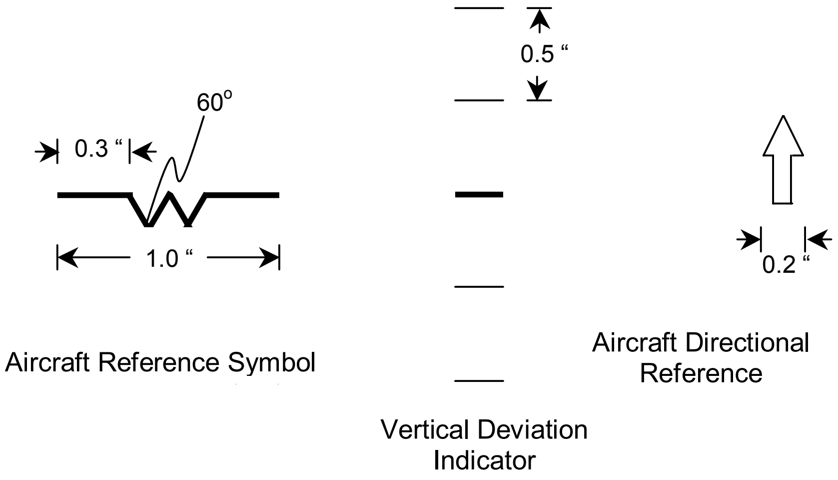

Figure 24. Symbol Subtense Conversion to Inches

VI. The front panel and block diagrams for the altimeter as tested are displayed in Figures 33 and 34 of Appendix C.

Early testing to the laser range finder revealed that the laser's processor was too noisy to ensure a continuous signal. As a result, the design of the display continued concurrently with the design of the laser. As the first iteration of the design process for the display concluded there was still no workable laser to provide a signal, so an alternate sensor had to be located. A decision was made to use the atmospheric pressure sensor from an instrumented aircraft to supply an altitude signal for the display. The signal would produce an altitude in MSL. By subtracting the field elevation from the processed signal, it was possible to simulate a sensor, which could measure absolute altitude.

The rate information was calculated by differentiating the altitude signal with respect to time. Rate is a measure of a change in position over a corresponding change in time:

$$R_{avg} = \Delta x / \Delta t$$

This is referred to as the average rate of an object. As the change in time becomes increasingly smaller so that Δt approaches 0, it is possible to determine instantaneous rate:

$$R_{instant} = \lim_{\Delta t \to 0} \Delta x / \Delta t$$

One of the disadvantages of using this technique to determine rate is that any noise in the system is also differentiated and amplified.

For this reason a filter was incorporated into the software to filter unwanted signals above a specified frequency. The filter chosen for the display was a second order butterworth lowpass filter. In addition to using a filter, an iterative loop was applied to both the digital readout display and to the VSI. The purpose of looping the calculations was to further smooth the signal by averaging and to provide the ability to adjust the output frequency of the signal to the designed update rates of 1 Hz for the digital display (quantitative information) and 30 Hz for the graphical display elements (qualitative information). Figure 25 illustrates the logic the data processor utilized in determining rate and trend information.

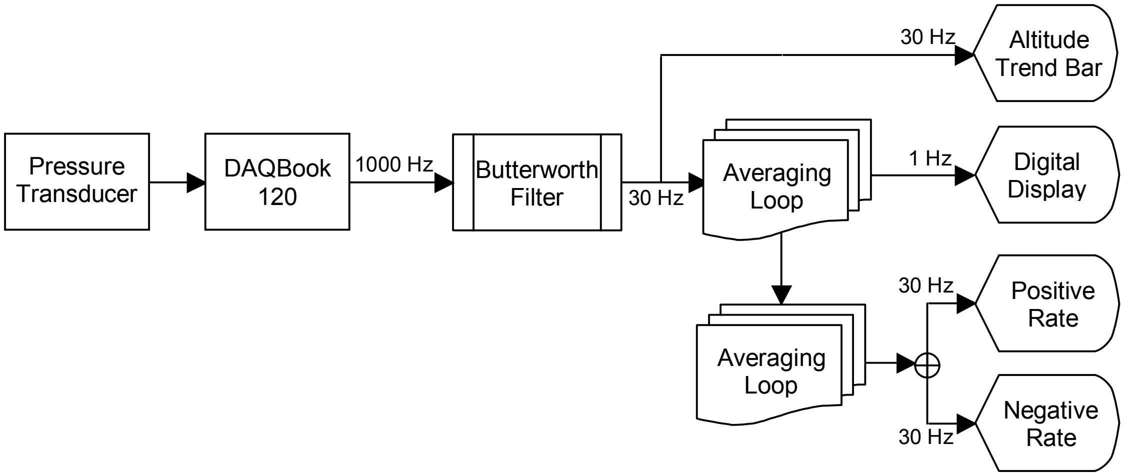

Figure 25. Data Processor Logic

The design of the symbology used during the evaluation was slightly different from the conceptual symbology design. This was due to limitations associated with the software chosen to construct the symbology, LabVIEW 6.0 ™. In the conceptual design, a tapered slide was chosen to represent the exponential nature of the altitude trend bar, however, LabVIEW had no method to construct a tapered slide so a linear slide was chosen instead. Additionally, the chevron selected to draw the eye to the top of the trend bar could not be constructed so a triangle was used. The position of the triangle was fixed to the left side of the trend bar and could not be moved to the right as was designed. Lastly, there was no method of drawing an arrow on the VSI slide so a traditional bar slide was chosen. In all other respects, the display used during the evaluation remained consistent with the design. The construction of the actual display symbology for the laser altimeter will most likely be accomplished using a programming language so there will likely be no such limitations associated with COTS programs such as LabVIEW. Figure 26 shows the arrangement of the symbology as it was tested.

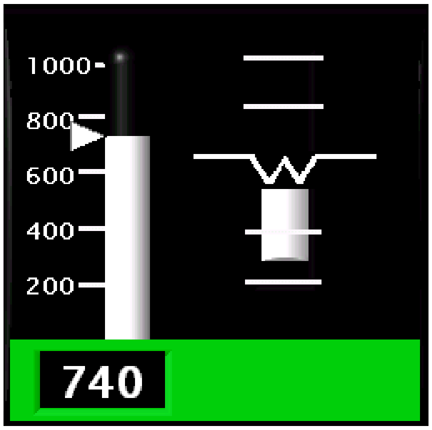

Figure 26. Laser Altimeter Display Symbology Design (As Evaluated) – Actual Size

VII. Prototype Validation – Test Plan and Evaluation

Purpose

The purpose of the evaluation was to validate the design of the display symbology to ensure that the operational requirements were met. This step completes the first iteratation of the systems engineering design process.

Description of Test Aircraft

The test aircraft was an OH-58A+ Kiowa, tail number N88UT (Figure 27). The OH-58A+ is a US Army, four place, light observation helicopter, operated by the University of Tennessee Space Institute as a flying laboratory for courses and for research. The maximum gross weight of the aircraft is 3,200 pounds through a CG range from station 107.0 to station 111.4. N88UT was chosen for its ability to provide a pressure sensor for the display. Additionally, as a public category aircraft, no STC was required for modification of the instrument panel.

Figure 27. OH-58A+ (N88UT) on UTSI Ramp

The OH-58A+ maximum airspeed is 120 knots, or 100 knots with any door removed. While this airspeed is below that of a typical GA aircraft, it was still sufficient to demonstrate the ability of the display to function during normal airspeeds and vibrational loads. Standard cockpit instrumentation used during the evaluation included: an engine oil driven torque-meter gauge (%Q), an engine (N_2) and rotor (N_R) dual-tachometer gauge (%RPM), airspeed indicator, vertical speed indicator, and standard sensitive altimeter. A more complete description of the aircraft system and its standard instrumentation can be found in the Operator's Manual, US Army TM 55-1520-228-10.

The aircraft was instrumented with the IO Tech DAQBook 120 ©, which was capable of providing altitude information via a pressure transducer connected to the boom pitot-static source. Additional instrumentation included a laptop computer to generate the display symbology and to collect data in voltage from 0 – 5 VDC. Qualitative comments were recorded manually on kneeboard cards and via a cockpit voice recorder.

The aircraft's ADF was removed and a mounting plate was installed in its place. The display was mounted to the mounting plate with a swivel head to orient the displays face normal to the pilot. This was to reduce the distractions associated with parallax, glare, and reduced brightness with off axis viewing. The location was selected because of the size of the display. The location selected allowed the display to be visible without obscuring any primary flight instrument. Additionally, by mounting the display on the instrument console vs. the top or side of the instrument panel the vibrations imparted to the display would also be minimized. The location chosen was outside the pilot's primary Field of View (FOV), however, since the instrument was designed as a secondary instrument the location approximated the locations surveyed during the cockpit evaluations. A voltage regulator designed to reduce the aircraft power from 24 volts AC to 12 volts DC to provide power to the cockpit display was installed. Figure 28 shows the installation of the display hardware on the OH-58A+ instrument panel.

Figure 28. Display Mounted in N88UT

Scope of Test

Test and Test Conditions

The evaluation was conducted at Tullahoma Regional Airport, Tullahoma, Tennessee under daylight visual meteorological conditions. The evaluation consisted of one ground test lasting .6 hours, and 2 flight tests lasting a total of 1.6 flight hours. Test conditions are presented in Table 11, Test and Test Conditions Matrix. Testing was conducted within the limits of the operator's manual.

Method of Test

The method of test used consisted of a qualitative evaluation of the workload associated with altitude maintenance tasks. The flight profiles flown during the evaluation were selected based on their applicability to the design objectives and included those tasks, which a GA pilot could reasonably be expected to utilize during the operation of the laser altimeter. The tasks evaluated in the OH-58A+ included: IGE and OGE hovering flight, Instrument Takeoff, level flight, and constant rate of descent approaches to a landing.

Table 11. Test and Test Conditions Matrix

Test Method	Altitude (ft MSL)	Airspeed (KCAS)	Aircraft GW (lbs)	Aircraft CG (in)	OAT (°F)	Remarks
Ground Test	0[2]	0	3002	110.14	76	Test of data filtering
Hovering Flight IGE	5[2]					5 ft hover maintenance
Hovering Flight OGE	50[2]					Climb to 50 ft – est. 50 ft Hover – descent to 5 ft
HQR – OGE Hover						Adequate perform - + 20 ft Desired perform - + 10 ft
Instrument Takeoff	1082 - 1482	60				Climb to 1000 ft
Level Flight	1482-1082	80				Maintain 1000 ft
HQR – Level Flight						Adequate perform - ± 100 ft Desired perform - ± 50 ft
Constant Rate of Descent		60				Maintain standard 500 fpm descent
Approach to Landing		60 - 0				Stop descent at 400 ft and at 200 ft

[1] Configuration – Forward doors installed, rear doors installed, high skid gear installed, and bleed air on.
[2] Altitude in feet AGL

The tasks were first flown without the use of the display to provide a baseline measurement to compare the increase or decrease in pilot workload.

Two pilots evaluated the display. Both pilots were experienced test pilots but with varied backgrounds. When evaluating flight displays, two aspects must be considered: readability of the display and the ability of the pilot to use the information gained to control the aircraft. Each pilot assessed the display using a modified Cooper-Harper Pilot Rating scale as shown in Figure 29 of Appendix A.

Results and Discussion

Ground Test

During the ground test, several parameters of the display hardware were analyzed. The purpose of the flicker test was to evaluate the display's temporal stability characteristics. The display was evaluated under varying lighting conditions from direct sunlight to full darkness. The colors chosen for the evaluation were red, green, and blue. There was no perceived variation in the continuity of the display recorded in either direct viewing or in off center viewing. The temporal stability characteristics of the display were satisfactory.

The purpose of evaluating the display size was to determine if the size of the display was appropriate for the display symbology to ensure the display elements were not cluttered. The size of the overall display measured 3 5/16 inches square. The font for the digital altitude display measured 3/8 inches high. The alphanumeric characters used for the altitude trend bar were 3/16 of an inch in height. The delineation marks of the altitude trend measured 7/16 of an inch wide, while the marks for the VSI measured 5/8 inches. The width of the aircraft reference symbol was 1 1/2 inches wide. The overall appearance of the display was uncluttered. The size of the display was satisfactory.

The purpose of evaluating the glare was to determine the effects of the ambient reflected light on the readability of the display. The display was evaluated under varying lighting conditions to include direct sunlight and full darkness. The effects of the reflected light under direct sunlight were not apparent until the observer was approximately 45^{o} from the display's normal axis. The diffuse glare from the reflected light from within the cockpit under full darkness was not a factor. The evaluation of the glare was satisfactory.

A manual vacuum pump was connected to the pressure transducer, which allowed the atmospheric pressure as measured at the transducer to be varied from current atmospheric conditions to a vacuum. This allowed manual control of the pressure to simulate a climb and descent. The purpose of this evaluation was to ensure proper interaction between the altitude trend bar, digital display, and the VSI, to qualitatively evaluate the accuracy of the display elements, and to ensure proper function of the signal smoothing software. The pressure was decreased and increased steadily in an attempt to maintain a 250, 500, and 750 fpm rate of ascent and descent. The interaction between the display elements were as expected and the rate of climb and descent could be maintained without apparent noise in the signal from the transducer. The evaluation of the interaction of the display elements was satisfactory and the decision to proceed with the flight evaluation was made.

Ease of Use and Readability

The following comments were taken from pilot evaluations of the display. The symbology was of large enough to allow the display to be read easily. The use of the colors on the display provided sufficient contrast.

The movement of the altitude trend bar and the VSI appeared smooth and continuous and did not distract or mislead the pilot. The vertical speed indicator correlated with the altitude display. One pilot commented on the use of the display during the OGE hovering task, "The display gives finer detail [cues to change in altitude] than visual references outside the cockpit." Overall, the display helped the pilot by reducing total workload. Qualitative assessments were performed on two mission tasks: level flight at low altitude and IGE/OGE hovering tasks. Table 12 presents the results of the pilot evaluations.

Table 12. Results of Qualitative Evaluation

Task	Pilot 1		Pilot 2	
	HQR	Variation	HQR	Variation
OGE/IGE Hover	1	± 3 ft	2	± 1 ft
Level Flight at Low Altitude	1	± 6 ft	3	± 7 ft

Comments on improving the display were received. During several maneuvers the VSI reached its maximum indicated value of ± 1000 fpm. The test pilot wondered if it were not important to know that the rate of descent was 1500 fpm instead of some value above 1000 fpm.

Display Accuracy

The system showed inaccuracies in the display of both the absolute altitude and vertical speed. The errors were caused by two sources: common instrument errors of the pitot-static system and errors associate with processing the transducer signal for presentation. The pitot-static system errors were expected. As power was applied to initiate a climb the pressure field around the aircraft increased causing the display to indicate a decrease in the altitude. As the power was reduced, the opposite effect occurred. The lag in the system caused by this error was measured at 7 seconds. Using a laser range finder as a sensor would eliminate this error from the system.

Additionally, the display demonstrated a lag when correlated to the aircrafts pitot-static system instruments. Since the pitot-static system, pressure source was common to both instruments it was concluded that the error was caused by the software used to smooth the signal for presentation. The software used two methods to smooth the signal and reduce the noise of the system: a second order butterworth low pass filter and an iterative loop to further smooth the signal. By changing the filtering rate it was possible to reduce the lag between the two instruments, however the noise of the signal increased.

IX. Conclusions

With the evaluation of the system, the first iteration of the SEP is complete. The qualitative evaluation of the symbology showed that the display reduces total pilot workload by presenting altitude information more intuitively than the current altimeter displays. This was accomplished by reducing the cognition required to determine position and rate information. However, several issues remain unresolved.

1. The use of color-coding as an effective alert to the pilot. Software limitations and time constraints did not allow proper testing of the caution, alert, and fault indication symbology sets.

2. The use of auditory warning signal as a more effective alert to the pilot of low altitude with a higher than normal sink rate.

3. The display showed a larger lag error than expected due to the method used to smooth the signal. Use of alternate filtering techniques may eliminate this error while still provide a smooth continuous display of rate information.

4. While qualitative data suggests the display is more intuitive, these assessments are based on subjective pilot opinion. Programming error did not allow these improvements to be quantified by recording pilot performance in executing the mission tasks.

5. During several mission maneuvers, it was impossible to determine an accurate quantitative value for the rate of climb or descents. This was due in part to the maximum value assigned to the VSI.

X. Recommendations

The following recommendations constitute the suggested changes to the design prior to the next iteration of the SEP. Although the display as tested achieved the design objectives of designing an intuitive display to provide absolute altitude in feet (AGL), one important requirement was not achieved, the accuracy of the display. These recommendations provide several improvements to the existing design, which can be implemented with no additional cost.

1. Test the symbology using a sensor, which could supply accurate distance to the earth such as radar or laser rangefinder. This would eliminate the errors inherent in using a pitot-static source.

2. By creating a Sub-VI for each of the symbology sets: normal, caution, alert, and fault indication, and writing a routine to compare the rate and altitude signals it is possible for LabVIEW to select a symbology Sub-VI based on predetermined parameters. This would allow testing of the caution and alert symbology sets.

3. Continue the evolution of the software to incorporate more effective filtering techniques. This would eliminate the lag errors present in the first iteration evaluation.

4. Incorporate a more effective method of recording the altitude information to allow for quantitative analysis. It should be possible to show the increase or reduction of pilot workload by comparison of aircraft altitude without use of the display to aircraft altitude using the display.

5. Increase the maximum value of the VSI from + 1000 fpm to + 2000 fpm. Additionally, the width of the VSI and the width of the altitude trend bar are identical and could be cause for confusion by some pilots. Coding the rate indicator using size could eliminate any confusion.

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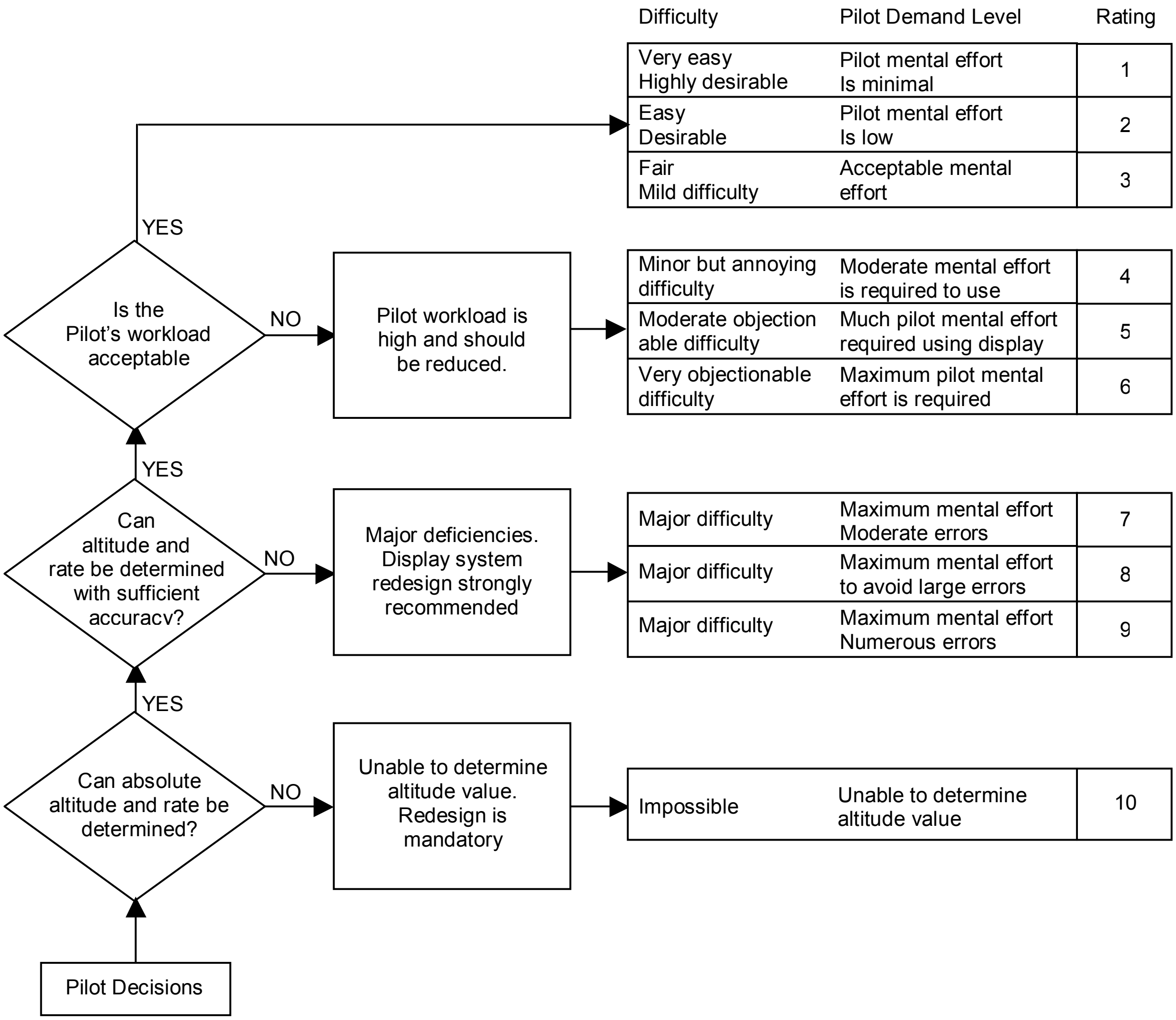
Appendices

Appendix A. Cooper-Harper Pilot Rating Scale



Difficulty	Pilot Demand Level	Rating
Very easy Highly desirable	Pilot mental effort Is minimal	1
Easy Desirable	Pilot mental effort Is low	2
Fair Mild difficulty	Acceptable mental effort	3
Minor but annoying difficulty	Moderate mental effort is required to use	4
Moderate objection able difficulty	Much pilot mental effort required using display	5
Very objectionable difficulty	Maximum pilot mental effort is required	6
Major difficulty	Maximum mental effort Moderate errors	7
Major difficulty	Maximum mental effort to avoid large errors	8
Major difficulty	Maximum mental effort Numerous errors	9
Impossible	Unable to determine altitude value	10

Figure 29. Display Rating Decision Tree: Ease of Reading Altitude

Appendix B. Cautionary and Warning Symbology Sets

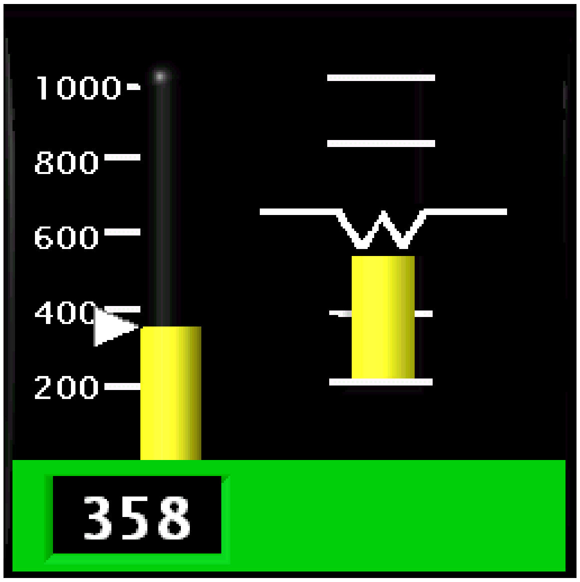


Figure 30. Display Cautionary Symbology

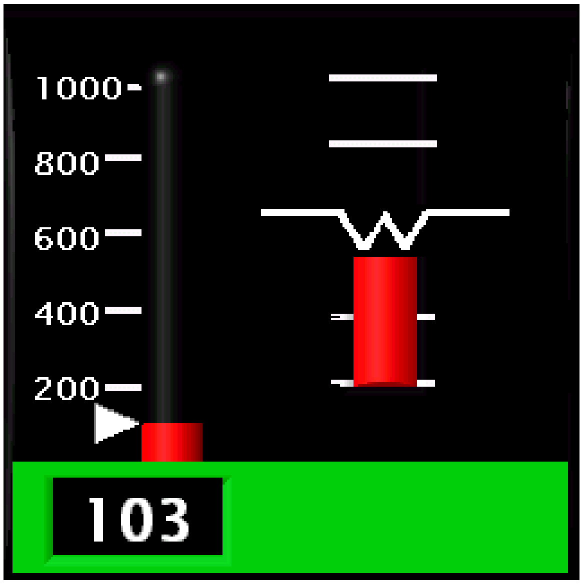


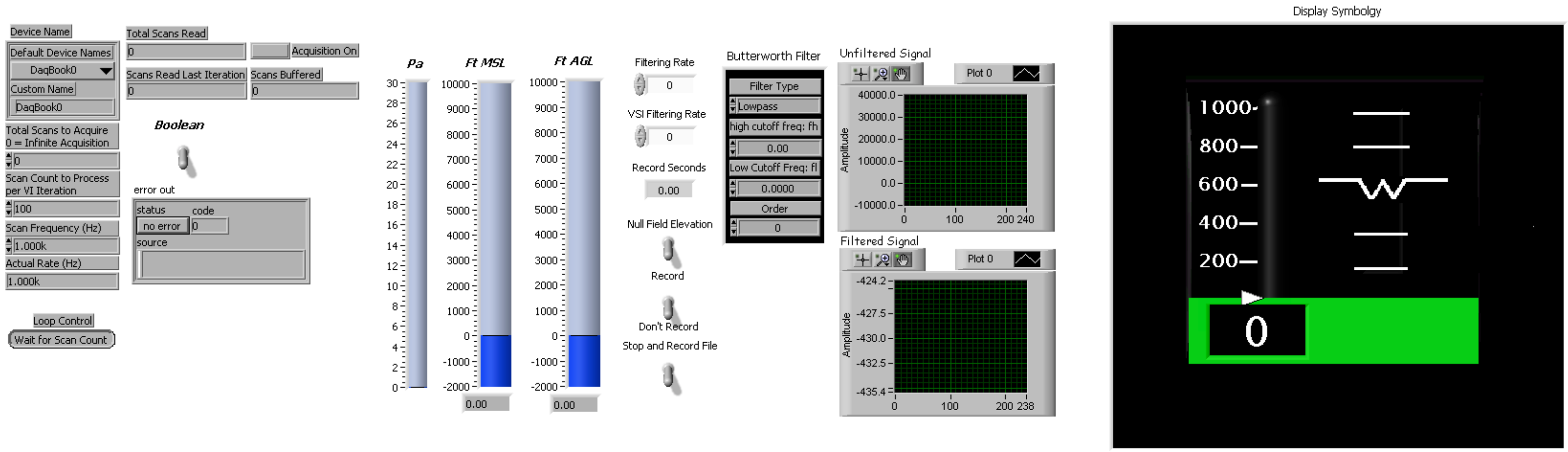
Figure 31. Display Alerting Symbology


Altitude is Unreliable

Do Not Use Altimeter

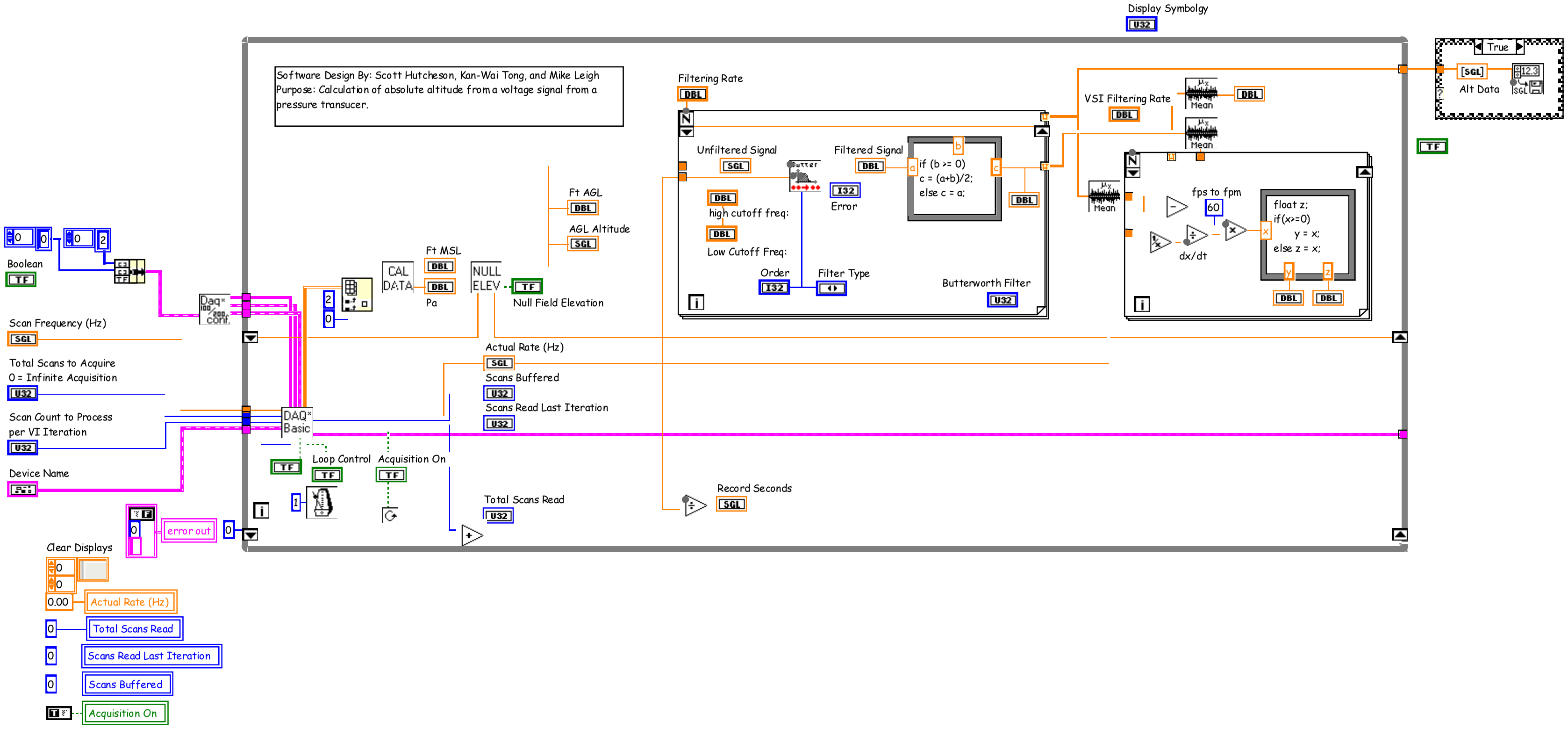
Figure 32. Display Fault Indication Symbology

Appendix C. LabVIEW Front Panel and Block Diagram



Device Name
Default Device Names: DaqBook0
Custom Name: DaqBook0
Total Scans to Acquire 0 = Infinite Acquisition: 0
Scan Count to Process per VI Iteration: 100
Scan Frequency (Hz): 1.000k
Actual Rate (Hz): 1.000k
Total Scans Read: 0
Scans Read Last Iteration: 0
Scans Buffered: 0
error out: status: no error, code: 0, source
Filtering Rate: 0
VSI Filtering Rate: 0
Record Seconds: 0.00
Butterworth Filter: Filter Type: Lowpass; high cutoff freq: fh: 0.00; Low Cutoff Freq: fl: 0.0000; Order: 0

Figure 33. LabVIEW Front Panel Controls


Software Design By: Scott Hutcheson, Kan-Wai Tong, and Mike Leigh
Purpose: Calculation of absolute altitude from a voltage signal from a pressure transucer.

```
if (b >= 0)
c = (a+b)/2;
else c = a;
```

```
float z;
if(x>=0)
    y = x;
else z = x;
```

Figure 34. LabVIEW VI Diagram

VITA

CW3 Scott Edward Hutcheson was born in Schulthorpe, England on April 16, 1961. He graduated from Eau Gallie High School in June 1979. Scott attended the US Air Force Academy in June of 1983 but left before completing his degree. He entered the US Army in September of 1987 and was selected for flight school in June 1989. Upon graduation in July 1990, he was assigned as a member of 2nd Squadron, 4th Cavalry Regiment, 24th Infantry Division as an attack helicopter pilot flying the AH-1F Cobra. In August of 1990, Scott was deployed along with his division to Saudi Arabia as a participant in Operation Desert Shield/Desert Storm. Since then he has accumulated over 1700 flying hours in 6 different airframes, most recently the AH-64D Longbow Apache. Scott graduated from Embry-Riddle Aeronautical University with a Bachelor of Science in Aeronautics in December of 1997.

Upon graduation from the University of Tennessee, Scott will attend the US Naval Test Pilot School at Patuxent River, Maryland.