To the Graduate Council:

I am submitting herewith a thesis written by A. Lawrence Dublenko entitled "Flight Test and Performance Evaluation of a Ground Collision Avoidance System in the CC-130 transport Aircraft." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for a degree of Master of Science, with a major in Aviation Systems.

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And Dean of the Graduate School

Flight Test and Performance Evaluation of a Ground Collision Avoidance System in The CC-130 Transport Aircraft

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

A. Lawrence Dublenko

May, 1998

DISCLAIMER

The information presented in this thesis is based on the data collected during the CC-130H(T) Hercules Tanker Ground Collision Avoidance System Flight Test Program. All comments are the sole opinion of the author and in no way represent the official position of the Canadian Department of National Defence or the Aerospace Engineering Test Establishment. Similarly, the conclusions and recommendations are presented by the author for the sole purpose of fulfilling the requirements of this thesis.

ACKNOWLEDGMENTS

Many thanks are extended to Captain Darcy Granley and Major Terry Kirkoski, the flight test pilots who flew all of the test profiles, and to Sargent Rick Lee, Sargent Ken Huffman, and Sargent Brian Cornish, the flight engineers who also endured the endless dives and recoveries to validate the ground collision warning algorithms.

Although the focal point of flight test programs often lies with the project officer and flight test aircrew, support for the evaluation of the CC-130 ground collision avoidance system required the concerted effort of many ground technicians and data reduction personnel. The dedicated efforts of the Primrose Lake Evaluation Range personnel under the direction of Captain Steve Ellis and Captain Dennis Letallier captured each of the CC-130 passes over the range on photo-theodolite film and allowed for the calibration of both the existing aircraft flight instruments and the validation of aircraft recovery altitudes.

All of the resulting film was subsequently read into computer data files and reduced by the technicians at the Aerospace Engineering Test Establishment Flight Test Processing Centre under the expert direction of the project data engineer, Amanda Kushko.

I wish to extend my sincere appreciation to the flight test crew, the Primrose Lake Evaluation Range personnel and Flight Test Processing Centre personnel for their exemplary efforts in supporting the evaluation of the CC-130 ground collision avoidance system.

ABSTRACT

The AN/AYQ-504(V) ground collision avoidance system (GCAS) was installed in five Canadian CC-130H(T) Hercules aircraft during the Tanker Avionics Upgrade Program in 1993. The impetus for the installation was that it would avert accidents such as the CC-130 crashes at Fort Wainright, Alaska, and Alert Air Force Station, North West Territories. The original CC-130 GCAS implementation exhibited many nuisance warnings and failed to provide adequate warnings for controlled flight into terrain (CFIT). Software modifications were made and testing was conducted which included evaluation of CFIT warnings, tactical mode silencing of CFIT warnings, and annunciations for descent through a reference altitude, glideslope deviation, altitude loss on take-off, flap overspeed, and system failure.

Performance was satisfactory for CFIT warnings over level terrain throughout the flight test envelope up to bank angles of 30°. Profiles with bank angles of 45° exhibited a delayed warning. Some dive profiles resulted in simultaneous altitude advisories and CFIT warnings causing delayed recovery. Warning performance over mountainous terrain was similar to the level terrain results but showed that level flight over mountainous terrain, even at terrain clearance altitudes, could trigger nuisance CFIT warnings. Tactical mode was intended to inhibit only CFIT warnings during low level operations but instead silenced all GCAS warnings and annunciations. All other GCAS annunciations performed as expected.

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Chapter 1

INTRODUCTION

The AN/AYQ-504(V) ground collision avoidance system (GCAS), manufactured by Cubic Defense Systems, Inc. of San Diego, California, was installed in five CC-130(H)T Hercules tanker aircraft during the Canadian Department of National Defence's Tanker Avionics Upgrade Program in 1993. The impetus for the installation was that it would have averted accidents such as the CC-130 crashes at Fort Wainwright, Alaska, and Alert Air Force Station, Northwest Territories. The original CC-130H(T) GCAS implementation was tested during the period 1993 to 1995. Results showed numerous nuisance warnings and failure to provide adequate warnings for controlled flight into terrain (CFIT).

Problems identified during the original tests were:

a. inadequate warnings when in a CFIT flight regime;

b. nuisance warnings when in approach configuration;

c. nuisance warnings from spurious APN-512 radar altimeter sidelobe reflections off the nosewheel door;

d. nuisance warnings from electrical power bus transients and bus loading by other aircraft electrical equipment such as the auxiliary fuel pumps; and

e. inadequate flap overspeed warnings.

The radar altimeter antennas were rotated 180° to alleviate the sidelobe problem and a new software program version was produced to improve CFIT predictions and reduce nuisance warnings. The Aerospace Engineering Test Establishment (AETE) in Cold Lake, Alberta, Canada was subsequently tasked to conduct flight tests of the revised AN/AYQ-504(V) GCAS installed in a CC-130H(T) aircraft. A sensor validation flight and initial trial of the AN/AYQ-504(V) were conducted on aircraft CC-130338 on 22 March 1996, followed by a performance evaluation on aircraft CC-130339 from 19 April 1996 to 24 May 1996.

The CC-130H(T) Hercules aircraft and ground collision avoidance system are described in Chapter 2. Test objectives and test planning details are discussed in Chapters 3 and 4, respectively. Test conditions and methods are then described in Chapter 5 and are followed by results and discussion in Chapter 6. Finally, a summary of the GCAS evaluation is given in Chapter 7. Data tables and plots of the flight test instrumentation validation, CFIT warning performance, CFIT recovery performance, flight hours can be found in Appendices A through F.

Chapter 2

EQUIPMENT UNDER TEST

Aircraft

The CC-130H Hercules is an all metal, high wing, long range, four engine turboprop aircraft designed for rapid transport of personnel or cargo and delivery through parachute or landing. The tanker version, designated CC-130H(T), includes external refueling pods and a fuel tank mounted in the aircraft cargo compartment for aerial refueling. The aircraft is instrument flight rules (IFR) certified and requires a minimum crew consisting of pilot, co-pilot, and flight engineer. The four engines are Allison T56 constant-speed turboprop, each providing 4,910 shaft horse power (100% RPM, standard day) to a four blade Hamilton Standard hydromatic, constant-speed, full-feathering, reversible-pitch propeller. Basic aircraft weight is 82,000 pounds with a maximum fuel and payload weight of 73,000 pounds, adding up to a maximum gross take-off weight of 155,000 pounds. The normal landing weight of the Hercules is 130,000 pounds with a maximum touchdown rate of 540 feet per minute. However, landings can be performed at 155,000 pounds as long as the touchdown rate does not exceed 300 feet per minute. Aircraft roles vary and include long range airlift, tactical airlift, aerial refueling, and search and rescue.

Ground Collision Avoidance System

General

The Cubic Defense Systems, Inc. AN/AYQ-504(V) performance requirements were defined in the Specification for a Ground Collision Avoidance System [1] and the implementation that was evaluated in the CC-130H(T) Hercules aircraft consisted of the following components [2]:

a. one GCAS computer;

b. one GCAS air data computer; and

c. two control and annunciator panels, one located on the pilot side of the glareshield and the other located on the copilot side of the glareshield.

The control and annunciator panels each contained five annunciator lamps which illuminated to provide warnings. One lamp, labeled "INOP", was used to indicate system failure and also contained a momentary contact push button switch that was used to initiate a system test while the aircraft was still on the ground. For purposes of flight test, this same switch was used to engage and disengage tactical mode when the Hercules was airborne.

The primary function of the GCAS was to provide audio and visual warnings for aircrew to initiate immediate recovery if the aircraft attitude and trajectory would cause a descent below a minimum ground clearance altitude - that is, impending controlled flight into terrain (CFIT). The GCAS used the radar altimeter as its primary sensor and continually tracked the aircraft height above ground. If the radar altimeter entered a no-track state due to aircraft roll angle or high altitude, aircraft height above ground was computed using pressure altitude and altitude rate inputs.

The GCAS was also capable of providing warnings for descent below a reference altitude (800 feet AGL), excessive deviation below glideslope, altitude loss during take-off and go-around, system failure, and flap overspeed.

Aircraft Interfaces

The CC-130H(T) GCAS installation was powered from a single phase of the aircraft 115 VAC/400 Hz electrical power system. The GCAS also had an interface to the aircraft intercommunication system for aural annunciations as well as interfaces to other aircraft systems to monitor the following aircraft parameters [3]:

a. radar altimeter height above ground;

b. radar altimeter validity;

c. glideslope deviation;

d. glideslope enable;

e. glideslope validity;

f. localizer deviation;

g. flap position;

h. pitch attitude (from the aircraft avionics vertical gyro);

i. roll attitude (from the aircraft avionics vertical gyro);

j. landing gear position; and

k. weight on wheels.

The GCAS test installation also included its own air data computer to monitor indicated airspeed, true airspeed, pressure altitude and vertical velocity.

Controlled Flight Into Terrain Warnings

The GCAS software used a predictive algorithm to determine excessive terrain closure rates. It continuously predicted altitude loss for the current aircraft attitude and airspeed as a sum of the following:

a) altitude loss due to pilot response time[1];

b) altitude loss during roll recovery; and

c) altitude loss during aircraft dive recovery.

Aircraft recovery altitude was computed by subtracting the predicted altitude loss from the computed height above ground. If the predicted recovery altitude was less than the programmed minimum ground clearance altitude for three tenths of one second, a warning was issued. The warning consisted of four flashes of the annunciator panel pull-up lamp and an aural "Whoop, whoop, pull up, pull up" on the aircraft intercommunication system. The CFIT warning re-armed once the aircraft climbed through 250 feet above the programmed minimum recovery altitude.

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[1] The CC-130H(T) GCAS implementation used a constant one second delay time to match an assumed pilot response time of one second.

The CC-130(H)T GCAS implementation used two minimum ground clearance altitude settings, 50 feet AGL for enroute warnings, and ground level (zero feet) for warnings on approach. The 50 foot enroute setting could be altered for flight test safety reasons, and was set initially to 1000 feet AGL. Once confidence was gained in the system, the minimum ground clearance altitude was set to 500 feet AGL to obtain better radar altitude data. The approach setting was hard coded into the software program to zero feet, ground level, and to minimize nuisance warnings, CFIT warnings were disabled once the aircraft descended below 50 feet AGL.

Tactical Mode

The GCAS had a tactical mode which, when activated, disabled CFIT warnings. The CFIT warnings re-armed when the GCAS power was cycled, the radar altimeter exceeded 3,000 feet AGL, or the aircraft landed. For purposes of flight test, the annunciator panel "INOP" lamp built-in test switch was modified to allow the pilot to engage and disengage tactical mode when the aircraft was airborne.

Glideslope Warning

The glideslope warning was armed when the aircraft landing gear were extended, the aircraft had descended below 1500 feet AGL, and the aircraft was within two dots of localizer centerline while descending on a valid glideslope path. If the aircraft then descended below two dots beneath the glideslope, the GCAS issued four flashes of the annunciator panel glideslope lamp and an aural "Below glideslope, below glideslope". The glideslope warning was re-armed once the aircraft became re-established on the glideslope.

Altitude Loss Warning on Take-off or Go-around

Once the GCAS detected that the aircraft had taken off, that is, the weight on wheels switch indicated a logical false condition, and that the aircraft was climbing, the GCAS monitored pressure altitude from its air data computer. If more than 50 feet of altitude were lost during the climb, the GCAS issued four flashes of the annunciator panel pull-up lamp and an aural "Don't sink, don't sink". Once the aircraft had climbed through 600 feet AGL or 60 seconds had passed from take-off, the altitude loss warning was disabled.

During a go-around from an approach to landing, or a touch and go, the altitude loss warning was re-armed when the main landing gear up-lock switch registered a logical true condition, that is, the main landing gear were fully retracted, or the weight on wheels switched registered a logical true condition.

System Failure Warnings

The GCAS continually monitored its operation through built-in test (BIT) routines. Non-critical failures were signaled by an aural "GCAS fault" on the aircraft intercommunication system and continuous illumination of the "INOP" lamp on the annunciator panel. Critical GCAS failures (e.g., CFIT warnings were not possible) were signaled by an aural "GCAS fault" and continuous flashing of the "INOP" lamp. If the failure condition was corrected, the "INOP" lamp was extinguished and an aural "GCAS ready" was issued.

Altitude Advisories

When the aircraft was in flight and descended through 800 feet AGL, the GCAS issued four flashes of the annunciator panel altitude lamp and an aural "Altitude, altitude" on the aircraft intercommunication system. The altitude advisory re-armed once the aircraft climbed above 1,300 feet AGL.

Flap Overspeed

The CC-130H(T) aircraft flap speed limits [4] were programmed into the GCAS software with a five knot buffer to eliminate false warnings. If the aircraft had exceeded the flap speed limit plus the five knot buffer, the GCAS issued four flashes on the flaps lamp on the annunciator panel and an aural "Flaps, flaps". The GCAS continuously monitored airspeed for flap overspeeds and, unlike the other warnings, did not require re-arming.

Chapter 3

OBJECTIVES

The objectives for the evaluation of the AN/AYQ-504(V) GCAS installation in the CC-130H(T) Hercules aircraft were:

a) evaluate the performance of the CFIT warning for the CC-130H(T) search and rescue and aerial refueling configurations and flight regimes over level and mountainous terrain;

b) evaluate performance during aerial refueling with a receiver aircraft;

c) evaluate tactical mode manual engagement, performance for low level flight, and automatic disengagement;

d) evaluate glideslope warnings during instrument landing system (ILS) approaches;

e) evaluate altitude loss warnings during take-off and during a go-around (overshoot) from a low approach;

f) evaluate degraded performance and system failure annunciations during:

   i) prolonged flight above radar altimeter range, that is, above 5000 feet AGL;

   ii) prolonged flight at high bank angles;

iii) loss of radar altimeter signal;

iv) loss of attitude signals; and

v) loss of air data computer signals;

g) evaluate altitude advisories when the CC-130H(T) descended through 800 feet AGL and altitude advisory re-arming;

h) evaluate flap overspeed warnings;

i) collect data on all GCAS warnings to determine percentage of valid and invalid warnings; and

j) provide a human factors assessment of the GCAS control and annunciator panel.

Chapter 4

TEST PLANNING

TEST MATRIX AND SAMPLE SIZE

The system specification [1] primarily dealt with performance throughout the Hercules flight envelope for recoveries from CFIT warnings and called for a 99% confidence level in recoveries occurring at the operational ground clearance altitude of 50 feet. The evaluation was designed to measure the performance of the average recovery altitude when a pull-out was executed by the pilot in conformance with the specification.

The flight envelope that was used for the CFIT portion of the test program included speeds from 1.3 times the aircraft stall speed to maximum aircraft speed, pitch angles from -5° to -15°, and bank angles from 0° to 45°. Flap settings of 0%, 50% and 100% were utilized in the evaluation with the resulting test matrix shown in Table 7, Appendix A.

Selection of sample size was initially based on *Sample Size per Experimental Condition* in *Understanding Industrial Designed Experiments* [5, Appendix M] and yielded a sample size of 11 per test condition. An estimated 120 flight hours would have been required to conduct such a program. Time and cost factors were analyzed and allowed for a sample size of only six runs per CFIT test condition. Further refinements in test estimates were conducted based on *Statistical Methods* [6] using a mean minimum recovery altitude of 50 feet [1], that is $\mu=50$. The assumption was then made that 99.7%

of recoveries were required to occur between 50 ±50 feet, that is, $\mu \pm 3\sigma$. The assumed standard deviation was then $\sigma = 16.7$ feet.

The desired difference, D, between the average of the sample set and the parent population was very small and could not be obtained with a sample size of six per CFIT test condition. The converse was then explored using the normalized random variable $z_{\alpha/2}$, the standard deviation σ, and equation 7.6 in *Statistical Methods* [6]:

$$n = \frac{z_{\alpha/2}^2 \sigma^2}{D^2}$$

Using the cumulative normal distribution table, values of $z_{\alpha/2}$ for confidence levels of 99% and 95% were found to be 2.57 and 1.96, respectively. Then using the above equation, it was determined that, with a sample size of six, there would be a 99% confidence level that the sample mean would be within 17.6 feet of the population mean, or a 95% confidence level that the sample mean would be within 13.4 feet of the population mean. These were deemed acceptable but the exercise indicated that close attention would be required regarding the sample means and deviations.

CONSTRAINTS AND LIMITATIONS

The primary limitation encountered in the CFIT performance evaluation of the GCAS was that of time and resources. As such, the CFIT protection was evaluated throughout the Hercules flight envelope but limited to six runs for each test condition.

A second limitation was encountered with CFIT tests in the landing configuration. The minimum recovery altitude used for approach and landing was hard coded to ground level (zero feet) and could not be altered for flight test. As such, the CFIT test points for the landing state could not be safely tested and were deleted from the test matrix.

A third limitation was encountered during CFIT tests over level terrain. Test points 78, 79, and 80 of Table 7, Appendix A, required conditions of 125 KIAS, 100% flaps, and 45° bank with pitch at -5°, -10°, and -15°, respectively. During the first two runs of each of these test maneuvers, the aircraft exhibited rudder buffeting, which could have led to rudder stall. These test points were removed from the matrix.

A fourth limitation was encountered during the tests over mountainous terrain. To provide meaningful, repeatable results, all CFIT test points needed to be conducted over the same area of sloping terrain. Duplicating dive points with wings level over the same point above the slope proved to be a challenge. All test points with non-zero bank angles would have been impossible to duplicate. As such, only the test points with zero bank angle were retained.

A final limitation was encountered regarding the flap overspeed warnings. The flap warnings would not have been issued until the flap speed limit had been exceeded by five knots, a condition which was not authorized for this trial. As such, flap overspeed warning evaluation was deferred to a ground test program.

Chapter 5

TEST METHODS AND CONDITIONS

GENERAL

The GCAS evaluation was broken into several sub-tasks as follows:

a) validate GCAS sensors and perform a calibration check;

b) evaluate CFIT warning performance over level terrain;

c) evaluate CFIT warnings over mountainous terrain;

d) evaluate GCAS performance during aerial refueling;

e) evaluate tactical mode;

f) evaluate glideslope deviation warnings;

g) evaluate altitude loss warnings during take-off and go-around;

h) evaluate GCAS degraded performance during:

   i) prolonged flight above the radar altimeter range;

   ii) prolonged flight at high bank angles;

   iii) radar altimeter failure;

   iv) loss of attitude information; and

   v) loss of air data computer information;

i) evaluate altitude advisories on descents through 800 feet AGL;

j) collect data on all GCAS warnings; and

k) obtain human factors assessments on the GCAS control and annunciator panel.

TEST METHODS

Sensor Validation

Passes were flown over the Primrose Lake Evaluation Range while tracking the test aircraft with phototheodolites for each of the airspeeds and altitudes listed Table 6, Appendix A.

CFIT Warning Evaluation Over Level Terrain

Evaluation of all level terrain CFIT warnings was conducted at the Primrose Lake Evaluation Range using phototheodolites as the truth data source. For evaluation safety, the minimum ground clearance altitude was set in the GCAS software to 1,000 feet AGL for initial test runs with a test hard deck recovery altitude of 500 feet AGL. Once confidence was gained in the ability of the GCAS to consistently issue warnings that resulted in pull-outs prior to 1,000 feet AGL, the minimum ground clearance altitude was lowered in the GCAS software to 500 feet AGL and the test hard deck to 250 feet AGL.

Recoveries for all CFIT test profiles, shown in Figure 1, were executed by the pilot after each "Pull-up" annunciation by:

a) waiting one second after warning to match delay built into GCAS algorithm;

b) rolling the aircraft to wings level; and

c) performing a symmetric pull-up using the g-onset and load factors shown in Table 1.

Table 1 - CC-130H(T) Recovery Load Factors

FLAP SETTING (%)	LOAD-ONSET (g/sec)	LOAD FACTOR (g)
0	0.3	1.85
50	0.15	1.5
100	0.15	1.5

Source: CC-130H Aircraft Operating Instructions [4]

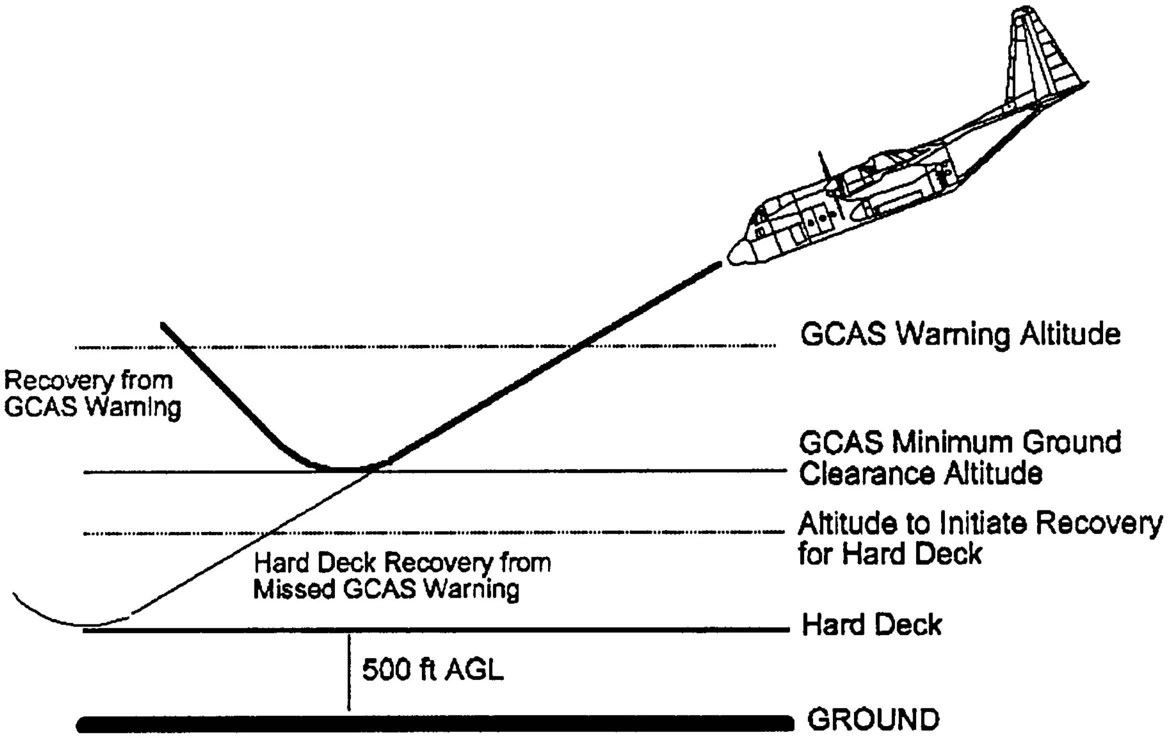

Figure 1 - Dive Recovery Altitudes for GCAS Test Over Level Terrain

Had any missed warning occurred, recovery would have been initiated at the hard deck recovery altitude, shown in Figure 1, as follows:

a) for speeds below 160 KIAS:

  i) roll the aircraft to wings level;

  ii) pull control column to maximum allowed load factor (Table 2);

  iii) push the throttles to maximum; and

  iv) maintain control column at maximum load factor until dive recovery has been complete; and

b) for speeds above 160 KIAS:

  i) roll aircraft to wings level;

  ii) pull control column to maximum allowed load factor (Table 2);

  iii) pull the throttles to idle; and

  iv) maintain control column at maximum load factor until dive recovery has been complete.

To ensure satisfactory stall margins based on Table 2, the maximum allowable load factor for the clean configuration was 3.0 g above 195 KIAS, 2.5 g above 178 KIAS, and 2.0 g above 161 KIAS. The maximum allowable load factor for all speeds with flaps extended was 2.0 g.

At the start of the flight test program, no Hercules dive recovery data were available. Initial predicted altitude losses were based on a comparison of aircraft dive performance from simulator results of all of the test profiles listed in Table 7, Appendix A.

CFIT Warning Evaluation Over Mountainous Terrain

Coliseum Mountain, near Nordegg, Alberta, was chosen as the test site for mountainous terrain CFIT warnings because of its uniform 30° western slope and safe dive recovery areas. Test profiles, shown in Figure 2, were flown west to east using the recovery techniques discussed above.

Table 2 - CC-130H(T) Stall Speeds

	POWER OFF STALL SPEEDS (KIAS) FROM AIRCRAFT OPERATING INSTRUCTIONS [4]			
CONFIGURATION	1.0 g	2.0 g	2.5 g	3.0 g
Clean	108	153	170	187
50 % Flaps	92	130	--	--
100 % Flaps	82	116	--	--

NOTES:
1. Maximum symmetric g for flaps down is 2.0 g.
2. All values were based on aircraft weight of 110,000 lb.
3. All values based on aircraft fuel load and cargo load in area A of the Weight Limitations Chart in the CC-130H Aircraft Operating Instructions.[4].

Again, for evaluation safety, the minimum ground clearance altitude was initially set to 1,000 feet AGL and the hard deck to 500 feet AGL above the peak of the test terrain. Unlike the tests over level terrain, the challenges encountered with test point repeatability dictated that the minimum ground clearance altitude and hard deck be maintained at 1,000 feet and 500 feet, respectively.

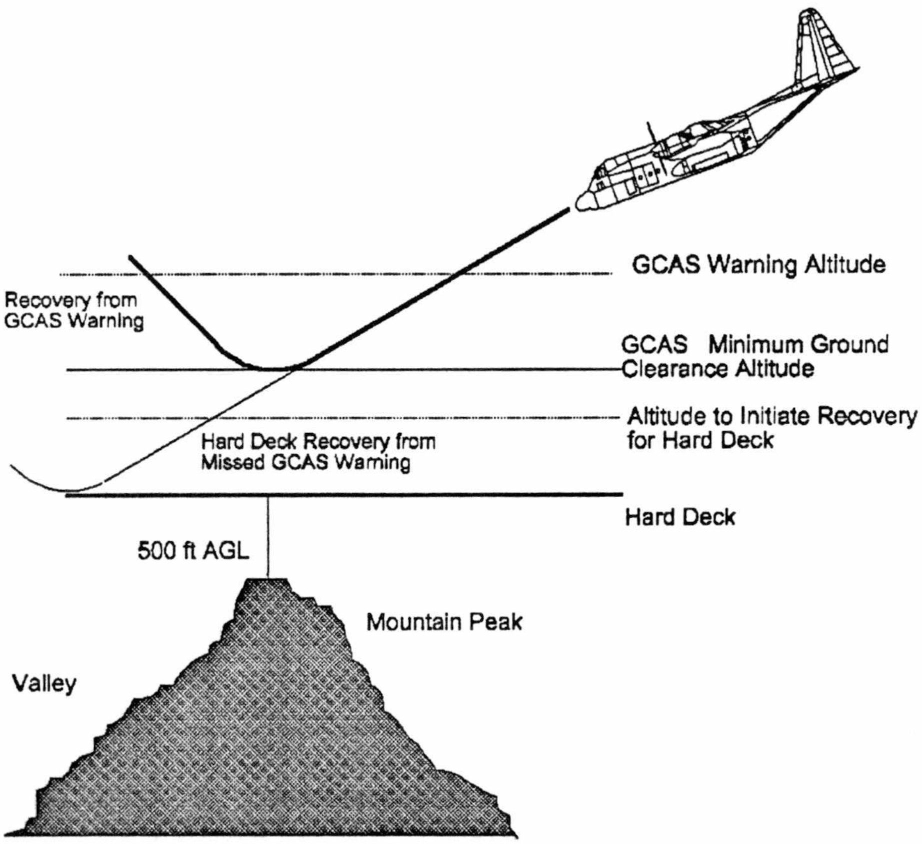

Figure 2 - Recovery Altitudes for CFIT Tests Over Mountainous Terrain

Performance During Aerial Refueling

GCAS data were collected while receiver aircraft conducted the following sequence:

a) approach and join the tanker off the right wing tip;

b) move to the right hose pre-contact position;

c) move to the right hose contact position;

d) move to the right hose pre-contact position;

e) move to the left hose pre-contact position;

f) move to the left hose contact position;

g) move to the left hose pre-contact position;

h) move left and aft of the left wing tip; and

i) depart the tanker.

Tactical Mode Evaluation

In conjunction with the CFIT evaluation over mountainous terrain, profiles known to cause CFIT warnings were flown in tactical mode. The effect of tactical mode on degraded GCAS operation was also evaluated by individually pulling and resetting the circuit breakers for the radar altimeter, GCAS air data computer, and the aircraft avionics vertical gyro while tactical mode was engaged.

Glideslope Deviation Warning

The glideslope deviation warning was evaluated at the conclusion of selected test flights by inducing a two dot deviation below the glideslope and then recovering back to glideslope upon the pilot hearing the "Below glideslope" annunciation.

Altitude Loss Warnings On Take-off or Go-around

The GCAS altitude loss warning was evaluated during selected take-offs by conducting a 50 foot descent prior to climbing through 600 feet AGL. As well, to evaluate altitude loss warnings during go-around, six approaches were flown with an overshoot initiated below 600 feet AGL. Once the aircraft landing gear were up and locked, and prior to climbing through 600 feet AGL, a 50 foot descent was flown.

Degradation at High Bank Angles

Evaluation of the effect of high banks angles on GCAS performance was conducted by post-flight analysis of the computed height above ground during test maneuvers that included sustained high bank angle turns.

Degradation During Flight Above Radar Altimeter Range

Evaluation of the effect of flight above the radar altitude range on GCAS performance was conducted by post-flight analysis of the computed height above ground level.

Degradation with Sensor Failure

Response to sensor failure was tested by individually pulling and resetting the circuit breakers for the aircraft avionics vertical gyro and the GCAS air data computer and by turning off the radar altimeter during both normal and tactical mode operation.

Altitude Advisory

Evaluation of the GCAS altitude advisory was accomplished through post-flight analysis of each descent through 800 feet AGL.

Flap Overspeed Warnings

Flap overspeed warnings could not be safely tested in flight and were deferred to a ground test program.

Warning Data Collection

All warnings and advisories issued by the GCAS were analyzed to determine their validity. As well, any condition that warranted a GCAS warning or advisory that was not annunciated was counted as a missed warning.

Human Factors Assessment

At the completion of testing, the aircrew provided comments on the location and mechanization of the GCAS control and annunciator panel as well on the adequacy of GCAS aural and visual annunciations.

TEST CONDITIONS

Test Matrices

The test sequence entailed sensor validation, CFIT warnings over level terrain, and CFIT warnings over mountainous terrain with the remaining tests included on an opportunity basis. All test matrices are included as Appendix A and are summarized in Table 3.

Test Point Tolerances

The tolerances used by the test pilot while flying each test point were:

a) baro-altitude ±100 feet;

b) airspeed ±10 knot;

c) pitch angle ±1°;

d) roll angle ±5° ; and

e) recovery load factor ±0.1 g.

Test Item Description

Aircraft CC-130338 and CC-130339 were used in the tanker configuration for the GCAS flight test program. For purposes of flight safety during CFIT evaluations, aircraft fuel and cargo weight were maintained within Area A of the Weight Limitation Chart [4] to allow for a maximum 3 g load factor during dive recovery.

Table 3 - List of Test Matrices

TEST	
Calibration Check	Table 6
CFIT Over Level Terrain	Table 7
CFIT - Level Flight Over Mountainous Terrain	Table 8
Tactical Mode	Table 8
CFIT- Dive Profiles Over Mountainous Terrain	Table 9
Aerial Refueling	Table 10
Altitude Loss Warning on Take off or Go Around	Table 10
Degraded Performance - Flight above radar altimeter range	Table 10
Degraded Performance - High Bank Angles	Table 10
Degraded Performance - Sensor Failure	Table 10
Altitude Advisories	Table 10

Note: All test point tables are included as Appendix A.

The fuel load was also maintained such that the maximum aircraft weight at the commencement of all test points was less than 110,000 pounds to maintain safe margins above the test point stall speeds (Table 2).

Test Location and Setting

Sensor validation and level terrain CFIT tests were conducted at the Primrose Lake Evaluation Range near Cold Lake, Alberta while mountainous terrain CFIT tests were conducted at Coliseum Mountain near Nordegg, Alberta. All tests were conducted using visual flight rules weather minima [7] with a minimum ceiling of 3,000 feet and visibility of three nautical miles in the test areas. Atmospheric conditions entailed flight through relatively calm air and did not include evaluation of the effects of turbulence on the GCAS performance.

Instrumentation

The Primrose Lake Evaluation Range phototheodolites provided truth data for aircraft position and speed and were used for determination of accuracy of GCAS data for all tests conducted over level terrain.

On-board flight data were collected from the GCAS and production sensors whose range and accuracy are listed in Table 11, Appendix B. Aircraft flight data were continuously transferred from the GCAS through a serial data-link to a laptop computer. Using software similar to the GCAS program, flight parameters, computed recovery altitude, and height above ground level were displayed on the computer and flight data were stored on the hard disk drive.

Data Reduction

Phototheodolite data from the calibration check flights and the CFIT dives at the Primrose Lake Evaluation Range were used for comparison to GCAS parameters and to produce an estimate of the accuracy of the aircraft sensors. As well, the phototheodolite data were used to generate CFIT warning and recovery plots for comparison to similar plots based on GCAS data. The final step was to generate GCAS warning performance curves for comparison to the CFIT dives over the mountainous terrain.

Chapter 6

RESULTS AND DISCUSSION

Sensor Validation

Comparison of GCAS data with phototheodolite data yielded error data for radar altimeter, radar altimeter rate, pressure altitude, pressure altitude rate, and true airspeed and are summarized in Table 4.

CFIT Warning Performance Over Level Terrain

Each level terrain CFIT test point was flown six times and analyzed using plots of warning and recovery altitudes versus initial descent rate. Outlying data points were traced back to unloaded test point entry conditions (i.e., load factor less than one) which

Table 4 - Summary of Parameter Errors

LEVEL FLIGHT DATA	RANGE	MAXIMUM ERROR
True airspeed (kt)	120 - 300	7%
Radar Altitude (ft)	500 - 2000	4%
Pressure Altitude (ft)	2400 - 3900	1.5%
DIVE PROFILE DATA	RANGE	MEAN ERROR
True airspeed(kt)	152 - 334	2.35
Radar Altitude(ft)	458 - 2228	-10.4
Terrain Closure Rate (fpm)	0 - 6600	748
Air Data Computer Vertical Velocity (fpm)	0 - 8065	708

Sources: Appendix C, Figure 8, Figure 9, Table 12, and Table 13.

caused excessive recovery altitude computations, early warnings, and high recovery altitudes. Aggressive push-over maneuvers often caused nuisance warnings. Appendix D contains the data plots of warning altitudes and recovery altitudes versus initial descent rates.

Comparison of results from the GCAS with results from the phototheodolites indicates that the GCAS warning and aircraft recovery altitudes were comparable with the phototheodolite truth source. The 1,000 foot minimum ground clearance test points and high bank angle test points contained more scatter in the data than the 500 foot minimum ground clearance altitude test points and 0° bank angle test points. As such, the data plots are organized by minimum ground clearance setting and bank angle.

Based on work done on high performance aircraft [8], a second order curve fit was applied to the CFIT warning data. The data plots in Appendix D show that the A_2 terms are negligible for CC-130H data and that a first order fit would suffice. Linear regression was performed on the recovery altitude data and yielded trend lines for the CFIT recovery performance. Recovery from CFIT profiles initiated on GCAS warnings showed satisfactory performance over level terrain for the test flight envelope of:

a) airspeed 135 to 310 knots;

b) flaps 0 to 100%;

c) pitch -5° to -15° ; and

d) bank 0° to 30° .

The recovery data were also analyzed to determine the probability of recovery above ground level and the probability of absence of nuisance warnings based on the specification [1] criteria. Since the scatter in the data was higher than originally assumed, a t-distribution was used to determine the probabilities. Results are listed in Table 14 of Appendix D. Each case shows a low probability of nuisance warnings and, for most cases, a high probability of safe recovery. However, the CFIT warning performance for 45° bank angles shows a notable decrease in the probability of recovery.

Qualitative observations made during 500 foot minimum ground clearance altitude flight tests indicated that CFIT warnings were delayed when the test point entry bank angle was 45° as shown in Figure 17 and Figure 25, Appendix D. The recovery trend line indicates that the GCAS issued delayed warnings when the aircraft had 45° of bank with a descent rate greater than 3,000 feet per minute. The delayed warning trend was not noticed during the 1,000 foot minimum ground clearance altitude tests, likely due to the wider tolerance and scatter of radar altimeter data at the higher altitudes. Based on the current observations, further study of the GCAS CFIT warning performances with 45° aircraft bank angle would be warranted.

One other issue that became apparent during the CFIT evaluation at Primrose Lake was that of GCAS annunciation priority. When the closure rate between the aircraft and the terrain caused a CFIT warning to be issued at 800 feet AGL, there was a conflict between the CFIT warning and the altitude advisory. If the altitude advisory was issued first, the CFIT warning was not issued until annunciation of the altitude call was complete. This conflict was encountered during three 500 foot minimum ground clearance altitude test points and resulted in recoveries at 340 feet AGL, 160 feet below the minimum ground clearance altitude. This becomes significant when consideration is given to the 50 foot AGL operational minimum ground clearance altitude.

The CFIT warnings were not tested during the approach and landing phase of flight. However, during two rapid descent approaches, nuisance warnings were issued. Nuisance warnings could erode aircrew confidence in the GCAS. Analysis of the recorded nuisance warning indicated that the 1,000 foot per minute descent caused the predicted recovery to be lower than 0 feet AGL within 0.3 seconds of passing through the 50 foot CFIT warning disable point. Although this nuisance warning was well within the specification, raising the CFIT disable altitude to 75 feet would give a larger margin from nuisance warnings.

CFIT Warning Performance Over Mountainous Terrain

Level flight profiles were planned using Figure 26, Appendix E and flown to determine CFIT warning performance while flying at a constant altitude over rising terrain. Warnings were issued in all cases with both 1,000 foot and 500 foot minimum ground clearance altitudes set within the GCAS. Analysis of level flight CFIT warnings over mountainous terrain (Figure 27, Appendix E) shows that nuisance warnings are probable at various speeds, altitudes, and terrain gradients.

To allow for repeatability in the test conditions for CFIT test dives over mountainous terrain, only test points with 0° bank angle were flown. Aircraft flight path angle for each test condition was derived from the CFIT tests over level terrain and used in conjunction with aircraft true airspeed, slope data for Coliseum Mountain, and the warning altitude plots from Appendix D to determine test flight profiles and anticipated warning altitudes. This method proved to be accurate in the flight test. Closure rate and radar altimeter at each CFIT warning were then recorded and plotted for comparison to the level terrain test data. The correlation with level terrain data is high, as shown in Figure 28 and Figure 29, Appendix E. Note that dive recovery ground clearance could not be determined due to the uneven terrain.

Of the 144 test dives conducted at Coliseum Mountain, the GCAS issued secondary nuisance CFIT warnings during recovery from 29 of the dives. These nuisance warnings were a result of noise content on the radar altimeter signal. As the aircraft nose was pulled up during dive recovery and the mountain peak was passed, the aircraft pitch angle and descending mountain face drove the radar altimeter into an instantaneous no-track state and resulted in the noise on the radar altimeter signal.

Performance During Aerial Refueling

Two separate aerial refueling profiles were flown, one using a CT-133 T-bird and one using a CF-188 Hornet aircraft. In both cases, the profiles were flown above radar altimeter range and there were no false warnings while the receiver aircraft followed normal aerial refueling profiles. During the second aerial refueling sortie, the Hornet flew under the Hercules causing a radar altimeter return and, with the 500 foot minimum ground clearance setting, triggered a CFIT warning. As well, the GCAS computed height above ground level was corrupted with the "new ground level", as shown in Figure 3, and was not corrected until the Hercules descended to less than 5,000 feet AGL. Had the minimum ground clearance altitude been set to the operational value of 50 feet, the GCAS would not have issued the CFIT warning due to the fact that the predicted recovery altitude did not reach the 50 foot value as shown in Figure 4. Regardless of the minimum ground clearance altitude setting, corruption of the computed height above ground level corruption. The CFIT warnings were not degraded in either case and , the height above ground level computation was corrected as soon as the aircraft descended and radar altimeter information was available as shown in Figure 7.

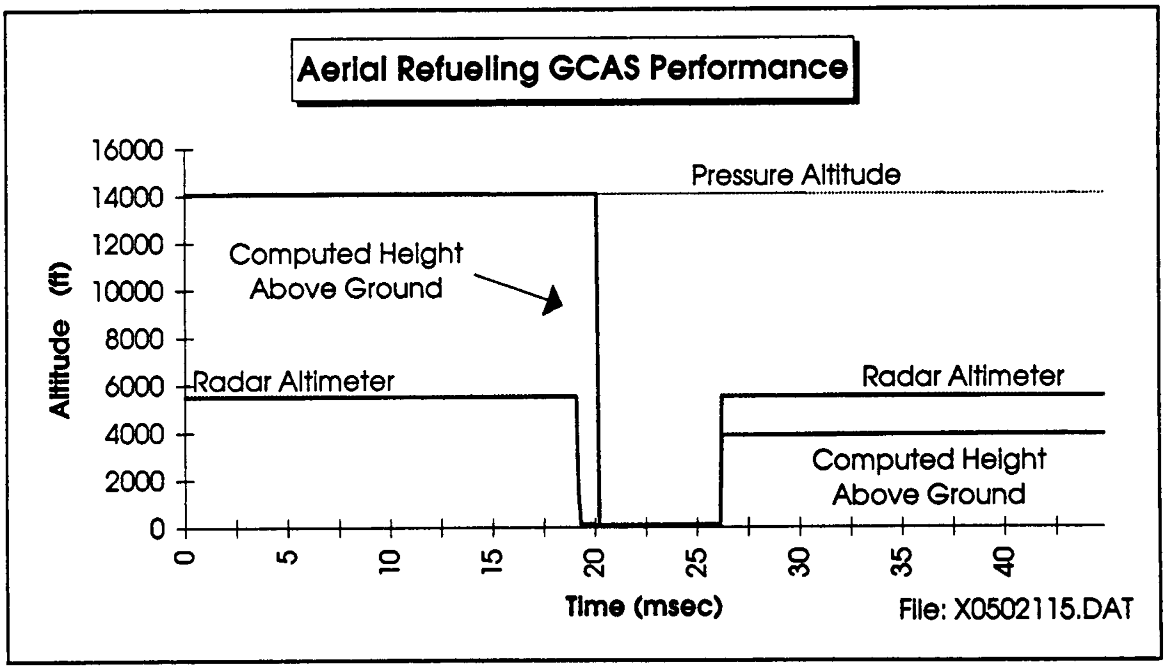

Figure 3 - GCAS Performance During Aerial Refueling

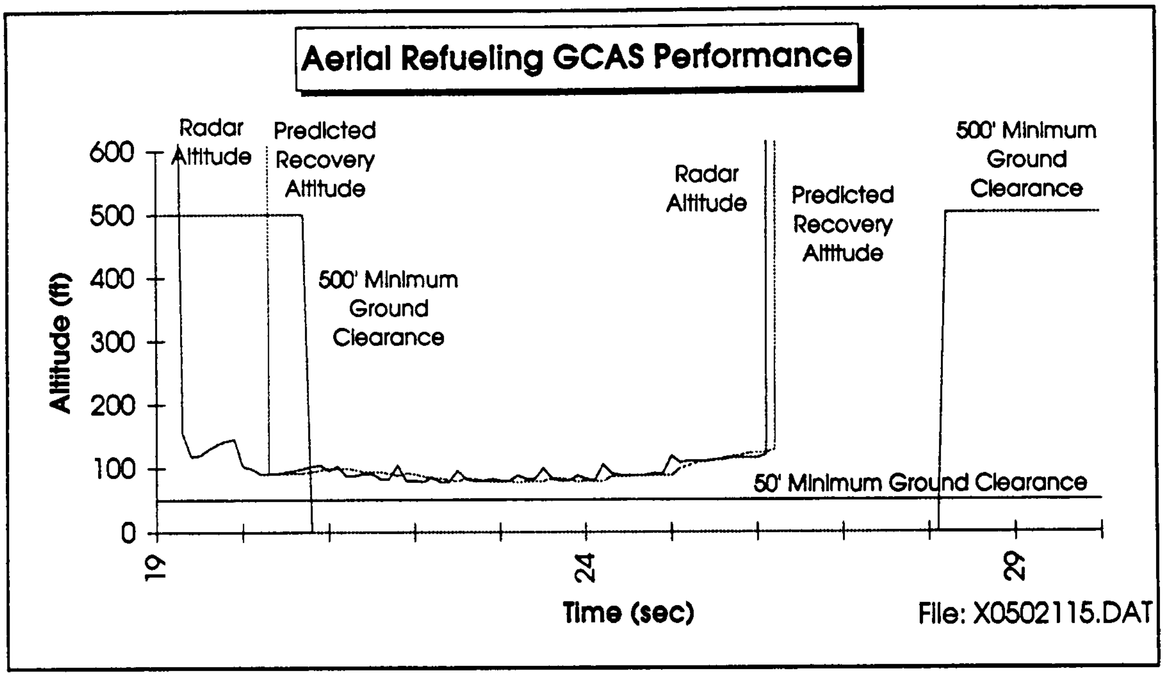

Figure 4 - Aerial Refueling - GCAS Performance Details

Tactical Mode

Activation of tactical mode inhibited all CFIT warnings for each CFIT profile flown. However, there was no indication of tactical mode status or mode changes, that is, aircrew were not advised whether CFIT protection was active or not. Contrary to the system specification [1], GCAS failure annunciations were also silenced (discussed below) and the test implementation of tactical mode engage switch lacked an indication to aircrew of whether CFIT protection was active or not.

Glideslope Deviation Warning

During the test program, seven instrument approaches were flown with intentional deviations of two dots below glideslope. In each case, the GCAS issued an aural "Below glideslope, below glideslope" warning with four flashes of the annunciator lamp as soon as the aircraft descended through two dots below glideslope. Three of the approaches included a second intentional two dot low deviation which also caused the aural and visual GCAS warnings.

Altitude Loss Warnings on Take-off and Go-around

Intentional 50 foot descents were conducted on seven different take-offs and seven go-arounds. The GCAS issued aural "Don't sink, don't sink" warnings with four flashes of the annunciator pull-up lamp in all 14 cases. The average altitude loss from peak pressure altitude during take-off was 53.9 feet with a standard deviation of 2.6 feet.

Degradation at High Bank Angles

During flight test, sustained turns were flown during the calibration check phase (Table 6, Appendix A) with bank angles greater than 45°. Data from a sustained 50° bank turn is shown in Figure 5 and indicates that the GCAS computed height above ground tracked the radar altitude throughout the turn. All test points with sustained turns exhibited the same results, indicating accurate ground tracking by the GCAS.

Degradation During Flight Above Radar Altimeter Range

Once the aircraft climbed outside the range of the radar altimeter, the GCAS continually computed height above ground, assuming flat terrain, by adding the product of pressure altitude rate (vertical velocity) and elapsed time to the value of the height above ground at the start of each computation frame (Figure 6). When a valid radar altimeter signal became available, height above ground was corrected (Figure 7). GCAS operation during flight above 5,000 feet AGL was satisfactory.

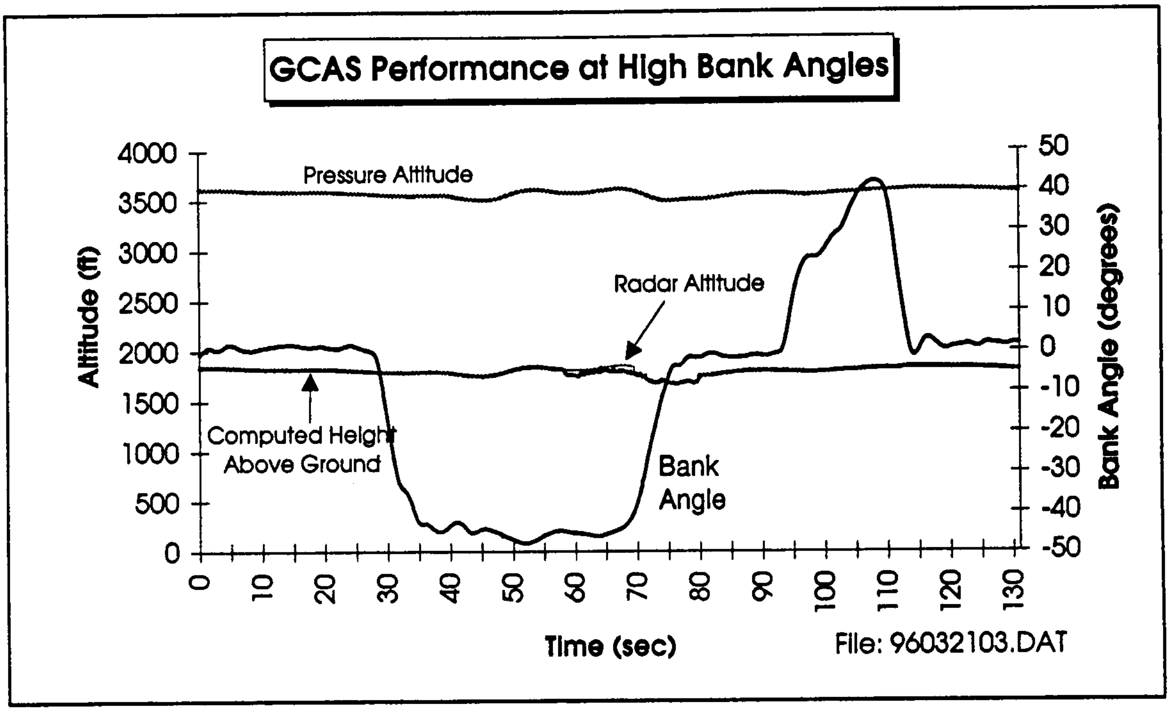

Figure 5 - GCAS Performance During Flight With High Bank Angles

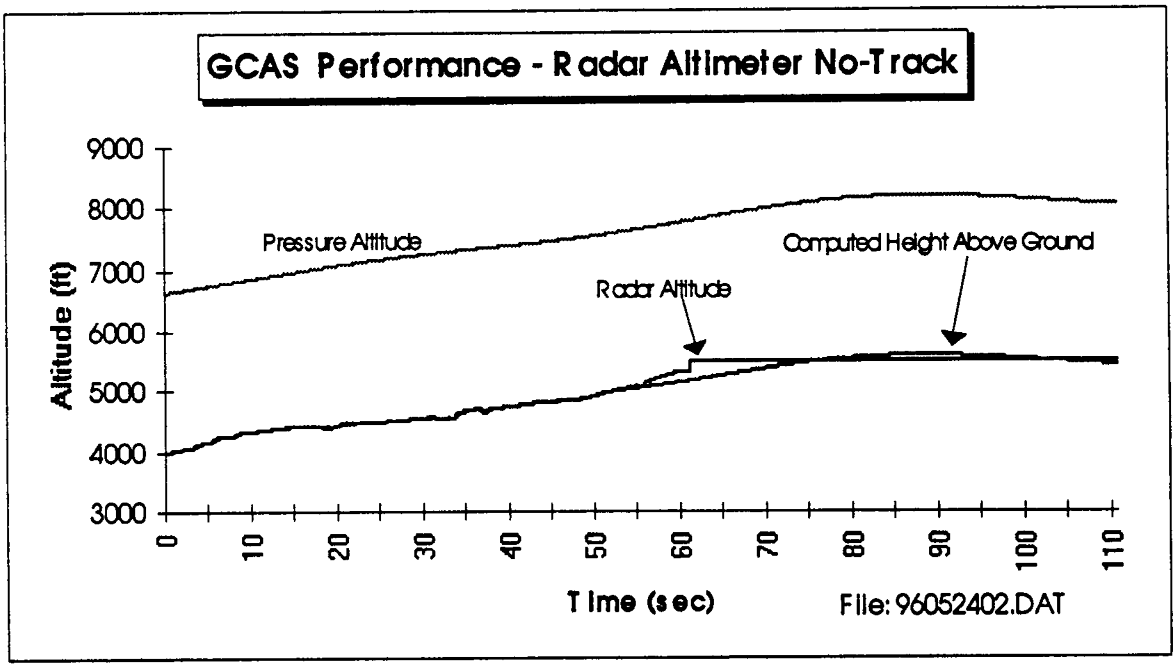

Figure 6- GCAS Performance During Flight Above Radar Altimeter Range

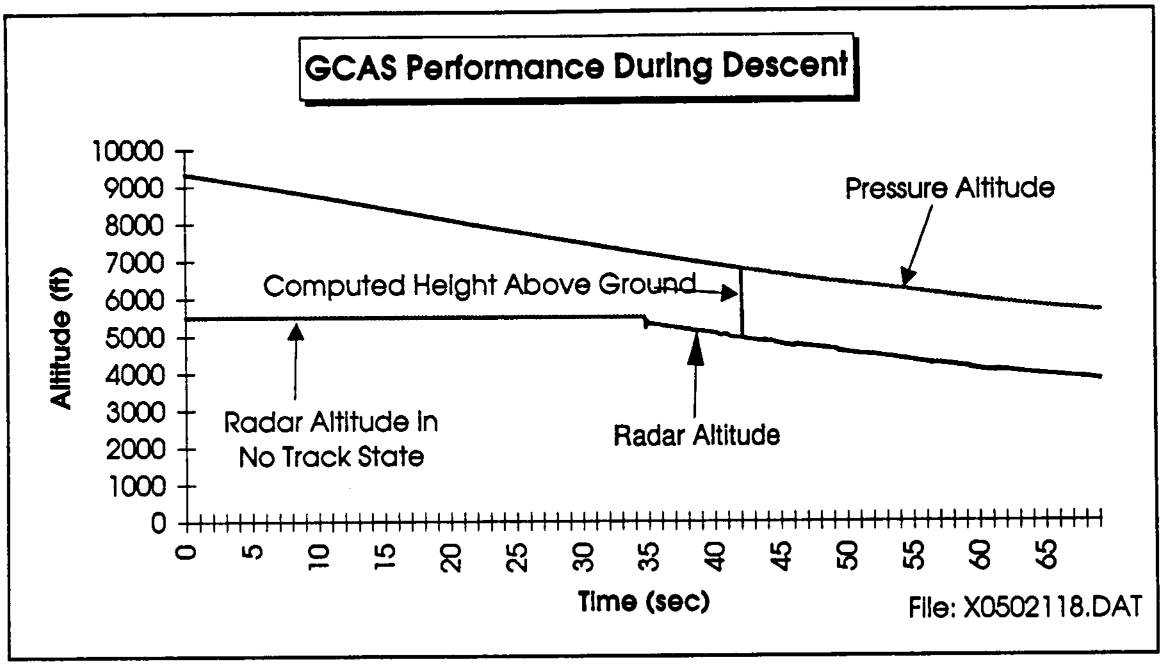

Figure 7 - GCAS Performance During Descent

Degradation with Sensor Failure

Failure annunciations were tested by individually pulling and then resetting the circuit breakers for the aircraft vertical gyro, and the GCAS air data computer and by turning off the radar altimeter. In each case the GCAS consistently issued an aural "GCAS Fault" warning and caused the INOP lamp to flash continuously. Warnings due to sensor failure were satisfactory while the GCAS was in the non-tactical mode.

When in tactical mode, the GCAS issued no warnings when the aircraft vertical gyro or the GCAS air data computer circuit breakers were pulled. However, when tactical mode was disengaged, the GCAS issued four flashes of the INOP lamp but no aural warning. Warnings must be accompanied with an aural annunciation and continuous flashing of the INOP lamp [1].

Failure of the radar altimeter while the GCAS was in tactical mode also caused no fault warnings and, unlike vertical gyro or air data computer failure, no warning was issued when tactical mode was disengaged. When the radar altimeter failed or was turned off while tactical mode was engaged, there was no indication of the GCAS failure, that is, no advisory to aircrew that CFIT protection was no longer available.

Altitude Advisory

Although more than 600 dives were conducted, the majority were recovered below the 1,300 feet AGL altitude advisory re-arm altitude resulting in a total of only 260 altitude advisory calls during the test program. Altitude advisories issued during the CFIT dives over mountainous terrain were often preceded by "Pull Up" warnings and had more scatter in the data when compared to level terrain results. Aircraft descent rate also had a small effect on the altitude at which the advisory was issued - in the order of -4 feet per 1,000 feet per minute of descent. A comparison of the level terrain and amalgamated test data is presented in Table 5. Note that there was one altitude call at 578 ft AGL that could not be correlated to terrain gradient or other GCAS warnings causing a delay and was counted as a missed warning. The 1,066 ft AGL call was made at the peak of Coliseum Mountain as the terrain fell away from the aircraft flight path and was deemed a valid call.

Flap Overspeed Warnings

In order to avoid frequent nuisance calls, the GCAS flap overspeed warning was designed so that warnings would not be issued until the flap speed limit had been exceeded by five knots. As such, evaluation of flap overspeed warnings were deferred to a ground test program.

Warning Data Collection

Thirty six nuisance warnings were issued during the test program. The warning confidence level was specified as [1]:

$$Warning\_Confidence = 100 - \frac{Missed\_or\_Nuisance\_Warnings}{Flight\_Hours} x100\%$$

The majority of nuisance warnings, 33 out of the 36, were secondary CFIT warnings during dive recoveries over mountainous terrain caused by noise on the radar altimeter signal. Once the aircraft had passed the peak of Coliseum mountain, the terrain fell away at the same time as CFIT dive recovery occurred and contributed to very erratic

Table 5 - GCAS Altitude Advisory Performance

	LEVEL TERRAIN	LEVEL AND MOUNTAINOUS TERRAIN
Number of Data Points	153	260
Minimum (ft)	726 AGL	578 AGL[1]
Maximum (ft)	814 AGL	1066 AGL[2]
Average Advisory Altitude (ft)	780 AGL	774 AGL
Standard Deviation (ft)	11.6	44.8

Sources: 1. Data file 96050209.DAT
2. Data file 96050230.DAT

transitions on the radar altimeter signal. These transitions exceeded the GCAS re-arm altitudes and the signal's subsequent rate of change would fall into the CFIT warning criteria. However, based on the 47.8 hr flown (Table 15, Appendix F) during the GCAS evaluation program, the confidence level was 99.25% and was satisfactory compared to the 99% specification limit.

Human Factors Assessment

Pilot comments on the GCAS annunciator panel indicated that its location and configuration were satisfactory. However, the mechanization of tactical mode for the test program did not provide a positive indication of tactical mode engagement or disengagement to advise aircrew whether CFIT protection was active or not.

Chapter 7

CONCLUSIONS

The Cubic Defense Systems, Inc. GCAS was evaluated to determine its performance in several areas: CFIT warnings over both level and mountainous terrain, warnings for excessive glideslope deviation, altitude loss warnings during take-off or go-around, advisories during descent through a reference altitude, performance during aerial refueling, and performance during degraded operations. All of the evaluated modes and warning and advisory annunciations performed as expected with a few noteworthy exceptions as detailed below.

Warning performance for CFIT conditions was the crux of the GCAS flight test evaluation and yielded satisfactory results for most of the CC-130H Hercules flight envelope over level terrain. The GCAS performance exhibited a high probability of providing CFIT warnings to allow a safe recovery and a low probability of nuisance warnings.

However, test results showed delayed CFIT warnings when the aircraft had 45° of bank, an occasional conflict between altitude advisories and CFIT warnings, and nuisance warnings during high descent rate approaches. The data plots for the 45° CFIT test points show a lower probability of safe recovery as well as inadequate warnings as aircraft descent rates were increase. Further study would be warranted on the effects of bank angle on CFIT warning performance.

The noted conflict between CFIT warnings and altitude advisories might be alleviated by allowing high priority calls to interrupt low priority annunciations while the approach nuisance warnings might be eliminated by terminating CFIT warnings at 75 feet AGL instead of the current 50 feet AGL.

Evaluation of CFIT warning performance over mountainous terrain showed that it was an extension of the 0° bank angle performance over level terrain. The results also showed that the GCAS will respond to terrain closure rates, even when flying at terrain clearance altitudes. GCAS performance over mountainous terrain could be an area of further study.

One final point regarding the GCAS evaluation was that of air turbulence. The entire evaluation was performed in relatively calm atmospheric conditions. The effects of turbulence on CFIT warning performance were not evaluated and could be another area of further study.

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BIBLIOGRAPHY

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APPENDICES

APPENDIX A - TEST MATRICES

Table 6- Test Matrix A - Sensor Validation

TEST POINT	ALTITUDE (AGL)	ALTITUDE (MSL)	KIAS	FLAPS (%)	ROLL ANGLE (deg)	STALL SPEED (KIAS)	STALL MARGIN (kt)	NOTES
1	2000	3964	200	0	0	108	92	
2	2000	3964	200	0	45	124	76	180° HDG change
3	2000	3964	200	0	0	108	92	
4	2000	3964	250	0	0	108	142	
5	2000	3964	300	0	0	108	192	achieve maximum level KIAS
6	2000	3964	170	50	0	92	78	
7	2000	3964	125	50	0	92	33	
8	2000	3964	140	100	0	86	54	
9	2000	3964	115	100	0	86	29	
10	1500	3464	200	0	0	108	92	
11	1500	3464	200	0	45	124	76	180° HDG change
12	1500	3464	200	0	0	108	92	
13	1500	3464	250	0	0	108	142	
14	1500	3464	300	0	0	108	192	achieve maximum level KIAS
15	1500	3464	170	50	0	92	78	
16	1500	3464	125	50	0	92	33	
17	1500	3464	140	100	0	86	54	
18	1500	3464	115	100	0	86	29	
19	1000	2964	200	0	0	108	92	
20	1000	2964	200	0	45	124	76	180° HDG change
21	1000	2964	200	0	0	108	92	
22	1000	2964	250	0	0	108	142	
23	1000	2964	300	0	0	108	192	achieve maximum level KIAS
24	1000	2964	170	50	0	92	78	
25	1000	2964	125	50	0	92	33	
26	1000	2964	140	100	0	86	54	
27	1000	2964	115	100	0	86	29	
28	500	2464	200	0	0	108	92	
29	500	2464	200	0	45	124	76	180° HDG change
30	500	2464	200	0	0	108	92	
31	500	2464	250	0	0	108	142	
32	500	2464	300	0	0	108	192	achieve maximum level KIAS
33	500	2464	170	50	0	92	78	
34	500	2464	125	50	0	92	33	
35	500	2464	140	100	0	86	54	
36	500	2464	115	100	0	86	29	

Table 7 - Test Matrix B - CFIT Dives Over Level Terrain

TEST POINT	GCAS WARNING ALTITUDE (MSL)	KIAS	FLAP POSITION	PITCH ANGLE (deg)	ROLL ANGLE (deg)	HARD DECK RECOVERY ALTITUDE (MSL)	SIMULATOR ALTITUDE LOSS	PREVIOUS FLIGHT DATA ALTITUDE LOSS
1	2704	165	0 %	-5	0	2454	180	240
2	2794	165	0 %	-10	0	2544	240	330
3	2914	165	0 %	-15	0	2664	320	450
4	2634	200	0 %	-5	0	2384	110	170
5	2774	200	0 %	-10	0	2524	215	310
6	2864	200	0 %	-15	0	2614	320	400
7	2634	250	0 %	-5	0	2384	170	130
8	2744	250	0 %	-10	0	2494	260	280
9	2904	250	0 %	-15	0	2654	440	340
10	2614	310	0 %	-5	0	2364	110	150
11	2734	310	0 %	-10	0	2484	270	270
12	2994	310	0 %	-15	0	2744	525	530
13	2724	165	0 %	-5	-15	2474	260	110
14	2794	165	0 %	-10	-15	2544	330	250
15	3174	165	0 %	-15	-15	2924	370	710
16	2804	200	0 %	-5	-15	2554	180	340
17	2864	200	0 %	-10	-15	2614	370	400
18	3064	200	0 %	-15	-15	2814	465	600
19	2754	250	0 %	-5	-15	2504	250	290
20	2914	250	0 %	-10	-15	2664	380	450
21	3284	250	0 %	-15	-15	3034	820	320
22	2684	310	0 %	-5	-15	2434	120	220
23	2984	310	0 %	-10	-15	2734	520	380
24	3324	310	0 %	-15	-15	3074	860	650
25	2704	170	0 %	-5	-30	2454	240	140
26	2944	170	0 %	-10	-30	2694	480	430
27	3154	170	0 %	-15	-30	2904	600	690
28	2764	220	0 %	-5	-30	2514	220	300
29	2974	220	0 %	-10	-30	2724	450	510
30	3184	220	0 %	-15	-30	2934	720	530
31	2704	270	0 %	-5	-30	2454	240	240
32	2974	270	0 %	-10	-30	2724	510	250
33	3434	270	0 %	-15	-30	3184	970	660
34	2704	310	0 %	-5	-30	2454	210	240
35	3104	310	0 %	-10	-30	2854	640	460
36	3684	310	0 %	-15	-30	3434	1220	660
37	2632	135	50%	-5	0	2382	130	168
38	2705	135	50%	-10	0	2455	180	241
39	2744	135	50%	-15	0	2494	220	280
40	2614	125	100%	-5	0	2364	150	90
41	2634	125	100%	-10	0	2384	160	170
42	2774	125	100%	-15	0	2524	180	310
43	2534	140	100%	-5	0	2284	50	70
44	2594	140	100%	-10	0	2344	130	120
45	2714	140	100%	-15	0	2464	190	250
46	2594	170	50%	-5	0	2344	60	130
47	2614	170	50%	-10	0	2364	150	150
48	2824	170	50%	-15	0	2574	250	360
		Six runs per test point						

Table 7 - Test Matrix B - CFIT Dives Over Level Terrain (Cont'd)

TEST POINT	GCAS WARNING ALTITUDE (MSL)	KIAS	FLAP POSITION	PITCH ANGLE (deg)	ROLL ANGLE (deg)	HARD DECK RECOVERY ALTITUDE (MSL)	SIMULATOR ALTITUDE LOSS	PREVIOUS FLIGHT DATA ALTITUDE LOSS
49	2674	135	50%	-5	-15	2424	200	210
50	2664	135	50%	-5	-15	2414	200	DELETED
51	2854	135	50%	-10	-15	2604	260	390
52	3064	135	50%	-15	-15	2814	280	600
53	2604	125	100%	-5	-15	2354	140	100
54	2704	125	100%	-10	-15	2454	240	190
55	2884	125	100%	-15	-15	2634	420	250
56	2594	140	100%	-5	-15	2344	130	50
57	2754	140	100%	-10	-15	2504	290	130
58	2714	140	100%	-15	-15	2464	250	200
59	2614	170	50%	-5	-15	2364	150	140
60	2774	170	50%	-10	-15	2524	240	310
61	3024	170	50%	-15	-15	2774	320	560
62	2724	135	50%	-5	-30	2474	250	260
63	2714	135	50%	-5	-30	2464	250	DELETED
64	2934	135	50%	-10	-30	2684	360	470
65	2994	135	50%	-15	-30	2744	330	530
66	2704	125	100%	-5	-30	2454	240	150
67	2794	125	100%	-10	-30	2544	310	330
68	2934	125	100%	-15	-30	2684	420	470
69	2664	140	100%	-5	-30	2414	200	80
70	2714	140	100%	-10	-30	2464	250	170
71	2824	140	100%	-15	-30	2574	320	360
72	2604	170	50%	-5	-30	2354	100	140
73	2754	170	50%	-10	-30	2504	260	290
74	3074	170	50%	-15	-30	2824	420	610
75	2774	135	50%	-5	-45	2524	310	260
76	2884	135	50%	-10	-45	2634	420	350
77	2934	135	50%	-15	-45	2684	470	470
78	2784	125	100%	-5	-45	2534	250	DELETED
79	2854	125	100%	-10	-45	2604	390	DELETED
80	2939	125	100%	-15	-45	2689	475	DELETED
81	2734	140	100%	-5	-45	2484	270	160
82	2814	140	100%	-10	-45	2564	350	200
83	2864	140	100%	-15	-45	2614	340	400
84	2624	170	50%	-5	-45	2374	160	160
85	2774	170	50%	-10	-45	2524	300	310
86	2984	170	50%	-15	-45	2734	520	400
		Six runs per test point						

Table 8 - Test Matrix C - CFIT Warnings in Level Flight Over Mountainous Terrain

TEST POINT	FUNCTION / TERRAIN	ALTITUDE (AGL)	KIAS	NOTES	FLAP SETTING	PITCH ANGLE (deg)
1	CFIT in Level Flight	Ridge + 1000	125		50 %	0
2		Ridge + 1000	250		0%	0
3	Coliseum Mountain	Ridge + 1000	300	Torq limited	0%	0
4	Nordegg, Alberta	Ridge + 1000	125		50 %	0
5		Ridge + 1000	250		0%	0
6		Ridge + 1000	300	Torq limited	0%	0
7		Ridge + 1000	130		50 %	0
8		Ridge + 1000	250		0%	0
9		Ridge + 1000	300	Torq limited	0%	0
10		Ridge + 500	125		50 %	0
11		Ridge + 500	250		0%	0
12		Ridge + 500	300	Torq limited	0%	0
13		Ridge + 500	125		50 %	0
14		Ridge + 500	250		0%	0
15		Ridge + 500	300	Torq limited	0%	0
16		Ridge + 500	130		50 %	0
17		Ridge + 500	250		0%	0
18		Ridge + 500	300	Torq limited	0%	0
19	Tactical Mode	Ridge + 500	125		50 %	0
20	Gear Up	Ridge + 500	250		0%	0
21	Should see no warnings	Ridge + 500	300		0%	0

Table 9 - Test Matrix D - CFIT Dives Over Mountainous Terrain

TEST POINT	GCAS WARNING ALTITUDE (MSL)	KIAS	FLAP SETTING	PITCH ANGLE (deg)	ROLL ANGLE (deg)	HARD DECK RECOVERY ALTITUDE (MSL)	SIMULATOR ALTITUDE LOSS (ft)	PREVIOUS FLIGHT DATA ALTITUDE
1	7800	165	0 %	-5	0	7345	180	240
2	7900	165	0 %	-10	0	7435	240	330
3	8150	165	0 %	-15	0	7555	320	450
4	7750	200	0 %	-5	0	7275	110	170
5	7950	200	0 %	-10	0	7415	215	310
6	8050	200	0 %	-15	0	7505	320	400
7	7800	250	0 %	-5	0	7275	170	130
8	8100	250	0 %	-10	0	7385	260	280
9	9300	250	0 %	-15	0	7545	440	340
10	7800	310	0 %	-5	0	7255	110	150
11	8100	310	0 %	-10	0	7375	270	270
12	8350	310	0 %	-15	0	7635	525	530
37	7800	135	50%	-5	0	7273	130	168
38	7900	135	50%	-10	0	7346	180	241
39	8000	135	50%	-15	0	7385	220	280
40	7650	125	100%	-5	0	7255	150	90
41	7800	125	100%	-10	0	7275	160	170
42	8050	125	100%	-15	0	7415	180	310
43	7550	140	100%	-5	0	7175	50	70
44	7700	140	100%	-10	0	7235	130	120
45	7900	140	100%	-15	0	7355	190	250
46	7800	170	50%	-5	0	7235	60	130
47	7800	170	50%	-10	0	7255	150	150
48	7900	170	50%	-15	0	7465	250	360
		Six runs per test point						

Table 10 - Test Matrix E - Miscellaneous GCAS Evaluations

TEST POINT	FUNCTION	ALTITUDE (AGL)	KIAS	FLAP SETTING	ROLL ANGLE (deg)
1	Air-to-Air Refuelling	>2000	250	0 %	0
2	Glideslope Deviation	Approach	Vapp	Approach	0
3	Altitude Loss on Take-off	> 50	155	0 %	0
4	Altitude Loss on Go-around	Approach	200	G/A	0
5	Degraded Performance - > 5000AGL	>5000	Any	0 %	0
6	Degraded Performance - high bank angle	<2000	200	0 %	60
7	Degraded Performance - sensor failure	N/A	Any	Any	0
8	Altitude Advisory	800	Any	Any	Any
9	Flap Overspeed	und Test at Contr	N/A	N/A	N/A
10	Valid / Nuisance Warning Data Collection	Post Flight Analysi	N/A	N/A	N/A
11	Human Factors Assesment	st Flight Comme	N/A	N/A	N/A

APPENDIX B - AIRCRAFT/GCAS SENSOR ACCURACY DATA

Table 11 - Aircraft Sensor Range and Accuracy Data

PARAMETER	RANGE	RESOLUTION
Radar Altimeter height above ground	0 to 5,500 ft	±2 ft
Radar Altimeter rate	0 to 500 fps	±1 fps
Pressure altitude	0 to 50,000 ft	±10 ft
Pressure altitude rate	0 to 300 fps	±1 fps
Indicated airspeed	0 to 600 fps (355 kt)	±4 fps (2.4 kt)
True airspeed	0 to 600 fps (355 kt)	±4 fps (2.4 kt)
Pitch	±60°	±0.5°
Roll	±60°	±0.5°
Flap position	0 to 100 %	No data
Glideslope deviation	±2.0 dot	No data
Glideslope enable	0 to 1 (1 = glideslope enabled)	N/A
Glideslope validity	0 to 1 (1 = glideslope valid)	N/A
Localizer deviation	±2.0 dot	No data
Normal acceleration	0 to 6 g	0.01 g
Data Sources: Cubic GCAS Interface Control Document [3] Rosemount D9220181 Air Data Computer Specification [9]		

APPENDIX C - AIRCRAFT/GCAS SENSOR VALIDATION PLOTS

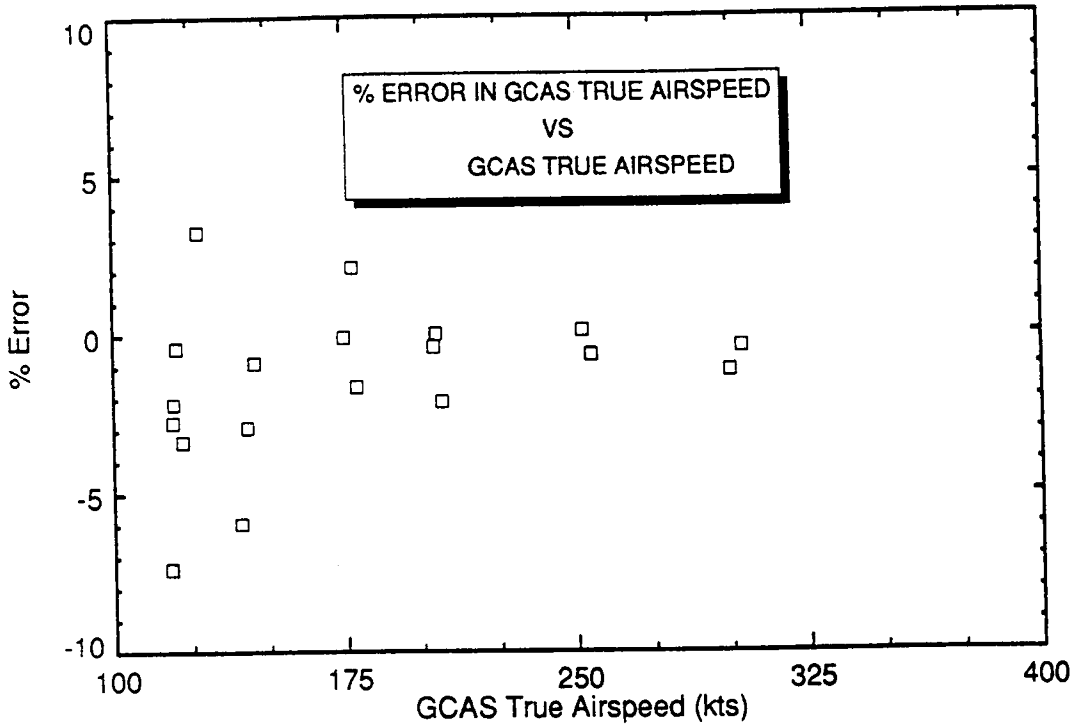

Figure 8 - % Error in GCAS True Airspeed versus True Airspeed

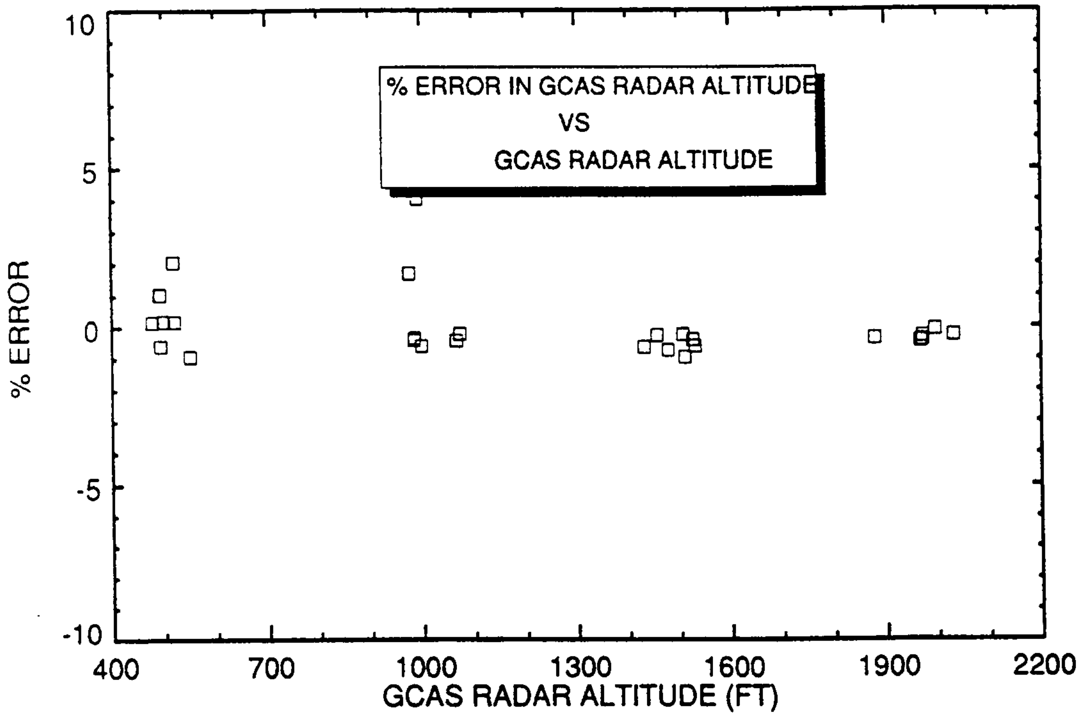

Figure 9 - % Error in GCAS Radar Altitude versus GCAS Radar Altitude

Table 12 - Level Flight Pressure Altitude Error Data

GCAS PRESSURE ALTITUDE (ft MSL)	PHOTO-THEODOLITE ALTITUDE (ft MSL)	ERROR
2403	2367	-1.5%
2886	2858	-1.0%
3410	3392	-0.5%
3895	3887	-0.2%

Table 13 - Dive Profile Measurand Error Data

FILE NAME	N[1]	TRUE AIRSPEED (kt)			RADAR ALTITUDE (ft)		
		RANGE	MEAN ERROR	STANDARD DEVIATION	RANGE	MEAN ERROR	STANDARD DEVIATION
96042307.DAT	198	297 - 334	5.75	2.46	1012 - 2228	-9.9	5.0
96043068.DAT	164	276 - 314	-0.32	1.31	924 - 1930	-14.8	10.1
96050904.DAT	130	152 - 167	-1.37	0.72	538 - 731	-5.0	4.1
96050936.DAT	131	281 - 296	3.46	7.92	458 - 1200	-10.9	11.8
TOTAL	623	152 - 334	2.35		458 - 2228	-10.4	

FILE NAME	N[1]	TERRAIN CLOSURE RATE (fpm)			GADC[2] VERTICAL VELOCITY (fpm)		
		RANGE	MEAN ERROR	STANDARD DEVIATION	RANGE	MEAN ERROR	STANDARD DEVIATION
96042307.DAT	198	0 - 7800	746	470	0 - 8065	846	489
96043068.DAT	164	0 - 7200	531	589	0 - 7001	638	716
96050904.DAT	130	0 - 1800	265	252	0 - 1762	364	286
96050936.DAT	131	0 - 6600	748	470	0 - 6559	931	626
TOTAL	623	0 - 7800	589		0 - 8065	708	

NOTE: 1. Number of samples
2. GCAS Air Data Computer

APPENDIX D - GCAS CFIT WARNING AND RECOVERY PLOTS FOR LEVEL TERRAIN

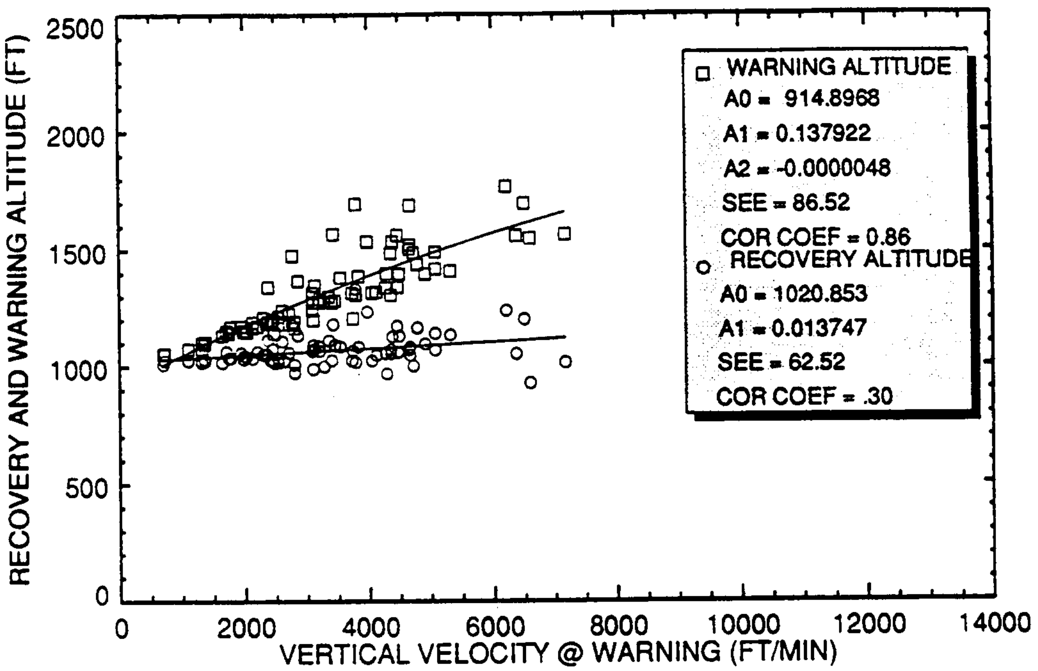

Figure 10 - GCAS Data, 1,000 ft Minimum Ground Clearance, 0° Bank

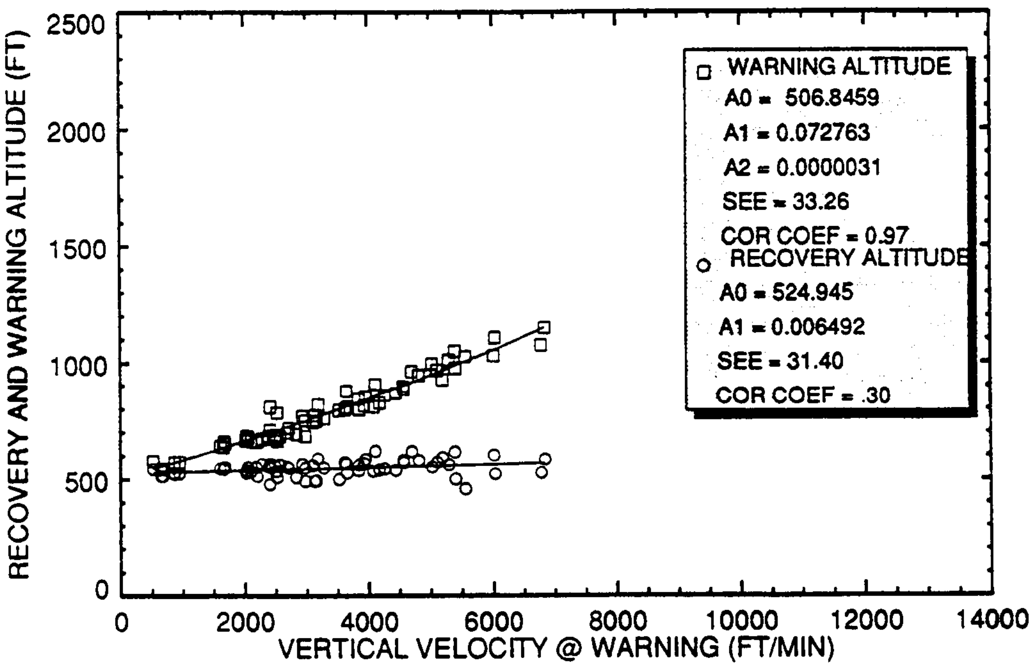

Figure 11 - GCAS Data, 500 ft Minimum Ground Clearance, 0° Bank

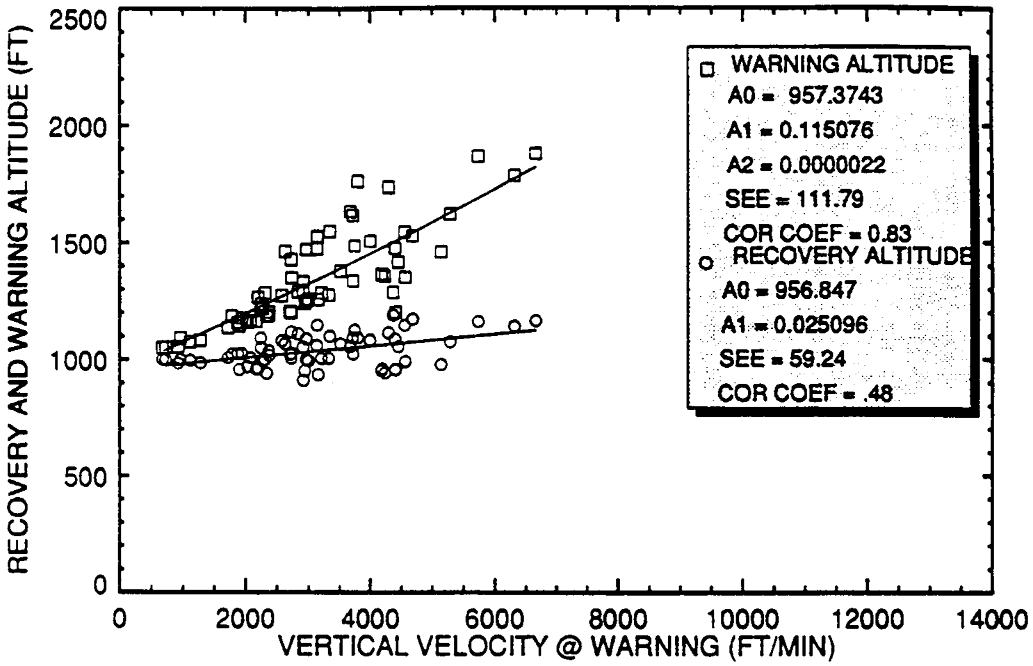

Figure 12 - GCAS Data, 1,000 ft Minimum Ground Clearance, 15° Bank

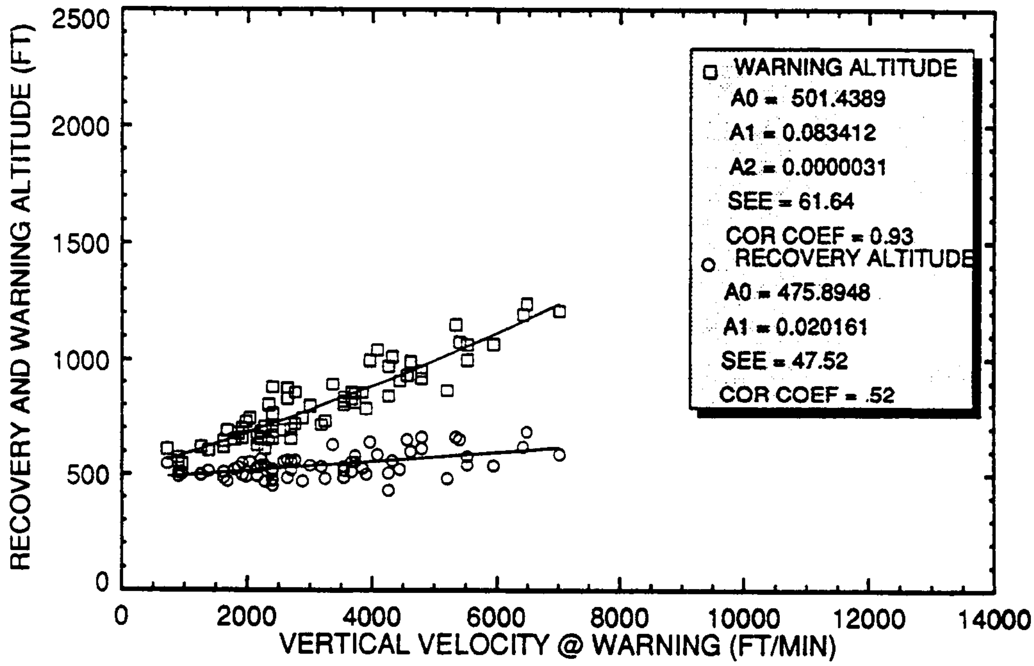

Figure 13 - GCAS Data, 500 ft Minimum Ground Clearance, 15° Bank

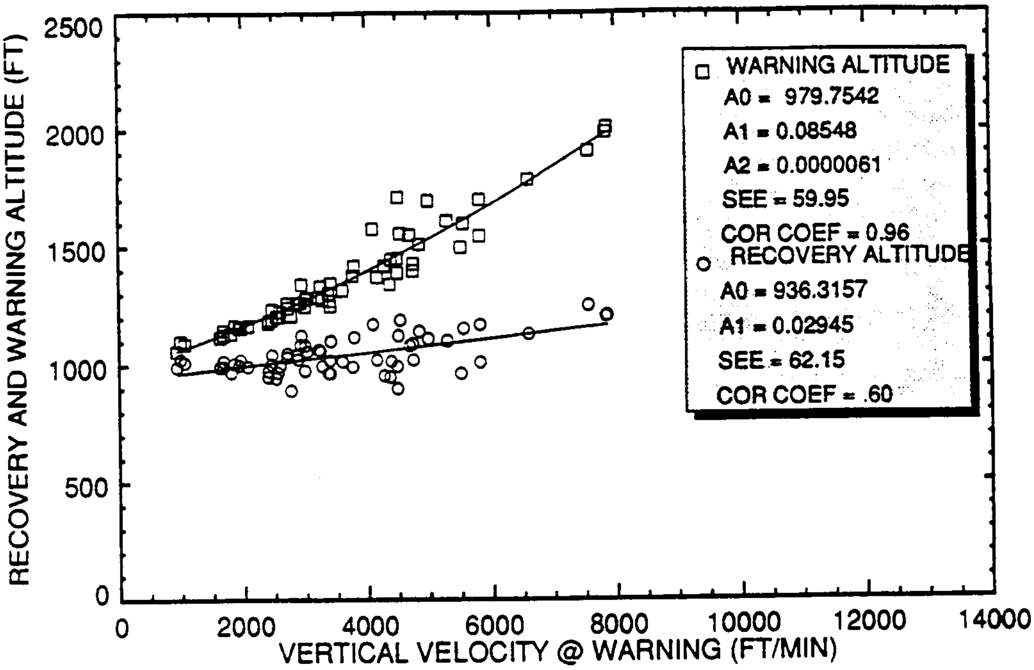

Figure 14- GCAS Data, 1,000 ft Minimum Ground Clearance, 30° Bank

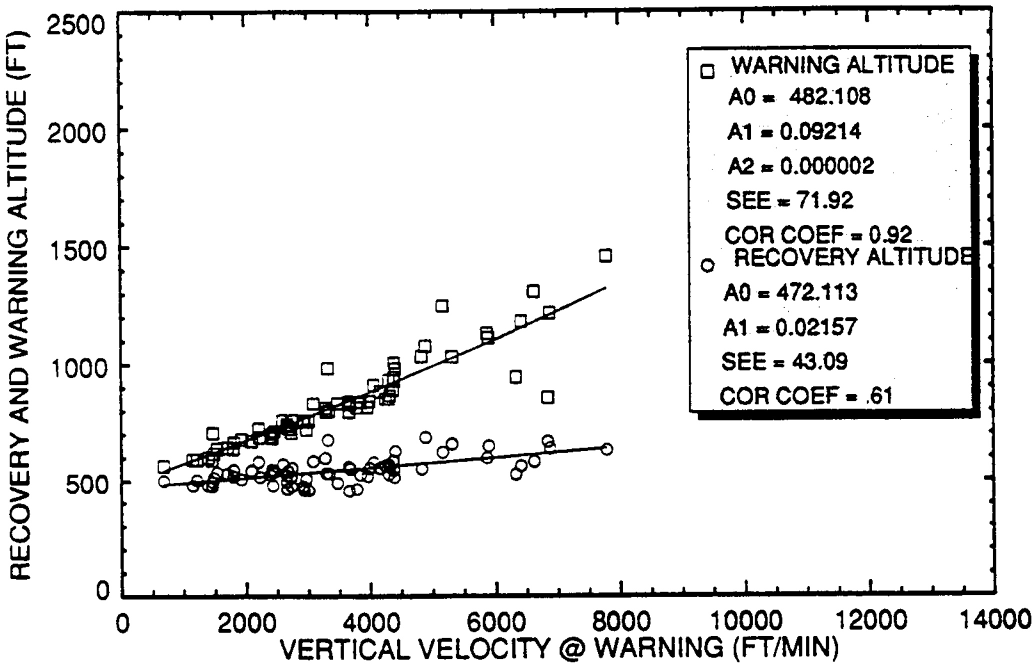

Figure 15 - GCAS Data, 500 ft Minimum Ground Clearance, 30° Bank

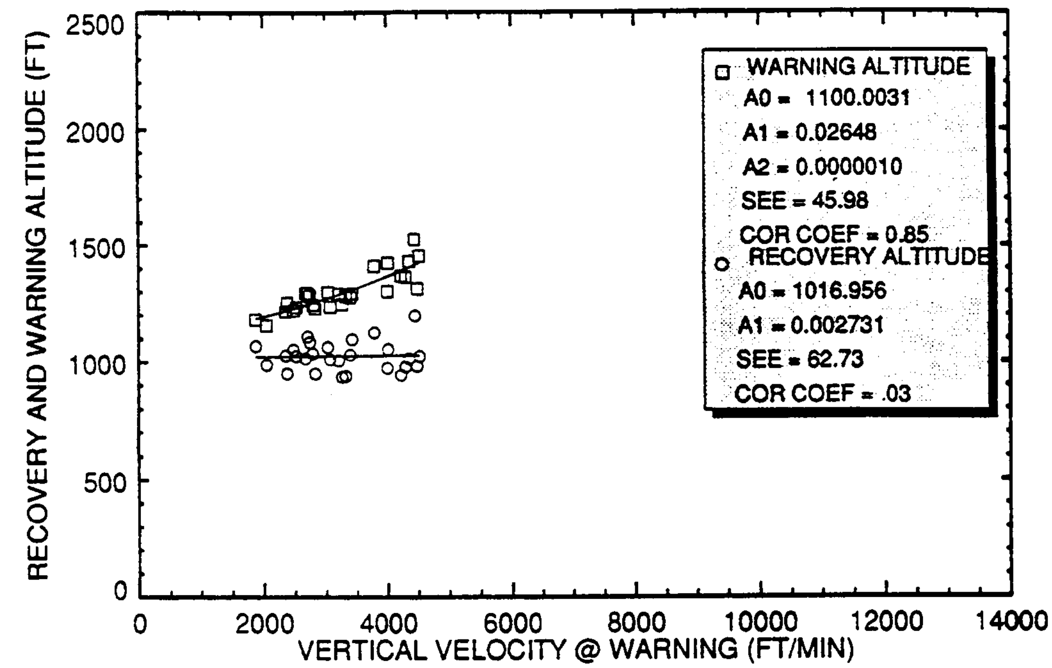

Figure 16- GCAS Data, 1,000 ft Minimum Ground Clearance, 45° Bank

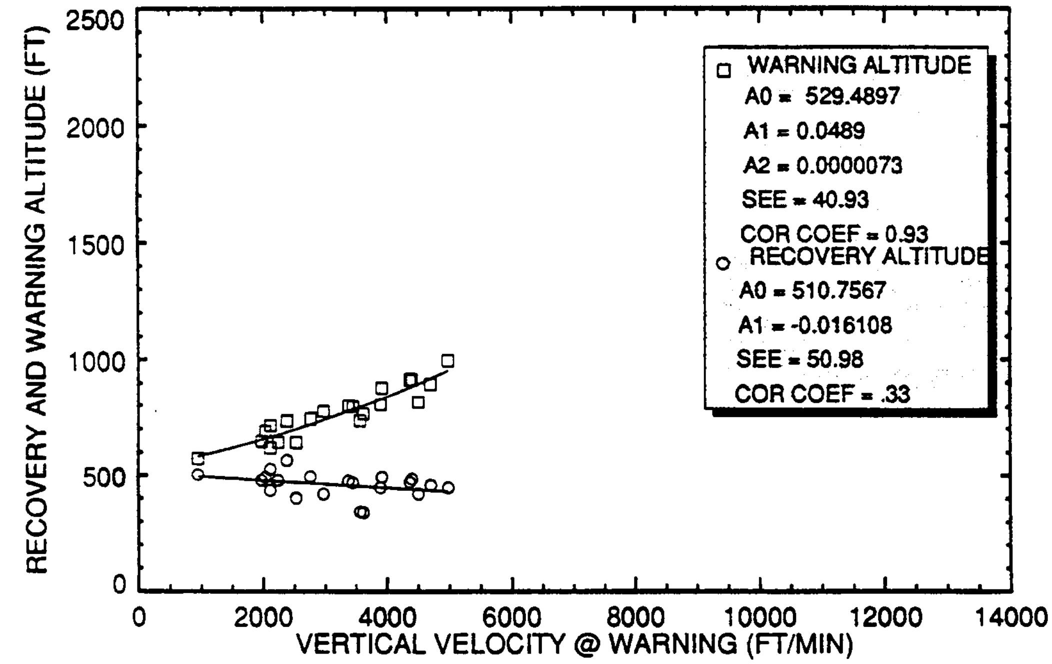

Figure 17 - GCAS Data, 500 ft Minimum Ground Clearance, 45° Bank

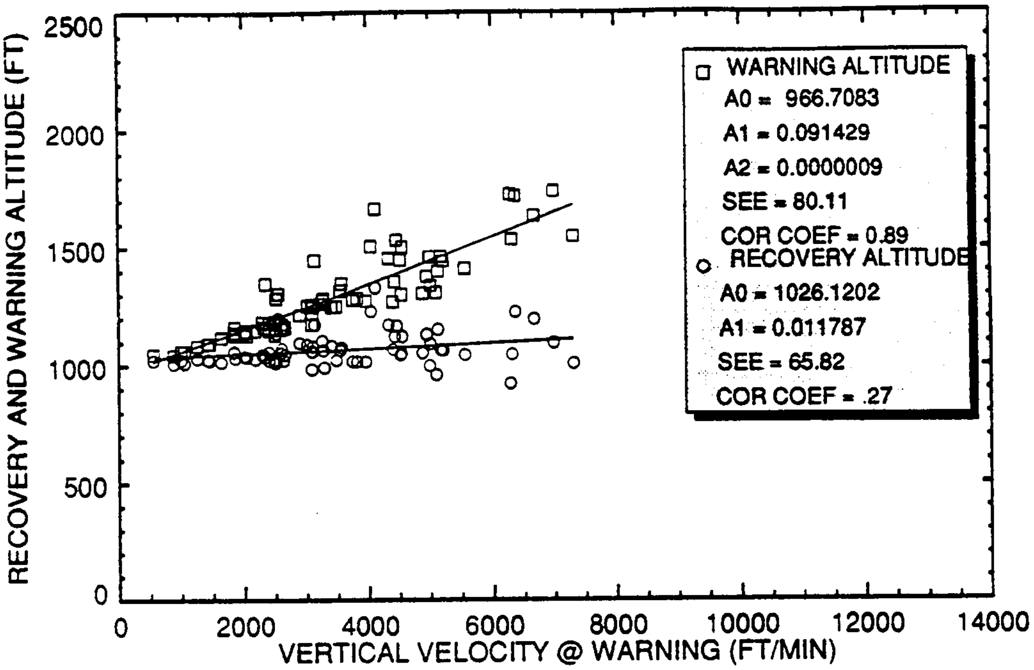

Figure 18- Phototheodolite Data, 1,000 ft Minimum Ground Clearance, 0° Bank

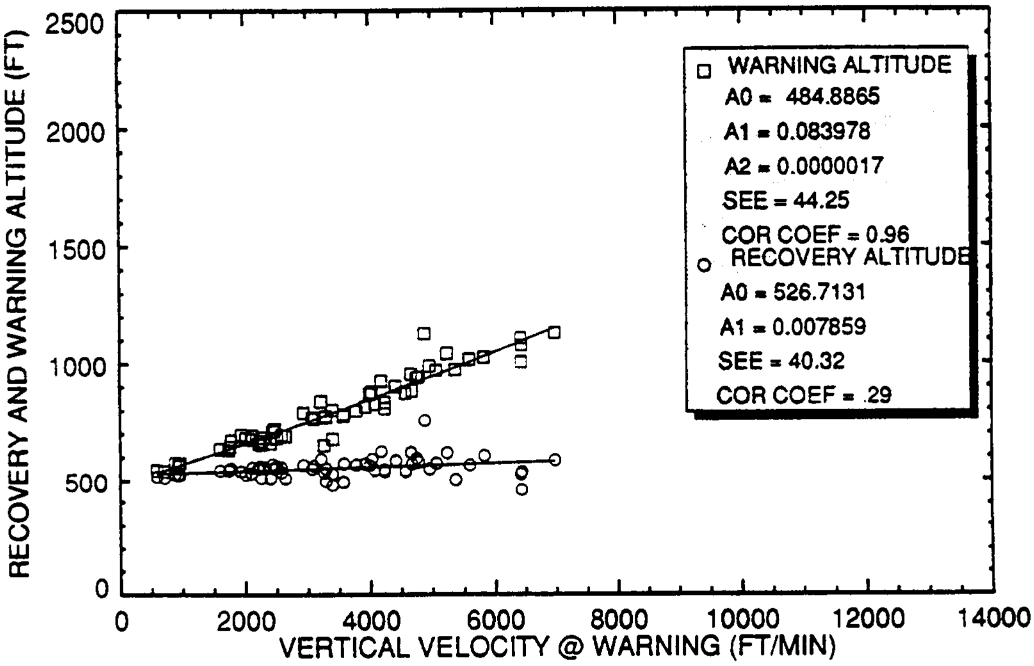

Figure 19 - Phototheodolite Data, 500 ft Minimum Ground Clearance, 0° Bank

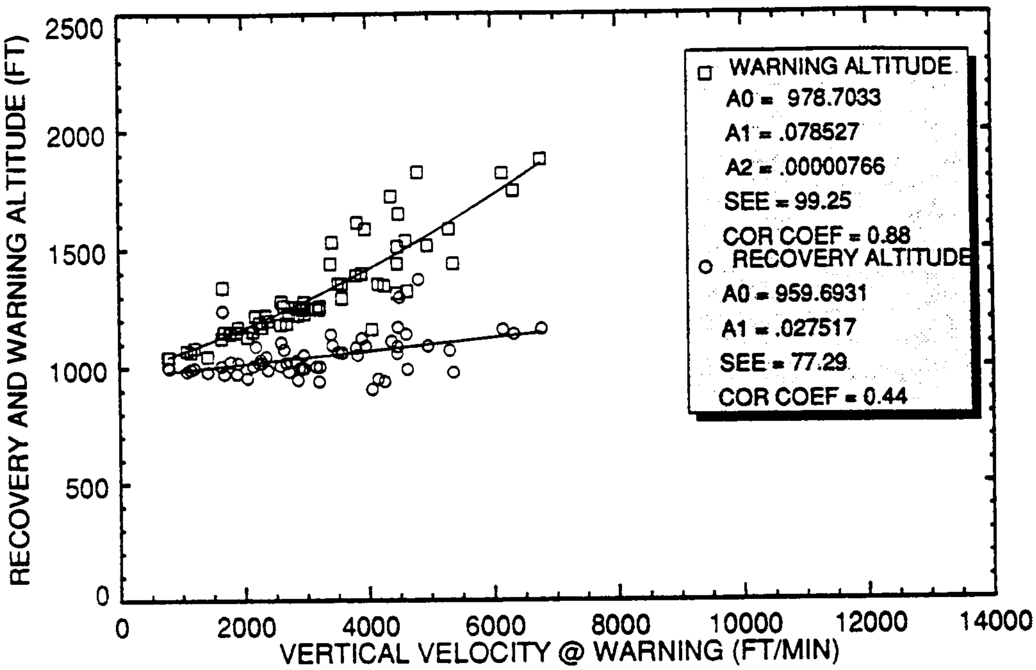

Figure 20- Phototheodolite Data, 1,000 ft Minimum Ground Clearance, 15° Bank

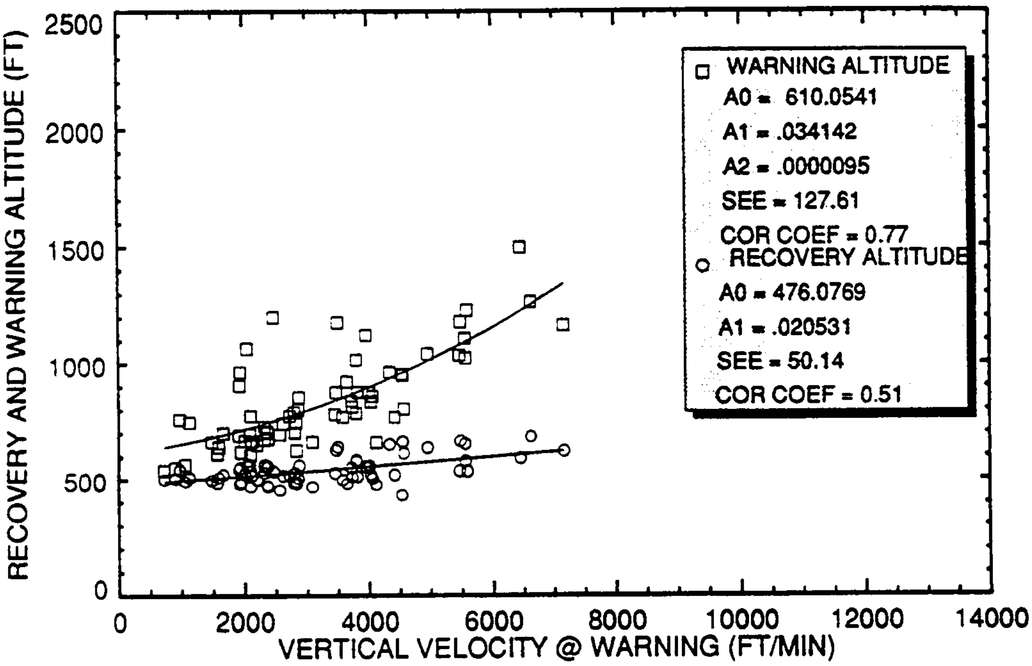

Figure 21 - Phototheodolite Data, 500 ft Minimum Ground Clearance, 15° Bank

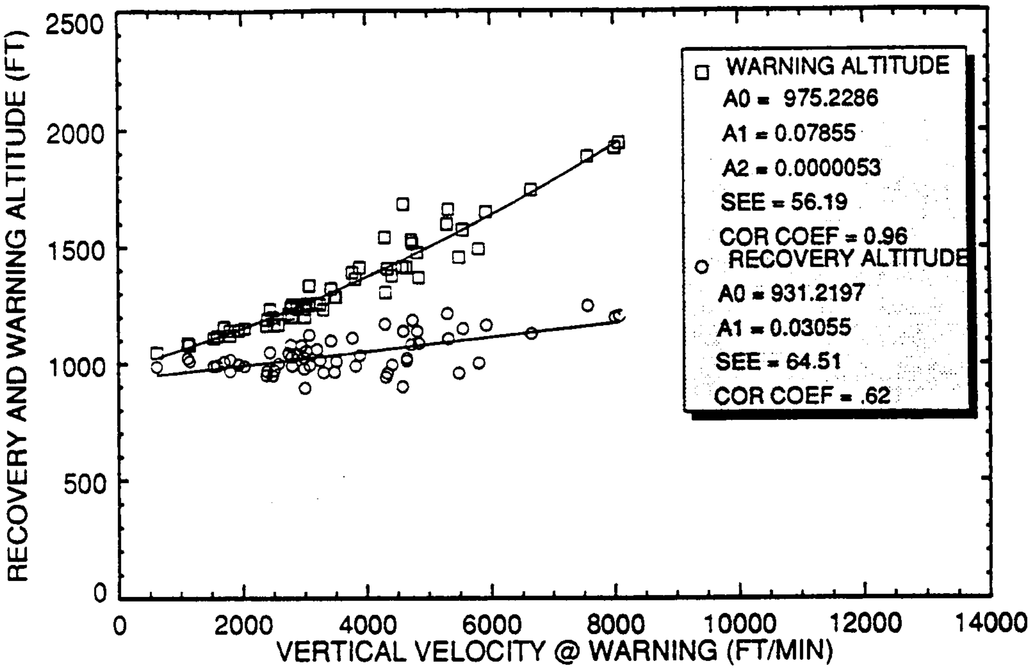

Figure 22- Phototheodolite Data, 1,000 ft Minimum Ground Clearance, 30° Bank

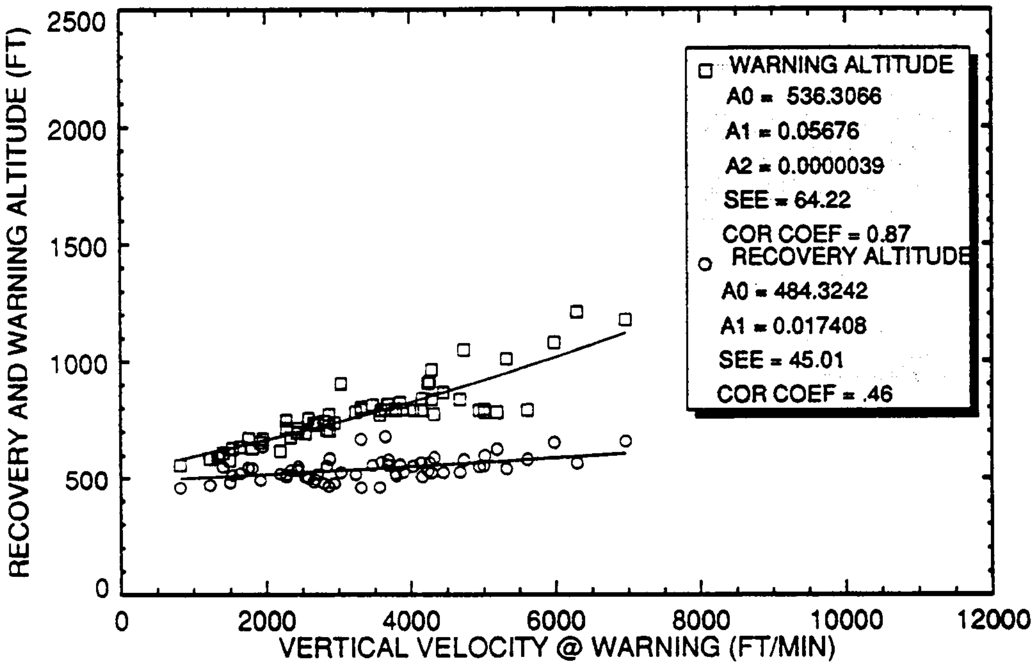

Figure 23 - Phototheodolite Data, 500 ft Minimum Ground Clearance, 30° Bank

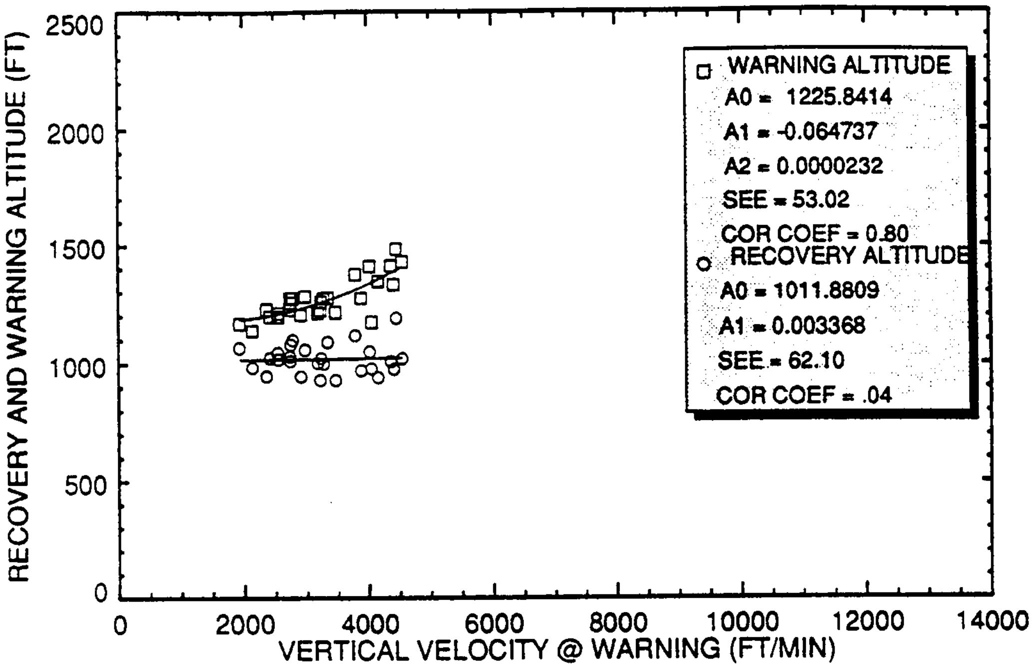

Figure 24- Phototheodolite Data, 1,000 ft Minimum Ground Clearance, 45° Bank

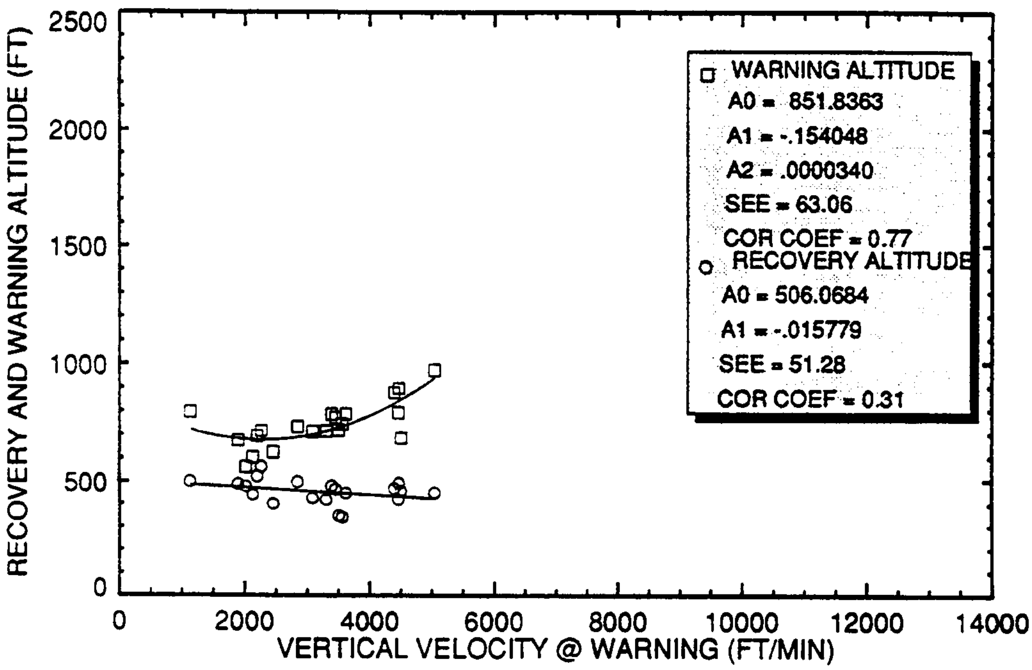

Figure 25 - Phototheodolite Data, 500 ft Minimum Ground Clearance, 45° Bank

Table 14 - Recovery Altitude Probabilities

Ground Clearance Setting = 500 ft.							
BANK ANGLE	n[1]	MEAN (ft)	STD DEV (ft)	t[2]	P($\bar{x}$ ≥450)[3]	t[2]	P($\bar{x}$ ≤650)[4]
0°	72	556	41.2	-21.8	1.00	19.4	1.00
15°	72	558	84.9	-10.8	1.00	9.2	1.00
30°	74	561	86.6	-11.1	1.00	8.8	1.00
45°	30	508	108.9	-2.9	0.996	7.1	1.00
All 500 ft data points	248	552	80.2	-20.1	1.00	19.2	1.00
Ground Clearance Setting = 1000 ft.							
BANK ANGLE	n[1]	MEAN (ft)	STD DEV (ft)	t[2]	P($\bar{x}$ ≥950)[5]	t[2]	P($\bar{x}$ ≤(1150)[6]
0°	80	1068	56.5	-18.6	1.00	13.1	1.00
15°	72	1058	82.7	-11.1	1.00	9.4	1.00
30°	72	1089	141	-8.4	1.00	3.7	1.00
45°	36	1117	189	-5.3	1.00	1.0	0.847
All 1000 ft data points	260	1078	116	-17.7	1.00	10.0	1.00

NOTES:

1. Number of samples.
2. t-random variable defined by [6]:

$$t = \frac{\bar{x} - \mu}{s / \sqrt{n}}$$

where $\bar{x}$ = sample mean
μ = population mean, i.e. either 500 ft. or 1000 ft.
s = standard deviation
n = number of samples

3. Probability that a CFIT recovery will occur above 450 ft. (The operational ground clearance setting will be 50 ft. above ground level).
4. Probability that a CFIT recovery will occur below 650 ft. (Recovery 150 ft. above the ground clearance setting is considered a nuisance warning [1]).
5. Probability that a CFIT recovery will occur above 950 ft.
6. Probability that a CFIT recovery will occur below 1150 ft.

APPENDIX E - GCAS CFIT WARNING PLOTS FOR MOUNTAINOUS TERRAIN

DETERMINATION OF DIVE PROFILE

Dive profiles for GCAS CFIT tests over mountainous terrain were determined as follows:

a. used the same test point matrix for 0° bank dives as done for level terrain CFIT tests;

b. closure rate was calculated by using flight path (dive) angles determined for each 0 bank dive from level flight:

$$Closure\_Rate = TAS * \sin\theta + \frac{dx}{dt} * \frac{dy}{dx}$$

or

Closure Rate = (TAS * sin θ) + (TAS * cos θ) * Terrain Gradient

Where: TAS = aircraft true airspeed,

θ = aircraft flight path angle,

dx/dt = aircraft ground speed (no wind),

dy/dx = terrain gradient (Coliseum Mountain Gradient = 0.3);

c. the GCAS warning altitude versus closure rate plots (Appendix D) for 0° bank were then used to determine anticipated warning altitudes for each test point closure rate; and

d. the intersection of the flight path angle with the warning altitude (AGL), shown in Figure 26, yielded anticipated warning altitudes (MSL) and distances from the mountain peak. Planning indicated that warnings for all of the test points would fall within a region 2,000 to 4,000 ft, horizontal, prior to the mountain peak. (Note: flight test results proved this to be true).

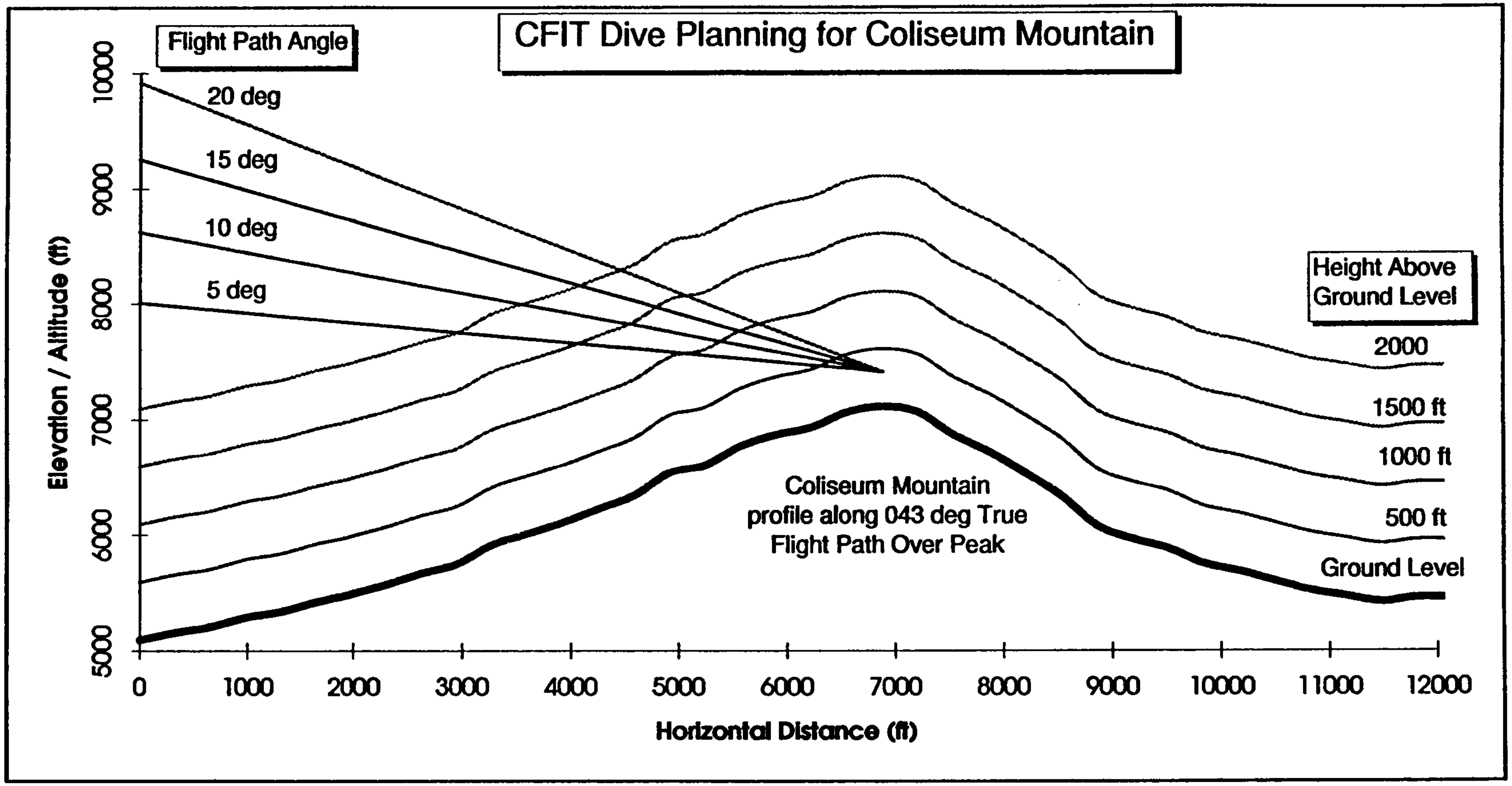

Figure 26- CFIT Dive Planning for Coliseum Mountain

DETERMINATION OF NUISANCE WARNINGS DURING LEVEL FLIGHT

Based on the results of the GCAS CFIT tests, there is the potential for nuisance GCAS "Pull-up" warnings in level flight over mountainous terrain. Using the equation for closure rate, and setting the aircraft flight path angle to zero, the closure rate becomes:

$$Closure\_Rate = TAS * \frac{6076 \frac{ft}{nm}}{60 \frac{\min}{hr}} * Terrain\_Gradient$$

where: Closure rate is in fpm, TAS is in kt, and Terrain Gradient is the tangent of the slope in degrees.

Using the coefficients from Figure 29 and changing the value of A0 from the flight test value of 1,000 feet to the operational ground clearance altitude of 50 feet yields the radar altitude at which the GCAS will issue a CFIT warning, as shown in Figure 27:

$$Warning\_Height = A_1 * Closure\_Rate + A_0$$

or

$$Warning\_Height = A_1 * TAS * \frac{6076 \frac{ft}{nm}}{60 \frac{\min}{hr}} * \tan(terrain\_slope) + Ground\_Clearance$$

where: Warning Height is in ft, TAS is in kt, terrain slope is in degrees, and ground clearance is in feet. Figure 27 shows the CFIT warning envelope for level flight versus terrain slope and TAS. Aircraft that maintain flight parameters above the warning surface in Figure 27 should not receive warnings. For example, a CC-130 flying at 200 kt, 6,000 MSL flying over mountainous terrain with peaks at 4,000 MSL and terrain gradients in excess of 40 will likely receive nuisance warnings from the GCAS.

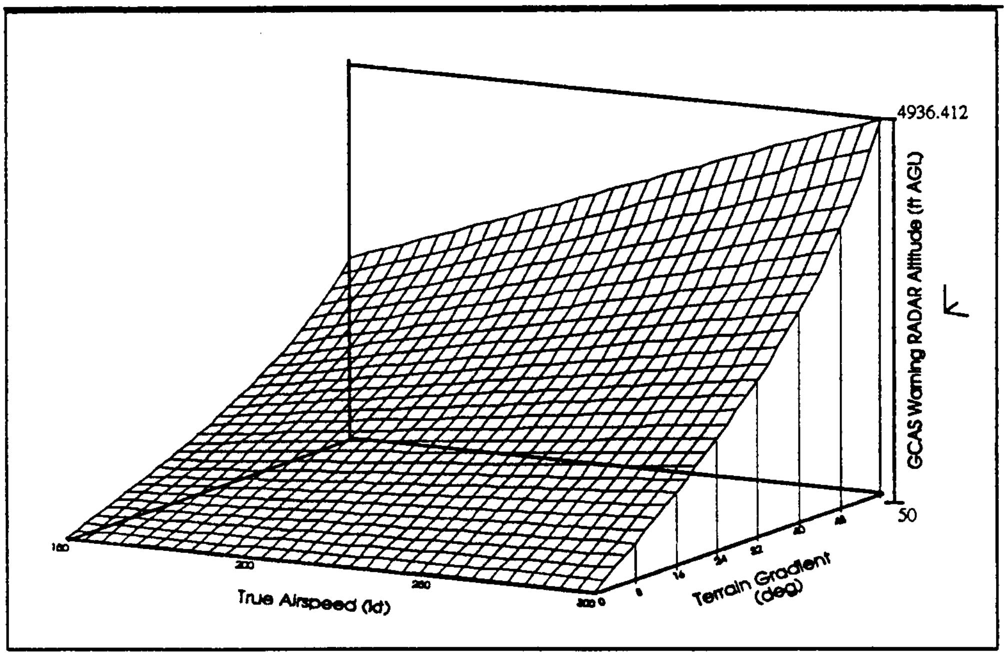

Figure 27 - CFIT Warning Response for Level Flight Over Mountainous Terrain

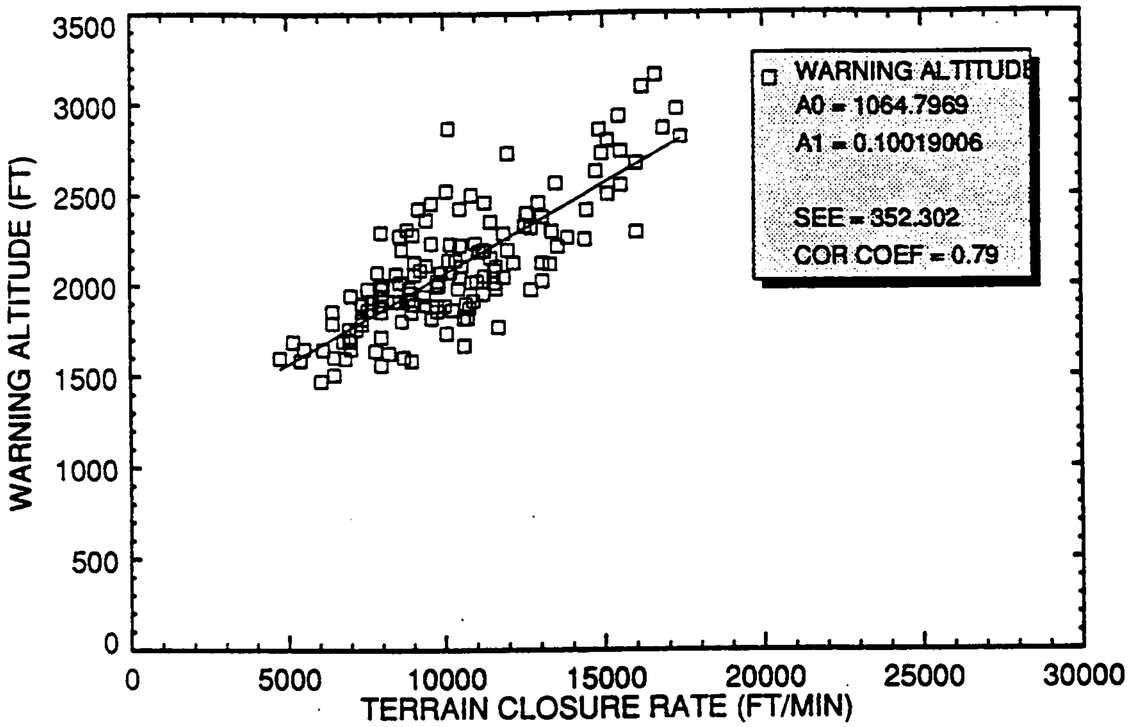

Figure 28 - CFIT Warning Envelope Over Mountainous Terrain

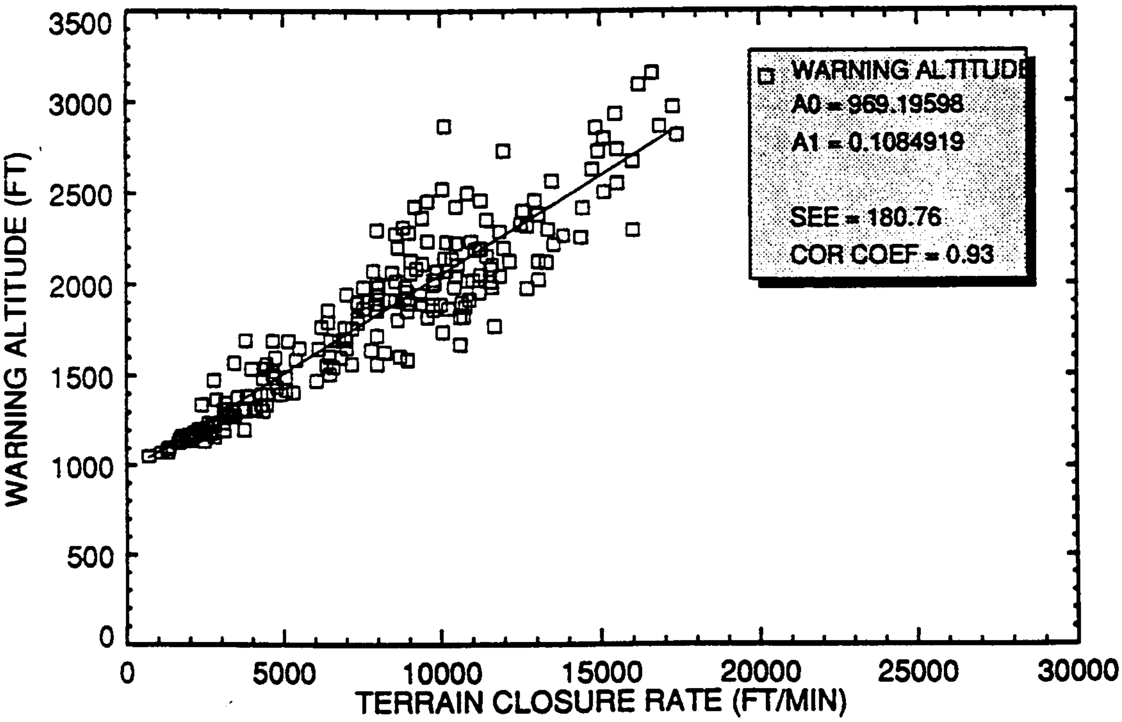

Figure 29 - CFIT Warning Envelope - Combined Level and Mountainous Terrain Data for 0° Bank

APPENDIX F - CHRONOLOGY OF EVENTS

Table 15 - Chronology of Events

DATE (1996)	EVENT / TEST POINTS	GCAS MGC*	HOURS FLOWN
21 March	GCAS calibration check fight on CC-130338	50 ft	2.0
17 April	Ferry fight of CC-130339 to Cold Lake	50 ft	0.8
22 April	Sensor validation - Test Points A1 to A36 CFIT over level terrain - Test Points B1 to Bll, Runs 1 and 2	1,000 ft	3.0
23 April	CFIT over level terrain - Test Points B12 to B33, Runs 1 and 2	1,000 ft	2.0
29 April	CFIT over level terrain - Test Points B36 to B6l, Runs 1 and 2	1,000 ft	2.6
30 April	CFIT over level terrain - Test Points B62 to B86, Runs 1 and 2 CFIT over level terrain - Test Points B1 to B17, Run 3	1,000 ft 1,000 ft	2.2
2 May	CFIT over level terrain - Test Points B18 to B86, Run 3	1,000 ft	2.2
2 May	CFIT over level terrain - Test Points B1 to Bll, Runs 4, 5, and 6	500 ft	2.2
3 May	Ferry flight of CC-130339 to Edmonton	500 ft	0.8
5 May	Level flight over mountainous terrain - Test Points C1 to C21, Runs 1 and 2	1,000 ft	3.3
8 May	CFIT over level terrain - Test Points B12 to B45, Runs 4 and 5	500 ft	3.1
8 May	Level flight over mountainous terrain - canceled due to low cloud	--	1.2
9 May	CFIT over level terrain - Test Points B46 to B61, Runs 4 and 5 CFIT over level terrain - Test Points B12 to B44, Run 6	500 ft	3.0
10 May	CFIT over level terrain - Test Points B62 to B74, Runs 4 and 5 CFIT over level terrain - Test Points B45 to B74, Run 6	500 ft	2.7
12 May	Level flight over mountainous terrain - Test Points C1 to C21, Run 3 Level flight over mountainous terrain - Test Points C10 to C21, Runs 4, 5, and 6	500 ft 500 ft	3.0
13 May	CFIT over level terrain - Test Points B75 to B86, Runs 4, 5, and 6	500 ft	2.3
21 May	CFIT over mountainous terrain - Test Points D1 to D24, Run 1 CFIT over mountainous terrain - Test Points D1 to D9, Run 2	1,000 ft	3.1
23 May	CFIT over mountainous terrain - Test Points D10 to D24, Run 2	1,000 ft	3.2
23 May	CFIT over mountainous terrain - Test Points D1 to D24, Runs 3, 4, and 5	1,000 ft	3.1
24 May	CFIT over mountainous terrain - Test Points D1 to D24, Run 6 End Of Test	1,000 ft	2.0
	TOTAL FLIGHT HOURS		47.80

Note: *Minimum Ground Clearance

LIST OF ABBREVIATIONS

LIST OF ABBREVIATIONS

The following abbreviations appear in this report:

ADC	Air-data Computer
AETE	Aerospace Engineering Testing Establishment
AGL	Above Ground Level
AOI	Aircraft Operating Instruction
BIT	Built-in Test
CFIT	Controlled Flight into Terrain
fpm	Feet Per Minute
fps	Feet Per Second
GCAS	Ground Collision Avoidance System
Hz	Hertz
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
KIAS	Knots Indicated Airspeed
kt	Knots
MSL	Mean Sea Level
nm	Nautical Mile
RPM	Revolutions Per Minute
VAC	Volts Alternating Current

GLOSSARY

GLOSSARY

Dots	- a measure of displacement from the intended flight path. For instrument landing systems (ILS) it is a measure of angular displacement. For glideslope, the optimal glidepath height is 3° with a beamwidth (top to bottom) of 1.4°. This equates to a full scale of 4 dots on the glideslope indicator in the aircraft cockpit, that is, ±2 dots for ±0.7° deviation from the glidepath.
Localizer	- provides lateral guidance for an instrument landing system. The center of the localizer beam is in line with the center of the runway.
Pressure Altitude	- aircraft altitude above sea level using standard atmospheric temperature and pressure for sea level conditions; +15° Celsius and a barometric setting of 29.92 inches of mercury.
Radar Altitude	- aircraft height above the ground.
Phototheodolite	- a camera used to track the test aircraft and record time, azimuth, and elevation at the edge of each film frame. Several cameras are used to track the aircraft and, through post flight data processing, provide position and rate information.
Tactical Mode	- used in the CC-130 Hercules GCAS implementation to disable CFIT "Pull-up" warnings when conducting intentional low level operations such as search and rescue missions.

VITA

VITA

Alexander Lawrence (Larry) Dublenko graduated from the University of Alberta in 1982 with a Bachelors of Science Degree in Electrical Engineering. He spent the next three years working in industry designing both hardware and software for applications in telephone user equipment, microprocessor oil field pump motor controllers, drivers for ultrasonic atomizers in thermoelectric generators, and data acquisition systems. During this time, he obtained his private pilot license and gained a keen interest in aircraft and aviation. In January 1986, he began working for the Canadian Department of National Defence's Aerospace Engineering Test Establishment (AETE) in Cold Lake, Alberta. Initially he was involved in the design and implementation of flight test instrumentation systems but also moved into areas of electromagnetic compatibility analysis and testing as well as avionics systems testing. During the period 1993 to 1995, he was seconded to the United States Air Force C-17 transport aircraft flight test program at Edwards Air Force Base, California and spent those two years as the lead avionics test engineer. Since returning to Cold Lake in 1995, he has been actively involved in evaluating CC-130 Hercules avionics systems as well as acting as the senior engineering advisor to AETE's Evaluation Squadron.