EVALUATION OF A TERRAIN PROXIMITY WARNING SYSTEM (DOWNWARD LOOKING RADAR) FOR POSSIBLE ENHANCEMENT OF FLIGHT SAFETY

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SEPTEMBER 1973

INTERIM REPORT

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

Prepared for

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington D. C., 20591
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# Evaluation of a Terrain Proximity Warning System (Downward Looking Radar) for Possible Enhancement of Flight Safety

**Abstract**

A review of all literature and available test results of an airborne independent altitude monitor based on radio altitude information was undertaken. Results indicated that limited flight safety enhancement is attainable by use of such a device.

## Key Words
- Altimetry
- Flight Safety
- Radio Altitude
- Approach and Landing Accidents
- Altitude Alerting
- Independent Altitude Monitor

## Distribution Statement

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INTRODUCTION

BACKGROUND.

A number of commercial (air carrier) accidents occur during the approach and landing or takeoff and initial climb phase of flight operations. Most of these accidents involve inadvertent controlled flight into the ground.

One of the factors, which may enhance flight safety in this area, is height information and its use by the flight crew. A program addressing itself to this area has been undertaken by the Federal Aviation Administration (FAA). This program, "An Independent Altitude Monitor (IAM)," includes both ground based and airborne devices and/or procedures.

It has been proposed that an airborne device based on more efficient use of existing radio altimeter (terrain clearance), information be considered.

OBJECTIVE.

The objective of this effort was the evaluation of an airborne Ground Proximity Warning System (GPWS). This device uses, as its primary control parameter, absolute height above the ground (terrain), as determined by an airborne radio (radar) altimeter.

The evaluation was based on the following:

1. A review of published reports and brochures.
2. A review and analysis of available industry flight test data.
3. A review and analysis of all FAA certification tests concerning the GPWS.

DISCUSSION

DESCRIPTION OF EQUIPMENT.

The GPWS consists of a small analog computer, Figure 1, and an aural and visual alarm system, Figure 2. The GPWS is so conceived that the computer can utilize existing aircraft aural and visual alarm systems or operate an independent alarm system.

The computer consists of three logic boards which provide four modes of alarm (warning) by processing the output electrical signals received from the radio altimeter, central air data computer (rate-of-climb), and landing gear position. Thus, all of the processed information comes from existing information currently available on most modern air carrier-type aircraft. The detailed specifications of the system are contained in Reference 1.
The system provides a noncancellable crew warning under the following conditions:

Mode 1 - Excessive Barometric Pressure Sink Rate (Negative Rate-of-Climb). A warning is provided when the height of the aircraft above the ground is less than 2,500 feet and the sink rate of the aircraft exceeds certain defined limits. The variations of this alarm mode are shown in Figure 3.

The current production version uses the warning envelope defined by curve "B." Any of the systems now in use can be modified to this operating envelope by substitution of one or more of the computer's logic boards.

Mode 2 - Descent in Wrong Configuration (Landing Gear Up). A warning is generated when the clearance of the aircraft above the ground is less than 480 feet when descending from any height of more than 760 feet.

Although the current production version uses the landing gear position input, it has the capability of utilizing the wing flap position instead. The enhancement of flight safety by use of the wing flap mode was recently brought to the attention of the manufacturer.

Mode 3 - Descent During Takeoff. A warning is annunciated whenever a negative sink rate is developed during the initial climb phase following a takeoff or execution of a missed approach (go-around) as long as the aircraft is less than 700 feet above the ground.

Mode 4 - Excessive Terrain Closure Rate. A warning is provided when the radio altitude information indicates a predefined terrain closure rate which may be due to the combination of the flight path angle, ground rise angle, and flight speed.

The operating envelope is designed to allow a safe clearance above the terrain to be developed by increasing the "g" forces experienced by the aircraft and passengers by 0.5g's (1.5g's total). The maximum assumed ground rise angle has to be less than 65°. The rise angle normally experienced in nature is less than 60°, except where the flow of water (rivers, etc.) has cut a gorge or a rock has produced a precipice.

It should be noted that this system concept is predicated on the cancellation of a warning only by a change in the flight path of the aircraft.
LITERATURE REVIEW.

A literature search produced published documents which are available to the general public, References 1 through 13, inclusive; and four proprietary documents which are not available for general dissemination. The latter are accordingly not referenced; however, the test data has been extracted from these documents and are contained herein.

Reference 6 contains the flight path profile of one-hundred and fifteen (115) commercial aircraft accidents which have occurred over the past twenty (20) years. According to this document eighty-eight (88) of these would have received a warning from the GPWS had it been installed.

A careful analysis of the information contained in Reference 6 indicates the following:

1. Twenty-eight (28) of the reported accidents were during the approach phase of flight operations. Of these, only nineteen (19) would have produced an alarm as the GPWS is designed and produced, Reference 1.

2. Five (5) of the reported accidents were during the takeoff phase of flight operations.

The total number of accidents for which the GPWS would have provided an alarm as it is currently manufactured would have been twenty-four (24). The contribution to safety in these cases require further qualification for such factors as errors in approach or takeoff power, flap configuration, and angle-of-attack. Thus, the total usefulness in these selected accidents has not been fully identified in Reference 6.

Reference 10 indicates that the initial "trip equation" (alarm), for Mode 4, terrain closure was

\[
h_{\text{trip}} = h_c \left( \frac{h_c + 50}{6.25} \right)
\]

where

\[
h_{\text{trip}} = \text{the radio height at which closure rate warning is activated.}
\]

\[
h_c = \text{ terrain closure rate (function of radio height rate} \ (h_r) \text{ and barometric altitude rate} \ (h_b) \text{)}
\]

Equation (1) was based on the following assumptions:

a. The pilot's reaction time is 3 seconds.

b. The aircraft shall clear the terrain with a margin corresponding to 5 seconds of height less at the initial rate of closure.

c. A constant 1.1-g pull-up is made.
The GPWS designed to Equation (1) resulted in many false warnings according to the cited reference. Accordingly, the "trip equation" was modified to reflect the following:

\[ H = h_c^{'} \left( \frac{h_c^{'} + T}{2ng} \right) \]  

(2)

where

\[ n = 0.4 \]
\[ g = 32.2 \text{ ft/sec} \]
\[ T = 0.3 \ h_c^{'} \]

The above equation represents the height loss in a 1.4-g pull-up maneuver plus a margin for reaction time which is a function of the closure rate (e.g. for a closure rate of 30 feet per second (1,800 ft/min) the margin is 9 seconds which is equal to a height of 270 feet above the terrain).

A detailed description and operation of the system is contained in Reference 7.

FLIGHT TESTS.

Several independent flight tests have been conducted by industry to evaluate one or more models of the GPWS. As previously noted, the documents related to four of these programs are proprietary and are not available for general dissemination.

In addition to the above, tests were conducted relative to FAA certification of the GPWS in several aircraft (References 12 and 13). During the later tests, the flight profile of four selected air carrier accidents were simulated in flight. The purpose of these later tests was to verify the probable alarm mode of the current production version of the GPWS under the simulated flight profile. Details of the test program, instrumentation, and test results are contained in Reference 13.

EVALUATION RESULTS.

The analysis of the flight test data using Mode 1 - Excessive Barometric Pressure Sink Rate is shown in Figures 4 through 7. The test results shown reflect that the system operates reasonably close to the particularly defined performance envelope. Figure 7 reflects the test results obtained in the tests conducted for the FAA in March, 1973 as described in Reference 13.

Figure 8 indicates the maximum operating envelope for Mode 1 based on the maximum sink rates developed during Boeing tests. This indicates that it is possible to enlarge the warning envelope without generating nuisance warnings.
Figure 9 shows the finalized production version operating envelope. Also shown are three accidents involving air carrier jet aircraft. In two of the three accidents, the GPWS would not have provided an alarm for this mode. However, the SAS DC-8-62 would have had an 8-second warning due to an excessive sink rate which would have alarmed at approximately 600 feet above the ground.

The test results for Mode 2 - Descent in Wrong Configuration - are shown in Figure 10. Again, the system performs within the design configurations.

Figure 11 indicates that for the three accidents shown, none would have produced an alarm using the landing gear position as the criteria for erroneous configuration. However, two of the aircraft involved in these accidents, namely, the AAL580 and EAL L-1011, would have had at least a 10-second warning if flap position were the criterion. It should be noted that only two of the three accidents selected were the same as those shown in Figure 9.

Figure 12 shows the test results for Mode 3 - Descent During Takeoff. Figure 13 shows the current production envelope for this mode. The transition point identifies the point at which Mode 3 becomes functional.

Figure 14 is a summary of all available flight test data for Mode 4 - Excessive Terrain Closure Rate. There are two nuisance alarms reported in the data and five undetected alarm conditions. The nuisance alarms generated are very close to the operating envelope and, therefore, should be considered acceptable. Some of the undetected alarm conditions may be due to the time constant of the GPWS which is approximately 2 seconds in the gear up and 7 seconds in the gear down positions.

Figure 15 indicates that the current production version would have provided an 8-second alarm for the SAS DC-8-62 accident. In the case of all other accidents noted in the previous figures, the GPWS would not have alarmed in this mode.
CONCLUSIONS

The following conclusions may be drawn from the test data incorporated herein:

1. This type of a system shows promise of being able to enhance flight safety in some specific areas.

2. The system has experienced nuisance alarms which were eliminated by reducing the operating envelope.

3. The time constant of the system, as currently designed, inhibits the usefulness of the system in some cases.

4. The optimum warning envelopes for each warning mode have not been defined nor documented.
REFERENCES


FIGURE 1. GROUND PROXIMITY WARNING COMPUTER
FIGURE 2. SUNDMSTRAND QUEEN AIR VISUAL WARNING DEVICE
FIGURE 3. SUMMARY OF EXCESSIVE SINK RATE OPERATING ENVELOPES (MODE 1)
FIGURE 4. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - BOEING
TEST NUMBER 1
FIGURE 5. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - BOEING
TEST NUMBER 2

- NO WARNING
- WARNING
FIGURE 6. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - DOUGLAS TESTS NUMBER 1 AND NUMBER 2
FIGURE 7. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - SUNDBRAND STC TESTS
FIGURE 8. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - MAXIMUM OPERATING ENVELOPE
FIGURE 9. MODE 1 - EXCESSIVE BAROMETRIC SINK RATE - PRODUCTION VERSION
Figure 10. Mode 2 - Descent in wrong configuration - Boeing and Douglas tests.
GEAR UP MODE (PRODUCTION MODEL) - NO WARNING
FLAP OTHER THAN LANDING (PROPOSED MODEL) - WARNING
EAL L-1011 - WARNING IF FLAP MODE USED INSTEAD OF GEAR (10 SEC.)
SAW DC-9 - NO WARNING
AAL-580 WARNING IF FLAP MODE USED INSTEAD OF GEAR (50 SEC.)

FIGURE 11. MODE 2 - DESCENT IN WRONG CONFIGURATION - PRODUCTION VERSION
FIGURE 12. MODE 3 - DESCENT DURING TAKEOFF - BOEING TESTS
FIGURE 13. MODE 3 - DESCENT DURING TAKEOFF - PRODUCTION VERSION
FIGURE 14. MODE 4 - EXCESSIVE TERRAIN CLOSURE RATE - BOEING AND DOUGLAS TESTS
FIGURE 15. MODE 4 - EXCESSIVE TERRAIN CLOSURE RATE - PRODUCTION VERSION