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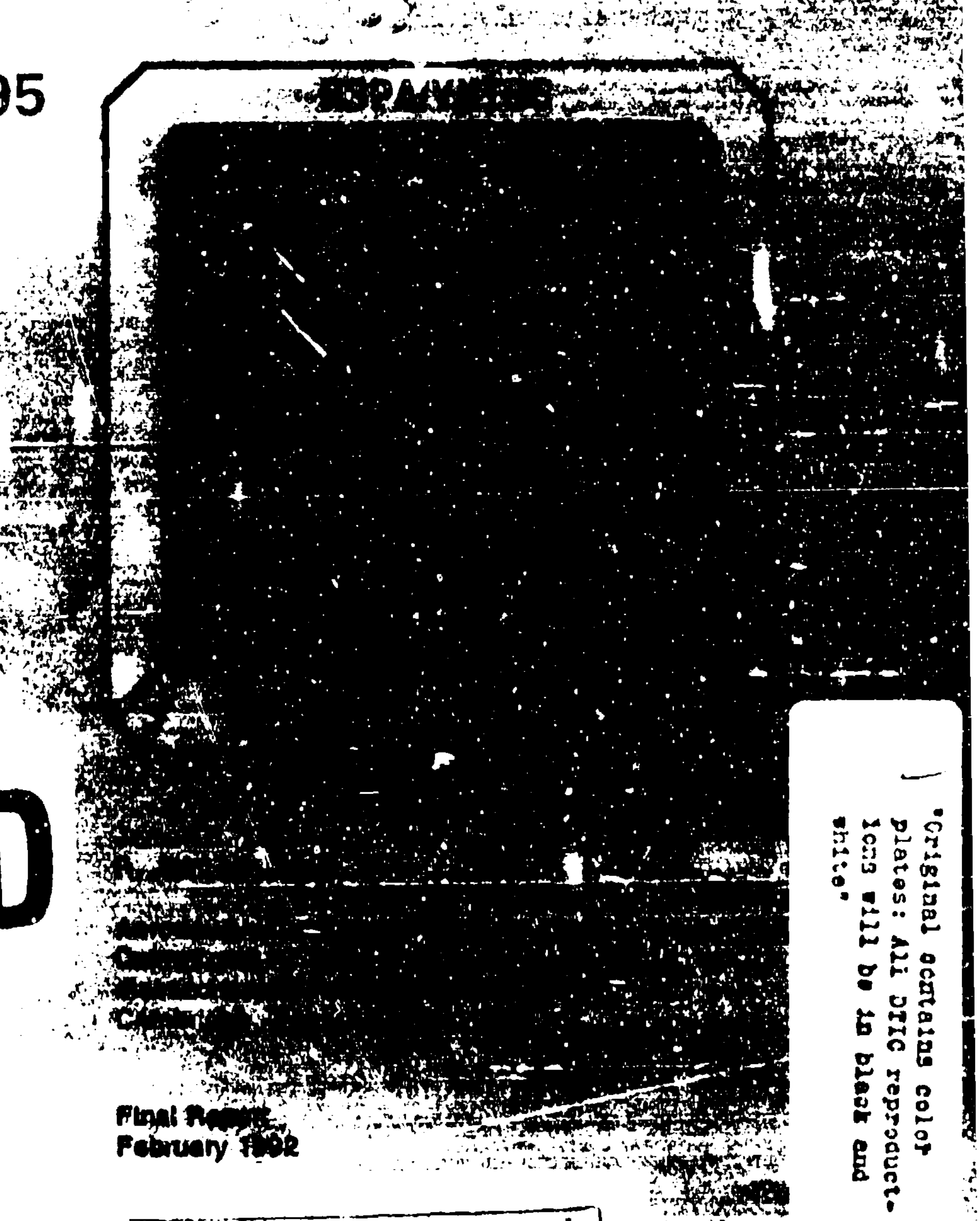
Washington, DC 20591

Advanced Terrain Displays for Transport Category Aircraft



Final Report
February 1992

U.S. Department of Transportation
Federal Aviation Administration

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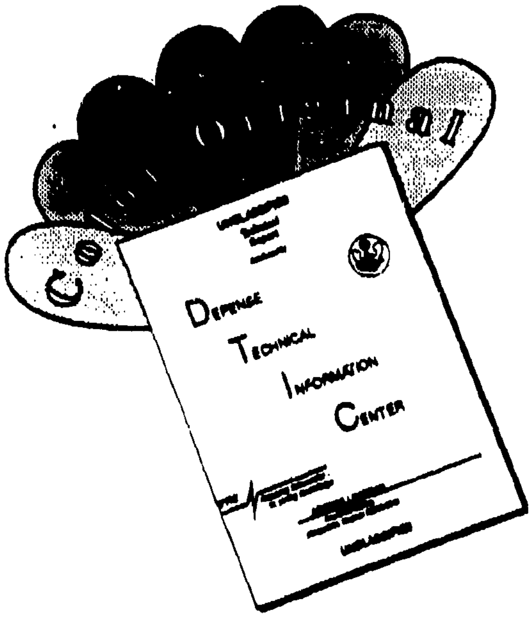
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16. Abstract

A preliminary evaluation of terrain information presentation methods was conducted in a part-task simulation study. Pilots qualified on autoflight aircraft used both paper and prototypical electronic instrument approach plate formats to obtain terrain information. Approaches were flown using the MIT Aeronautical Systems Laboratory Advanced Cockpit Simulator. During the simulation, terrain situational awareness was tested by issuing erroneous vectors into terrain. Pilots successfully detected and avoided terrain hazards only 3 out of 52 times (6%). This low-hazard recognition rate is thought to be due to high level of confidence in Air Traffic Control (ATC) clearances, and highlighted the fact that current terrain depiction methods appear to be inadequate.

To evaluate the increased effectiveness of advanced terrain depiction methods on electronic displays, several terrain situation display formats were designed and evaluated in a second simulation study. Spot elevation and smoothed contour terrain presentation techniques were examined using a separate moving map display dedicated to terrain information. In addition, a prototypical Graphical Ground Proximity Warning System (GGPWS) was developed and used to solicit pilot opinions and comments. Experimental methodology followed that of the preliminary terrain depiction study closely - erroneous vectors were again given by ATC, and pilot performance and opinion data were recorded.

When given vectors into terrain, there was an overall 50% hazard recognition rate when pilots used the spot elevation display, and a 78% recognition rate with the contour display. After the pilots became aware that they could not rely on ZTC for terrain separation, the hazard recognition rate increased to 62% for the spot elevation display and 93% for the contour display. Pilots were unanimously in favor of the contour display, and were receptive to a prototypical GGPWS system.

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Map Displays, Terrain Displays,
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Preface

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For the simulation experiments, the authors would like to acknowledge First Officer Gary Donovan for his invaluable help in recruiting subjects. The Delta Master Executive Council and the Air Line Pilot's Association provided us with the space and support with which to conduct the experiment in Atlanta, Georgia. We also thank the subject pilots who volunteered several hours of their spare time for the experiments, as well as those who responded to the survey.

The authors extend much appreciation to Don Sellers of Jeppesen Sanderson, Inc. for his input during and after the design of the experiment, and to Don Bateman of Sundstrand Data Control for his detailed CFIT data.

The authors thank Mark Mykityshyn, Craig Wanke, Ed Hahn, and Amy Pritchett for their help in conducting the simulation experiments. Rick Paxson and Amy Gardner also deserve credit for their aid in collecting and assimilating the data.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in.) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

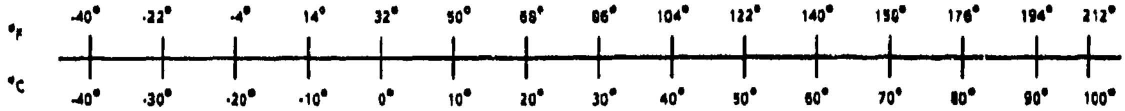
1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubir yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

Executive Summary

This report documents two studies investigating terrain information effectiveness and usage by air transport pilots. The first study examined current spot elevation terrain depiction methods on Instrument Approach Plates (IAPs). Pilots flew several approaches using the MIT Aeronautical Systems Laboratory part-task simulator. Erroneous Air Traffic Control (ATC) clearances into terrain were issued and the pilots' ability to recognize the threats was recorded.

The second study investigated two prototypical electronic Terrain Situational Awareness Displays. One display, the Spot Elevation Display, was based upon current terrain presentation methods. A second display, the Smoothed Contour Display, used shaded contours to convey terrain information to the pilot. In addition, a prototypical Graphical Ground Proximity Warning System was implemented and used to solicit pilot opinions on such a system. Erroneous vectors into terrain were also issued in this study.

These investigations resulted in the following conclusions:

1. The lack of effective terrain information in the cockpit seems to have led pilots to forfeit the responsibility for terrain clearance to air traffic controllers. In addition, reliance on ATC and the low rate of Controlled Flight Into Terrain (CFIT) accidents in the U.S. may have dulled pilot perceptions of the hazards posed by terrain.

2. Two distinct regimes of terrain information use exist for advanced displays. Terrain information is used for *Terrain Situational Awareness* in order to avoid potential hazards. When near hazardous terrain, *Terrain Alerting* may be used to provide the pilot with the situational information needed to elicit the correct evasive response.

3. Hazard recognition rates increased from 3% to 15% when a display of the aircraft's location was added to current terrain depiction methods. Displays which include aircraft location may relieve the pilot of the mental calculations required to orient the aircraft with respect to terrain.

4. Terrain display format was not a major factor in terrain avoidance performance when pilots did not accept responsibility for terrain clearance. Hazard recognition rates for a spot elevation display (20%) and a smoothed contour display (25%) were comparable when pilots assumed that ATC was providing adequate terrain separation.

5. When pilots assumed responsibility for terrain clearance, a smoothed contour display was found to be more effective than a spot elevation display. When responsibility for terrain separation was taken by the pilot, the hazard recognition rate for the smoothed contour display was 93% as opposed to 62% for the spot elevation display. This difference, however, is not statistically significant ($p>.05$) [19].

6. Pilot performance when using a moving map spot elevation display was found to be sensitive to obstacle symbol layout. After assuming responsibility for terrain clearance, pilots recognized the terrain hazard in every case in which a hazardous spot elevation symbol was shown directly on the aircraft's projected ground track. In contrast, hazards were recognized 44% of the time when the aircraft was vectored to fly between spot elevation symbols.

7. A Graphical GPWS system was found to be desirable by subject pilots.

1. Introduction

Controlled Flight Into Terrain (CFIT) accounted for more than 47% of transport aircraft fatalities between 1979 and 1989, making CFIT the single largest cause of air carrier accidents over the same period [1]. Changes in the design of aeronautical charts as well as the addition of Ground Proximity Warning Systems (GPWS) have made significant reductions in the number of CFIT accidents since the 1970s. However, deficiencies in terrain depiction practices and inefficient use of terrain information may still exist.

The instrument procedures involved in approach and departure operations are carefully engineered to provide adequate separation from terrain [2,3,4,5,6]. However, Air Traffic Control (ATC) may on occasion vector aircraft off of the routes depicted on charts available to the pilot. Terrain information is used in the cockpit to check for hazards when the aircraft is not on a published approach route. Currently, the primary source of approach procedure and terrain information for the pilot is the Instrument Approach Plate (IAP). IAPs have been in use for a number of years and have undergone modifications in design as deficiencies were recognized. Accordingly, the relatively high number of CFIT accidents has led to the reevaluation of terrain depiction methods.

Recent advances in computer and display technologies have provided a means by which terrain presentation methods may be improved. Such a move, though, poses additional design challenges if an advanced terrain depiction system is to be effective in concert with other information-rich displays in the cockpit.

In 1989, the MIT Aeronautical Systems Laboratory (ASL) began investigating the issues involved in moving from paper to electronic IAPs [7,8,9]. This thesis documents the parallel investigation of terrain information use on paper charts and its extension to the electronic environment. Following a preliminary study of the effectiveness of current terrain depiction methods, several prototypical electronic terrain displays were designed, evaluated, and tested in a part task simulation study using pilots qualified on autoflight aircraft. In addition, a Graphical Ground Proximity Warning System (GGPWS) was designed and evaluated in a simulation study.

Chapter 2 provides a background of current IAP design, terrain depiction methods, and Ground Proximity Warning System (GPWS) technologies. The simulation facilities used in the experimental studies are introduced in Chapter 3. The preliminary investigation of terrain information use is discussed in Chapter 4. Chapter 5 describes the electronic terrain display experiment and survey effort, and Chapter 6 provides a brief reiteration of the major conclusions of the thesis.

2. Background

As a result of preliminary analyses of terrain depiction methods conducted by the MIT Aeronautical Systems Laboratory (ASL), it was found that there are two distinct modes of terrain information utilization for advanced display systems. The first mode, Terrain Situational Awareness (TSA), is described in Section 2.1. Terrain Situational Awareness involves the presentation of terrain information in a manner which allows the pilot to create a mental view of the terrain surrounding the aircraft. When properly implemented, Terrain Situational Awareness should aid the pilot in recognizing potentially hazardous terrain. The second mode of terrain information use is Terrain Alerting, described in Section 2.2. When Terrain Situational Awareness fails and the potential for ground impact exists, Terrain Alerting signals the pilot that action must be taken to save the aircraft. The current form of such a system is the Ground Proximity Warning System (GPWS), which has been in wide use on transport category aircraft for the last fifteen years.

2.1. Terrain Situational Awareness

The IAP is the primary source of information for Terrain Situational Awareness in the terminal area[1]. This section provides a short description of the IAPs currently in use, with emphasis on the presentation of terrain information that may be used to locate potentially hazardous terrain. Issues relating to the depiction of terrain information using smoothed contours are also outlined.

2.1.1. IAP Background

Figure 2.1 shows one of the more complex IAPs in the format used by most U.S. air carrier pilots. IAPs provide the pilot with the detailed navigational information for use

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[1] The terminal area is a region within approximately 25 nautical miles of the destination airport.

within approximately 25 nautical miles of the destination airport. Each IAP depicts the approach procedure for a single type of approach to a single runway at an airport.

Two agencies produce the IAPs used in the United States. The National Oceanic and Atmospheric Administration (NOAA) publishes bound booklets of IAPs, which are redistributed every 58 days [7]. A private company, Jeppesen Sanderson, Inc., produces the charts used by more than 90% of U.S. commercial transport pilots [7]. Updated Jeppesen IAPs are distributed individually every 14 days, and must be correctly filed in the chart books by the pilots.

An earlier MIT ASL study, [7], found that IAPs were the result of an evolutionary process built around approach procedure rules defined in manuals such as *Terminal Instrument Procedures (TERPS)* [2], or the *ICAO Instrument Flight Procedures Construction Manual* [3]. However, standards for terrain depiction are established by the chart producers themselves [10]. Therefore, the terrain information content of a NOAA chart may not be the same as that of a Jeppesen chart for the same approach.

The driving factors for changing the design of IAPs are user feedback, past accidents or incidents, and concern over the liability of the chart producers should an accident occur in the future. The possibility of legal suits following accidents involving unpublished obstacles has been a large consideration when printing terrain information on charts [7].

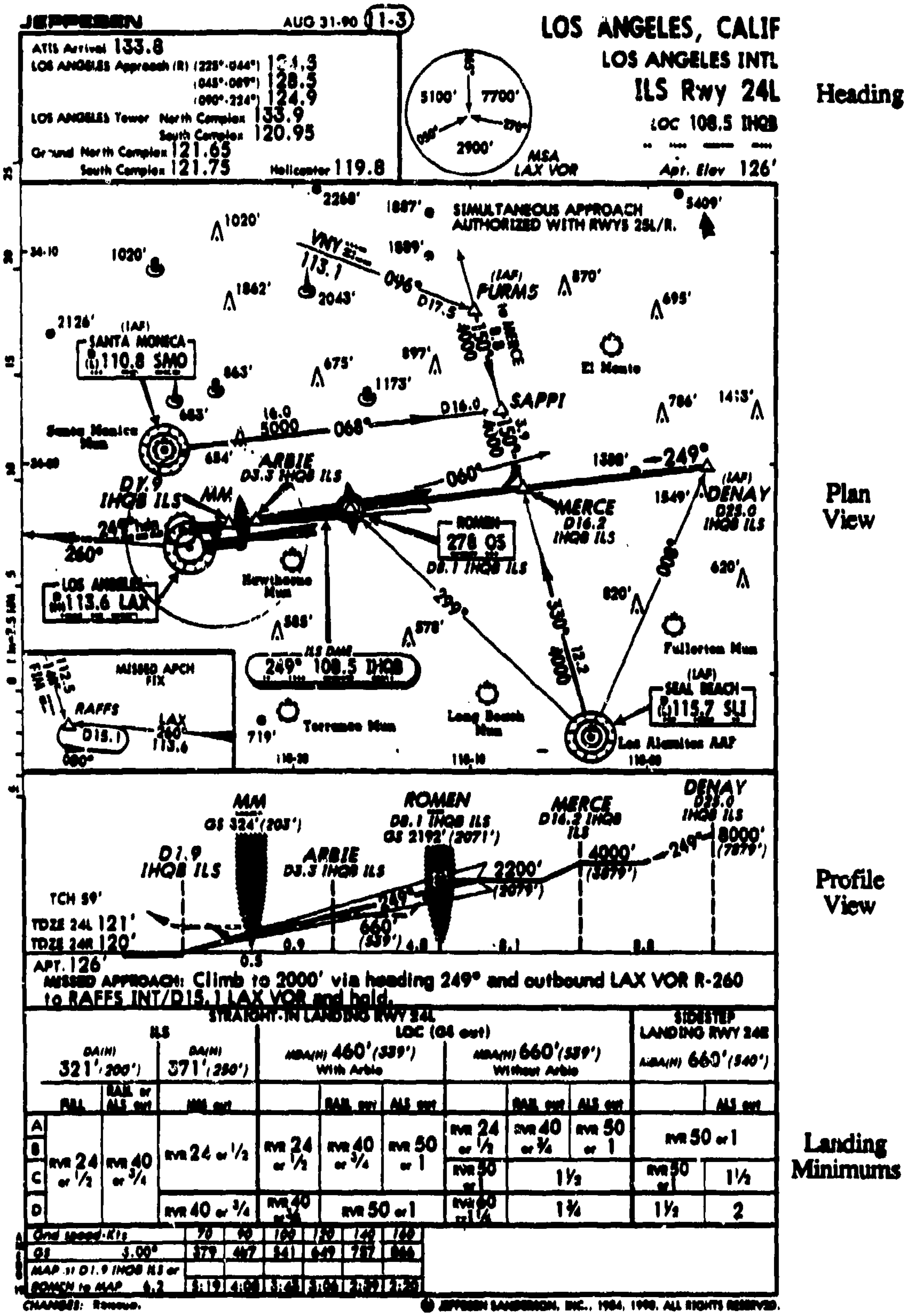

Figure 2.1
Example Instrument Approach Plate
Reproduced with permission of Jeppesen Sanderson, Inc.

2.1.2. IAP Layout

As shown in Figure 2.1, an IAP is approximately 5 x 8.5 inches in size and has four major partitions.

The top section of the IAP is used to identify the IAP and to provide radio communication information. The Minimum Safe Altitude (MSA) circle (described in detail in Section 2.1.3) is located near the top of the IAP.

The largest portion of the chart (approximately 4 x 5 inches in size) is a north-up overhead view of the terminal area, called the plan view. The plan view contains radio navigation aid (navaid) identification and frequencies, approach courses and altitudes, and the missed approach course and holding fix identification. Ground information such as airports, land features, and potentially dangerous terrain obstacles also appear in the plan view.

Below the plan view is a profile view of the approach, which shows the minimum altitudes to be used during descent on the final approach course. Altitudes above mean sea level (MSL) are shown in bold, above the course line. Altitudes above ground level (AGL) are shown in italics below the course line. In addition, the missed approach procedure is printed at the bottom of the profile view.

Located in the landing minimums section of the IAP are the minimum descent altitudes and decision heights to be used for several airport conditions. Minimum visibility requirements are also shown.

2.1.3. Current Terrain Information Presentation Methods

Terrain information is presented in several ways on the IAP. A coarse indication of terrain separation is provided by the Minimum Safe Altitude (MSA) circle, located above the plan view on the chart. Highly detailed terrain information is located within the plan view, in the form of spot elevation symbols and Minimum Enroute Altitudes (MEA) depicted next to published airways.

Minimum Enroute Altitude

Limited information concerning terrain is provided via minimum enroute altitudes (MEA), which are depicted in the plan view along approved airways. MEAs provide at least 1000' terrain clearance within 4 nautical miles of either side of a published route [11]. Thus, MEAs provide approximate measurements of terrain altitude. As an example, Figure 2.2 details one of the published airways from the IAP for Los Angeles given in Figure 2.1. The MEA along the route in Figure 2.2 is shown as 5000'.

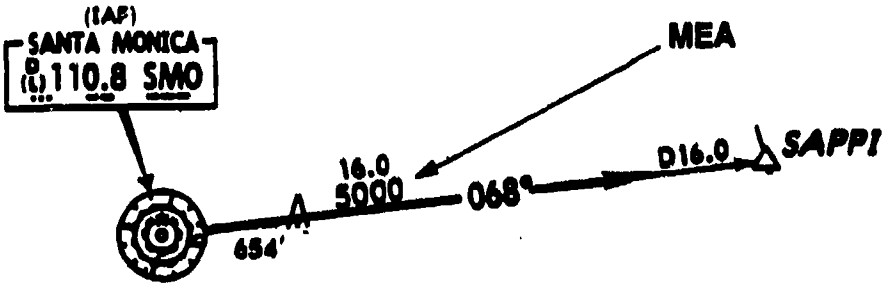

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Figure 2.2
Published Airway With
Minimum Enroute Altitude
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This Figure has been enlarged 150%

Minimum Safe Altitude (MSA)

Figure 2.3 shows a detailed view of the MSA circle from the IAP in Figure 2.1. MSA represents the lowest altitude for which 1000' of terrain clearance is guaranteed. The MSA terrain protection extends 25 nautical miles from the navaid which defines the MSA circle (Los Angeles VOR[2], in Figure 2.3), and is often partitioned into sectors defined by

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[2] A VOR (VHF Omni Directional Range) is a radio navaid.

magnetic headings. For example, with reference to Figure 2.3, if an aircraft were located west of the Los Angeles VOR, safe terrain clearance would be guaranteed down to 5100' MSL.

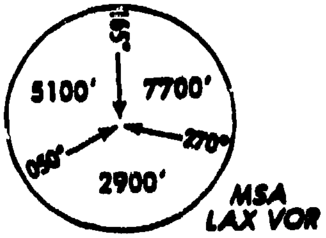

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Figure 2.3
MSA Circle Detail
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This Figure has been enlarged 150%

The pilot needs to perform a number of calculations to correctly use MSA information. For example, the aircraft's location and the MSA circle could be mentally superimposed on the plan view of the chart. For cases in which there are a number of sector divisions within the MSA circle, the pilot must estimate the aircraft's bearing from the navaid defining the MSA. Since the MSA circle is not necessarily centered near the airport and the plan view is oriented with true north up instead of magnetic north up, it may require additional effort to determine which sector applies to the aircraft for terrain clearance.

In practice, aircraft often fly below MSA. For example, the airway between Santa Monica VOR and SAPPI intersection (Figure 2.2) has an MEA of 5000', while the MSA for that sector is 7700'. In addition, ATC can vector aircraft below MSA when using Minimum Vectoring Altitudes (MVA). MVA still provides safe terrain clearance, and is similar to MEA in that 1000' of terrain clearance is guaranteed within a few miles of the aircraft's route.

MSA, then, can only provide a rough estimate of the lowest safe altitude in the terminal area. Pilots may not be able to use MSA throughout an approach if ATC vectors the aircraft below MSA. However, Federal Aviation Regulations state that the pilot is ultimately responsible for the aircraft [12]. The pilot is thus responsible for maintaining safe separation from terrain, although the pilot does not have access to the MVA altitudes used by ATC. Additional terrain information is therefore given to the pilot via spot elevation symbols and smoothed contours.

Spot Elevation Depiction

Hazardous obstacles or point obstructions such as mountains or towers are often depicted using spot elevation symbols. Spot elevation symbols, shown in Figure 2.4, provide detailed terrain altitude information at specific locations in the plan view. However, the pilot must estimate ground altitude in areas between spot elevation symbols.

Solid circles are used to represent natural hazards such as hills or mountains. Unidentified man-made reference points are shown using a peaked tower-like symbol. Buildings and other readily identifiable objects are depicted with specific symbols [11].

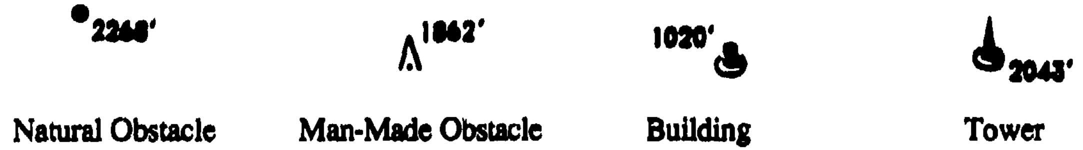

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Figure 2.4
Example Spot Elevation Symbols
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This Figure has been enlarged 150%

Spot elevation altitude data are presented in a uniform manner regardless of the chart manufacturer. The obstacle elevation, rounded to the next highest foot MSL, is depicted next to a graphic symbol. The highest obstacle(s) on the chart are either highlighted (on NOAA charts), or have a large arrow pointing at their altitudes (on Jeppesen charts).

Smoothed Contour Depiction

Another method of terrain depiction is the use of smoothed contour lines, as shown in Figure 2.5. Pilots have strongly supported the use of smoothed contours on paper IAPs. More than 90% of the 1377 respondents to a survey in *Air Line Pilot* magazine favored the use of IAPs which included smoothed contours [13,14]. Contours offer an advantage over spot elevation symbols in that terrain information is depicted throughout the plan view, providing a continuous representation of the terrain near the airport.

Figure 2.5 shows detail from the plan view of a Jeppesen chart which uses smoothed contour line depiction. The contour lines are printed in 1000' vertical increments.

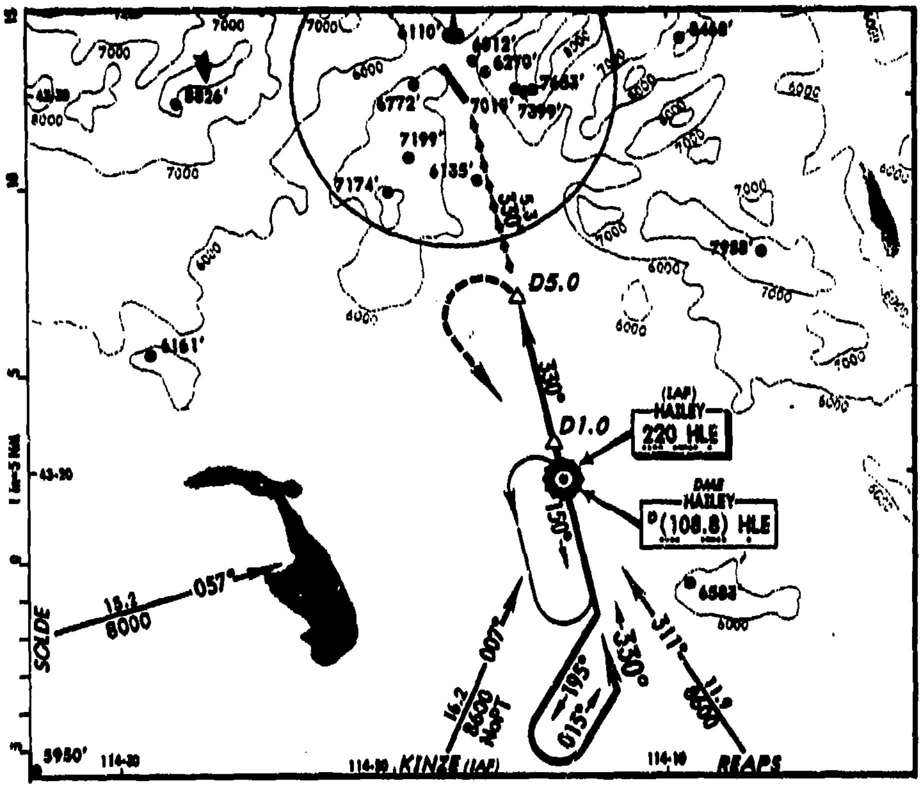

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Figure 2.5
Plan View Detail From Smoothed Contour IAP
Reproduced with permission of Jeppesen Sanderson, Inc.

Smoothed contour terrain depiction on IAPs includes several drawbacks. Generally, contour lines are spaced vertically every 500 or 1000 feet and hence provide less precise altitude information than spot elevations. A high density of contour lines, each with its printed altitude, may generate additional clutter on the IAP. Color may improve readability, but at an increased production cost. Finally, contour charts require a larger database than spot elevation charts, increasing cost and reliability concerns.

The electronic environment therefore seems well suited to the depiction of contour charts. Displays offer the pilot enough flexibility to select or deselect information to control chart clutter. Color is easily integrated into a display, though care should be taken to ensure that terrain information does not create excess difficulty in reading other information depicted in the display.

2.1.4. Smoothed Contour Depiction Issues

Contour chart design involves a number of depiction issues. The variable parameters in contour depiction methods should be balanced to provide an intuitive and useful representation of the terrain. This section outlines the major issues which may be addressed with respect to the design of smoothed contour charts.

Contour Altitude Depiction

Each contour should be clearly identified with an altitude. Two methods of contour altitude depiction are generally used. Jeppesen IAPs with smoothed contour lines use a depiction method in which the altitude of a contour is printed next to the contour line. In order to maintain similarity with the altitude depiction method used for spot elevation symbols (which are also present on these Jeppesen charts), the contour altitudes are printed as shown in Figure 2.5.

Another method of altitude depiction, termed Area Minimum Altitude (AMA), is recommended by ICAO standards, [4,5], and is currently used on VFR sectional charts and some Jeppesen enroute and area charts[3]. Figure 2.6 provides an example of smoothed contours using AMA altitude depiction.

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[3] VFR sectional charts are used to navigate under visual flight conditions. Enroute and area charts are used for IFR navigation between navaids.

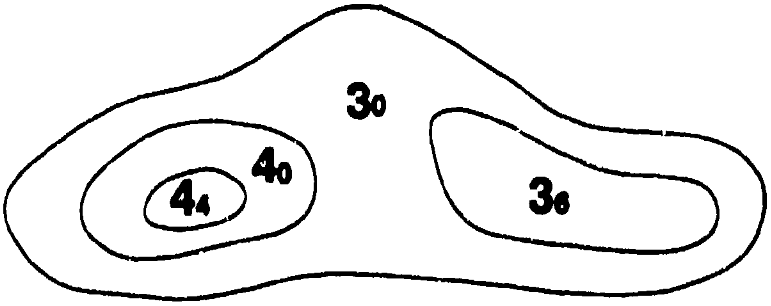

Figure 2.6
Area Minimum Altitude Contour Depiction

AMA altitudes are designed to show the highest altitude in a particular region, unlike contour line altitude depiction which indicates the altitude along a contour line. On a VFR sectional chart, for example, each AMA altitude represents the highest altitude within a rectangle one degree of latitude or longitude on each side. On contour charts, AMA regions are separated by contour lines. Many AMA charts use a shorthand methodology in which thousands of feet are shown in bold face, with hundreds of feet in a smaller, lighter typeface. However, AMA contour altitudes may also be printed in a single typeface in a manner similar to the contour line altitude depiction shown in Figure 2.5.

The resolution limitations of display technology may prohibit a detailed contour line altitude depiction method such as that shown in Figure 2.5. Since the readability of textual information on an electronic display decreases as the text is rotated[4], it may be necessary to depict text horizontally on a display. Contour altitudes must therefore be depicted in the most concise, readable, and intuitive manner possible. Since the shorthand AMA method of altitude depiction requires less text and is not as critical in the location of the text as is contour line altitude depiction, shorthand AMA altitudes may be well suited for use on electronic displays.

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[4] Text readability decreases greatly as it is rotated, due to aliasing effects. See Reference 18 for more information.

Altitude Spacing Between Contour Lines

Altitude intervals between contours should be designed to balance excess clutter against the level of detail and resolution of the chart. ICAO guidelines call for contour spacing of 500, 1000, or 2000 feet for paper approach charts, depending on the type of terrain in the terminal area [4,5]. For example, terrain with large changes in altitude may require large altitude intervals between contours to produce a readable chart.

An electronic flight display which is flexible enough to depict legible contours for a wide variety terrain situations might use variable contour spacing. Variable spacing could use small intervals between contours in flat areas, and large intervals in mountainous regions. The result is a readable, low density contour chart regardless of the terrain layout. However, since knowledge of the separation between contours is important for estimating ground altitudes between contour lines, such a display may need to provide the pilot with a simple method for determining the contour spacing. In addition, while contour spacing may be fairly coarse due to steep terrain, higher altitude resolution may be desired near the runway threshold where low altitude operations occur.

Another issue tied closely to contour spacing is that of determining the lowest altitude above the airport at which terrain should be placed within a contour. ICAO standards set the lowest altitude at which terrain should be placed within a contour as the next even 1000' at least 500' above the airport altitude [4,5]. Adhering to this standard may reduce clutter in areas near the airport.

Contour Shading

One form of contour chart depicts terrain using only a number of smoothed contour lines. However, if the regions between the contour lines are shaded according to the altitude of the terrain between the contour lines, there may be a marked increase in the intuitiveness of the chart. Figure 2.7 shows an example shaded contour representing the same terrain as shown in Figure 2.6.

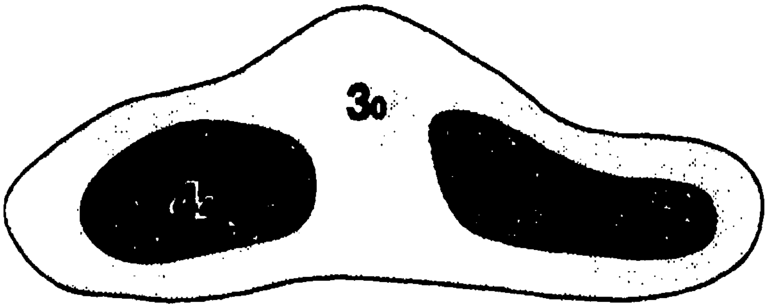


Figure 2.7
Smoothed Contours With Shading

Contour shading is not always used on black and white paper charts since the shading may obscure other chart information. When depicted in color, contour information may be more easily separated from the other information on the chart. The increased cost associated with the production of color paper IAPs on a large scale has led chart producers to accept the limitations of black and white depiction. In an electronic environment, however, color contour shading may be more feasible than shading on paper charts.

Obstacle Clearance Buffer Altitudes

A fundamental issue of terrain depiction involves the inclusion of safety buffers in the printed altitudes on a chart. For example, MSA sector altitudes incorporate a 1000' safety buffer above the highest obstacle in a sector (rounded to the next higher 100'). Thus, if the highest obstacle in a sector is 1762', the MSA will be depicted as 2800'. ICAO AMA and MEA altitudes also include a 1000' safety buffer in their depicted altitudes [4,5].

In contrast, spot elevation symbols indicate exact MSL altitudes, with no safety buffer. The same holds true for the altitudes of contour lines depicted on some Jeppesen

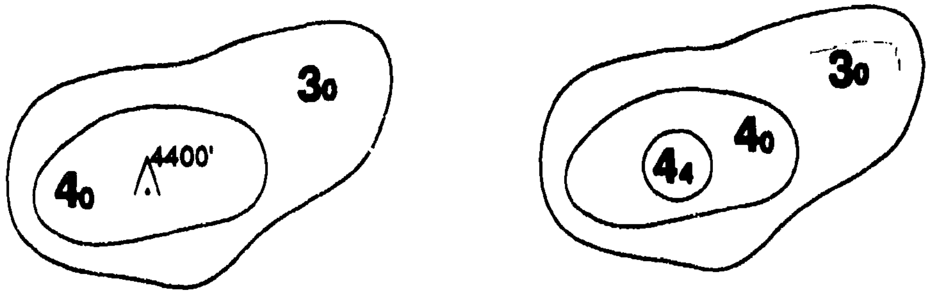
IAPs (Figure 2.5, above). In general, detailed terrain information is shown using exact MSL altitudes, thus providing the pilot with precise raw altitude data.

Obstacle clearance buffers provide an additional margin of safety for terrain avoidance. However, pilots may prefer raw altitude data to altitudes which include safety buffers since the former allow pilots to obtain a more precise view of terrain. For example, a 1000' safety buffer may be overly conservative for obstacles near the runway threshold, where terrain separation may be less than 500' [3,11].

The decision regarding the use of an obstacle clearance safety margin may be based on the tradeoff between the high accuracy of information afforded without a buffer, and the added flight safety which may result when using a buffer. However, when charts use a combination of altitudes with and without safety buffers, there is an increased possibility of errors in reading altitude information. For example, the pilot might mistakenly assume that a 1000' buffer was included in the altitude of a spot elevation symbol, and unintentionally fly dangerously near the obstacle. Therefore, terrain altitude depiction should be carefully designed to provide the pilot with precise altitude information in a consistent manner which will minimize interpretation errors.

Depiction of Point Obstructions on Contour Charts

Smoothed contour depiction methods may include provisions for the presentation of hazardous point obstructions such as towers or power lines. Figure 2.8 shows two possible methods for depicting point obstructions. One solution is to use spot elevation symbols such as those shown in Figure 2.4. The result is a hybrid chart with both smoothed contours and spot elevation information. Jeppesen IAPs which have smoothed contour lines use this method for depicting point obstructions. However, the addition of spot elevation symbols to the contour chart may increase clutter and forces the pilot to alternate between two modes of interpreting terrain information.



Spot Elevation Symbol Conical Safety Zone

Figure 2.8
Depiction of Point Obstructions in Contour Charts

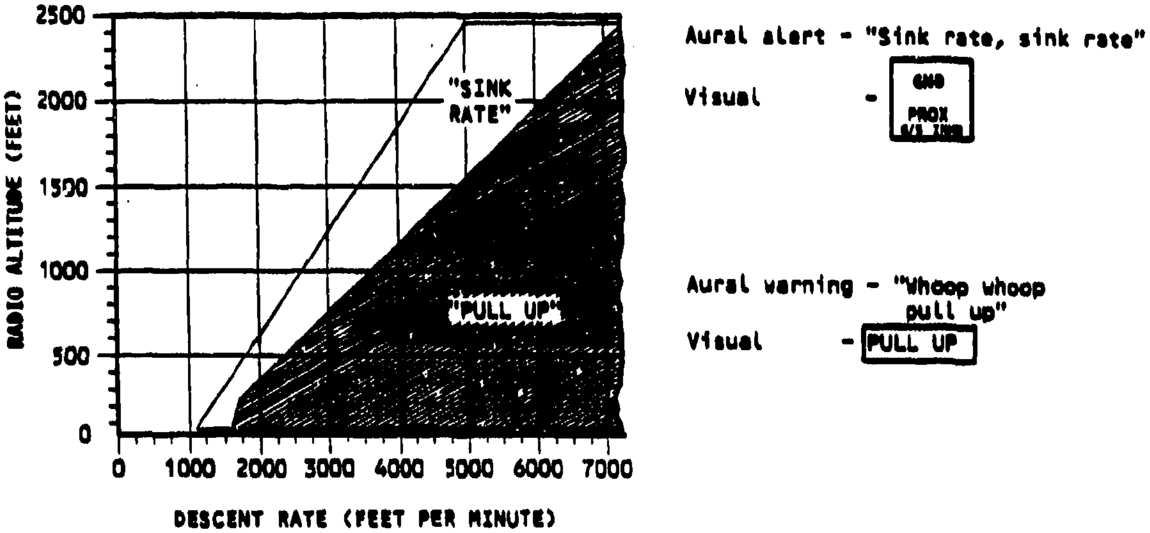
Another solution is to create a conical safety zone around each spot obstacle. This conical region is then considered as if it were solid ground, and depicted using contour lines. A limitation of this method of point obstruction depiction occurs if high resolution is desired. With high resolution, the safety zones become steep, resulting in small contours which may be difficult to interpret.

2.2. Terrain Alerting Systems

2.2.1. Ground Proximity Warning System Background

The Ground Proximity Warning System (GPWS) is the aircraft's last line of defense against a collision with the ground. Modern GPWS was developed and implemented on a wide scale in the United States following a number of CFIT accidents. A large push towards the requirement of GPWS systems occurred following the crash of a TWA 727 on approach to Dulles International airport in 1974 [15].

The current GPWS in use on aircraft such as the Boeing 767 employs a number of sensors to determine the level of hazard that terrain poses to the aircraft [16]. GPWS relies primarily on the aircraft's altitude above the ground (radio altitude), the rate of change of radio altitude, and the aircraft's vertical speed. Additional inputs to GPWS are derived from airspeed as well as flap and gear configuration. Figure 2.9 shows the alerting criteria for one of the four modes of the GPWS system in use on 767 aircraft [16].



Mode 1 - Excessive Descent Rate

Figure 2.9
GPWS Alerting Criteria for Boeing 767
Reproduced From The Boeing 767 Operations Manual, [16]

One shortfall of the GPWS systems used today is their inability to alert the flight crew to a controlled descent into terrain while in landing configuration. If the aircraft is in landing configuration (with landing gear down and full flap extension) and in a stable descent, the GPWS system assumes that the aircraft is landing and will not signal an alarm.

The warnings that GPWS provides are a combination of aural and visual alerts. Two warning lights in the cockpit, labeled "GND PROX" and "PULL UP", illuminate according to criteria such as those shown in Figure 2.9. In addition, an aural message is played in the cockpit, such as "whoop whoop, pull up!". Little other information is given to the pilot regarding the situation affecting the aircraft. GPWS alerts the pilot that action is required immediately, but the alarm may also be disorienting especially if the in hazard was unexpected. Such disorientation could slow the pilot's response enough to cause an accident.

2.2.2. Controlled Flight Into Terrain Accidents

Since the beginning of the widespread use of GPWS in U.S. air transport aircraft in 1975 and in the worldwide fleet since 1979, there has been a marked decrease in the number of CFIT accidents (Figure 2.10) [1]. Still, CFIT was the leading cause of worldwide fatal air accidents between 1979 and 1989 (Figure 2.11) [1].

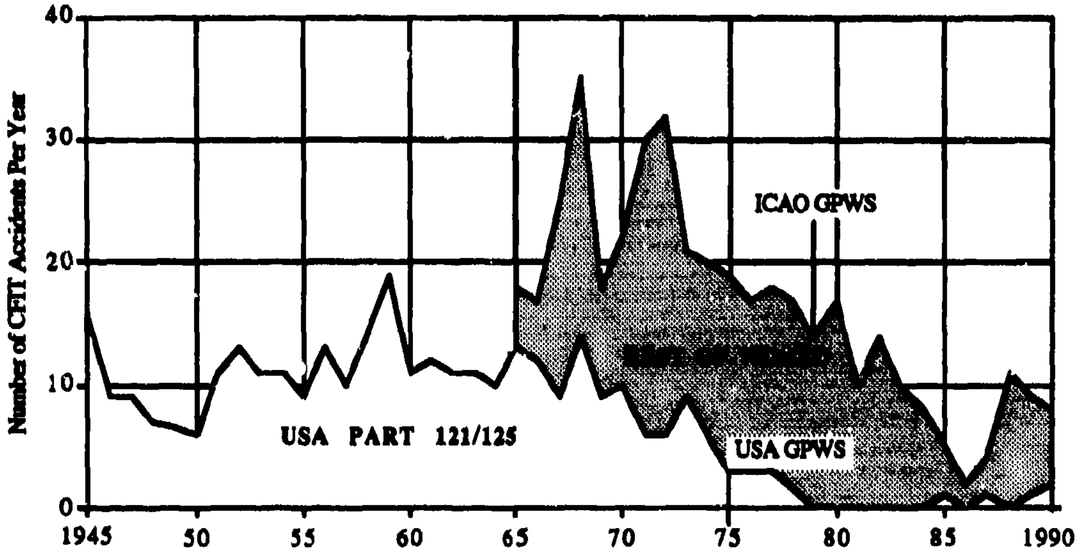


Figure 2.10
CFIT Accidents Per Year (Transport Aircraft)
Data reformatted from [1], with permission of author.

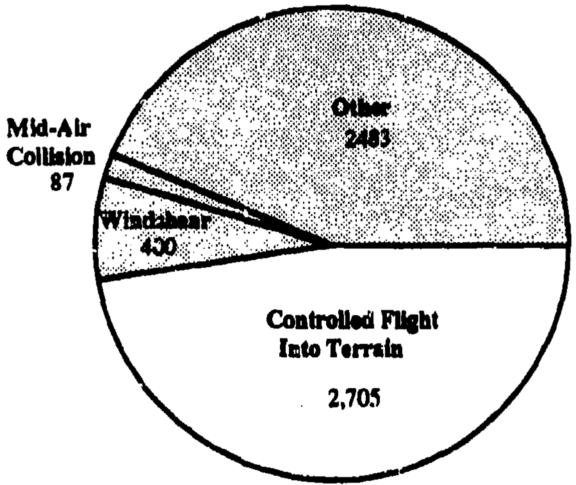


Figure 2.11
Worldwide Airline Fatalities 1979-1989

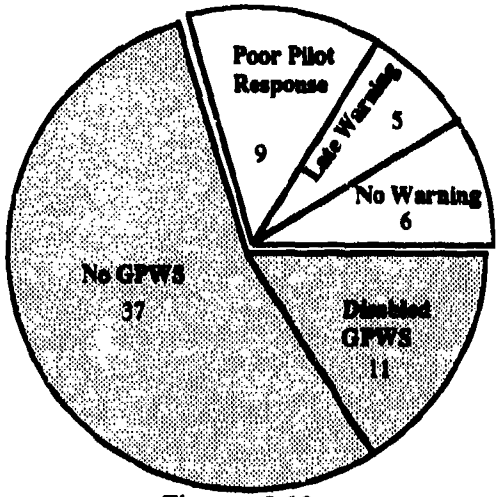


Figure 2.12
GPWS Status in Worldwide CFIT Accidents 1975-1989

Data reformatted from [1], with permission of author.

The high CFIT rate does not necessarily indicate that current GPWS systems are dangerously inadequate - most CFIT accidents involved aircraft without GPWS or with disabled equipment. Still, aircraft with a functioning GPWS account for approximately 30% of the CFIT accidents since 1975 [1]. Figure 2.12 shows the status of GPWS carried on aircraft involved in CFIT accidents between 1975 and 1989.

Of those aircraft which did carry a functioning GPWS, accidents occurred due to three primary reasons (see Figure 2.12):

1. *Late warning* leaving the pilot without adequate time to react (25% of the CFIT accidents involving aircraft with a functioning GPWS).

2. *Poor pilot response* (45% of functioning GPWS CFIT accidents). The GPWS system alerted the pilots to a terrain hazard, but confusion or disbelief delayed the response.

3. *No warning*, due to a controlled descent into terrain while in landing configuration (30% of functioning GPWS CFIT accidents). If the aircraft was in landing configuration, GPWS would not signal an alarm when descending into terrain.

Late ground proximity warnings were generally produced from older GPWS systems. In four of the five CFIT accidents in which GPWS generated a late warning, it is estimated that the mean warning time before impact would have increased from 7 seconds to 15.75 seconds had the aircraft been using more advanced models of GPWS [1]. The additional time afforded by such an improvement might have saved the aircraft.

The two other causes of CFIT accidents involving aircraft with functioning GPWS systems - slow pilot response and landing configuration descent short of the runway - may be preventable using advanced GPWS systems such as those described in Section 2.2.3. Pilot response may be improved by increasing pilot situational awareness, and landing configuration accidents may be preventable by using the increased intelligence of an advanced GPWS system.

2.2.3. Advanced Ground Proximity Warning Systems

Advanced ground proximity warning systems may reduce the likelihood of future CFIT accidents. Such systems could be based on internal terrain database or advanced sensor technologies. A comparison between terrain data and aircraft location as determined by the Inertial Navigation System (INS) or via the Global Positioning System (GPS), could provide the information needed to determine the level of hazard posed to the aircraft.

Impacting short of the runway has accounted for 30% of the CFIT accidents involving aircraft with a functioning GPWS, as shown in Figure 2.12 [1]. An advanced GPWS system could prevent this type of accident by determining that the aircraft was descending short of the runway by comparing aircraft location with terrain or runway data.

Additional aid may be given to the pilot by providing situational information regarding a terrain alert. Graphical GPWS (GGPWS) is one proposed system which could provide the pilot with locational information for hazardous terrain on an electronic flight display. GGPWS systems could alert the pilot to the severity of situations by using appropriate colors or patterns to denote different hazard levels. Alerting displays may be presented in plan view, profile view, or perspective view formats. An outline of the major factors involved in the design of these GGPWS display formats is provided below.

Plan View Alerting Systems

Plan view GGPWS systems provide commonality with existing terrain depiction methods, and may be incorporated in plan view terrain situational displays. Since this method of GGPWS uses a plan (or overhead) view, ground proximity alerts are best suited to provide the pilot with information about the distance and direction to threatening terrain.

Terrain Situational Awareness generally requires a large-scale view of terrain, on the order of 10 to 100 nautical miles, while Terrain Alerting may involve an area less than 10 nautical miles from the aircraft. Thus, if the GGPWS system is incorporated with a terrain situational display, the display design should include a method by which small hazardous terrain features may be recognized when the display is set to a large scale. One possible solution is to automatically rescale the display when an alert is triggered.

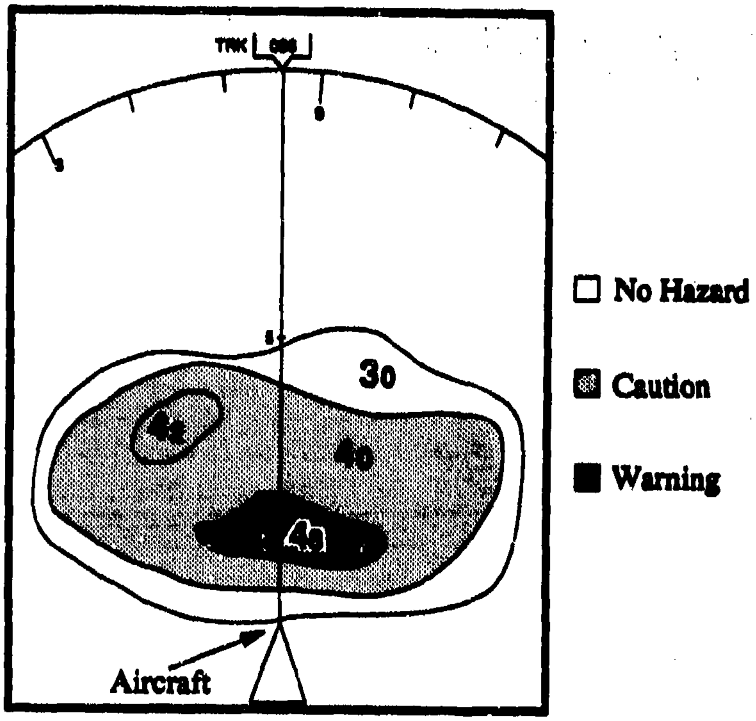
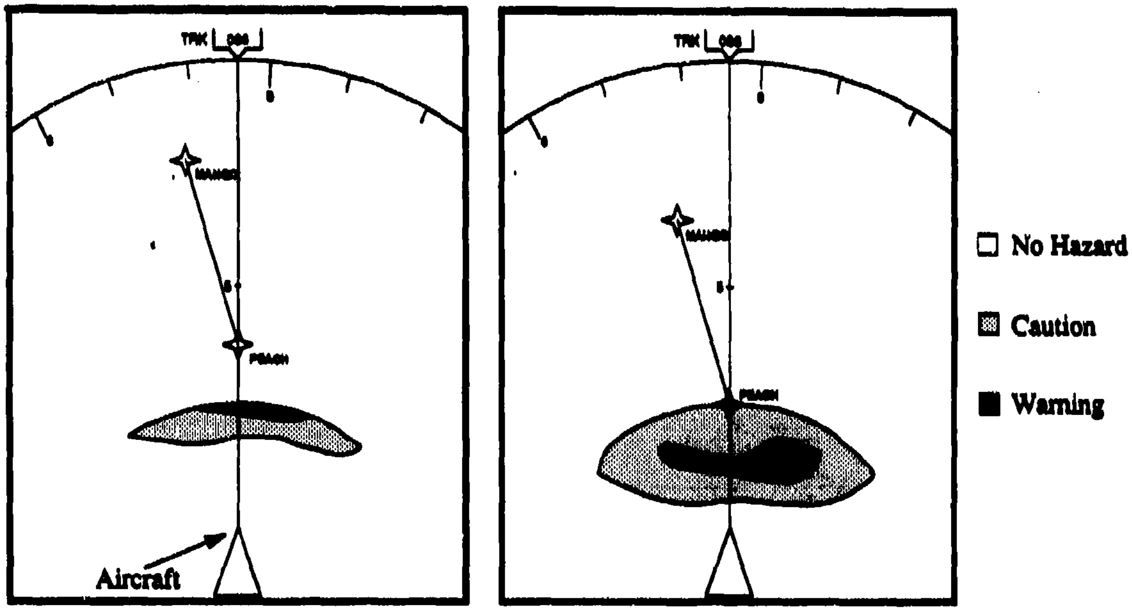


Figure 2.13
GGPWS Alerting - Contour Alerting Method

During the design of the experiment discussed in Chapter 5, two methods of plan view alerting were investigated, termed contour alerting and discrete alerting. Figure 2.13 shows one implementation of a GGPWS system which alerts using the contour method. In the contour alerting method, the contour lines form three dimensional solids which enclose all the terrain within their bounds. If any part of the contour area is determined to be hazardous from the alerting criteria, the entire contour will be displayed in a color or pattern corresponding to the severity of the situation. Thus, the contours used for situational awareness in the terrain display may also act as alert icons.

The discrete alerting method is well suited for use with sensor data. Each data point is examined for compliance with the alerting criteria. If a data point is considered hazardous, it will be displayed using a suitable color or pattern (see Figure 2.14). The result is an alerting display which may be more precise than that produced from the contour method (depending on the database resolution), and may not require any contours to be calculated or depicted on the display. The discrete alerting method may therefore be a more computationally efficient means of presenting terrain alerts than the contour alerting method.

As shown in Figure 2.14, however, as the aircraft moves, the size and shape of an alerted area will change. Without a clearly defined, unchanging depiction of terrain, the pilot may be uncertain about the layout of the hazard causing the alert. Hence, the discrete alerting method may be less intuitive to the pilot than the contour alerting method.



Initial Position

1 Nautical Mile Later

Figure 2.14
GGPWS Alerting - Discrete Alerting Method

The discrete method of Terrain Alerting is especially sensitive to the display scale. Databases or advanced sensors with fine resolution may result in small regions of alerted terrain which must be magnified or denoted by icons in order that the pilot may easily see the terrain causing the alert.

Profile View Alerting System

Profile GGPWS alerting is a method of terrain depiction which emphasizes the vertical separation and horizontal distance to hazardous terrain, rather than distance and direction as depicted on a plan view display. Since the profile view depicts flight in the vertical plane, the profile alerting system is consistent with current terrain avoidance procedures which call for a wings-level pull-up. The projected vertical flight path may be examined on the display to determine if terrain impact will occur in the future.

Figure 2.15 shows a schematic of one possible profile view terrain alerting display. The aircraft is located on the left side of the display, with the projected vertical flight path depicted to the right. Altitude and distance information are shown along the axes of the display. Terrain ahead of the aircraft (either from a database or advanced sensor) which violates the GGPWS alerting criteria is depicted on the profile view in an appropriate color or pattern.

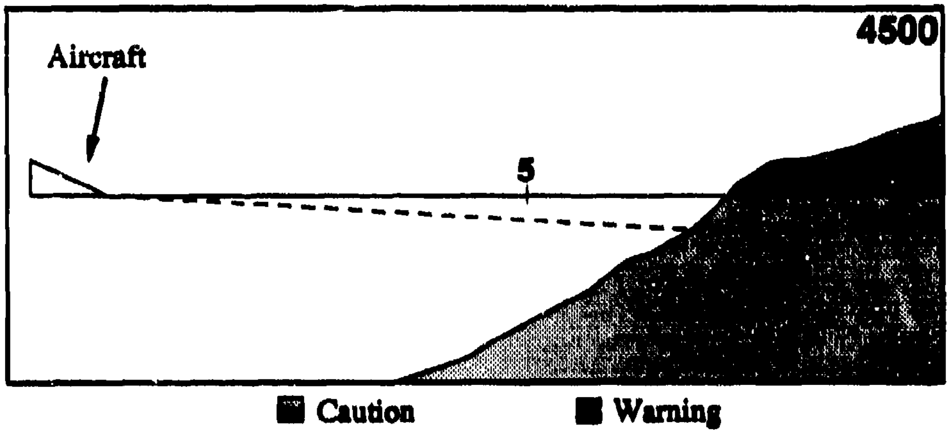
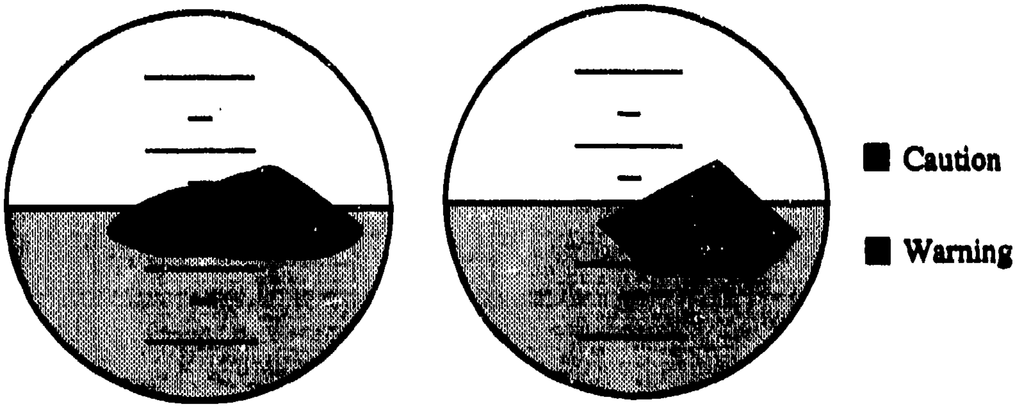


Figure 2.15
Prototypical Profile GGPWS Alerting Display

Perspective View Alerting Systems

A third method of Graphical GPWS is the use of a perspective view alert, either on the artificial horizon (ADI), or using a heads up display. Figure 2.16 shows two preliminary perspective view implementations on the ADI.

The perspective alerting display offers several advantages over the plan view and profile view alerting methods described above. Alert information is provided on the flight display that is the primary reference when performing evasive action. The pilot may then focus on the primary display both to check the location of terrain hazards as well as to monitor the aircraft's state. In contrast to the plan view and profile view systems, the perspective display system provides a three-dimensional view of the terrain which, if implemented correctly, may create an intuitive display to aid the pilot in developing an escape methodology.



High Resolution Database **Low Resolution Database**

Figure 2.16
Preliminary Perspective GGPWS Alerting Display
(Integrated with Artificial Horizon)

3. Experimental Facilities

Two experiments were conducted using the MIT ASL Advanced Cockpit part-task simulator to investigate several candidate IAP formats and terrain displays. The simulator facility was used to provide pilots with an environment in which they could evaluate displays in a setting consistent with flight conditions.

The first experiment, described in Chapter 4, examined spot elevation terrain depiction methods with paper and prototypical electronic IAP formats. The second experiment, discussed in Chapter 5, investigated prototypical spot elevation and smoothed contour terrain displays, as well as a prototypical GGPWS system.

This chapter is provided to describe the simulator facilities and experimental protocol common to both experimental efforts. Detailed design issues specific to each experiment are discussed in the respective chapters describing the experiments.

3.1. Simulator Configuration

The MIT ASL Advanced Cockpit Simulator is a part-task simulator based on Boeing 757/ 767 and 747-400 flight displays. The facility utilizes two computers and several control panels to emulate the autoflight systems, and was developed over 3 years by a number of graduate and undergraduate students.

A Silicon Graphics Personal IRIS 4D was used to simulate the aircraft dynamics and present the primary flight displays. Figure 3.1 shows the simulator displays when configured for the prototypical contour display experiment described in Chapter 5. Airspeed, altitude, and vertical speed were indicated using tape displays similar to those found on the 747-400. An Attitude Director Indicator (ADI) was provided, and was used to display the artificial horizon, ground speed, radio altitude, and ILS localizer and glideslope deviations.

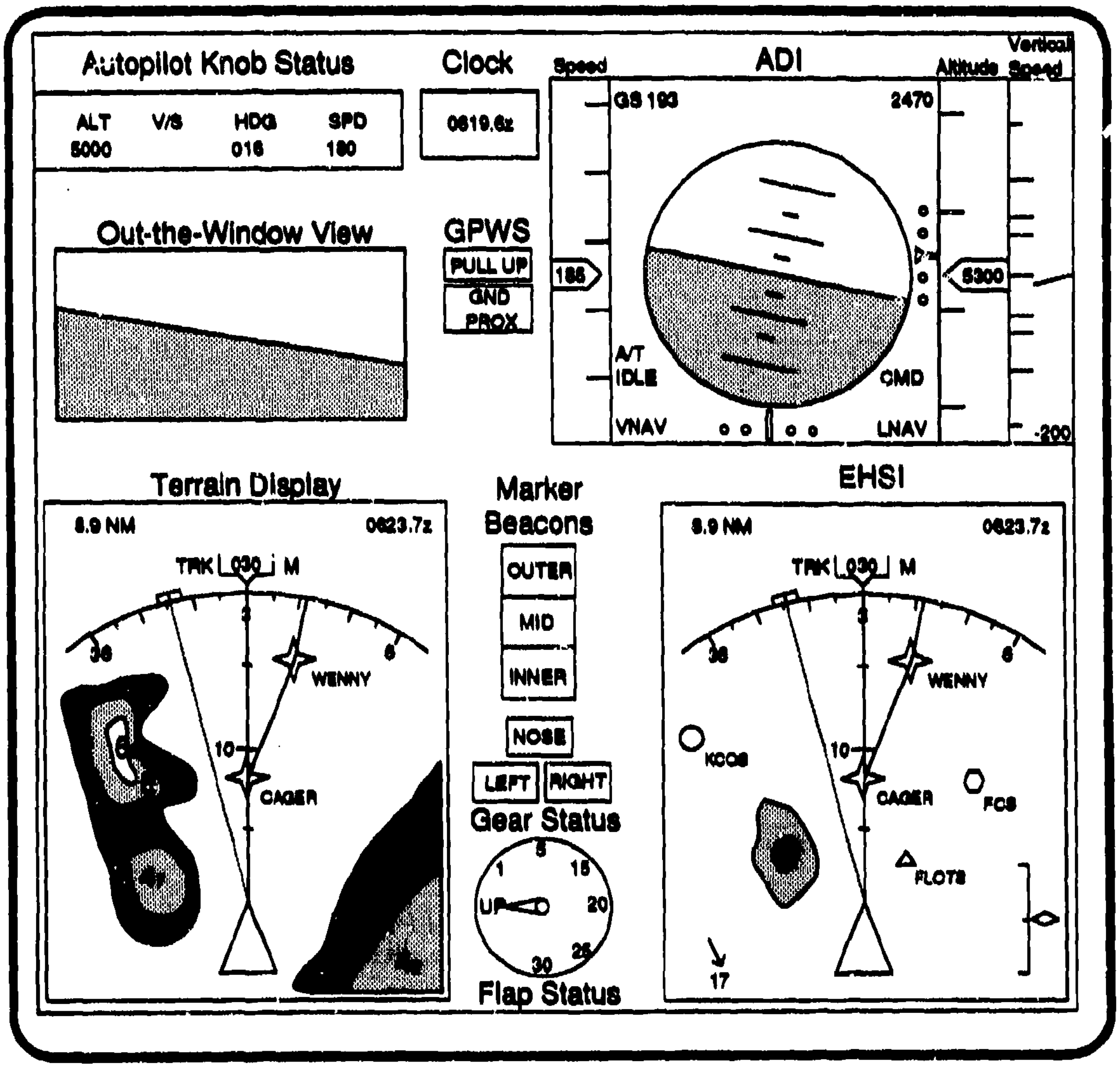


Figure 3.1
Simulator Instrument Layout

The Electronic Horizontal Situation Indicator (EHSI) was located below the ADI, as in the 757 or 767. The EHSI displayed the 757/767 map mode, including aircraft heading, ground track, and programmed route.

A control panel was provided to allow the pilot to configure the EHSI in a similar manner to the actual aircraft. The pilot could select and deselect airports, navaids, intersections, and weather information, as well as scale the map display from 10 to 360 nautical mile range.

Flap, gear, and marker beacon light displays were provided to the left of the EHSI. Controls were provided to allow the pilot to set the flaps and lower or raise the landing gear during the approach.

A simple perspective out-the-window view was provided as a means by which to cue the pilot that the aircraft had descended below the cloud deck. While in instrument conditions, the display appeared gray. When descending out of the cloud deck a single runway appeared, representing the airport.

The left side of the IRIS screen was used to display the prototypical electronic approach charts or terrain displays discussed in Chapters 4 and 5 respectively.

Flight control inputs were made using an emulation of the Boeing 757/ 767 Mode Control Panel (MCP), which was interfaced through an IBM PC-XT. Controls were available so the pilot could command airspeed, altitude, heading, and vertical speed. The aircraft autopilot modes could be selected as well, including LNAV[5], altitude capture and hold, vertical speed, heading select and hold, localizer and glideslope intercept, and go-around mode.

An experimenter acting as air traffic controller was stationed away from the pilot with a video display of the aircraft's EHSI, and was in contact with the pilot through a

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[5] LNAV is the mode in which the autopilot navigates the aircraft along a route programmed in the Flight Management Computer

simulated VHF link. The controller monitored the progress of the flight and issued vectors and approach clearance amendments according to a script for each approach scenario.

A second experimenter, acting as the Pilot Not Flying (PNF), was seated next to the pilot, and was available to answer any questions about the simulator that arose during the experiment.

The IRIS display was videotaped and the subject's comments were recorded for future reference and performance measurements.

3.2. Rapid Prototyping Software

Due to resolution limitations and the high density of information presented on electronic flight instruments, it is necessary to provide a display decluttering capability. Information presented on current flight displays is organized into layers which may be shown alone or in combination with other information layers. For example, four layers of information are available on the nominal EHSI: airports, intersections, navaids, and weather radar information. The process of layering information requires an object-based data set, in which symbols and text are treated as independent elements. These objects are then placed into distinct layers which may be selectively presented on a display.

Since a detailed object database was not available for use in the Advanced Cockpit Simulator, a software package was developed for the IRIS which facilitated the flexible, rapid creation of new display formats [17]. The program, called *Map*, is a menu-based application which presents a display as it would appear in the simulator. *Map* contains a library of common chart symbols, as well as a number of fonts for textual information. Lines, curves, polygons, and terrain contours can also be drawn. Objects may be colored, rotated, or reduced and enlarged as desired. For further information about *Map*, see Reference 18.

The database created by *Map* may be presented on displays in the Advanced Cockpit Simulator. Display formats in the preliminary terrain information study and terrain display experiment used databases created from *Map*. Paper IAPs given to the subject pilots were also produced using data files generated from *Map*.

3.3. Experimental Protocol

All subject pilots were volunteers who responded to advertising leaflets or were recruited from an alphabetical directory. Subjects were limited to current pilots qualified on autoflight aircraft to ensure that the subjects were familiar with the systems used on the simulator.

The simulation experiments took approximately 3 hours to perform with each subject. The pilot was asked to sign an informed consent statement and to complete a brief background questionnaire. The experiment was described briefly, and the subject was introduced to the simulator. Practice approaches were flown until the pilot felt comfortable with the control of the simulator and its displays. Finally, the pilot was told that he was to fly the simulator as responsibly as he would on a normal flight, and to feel free to ask ATC for additional vectors, should he feel it was necessary.

When the pilot was ready to begin, he was given an IAP for the approach he would be performing. Airport information (ATIS[6]) was then given to the pilot to describe weather conditions and other information usually received before an approach. Each scenario began with a route programmed into the aircraft's FMC and displayed on the EHSI.

After the pilot had reviewed the approach plate and was comfortable with the situation, the simulation was started. Amendments to the programmed route were issued

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[6] ATIS - Automatic Terminal Information Service. ATIS provides the pilot with weather conditions and runway status, and is generally obtained before maneuvering for the approach.

by the air traffic controller, and the pilot could change heading, airspeed, or altitude using the Mode Control Panel. The experiment consisted of 9 approach scenarios in the preliminary terrain information evaluation study described in Chapter 4, and 12 approach scenarios in the terrain display experiment described in Chapter 5.

In order to examine the effectiveness of terrain presentation methods, the aircraft was intentionally vectored into terrain in several of the scenarios. In each case, the clearance was issued near the start of the scenario, at a point when the pilot had ample time to study the situation. The erroneous clearance involved vectoring the aircraft close enough to terrain (within 1000') such that the ground proximity warning system would alert the crew on an actual aircraft. The aircraft never actually flew through terrain, as this would have reduced the realism of the simulation.

If the pilot did not notice that terrain was in his flight path, and subsequently flew within 1000' of terrain, it was recorded as a terrain fly-through event. If the pilot recognized the hazard, he was free to ask for a higher altitude or course change to avoid the hazard. ATC would then issue a proper, safe clearance.

The simulation was halted between the outer marker and the threshold. Between scenarios, the pilot was questioned about significant occurrences during the flight. At the conclusion of the experiment, the pilot was interviewed to obtain subjective opinion data on the chart or terrain display formats.

3.4. Simulator Ground Proximity Warning Systems

The simulator was configured with a Ground Proximity Warning System (GPWS) similar to that found in Boeing 767 aircraft. In addition, a candidate Graphical GPWS (GGPWS) system was designed and implemented in the prototypical terrain display experiment. The GPWS system required the design of a terrain modelling system for the simulator, described in Section 3.4.1. The GPWS and GGPWS systems used on the simulator are discussed in Section 3.4.2.

3.4.1. Terrain Modelling

A system was developed to calculate ground altitude during a flight so that the GPWS system could be simulated. The system that was used was chosen both for its simplicity and its ability to reasonably approximate sloping ground for the type of terrain used in the experiment. For future studies requiring a more detailed examination of ground proximity warning criteria, a more accurate terrain model would be necessary.

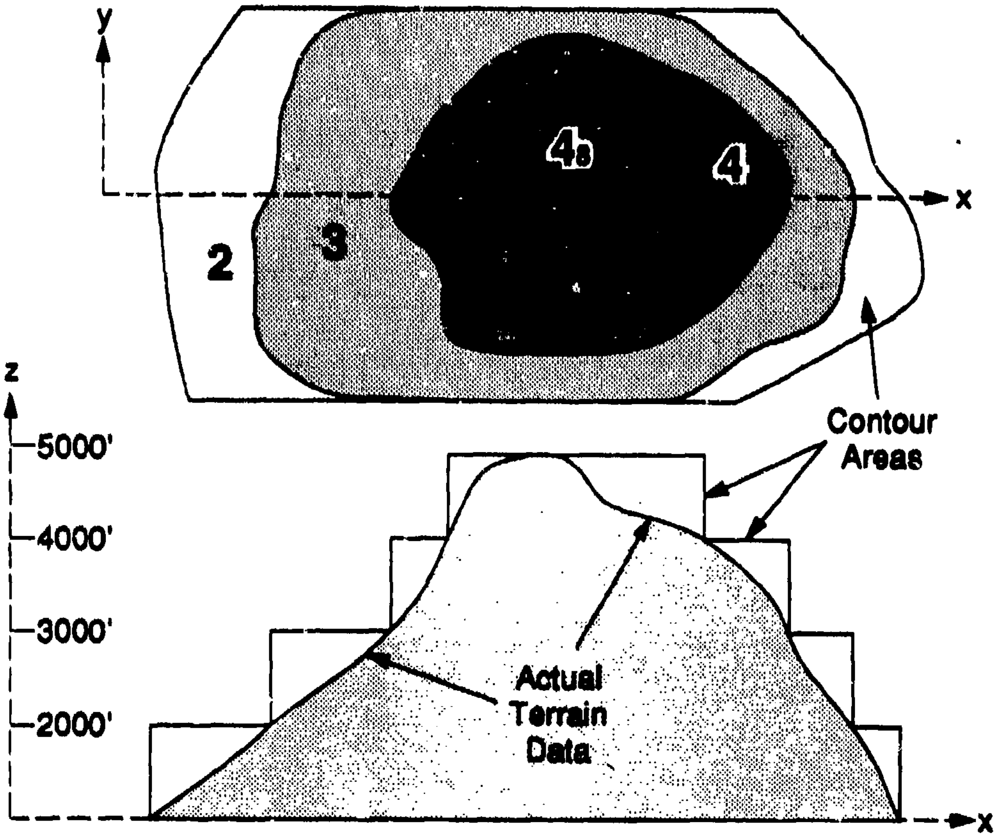


Figure 3.2
Coarse Terrain Model

A coarse model of the terrain was created using the chart prototyping software described in Section 3.2. Figure 3.2 shows plan and profile views of terrain as it might appear in the rough terrain model. Contours were spaced every 1000' vertically, with the altitude of the highest contour in a stack rounded to the next highest 100'. Each contour area enclosed all terrain from the altitude printed inside the contour to the next lower 1000'. Thus, a contour area labeled '4' included terrain between 3000' and 4000'. This rough model was used both for the depiction of contours in the terrain situation display, as well as for use in the prototypical GGPWS System described in Section 3.4.2.

The need for radio altitude and radio altitude rates for GPWS calculations drove the design of a more detailed terrain model. Detailed terrain modelling was conducted in real time during the simulation, thus avoiding the creation of a large terrain database. Ground altitude calculations were updated in each simulation loop (approximately every 150' that the aircraft flew), a resolution which would have required over 3 million data points for a pre-computed database covering the 25 nautical mile radius MSA circle.

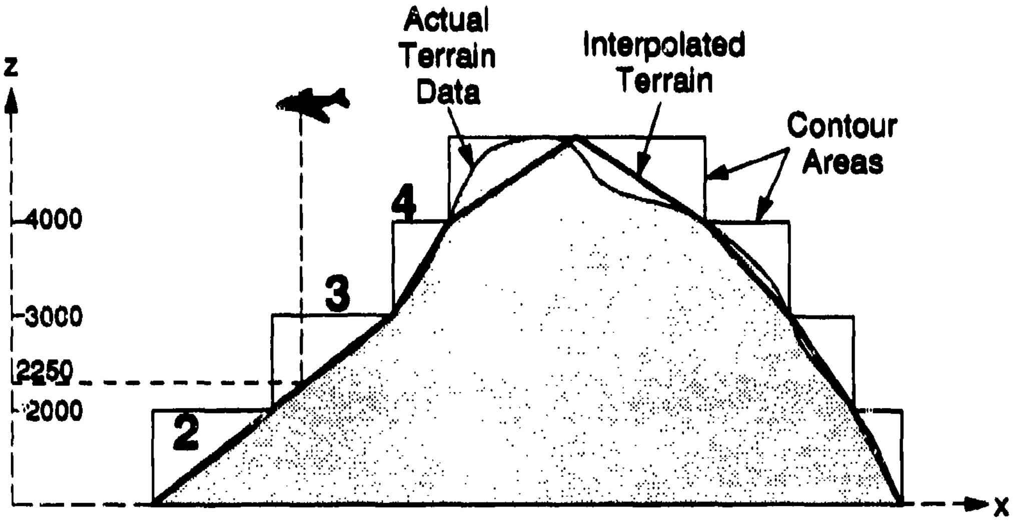


Figure 3.3
Terrain Altitude Interpolation

Recall that each contour was labeled with an altitude corresponding to the highest point of terrain within the contour. Therefore, if the aircraft were flying over a contour labeled '3', the ground altitude would be computed to be between 2000' and 3000'. The exact ground altitude was found by linearly interpolating ground altitudes between the contours in front and behind the aircraft, as shown in Figure 3.3. If the aircraft were located as shown in Figure 3.3, over a contour labeled '3', and one quarter the way between the contour labeled '2' and the contour labeled '4', the ground altitude would be interpolated as one quarter of the altitude between 2000' and 3000', or 2250'.

3.4.2. Ground Proximity Warning System Formats

767 Ground Proximity Warning System

The 767 GPWS alerting scheme was utilized in the terrain display experiment documented in Chapter 5. The GPWS system used radio altitude (altitude above ground), rate of change of radio altitude, aircraft vertical speed, airspeed, and flap and gear position to determine if an alert should be triggered. Figure 2.9 (Section 2.2.1) diagrams the alerting regimes for one of the 4 modes of operation of the GPWS.

The "GND PROX" and "PULL UP" warning lights were provided on the IRIS screen, and would illuminate when the appropriate criteria were met. Alerts were also given aurally on the IRIS, based on actual GPWS aural alerts.

Prototypical Advanced Ground Proximity Warning System

The advanced GPWS system was designed to provide the pilot with an intuitive graphical display which allowed the pilot to rapidly determine the severity of a hazardous situation and take appropriate corrective action. Such a system could also work in a planning mode by cueing the flight crew with additional advisory information before an immediate emergency reaction was required. For the purposes of the simulation experiments, the advanced GPWS alerting behavior was matched as closely as possible to the current GPWS behavior.

The advanced GPWS used on the simulator was designed to reasonably approximate a system that could be implemented in an actual aircraft. Whereas current GPWS uses aircraft state information in a one-dimensional environment (in which the distance and vertical velocity of the aircraft relative to the ground directly below is used), advanced GPWS uses three dimensions for determining whether or not to display a hazard.

The prototypical advanced GPWS system used two parameters to determine the level of hazard: estimated time for the aircraft to reach a contour within 15° of each side of the nose, and the difference in altitudes between the aircraft and the terrain. Vertical velocity or turn trends were not utilized in this simplified model. For the purposes of the experiment, each terrain contour was considered as an area of constant altitude into which the aircraft should not enter. Figure 3.4 shows the graphical alerting criteria for the advanced GPWS used in the experiment. No contour was alerted if it was more than 30 seconds flight time ahead of the aircraft. As the altitude difference between the aircraft and contour decreased, the amount of warning time increased as shown in Figure 3.4.

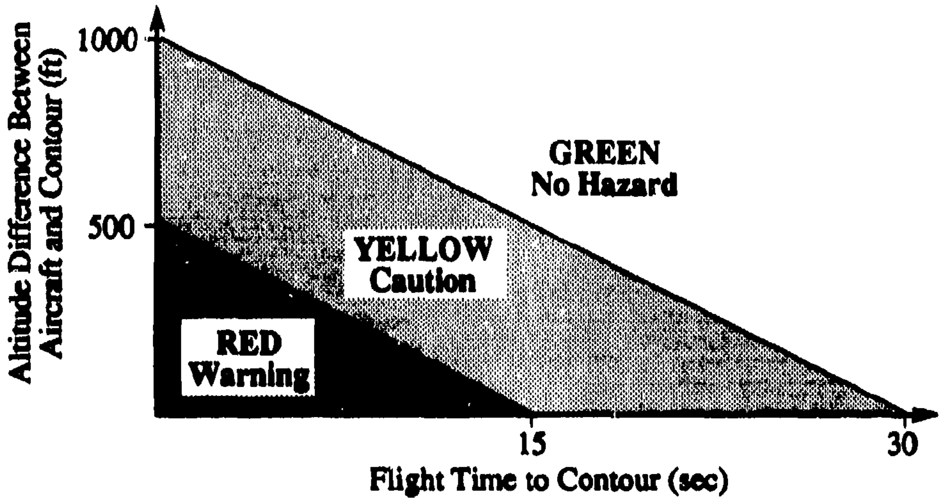


Figure 3.4
Prototypical GGPWS Contour Color Alerting Criteria

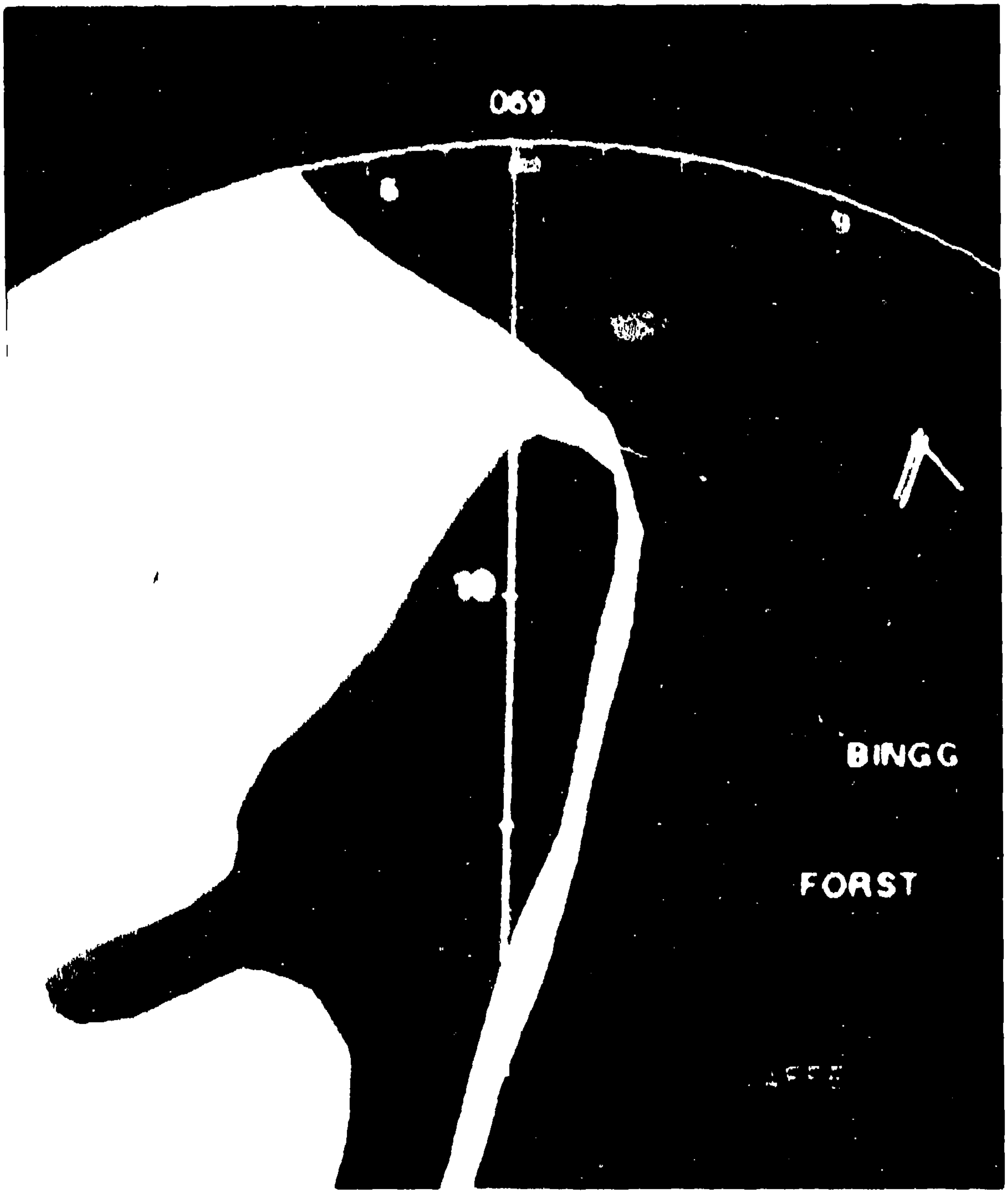


Figure 3.5
Example Simulator GGPWS Alert Incident

Contours were colored in yellow to show terrain which did not immediately pose a threat, but which could eventually activate the GPWS if the situation went unchecked. Red was used for terrain within 500' vertical of the aircraft which could pose an immediate danger.

An example of advanced GPWS graphical alerting is provided in Figure 3.5. The aircraft, at 9900', is shown approaching a mountain. Following the criteria set in Figure 3.4, the 9000' contour is depicted in yellow, indicating terrain clearance between 500 and 1000 feet. Contours 10000' and above are shown in red, indicating less than 500' clearance in areas ahead of the aircraft.

A comparison between the advanced GPWS alert characteristics used in the simulator and actual 767 GPWS alerts was performed using data from several previous CFIT accidents [18]. It was found that the advanced GPWS alerting scheme which was used in the simulator provided an amount of warning time consistent with current GPWS systems for the terrain configurations used in the experiment. The advanced GPWS alerting criteria were designed to cause alerts when needed in the simulation, while preventing false alarms when no terrain alert was desired during a scenario.

Figure 3.6 diagrams the time history of the GPWS and prototypical advanced GPWS alerts for the situation shown in Figure 3.5. The profile view is plotted along the aircraft track from Figure 3.5. A vertical scale is provided to the left of the diagram, and horizontal distance and elapsed time are given below the profile view. The behavior of the 767 GPWS and prototypical GGPWS systems are plotted separately at the bottom of the figure. For this example, the aircraft was assumed to be travelling at a constant altitude and at a ground speed of 220 knots.

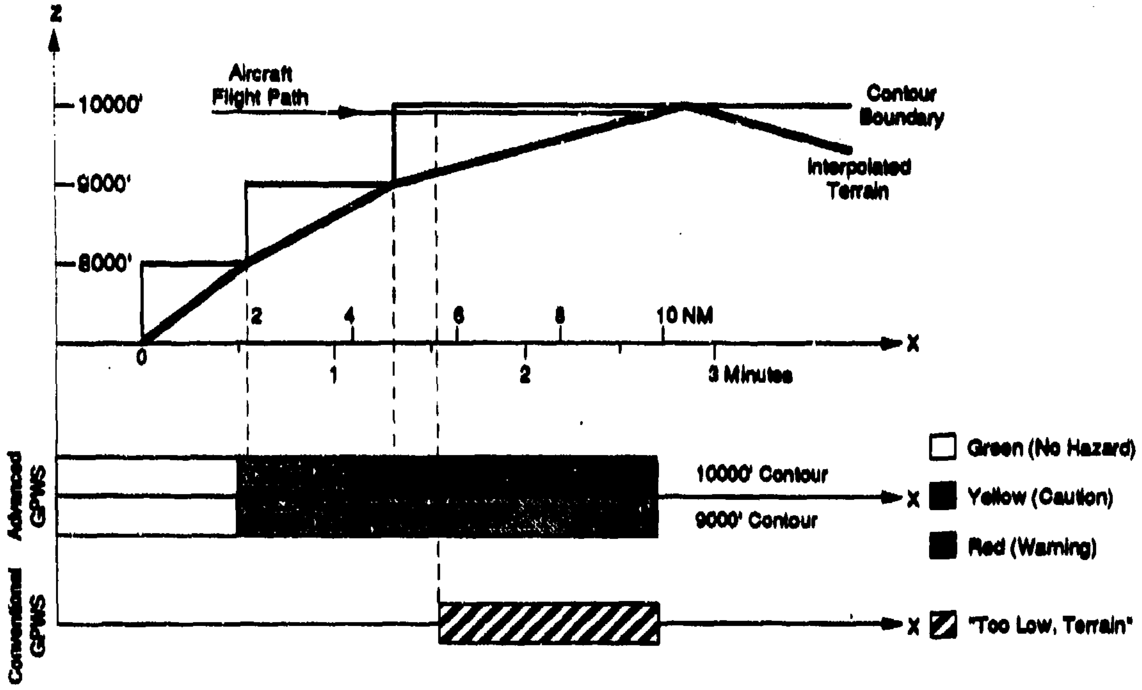


Figure 3.6
Time History of GPWS and GGPWS Alerts

As shown in Figure 3.6, the contours at 9000 and 10000 feet are depicted in yellow approximately 3 seconds before the aircraft crosses the 9000' contour line, as calculated by the GGPWS criteria shown in Figure 3.4. The 10000' contour is later colored in red 15 seconds before the aircraft reaches the 10000' contour line.

767 GPWS would alert the flight crew to the terrain hazard when the aircraft was approximately 750' above the terrain. The GPWS alert would involve a visual "GND PROX" light in the cockpit, accompanied by the aural alert "too low, terrain". In this example, the terrain does not rise fast enough to trigger a more assertive 767 GPWS alert such as "whoop whoop, pull up".

4. Preliminary Study of Terrain Depiction Effectiveness

4.1. Objectives

An experimental study was performed to evaluate the effectiveness of current terrain information presentation methods. The experiment was designed to address the following objectives:

1. Obtain preliminary data on the ability of current paper terrain depiction methods to provide pilots with the information required to avoid terrain hazards before evasive action is required. This baseline data is needed to compare the effectiveness of advanced terrain displays against current depiction methods.
2. Determine differences in terrain depiction effectiveness among several prototypical electronic IAPs with and without a real time presentation of aircraft location and heading.

4.2. Experimental Design

The experiment was conducted using the MIT ASL Advanced Cockpit Simulator, described in Chapter 3. Experimental protocol followed the details given in Section 3.3.

Terrain Situational Awareness information was provided using an IAP for each approach scenario. The IAP was located on the simulator display, to the left of the EHSI. Two major formats of IAP were used in the experiment and are shown in Figures 4.1 and 4.2.

Format 1 (Figure 4.1) was an IAP in which chart information content and layout was consistent with the IAPs currently used by commercial airline pilots. For a Format 1 IAP to be effective, the pilot must mentally superimpose the aircraft location in the plan view and check for terrain hazards along the route of flight. Paper, monochrome display, and color display IAPs were used in Format 1.

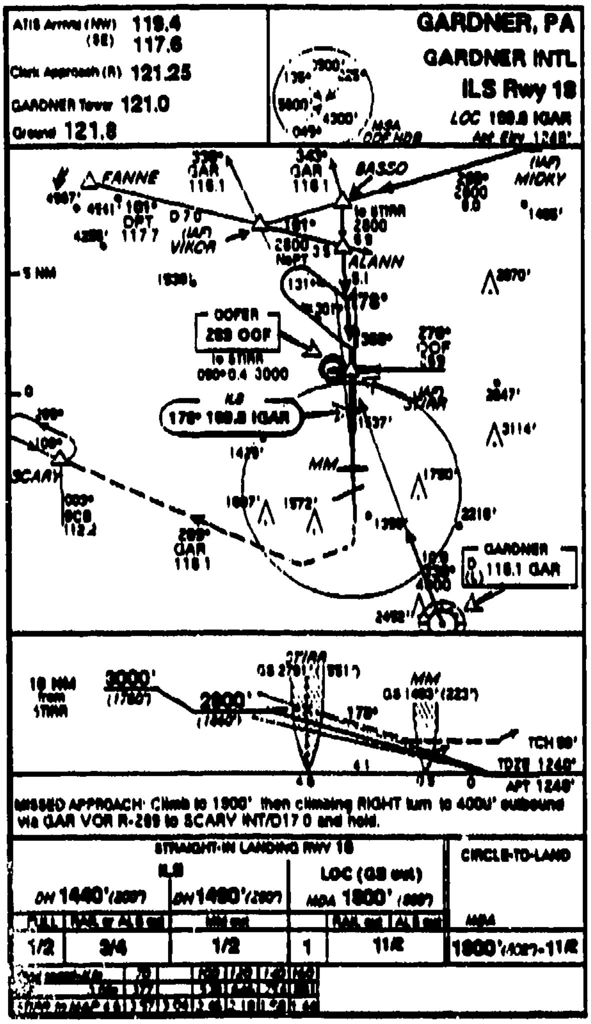
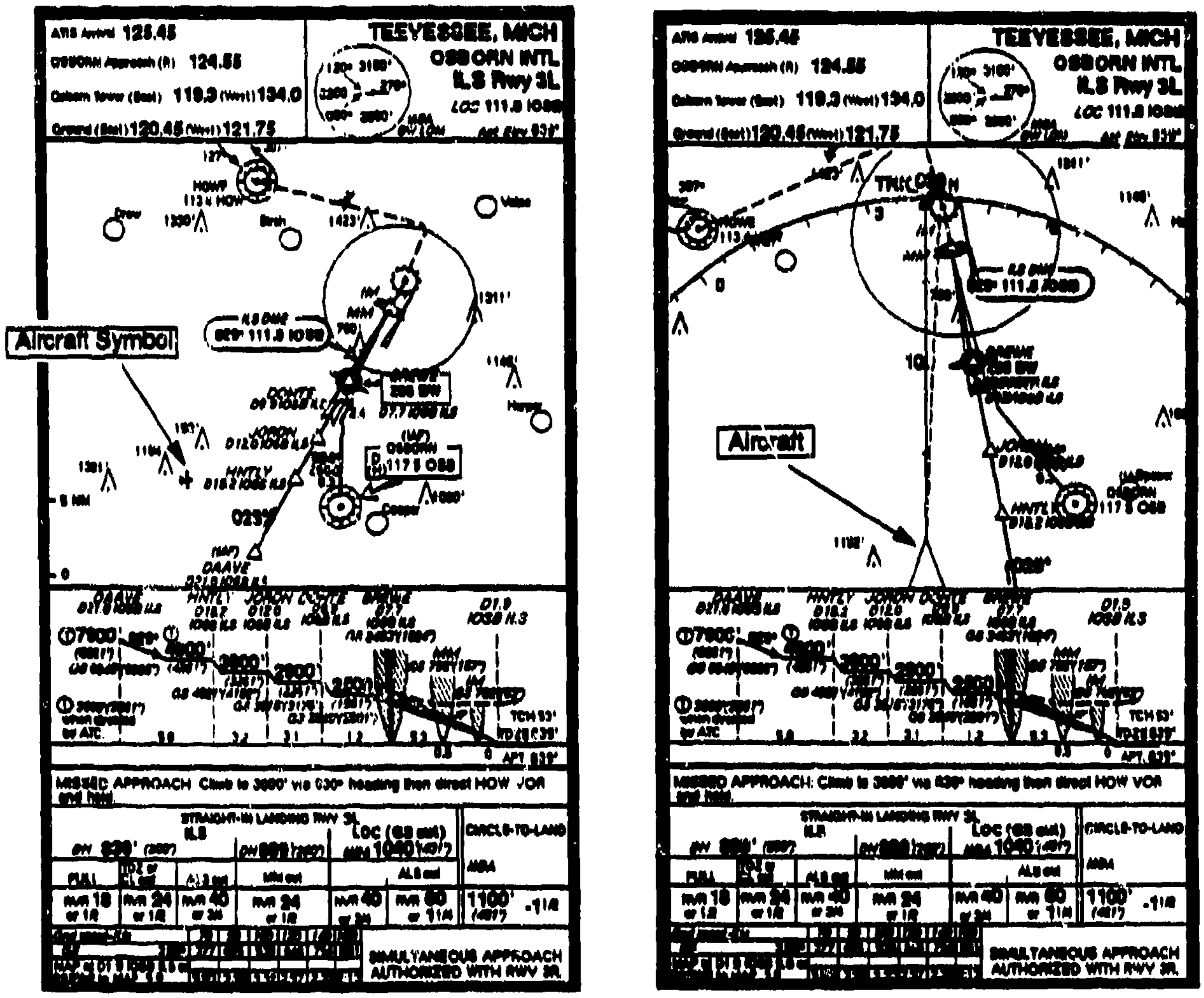


Figure 4.1
Example Format 1 IAP

Format 2 (Figure 4.2) involved an IAP display which depicted the aircraft's position and heading in relation to the approach procedure in the plan view. Thus, Format 2 IAPs relieved the pilot of the task of judging aircraft location with respect to terrain. Both north-up and aircraft track-up charts were used in Format 2. The north-up chart had the same information layout as the Format 1 IAPs, but in addition included a symbol representing the aircraft in the plan and profile views of the IAP. The track-up chart was based on the EHSI; IAP information moved and rotated around a fixed symbol at the bottom of the display signifying the aircraft.

All Format 2 IAPs also included an information decluttering capability. The pilot was able to select and deselect terrain and other IAP information using a number of control switches in a similar manner to the EHSI information controls.



North-Up IAP

Track-Up IAP

Figure 4.2
Example Format 2 IAPs

Each pilot flew six approach scenarios using Format 1. Three of these scenarios involved vectoring the aircraft into terrain. Using Format 2, three approach scenarios were presented to each pilot, of which one scenario included a vector into terrain. In this thesis, the term 'terrain fly-through' is used to describe an event in which a pilot flew within 1000' of terrain when not on final approach. A 'terrain fly-through scenario' denotes an approach scenario in which a vector into terrain was issued.

Each IAP in the experiment was derived from an actual approach, however names and frequencies were changed to reduce prior knowledge effects. All terrain was depicted using spot elevation symbols similar to those found on current paper IAPs. On color IAPs, terrain information was colored in yellow to distinguish it from other chart information.

The experiment was designed to investigate terrain information use when pilots were not suspecting terrain hazards. To eliminate cues that would alert the pilot that the aircraft was in a hazardous situation, the Ground Proximity Warning System (GPWS) was disabled in this experiment. In addition, the pilots were not informed that terrain information was a factor in the study, and terrain fly-through events were not mentioned.

It should be noted that two of the nine IAPs used in this experiment did not fully meet TERPS criteria. TERPS standards state that published airways and MSA sectors must provide 1000' of terrain clearance within 4 nautical miles of the depicted route or sector [2,11]. One of the charts which violated TERPS, shown in Figure 4.3, included spot elevation symbols higher than 4000' which were located within 4 nautical miles of an MSA sector with an altitude of 3500'. The second chart similarly depicted terrain obstacles within 4 nautical miles and 1000' of a published airway. Since the charts which violated TERPS were used in all terrain formats which were studied, they did not bias the terrain fly-through results.

One example terrain fly-through scenario is diagrammed in Figure 4.3. The aircraft began a few miles north-west of the SCARY intersection, at 5500'. The route to the airport (depicted by a thick black line in Figure 4.3, through waypoints named SCARY, FANNE, VIKOR, ALANN, and STIRR) was programmed into the simulator's flight management computer before the subject began flying. When the aircraft was approximately half the way between SCARY and FANNE, ATC issued a clearance for the aircraft to descend to 3500'. If the pilot accepted this clearance and descended, the aircraft would fly very near the 4567' obstacle near FANNE, producing a terrain fly-through event. If the pilot noticed that he would be flying too close to a hazard, the air traffic controller would advise the pilot to maintain 5500', and descend at pilot's discretion to 3500'.

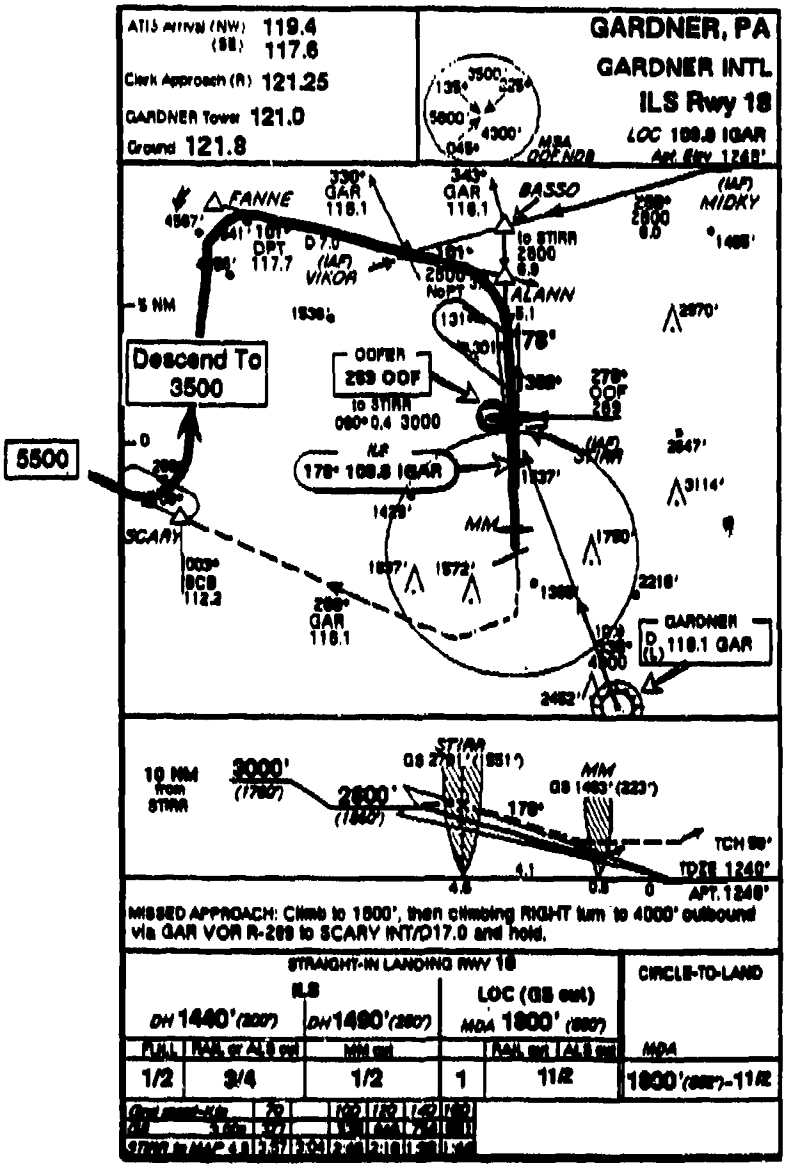


Figure 4.3
Example Terrain Fly-Through Approach Scenario

4.3. Results

A total of 13 subjects performed in this experiment. The average subject was 44 years old with 10,370 hours of civil flight time, and 1,850 hours in FMC equipped aircraft. The ratio of approaches in which pilots recognized a terrain hazard to the total number of terrain fly-through approaches is termed the *hazard recognition rate*.

There was an extremely low rate of pilot recognition of terrain hazards, as shown in Figure 4.4. Out of the 39 opportunities for terrain fly-through events when using Format 1, *only once* did a pilot notice the hazard, leading to a 3% hazard recognition rate for charts without a depiction of the aircraft location.

When using Format 2, pilots successfully recognized the terrain hazard 2 out of 13 times, generating an 15% hazard recognition rate. In each case in which the hazard was avoided, the pilot was using a track-up display.

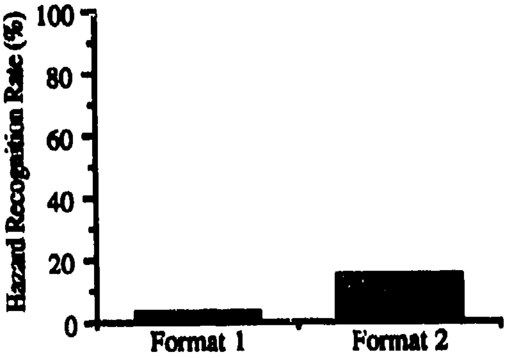


Figure 4.4
Overall Hazard Recognition Rate
The hazard recognition rate is the ratio of approaches in which pilots recognized a terrain hazard to the total number of terrain fly-through scenarios.

Additionally, there were two instances when using Format 2 with the north-up display in which pilots commented on the high terrain as the aircraft was flying through the hazard, but were not concerned enough to ask for a new clearance.

A difference in performance was noted between captains and first officers. Six of the thirteen subject pilots were captains, and captains were the only subjects to successfully recognize an ATC error and avoid a terrain hazard. However, due to the low number of subjects used in this experiment, this performance difference may not be statistically significant.

When using Format 2 charts, pilots deselected the terrain information in 5 out of the 13 terrain fly-through scenarios. Thus, 62% of the terrain fly-through incidents in Format 2 occurred when the pilot had deselected terrain information in an attempt at decluttering the IAP. It is possible that more terrain hazards would have been avoided had pilots always displayed the terrain information.

A number of pilots indicated that they never or only very rarely looked at the plan view terrain information when executing an approach. For these pilots, the primary mode of terrain clearance information was gained from the MSA circle or through trust in ATC.

4.4. Discussion

The high rate of terrain fly-through incidents in this experiment indicates that current methods of terrain depiction were not being used to their full potential. Although hazardous terrain information was printed on the chart, and the pilot was aware of the route of flight, the fact that a hazard existed was not easily evident to many pilots.

The improvement in terrain avoidance performance between Format 1 and Format 2 implies that a real time presentation of the aircraft's location with respect to terrain is more effective than the use of a chart without a specific display of aircraft location. Since the distance and bearing to hazardous terrain were easily inferred from charts which show the aircraft's location relative to terrain, the fact that a hazardous situation existed may have become more apparent to the pilot.

It became evident from the debriefing responses that the subject pilots placed a great deal of trust in the air traffic controllers with regard to terrain clearance. Pilots often accepted clearances without confirming that there was adequate terrain separation. In contrast, it was observed that some pilots were quick to request a new routing to avoid hazardous weather. This difference in the perception of the potential hazards posed by weather and terrain mirrors the type of information available to the pilot. The pilot does not have access to the MVA altitudes that ATC uses, but does have access to detailed weather information (which is not available to ATC). Therefore, the pilot may become more concerned with weather than terrain and assume that ATC will vector the aircraft safely.

5. Evaluation of Advanced Terrain Display Issues

The high terrain fly-through rate found in the preliminary terrain information study described in Chapter 4 lead to a second experiment designed to evaluate the effectiveness of terrain information presentation on advanced terrain displays.

5.1. Objectives

The primary objectives of this effort were to:

1. Evaluate differences in terrain avoidance performance between prototypical spot elevation and smoothed contour terrain situation display formats.
2. Obtain pilot opinions and comments regarding a prototypical plan view GGPWS system. This data may then be used to refine prototypical GGPWS formats for use in future studies.
3. Obtain pilot input regarding advanced terrain system issues. A pilot-oriented approach will facilitate the refinement of terrain situation and alerting displays in the future.

5.2. Experimental Design

The experiment was conducted using the MIT ASL Advanced Cockpit Simulator described in Chapter 3. The subjects were given a paper IAP for each approach scenario. Each IAP presented terrain information using spot elevation symbols in a manner consistent with current approach charts. In addition, the pilot was provided with a separate electronic display dedicated to terrain information located to the left of the EHSI.

An advanced GPWS system with graphical alerts was presented to pilots to determine pilot receptiveness to graphical terrain warnings and to obtain suggestions for future design considerations.

A survey (provided as Appendix B) was distributed to pilots to obtain opinions on terrain presentation issues not specifically examined during the simulation portion of the experiment. Copies of the survey were placed in the pilots' lounge at a major airline. Those pilots who were interested in the study completed the survey at their leisure.

5.2.1. Terrain Situation Display Formats

Subject pilots were given either a spot elevation terrain display or a smoothed contour terrain display in each approach scenario. The displays that were used in the experiment were refined from a number of candidate displays through the evaluation of presentation issues such as those discussed in Section 2.1.4.

In the preliminary study described in Chapter 4, it was observed that pilots were better able to recognize a terrain hazard when using an IAP which included a presentation of the aircraft location and heading. Accordingly, the terrain displays used in this experiment were based on the map mode of the EHSI, incorporating the aircraft's location with an aircraft track-up display of terrain information.

Figures 5.1 and 5.2 show the two terrain display formats used in the experiment. Aircraft track and heading were displayed along the compass rose at top, and the aircraft's programmed route was displayed in magenta. The MSA circle and sector altitudes were depicted to scale on the display in white. The destination airport was displayed at true scale, and was depicted with the full airport runway pattern. The terrain display scale was slaved to the scale on the EHSI, and terrain data was only displayed within the MSA circle for the approach programmed in the flight management computer.

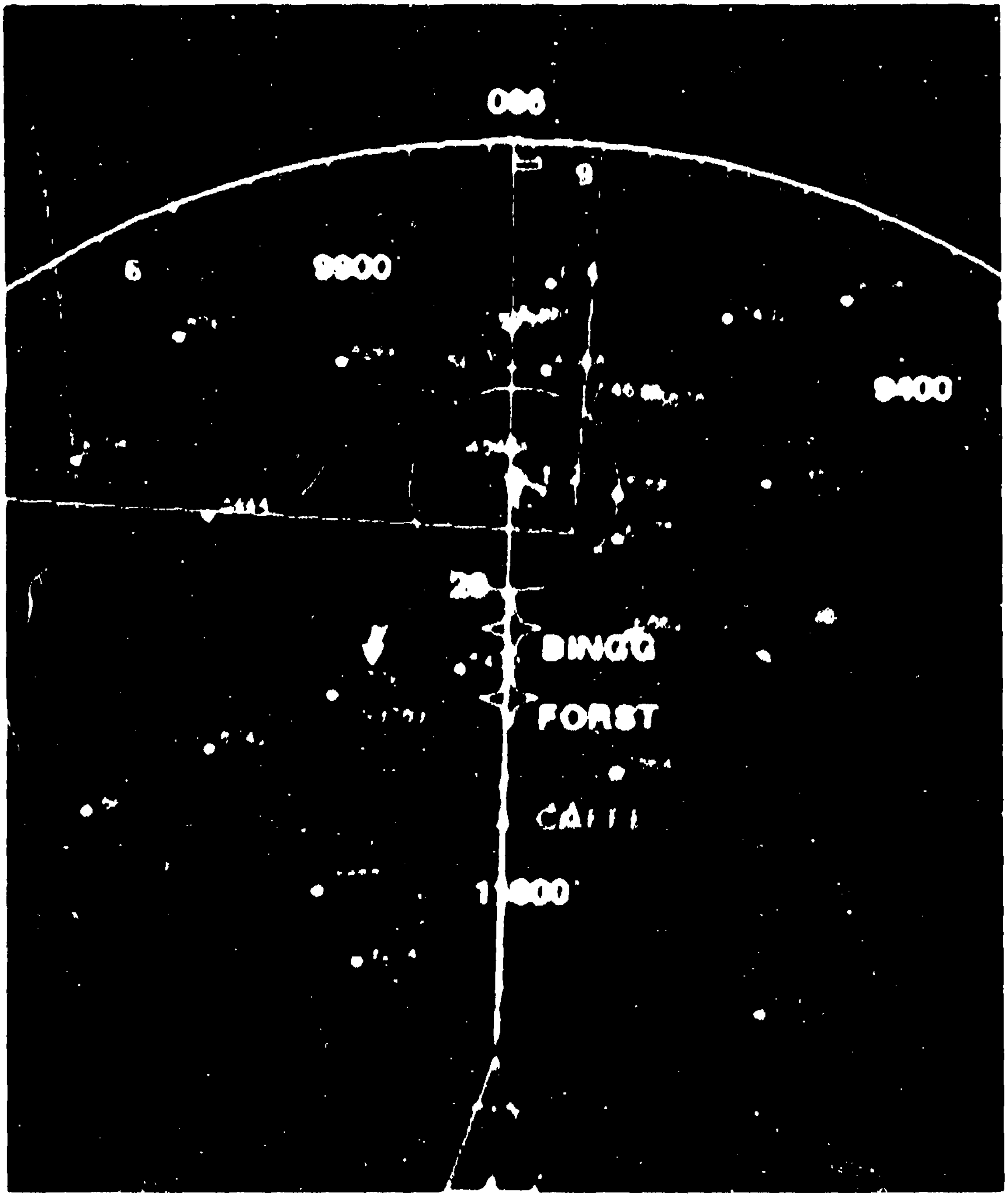


Figure 5.1
Prototypical Spot Elevation Display

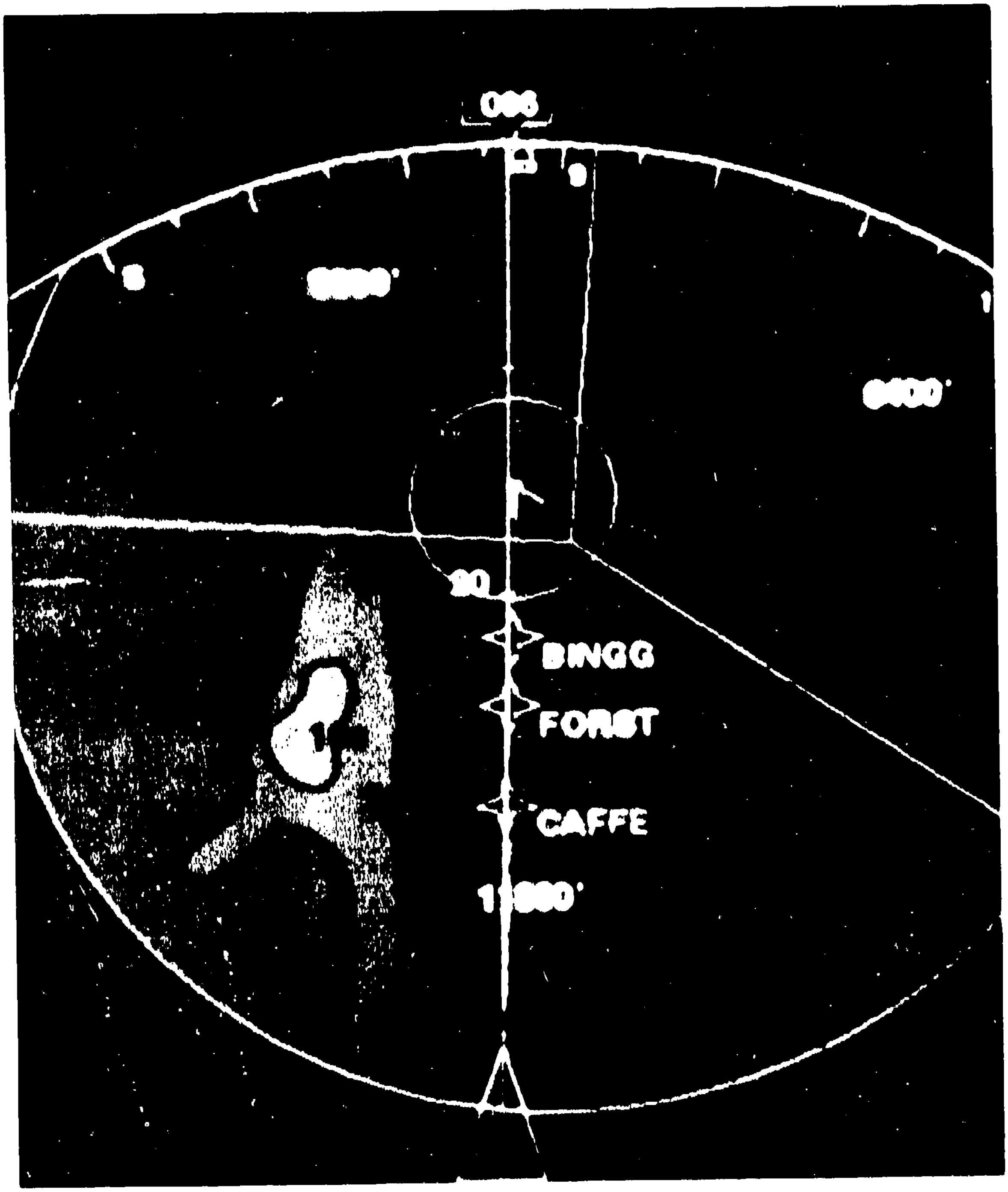


Figure 5.2
Prototypical Smoothed Contour Display

Spot Elevation Display

Figure 5.1 shows the spot elevation display as it appeared in one of the approach scenarios. The spot elevation display depicted obstacle symbols and text in yellow. Obstacle altitudes were displayed to the nearest foot, MSL, as on current paper IAPs, and were located at the upper right side of the obstacle symbols. The obstacle symbols and text were selectable using a switch on the EHSI control panel. For comparison, Figure 5.2 shows the same terrain as it appeared when using the smoothed contour display.

Smoothed Contour Display

After examining the terrain display trade issues discussed in Section 2.1.4, a prototypical smoothed contour display was implemented and is shown in Figure 5.2.

A number of contour spacing options were examined. For the purposes of this experiment, 1000' spacing was used and provided a good compromise between excess clutter in mountainous areas and a lack of information in flat areas. This altitude spacing also matched that used on the new Jeppesen paper IAPs which have contour lines in the plan view (see Figure 2.5).

The terrain display was designed to depict contour information in an intuitive manner. Green was used for nonhazardous terrain, with yellow and red reserved for the graphical GPWS system used in some approach scenarios. Contour areas which were considered nonhazardous by the GGPWS system were colored in varying shades of green, with high altitude areas shaded in lighter greens than low areas, producing an intuitive display.

Contour lines and altitude text were drawn in dark blue. Contour altitudes were depicted as absolute MSL altitudes spaced every 1000'. The ICAO AMA recommended

1000' safety buffer was not used in order to force the pilots to establish a level of terrain clearance which they felt was appropriate. The contour altitudes were rounded to the next higher 100', and presented in a format such that 3,567' would be depicted as 36. To reduce clutter at low altitudes, terrain less than 1000' above the airport was not included in contours.

The contours, like the obstacle symbols on the spot elevation display, could be selected or deselected by the pilot using a terrain switch on the EHSI control panel.

5.2.2. GPWS and Terrain Alerting Display Format

The Boeing 767 GPWS scheme was implemented on the simulator using the terrain modelling technique described in Section 3.4.1. GPWS warning lights were added to the display screen, and aural alerts were sounded when appropriate.

A plan view contour GGPWS system was designed for Terrain Alerting as was described in Section 3.4.2. This GGPWS system was integrated with the terrain situation display located on the simulator. The alerting method depicted entire contours in solid yellow or red according to the criteria shown in Figure 3.4. Alerted contours in yellow or red were not additionally shaded to denote different altitudes. Figure 3.5 shows the GGPWS system when alerting the pilot to a terrain hazard.

5.2.3. Experimental Procedure

Before beginning the simulation, the subjects were instructed in the interpretation of the spot elevation and contour displays. The subjects were also told that safety buffers were not included in depicted terrain altitudes. The 767 GPWS and prototypical GGPWS systems used on the simulator were also described and demonstrated prior to commencing the experiment. In all other respects, the experimental procedure followed the protocol described in Section 3.3.

Each subject used four terrain display formats:

1. Spot elevation display, without GGPWS
2. Spot elevation display, with GGPWS
3. Contour display, without GGPWS
4. Contour display, with GGPWS

Each display format was used in three consecutive approach scenarios, making a total of twelve approach scenarios in all. The order in which each display format was presented to the pilot was rotated among the subjects to reduce learning effects. The approach scenarios were always flown in the same order, regardless of the sequence in which display formats were presented.

As shown in Figure 5.3, one approach scenario in each display format block included an intentional vector into terrain. In order to keep the pilots from expecting erroneous clearances in every approach, the other two scenarios in each display format block did not involve vectoring the aircraft into terrain.

Approach Scenario	Vector Into Terrain	Display Format
1	X	2
2		
3		
4		1
5	X	
6		
7		3
8	X	
9		
10		4
11		
12	X	

Figure 5.3
Typical Experimental Matrix

If the pilot did not recognize the terrain threat, the simulator's GPWS system (as well as the GGPWS system, if used in that scenario) would alert the pilot, and a terrain fly-through event was recorded. Note that 'terrain fly-through' refers to an event in which the GPWS system alerted the pilot to insufficient terrain separation. In no case did a pilot actually impact terrain during the simulation.

The pilot was interviewed at the conclusion of the experiment, using the questionnaire shown in Appendix A. The interview was designed to solicit specific pilot opinions on the display formats.

5.2.4. Scenario Design

All but one approach scenario fully met TERPS specifications for terrain clearance [2,11]. The IAP (shown in Figure 5.4) which violated TERPS standards depicted terrain within 4 nautical miles of an airway with an MEA less than 1000' above the terrain.

The terrain fly-through scenarios were designed to create situations in which ATC could vector the aircraft into terrain. Approach scenarios which did not involve vectoring the aircraft into terrain were designed to provide sufficient terrain separation to avoid false alarms from the GPWS system.

Terrain displays should provide an effective depiction of hazards in a wide variety of situations. A major shortcoming of spot elevation symbology is the fact that the pilot can only estimate the ground altitude in areas between spot elevation symbols. To determine if the location of obstacle symbols influences spot elevation display effectiveness, three of the four terrain fly-through scenarios involved vectoring the aircraft between hazardous spot elevation symbols spaced several miles apart. The fourth terrain fly-through scenario involved vectoring the aircraft to fly directly towards a hazardous spot elevation symbol.

Figure 5.4 diagrams an example terrain fly-through scenario in which the aircraft was vectored to fly at 3100' between two obstacle symbols. In this example, the obstacles (with elevations of 2983' and 2961') were spaced approximately 3 nautical miles apart.

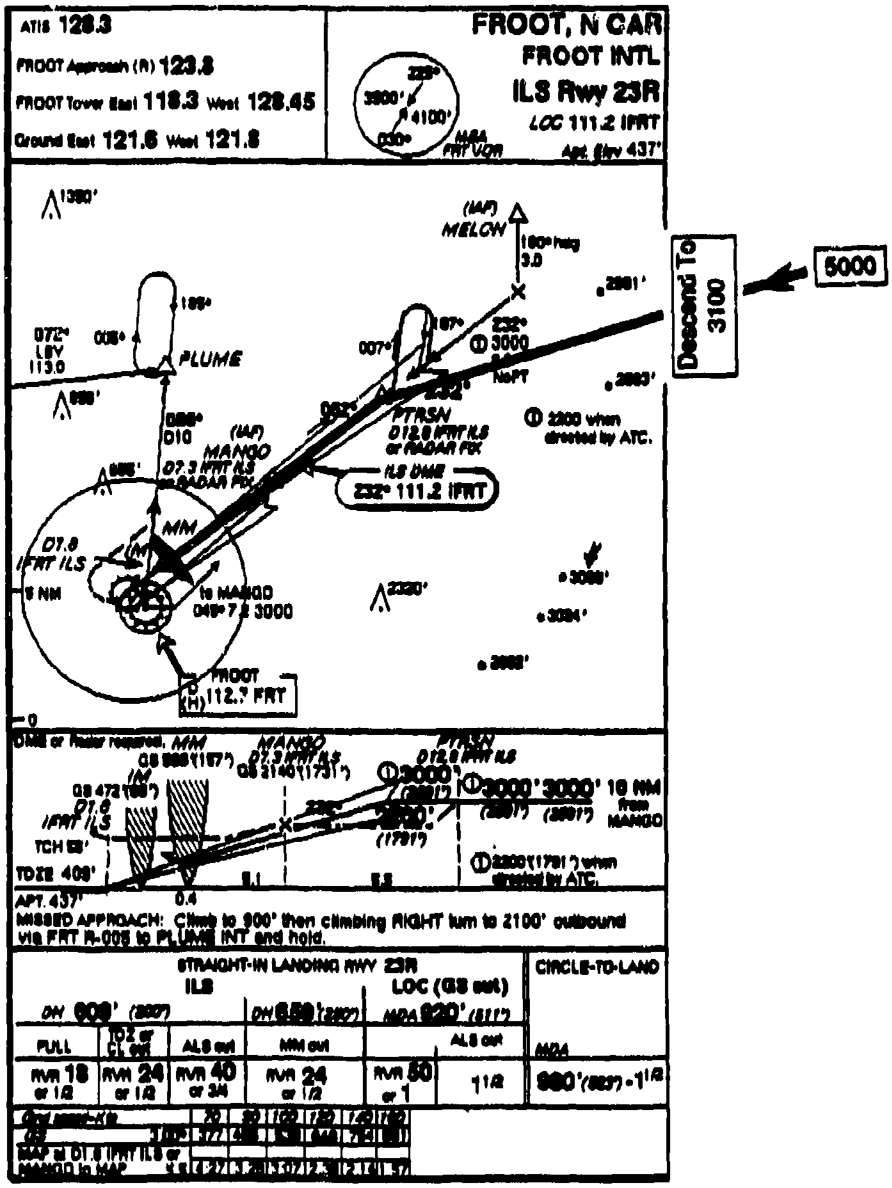


Figure 5.4
Example Terrain Fly-Through Scenario
With Separated Obstacle Symbols

5.3. Results

Many of the results which are presented below refer to the *hazard recognition rate*. The hazard recognition rate for a display format is defined as the ratio of incidents in which pilots determined that a hazard existed to the total number of terrain fly-through scenarios used with that format.

5.3.1. Experimental Results

Nine pilots performed in this experiment. The average subject was 44 years old, with 6,400 hours of civil flight time, and 1,275 hours in autoflight aircraft. Overall, 36 terrain fly-through vectors were issued in the experiment, of which 18 were given when the subjects were using the spot elevation display, and 18 when using the contour display. It should be noted that the low number of subjects performing in this experiment indicates that the results given below do not necessarily reflect the performance of the pilot population as a whole.

Display Effectiveness

As shown in Figure 5.5, pilots recognized terrain hazards in 9 out of 18 cases (50%) when using the spot elevation display, and 14 out of 18 times (78%) when using a contour display.

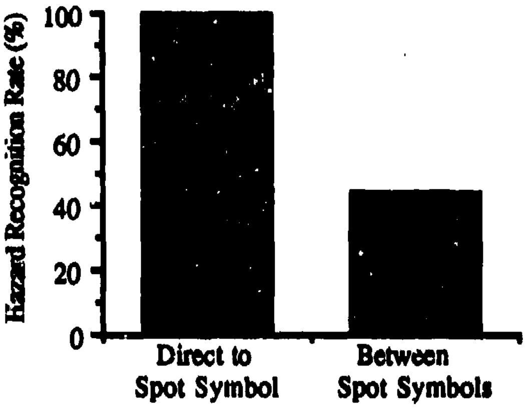


Figure 5.11
Effect of Obstacle Layout on
Spot Elevation Display Hazard Recognition Performance

Recall that the pilots were using a track-up moving map spot elevation display. It may therefore have been easier for pilots to determine that a hazard existed when a spot elevation symbol was depicted directly along the aircraft's track, as opposed to situations in which no obstacle symbols were present along the aircraft's route of flight.

Due to this dependence on the layout of spot elevation terrain information, it must be noted that the performance results may be contaminated by the specific situations in which erroneous vectors were given. For example, had all the terrain fly-through scenarios been designed such that aircraft were consistently vectored directly towards spot elevation symbols, the hazard recognition rate for the spot elevation display may have been higher.

GGPWS

Pilot opinion was favorable towards the use of an advanced GPWS system with graphical alerts. Terrain display formats with a GGPWS system were consistently considered superior to the formats without GGPWS.

5.3.2. Survey Results

50 surveys were distributed at the pilots' operations center at a major airline, of which 27 were returned (54% response rate). The average respondent to the distributed

survey was 43 years old, with 8,225 hours of civil flight time and 1,625 hours in FMC equipped aircraft.

The low number of surveys distributed and returned indicates that the data analyzed below cannot be considered as representative of the general pilot population. The respondents in this survey were also self-selected, and therefore may have had opinions regarding terrain information different than the pilot population as a whole.

Frequency of Terrain Information Use

Only 15% of the respondents agreed that pilots routinely check the chart for terrain information while maneuvering in the terminal area. This low level of concern over terrain information is thought to be due both to confidence in ATC and high workload levels during the approach.

The high level of confidence in ATC was expressed in several pilot comments:

> *"I have been conditioned to accept ATC procedures ... MVA altitudes are available to controllers that are not depicted on my charts."*
>
> *"Perhaps I have been complacent, but in a terminal area I am depending on ATC not to vector me below a safe altitude."*

Comments regarding the effect of high workload levels on terrain information use included:

> *"The time to check for terrain is prior to maneuvering. We don't want to bury our scan in the cockpit below 10,000'."*
>
> *"[Pilots will not check for terrain] unless they suspect problems or have seen the terrain features previously on another flight."*

Pilot Preferences for MSA and Spot Elevation Information

In an effort to determine pilot preferences for spot elevation versus MSA terrain information, pilots were asked to indicate their primary source of terrain information on the

IAP. As shown in Figure 5.12, the majority of pilots used some combination of MSA circle and spot elevation symbols, though there was a slight tendency to rely on the MSA circle more than the spot elevation symbols.

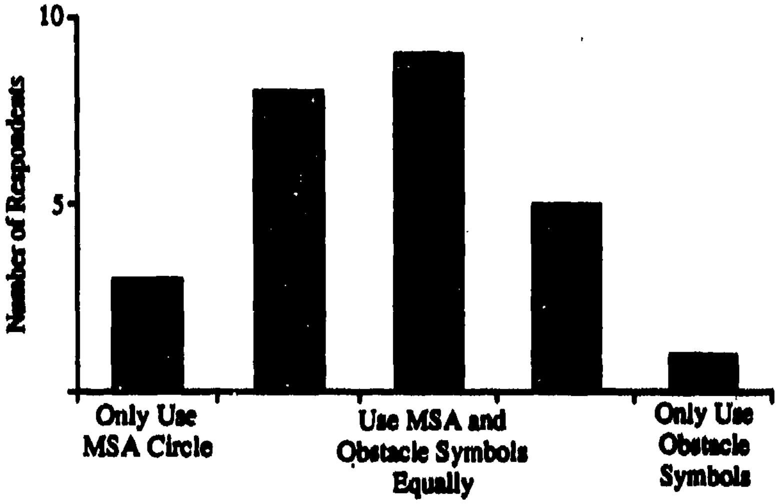


Figure 5.12
Pilot Preferences for MSA Circle Versus Spot Elevation Symbols

The use of spot elevation symbols requires a detailed examination of chart information. Spot elevation data must be pulled from background clutter caused by approach procedure information. Use of the MSA circle also has drawbacks. Additional effort is required to locate the navaid which defines the MSA, and errors may occur in determining which sector applies to the aircraft. One respondent commented:

> *"Sometimes it's difficult to reconcile MSA with geographic position."*

Pilot Perceptions of the Importance of Terrain Information

It was observed during the simulation that pilots were often hesitant to fly near hazardous weather, but were not concerned or did not notice when they flew near hazardous terrain. The survey included a question designed to obtain pilot impressions of the relative hazards of weather and terrain. The question avoided reference to specific types of terrain or weather to allow pilots to form and express their own opinions. Figure 5.13

shows the respondents' perceptions of the relative importance of weather and terrain information.

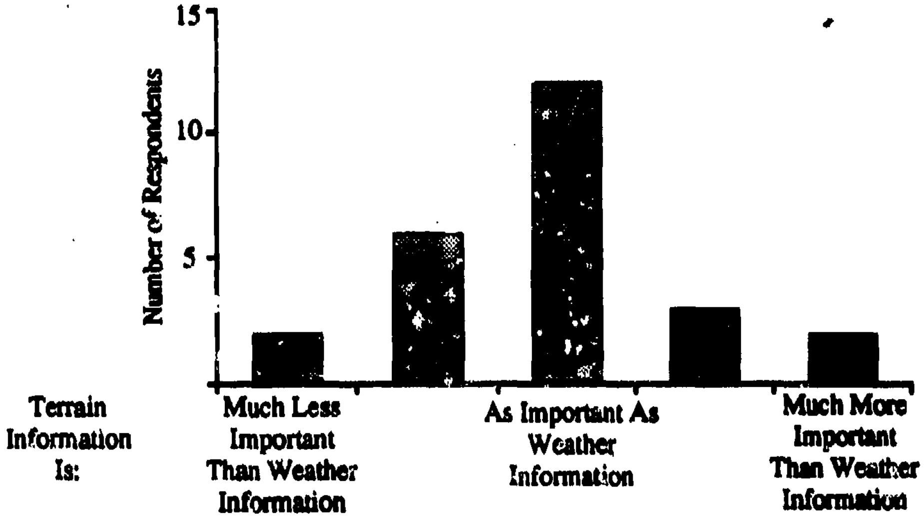


Figure 5.13
Pilot Impressions of the Relative Importance of Weather and Terrain Information

Some respondents commented that the importance of terrain information was dependent on past experiences specific to an approach.

> *"Quite frequently approach control will vector you below the 'published' intercept altitude. This is generally not a problem. However, in places like Salt Lake City and Mexico City, you must exercise 'extra' precautions, as at both locations I've been vectored ... into rising terrain ... and then the controller was distracted and forgot about us. Also one occasion in Las Vegas ... when both my aircraft and a 727 were vectored to the west into high terrain."*

In addition, pilot perceptions about the importance of terrain and weather information may be based on the availability of that information in the cockpit.

> *"Generally, weather data is more important, as it is fluid, while experience tells us about the static terrain."*

If the pilot does not have access to certain information, that information may not be deemed important. In current transport aircraft, the pilot has access to detailed weather information, but does not have access to the MVA altitudes used by ATC. Therefore, it may be natural for pilots to feel that weather information is more important than terrain information.

Spot Elevation Altitude Depiction Preferences

Finally, one question on the survey was designed to solicit pilot opinions for several methods of altitude depiction for spot elevation symbols. Survey respondents strongly favored depicting spot elevation symbol altitudes rounded up to the next higher 100', rather than to the nearest foot as is done today (Figure 5.14). 59% indicated that they would prefer such an altitude depiction, and 89% preferred some form of altitude depiction other than that currently used. It appears that pilots are not concerned about the actual altitude of an obstacle, but more with maintaining a safe distance from the obstacle.

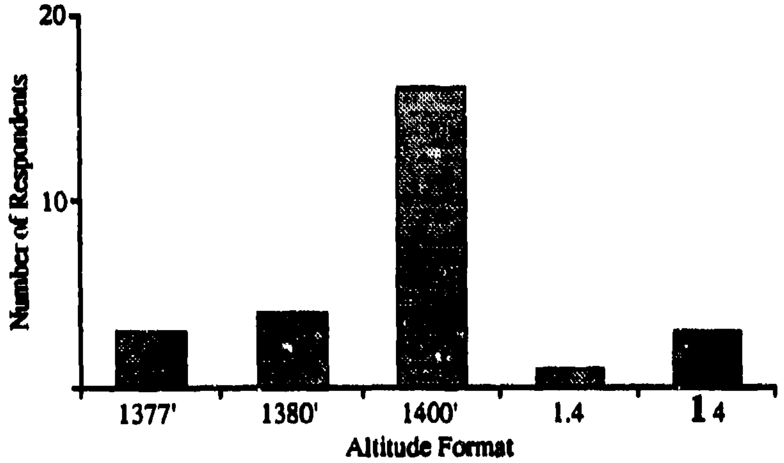


Figure 5.14
Altitude Format Preferences

5.4. Discussion

It should be noted that the high number of terrain fly-through incidents recorded in this experiment does not indicate a dangerous level of unpreparedness on the part of air carrier pilots. Procedures for terrain avoidance, like most systems in air transport today, includes a number of checks and balances designed to prevent accidents. Still, ATC may mistakenly vector an aircraft into terrain, and pilots may overlook such errors. It is therefore believed that improvements are needed in terrain situation and alerting methods.

The combination of high workload levels and the fact that pilots do not have access to the MVA information available to ATC appears to be a primary factor in the low hazard recognition rates observed in the experiment. The survey data suggests that pilots are concerned about terrain hazards, but the lack of effective terrain information in the cockpit has led pilots to pass the responsibility for terrain separation to ATC.

An advanced terrain display could afford pilots with an effective means by which terrain information is presented in the cockpit. Pilots may then be able to verify terrain separation and assume responsibility for clearing obstructions. Once pilots have the information needed to take responsibility for terrain clearance, performance data from this experiment suggest that a smoothed contour display may be more effective than a spot elevation display in providing situational awareness of terrain.

6. Conclusions

In summary, the major conclusions of this thesis are the following:

1. The lack of effective terrain information in the cockpit seems to have led pilots to forfeit the responsibility for terrain clearance to air traffic controllers. In addition, reliance on ATC and the low rate of CFIT accidents in the U.S. may have dulled pilot perceptions of the hazards posed by terrain.

2. Two distinct regimes of terrain information use exist for advanced displays. Terrain information is used for *Terrain Situational Awareness* in order to avoid potential hazards. When near hazardous terrain, *Terrain Alerting* may be used to provide the pilot with the situational information needed to elicit the correct evasive response.

3. Hazard recognition rates increased from 3% to 15% when a display of the aircraft's location was added to current terrain depiction methods. Displays which include aircraft location may relieve the pilot of the mental calculations required to orient the aircraft with respect to terrain.

4. Terrain display format was not a major factor in terrain avoidance performance when pilots did not accept responsibility for terrain clearance. Hazard recognition rates for a spot elevation display (20%) and a smoothed contour display (25%) were comparable when pilots assumed that ATC was providing adequate terrain separation.

5. When pilots assumed responsibility for terrain clearance, a smoothed contour display was found to be more effective than a spot elevation display. When responsibility for terrain separation was taken by the pilot, the hazard recognition rate for the

smoothed contour display was 93% as opposed to 62% for the spot elevation display. This difference, however, is not statistically significant ($p>.05$) [19].

6. Pilot performance when using a moving map spot elevation display was found to be sensitive to obstacle symbol layout. After assuming responsibility for terrain clearance, pilots recognized the terrain hazard in every case in which a hazardous spot elevation symbol was shown directly on the aircraft's projected ground track. In contrast, hazards were recognized 44% of the time when the aircraft was vectored to fly between spot elevation symbols.

7. A Graphical GPWS system was found to be desirable by subject pilots.

5. "I only want to see terrain information when a hazardous situation exists."

1	2	3	4	5
Strongly Disagree		Neither Agree nor Disagree		Strongly Agree

Comments:

6. "Pilots routinely check the chart for terrain hazards while maneuvering in the terminal area."

1	2	3	4	5
Strongly Disagree		Neither Agree nor Disagree		Strongly Agree

Comments:

7. "I feel that I was adequately trained in terrain avoidance procedures."

1	2	3	4	5
Strongly Disagree		Neither Agree nor Disagree		Strongly Agree

Comments:

8. Please indicate where you usually obtain terrain information on a paper approach chart:

1	2	3	4	5
Only Use MSA Circle		Use MSA and Obstacle Symbols Equally		Only Use Obstacle Symbols

Comments:

9. On average, how frequently are you vectored below MSA before intercepting the localizer?

1	Less Than 25% of approaches
2	25-50% of approaches
3	50-75% of approaches
4	75-100% of approaches

Comments:

10. Please rank your impression of the importance of terrain information relative to weather information:

1	2	3	4	5
Much Less Important Than Weather Information		As Important As Weather Information		Much More Important Than Weather Information

Comments:

11. Circle the format below which you would find most desirable for depicting the altitude of a 1377' obstruction:

Nearest foot:	1377'
Next even 10 feet above obstacle:	1380'
Next even 100 feet above obstacle:	1400'
Thousands.Hundreds:	1.4
Sectional Chart depiction:	14

Comments:

Your participation in this survey is greatly appreciated. The information you have provided will be very valuable in our research. Thank you again for your time and effort!

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