GPS-Based Terrain Avoidance Systems - A Solution for General Aviation Controlled Flight into Terrain

Jonathan Baldwin, Rick Cassell, Alexander Smith
Rannoch Corporation, Alexandria, VA

BIOGRAPHIES

Mr. Baldwin received his BSEE and MSEE from the University of Wales in 1985 and 1988 respectively. He is a private pilot, Registered Professional Engineer, Member of the Institute of Electrical Engineers (IEE), and a Chartered Member of the Engineering Council, U.K.

Mr. Cassell has 19 years of experience providing FAA systems engineering support. He has extensive experience with safety critical systems, specifically precision landing systems. He has worked for the last 10 years as an advisor to the U.S. representative on the International Civil Aviation Organization All Weather Operations Panel. He has a Bachelor's Degree in Electrical Engineering from Villanova University.

Mr. Smith received his MSEE in Aerospace Systems from Cranfield Institute of Technology in 1983 and his MBA from London Management Center in 1987. He is a Registered Professional Engineer, Member of the Institute of Electrical Engineers, and a Chartered Member of the Engineering Council, U.K.

ABSTRACT

Of the 2,533 fatal general aviation (GA) accidents from 1982-1988, a total of 646 fatal accidents (nearly 26%) were attributed to controlled flight into terrain (CFIT). This category of accident was the single biggest cause of GA aircraft fatalities during this period. This paper discusses a concept for a low-cost GA Ground Proximity Warning System (GPWS) that can satisfy the operational requirements for avoiding CFIT incidents, thereby improving the utility and safety of GA flight activities. The results from this work are expected to validate the concept of operation, determine the functional and physical characteristics of the device, and validate the design through modeling and simulation. Assuming a successful conclusion to the concept validation stage, fabrication of a preliminary hardware prototype will also be initiated in preparation for flight testing.

The device relies on two extensive databases and a GPS sensor to develop a low-cost GPWS designed specifically for the small, single engine, single pilot GA aircraft— referred to as the TWAS (Terrain Warning and Avoidance System).

INTRODUCTION

Over the past five years GPWS units have been steadily introduced into air transport category aircraft and have undoubtedly contributed to the improved safety record of commercial operations. The perceived benefit of GPWS was recently reinforced by a U.S. initiative to have FAR Part 135 (commuter/regional operators) equip with GPWS by April 1994, and efforts to encourage the 300 or so large transport aircraft operated outside of the U.S. and Europe to equip with GPWS [1]. Part 121 and 125 operators in the U.S. have long since been required to install GPWS. However, because of the high price ($10,000 - $20,000) of systems employing this technology, the broader GA owner/operators have essentially been prevented from benefiting from the improved levels of safety that GPWS units offer. The following describes the problem of CFIT and discusses the issues associated with developing a low-cost GA GPWS.

Of the 2,533 fatal GA accidents from 1982-1988, a total of 646 fatal accidents (nearly 26%) were attributed (in some form) to CFIT, or maneuvering at low level during cruise or the en route phase of flight [2]. This category of accident was the single biggest cause of GA aircraft fatalities during this period. A very close "second place" cause was inclement weather (approximately 25%). There are many activities underway to provide the pilot with improved weather and traffic data in the cockpit. Unfortunately, there appear to be few initiatives to develop an equivalent to the air transport category GPWS for GA. On first inspection this is hardly surprising, since the existing GPWS requires data from a multitude of preexisting avionics equipment with which the small, single engine aircraft is rarely equipped. Also, the $11,000 price tag for the most reasonably priced GPWS, excluding the other specialized avionics equipage (e.g., radar altimeters), puts this well beyond the average GA aircraft owner's budget.

However, GPS holds the potential to overcome these problems, and Rannoch has devised a concept for a low-cost GA GPWS that can satisfy the operational requirements for avoiding the majority of CFIT incidents, thereby improving the utility and safety of GA IFR flight activities. The concept requires the use of a GPS sensor and several integral databases to accomplish its mission. Consequently, equipping and interfacing with many other aircraft sensors is minimized and the cost of the unit can be reduced significantly.

Use of GPWS in Civil Air Transport Aircraft

GPWS units have been used on large air transport aircraft for many years and are now, or soon to be, a standard feature in the regional aircraft cockpit. The existing GPWS is essentially a sophisticated computer that analyzes data collected from several common avionics sensors and, according to predetermined algorithms or modes, determines whether there is any impending risk of a collision with terrain. Pilots are urged to react immediately to a GPWS warning by pulling up and climbing until the warning stops. The only exception is during VFR, when it is clear to the pilot that there is no hazard. A typical GPWS arrangement is shown in Figure 1. It can be seen that the unit is very specialized and designed specifically to employ existing aircraft sensors and inputs.

The current minimum performance standards (MPS) for GPWS [3] essentially defines five modes of operation or protection:

1. Excessive rates of descent
2. Excessive closure rate to terrain
3. Negative climb rate or altitude loss after take-off
4. Flight into terrain when not in landing configuration
5. Excessive downward deviation from an ILS glideslope.

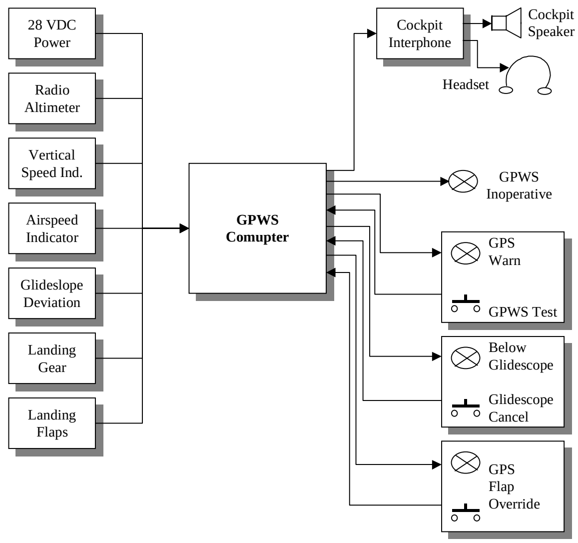

Figure 1. Typical GPWS Interface Arrangement

Based on Rannoch's analysis, it is worth noting that Modes 4 and 5 protect against the most common type of CFIT accidents. The general MPS features of a GPWS system are described in RTCA DO-161A and can be synopsized as:

Aural Warning/Alert: Modes 1 through 4 require an aural warning/alert of "whoop-whoop" followed by a "pull-up" or a "terrain" annunciation repeated until the hazardous condition no longer exists. For Mode 5, the aural annunciation consists of "glideslope" repeated until the hazard no longer exists.

Visual Warning: The visual warning provided for Modes 1 through 4 shall be distinctive under all normal lighting conditions and commensurate with other cockpit warnings.

Emergency/Planned Abnormal Deactivation: Means to deactivate the warning indication (Modes 1 through 4) and the alert indication (Mode 5) must be provided for flight crew use in planned abnormal or emergency conditions.

False Warnings: The equipment shall be designed to minimize false warnings, including those attributable to sensor input signal variations caused by aircraft power fluctuations.

Failure Monitoring and Self Test: Shall be used to indicate equipment condition.

TWAS Functional Considerations

For the TWAS, the biggest challenge is determining, with any degree of reliability, the aircraft's height above the local terrain. In the standard GPWS, this is normally done with a radio altimeter for heights less than 2,500 ft. AGL. The problem is that small aircraft are not necessarily equipped with radio altimeters due to the costs involved (at least $2,000 to $3,000) just for the radio altimeter. Therefore, an alternative approach or sensor arrangement is required.

Another problem facing the TWAS designer is the fact that many CFIT accidents involve aircraft hitting the ground while lined up with the approach path to a runway - Mode 5 in the GPWS. Protecting against these approach accidents is even more challenging, since the aircraft is naturally going to be closer to the ground during the landing phase. This problem is conducive to high false alarm rates unless an approach to detect these scenarios can be devised. Here we propose to combine the data from an industry standard Jeppesen database, containing detailed data on airports such as runway locations and orientation, etc. to intelligently determine - through an algorithm similar to Mode 4 in the GPWS - flight into terrain when not in landing configuration. This is proposed instead of designing detailed interfaces to other aircraft systems, such as flaps, landing gear, and glideslope deviation, since these interfaces add to the cost and are not necessarily practical for all small aircraft types (e.g., fixed gear types).

The unique needs and operations of GA aircraft require slightly different modes of operation from the regular GPWS system. For example, small aircraft are frequently operated at low altitude and too many false alerts will undermine confidence in the system when it really does detect a hazardous situation. Consequently, we have initially identified the following modes of operation for the TWAS:

A. Any operations below 500 ft. AGL. A warning will be initiated since this is contrary to Federal Aviation Regulations (FAR) Part 91. The only exception will be when the aircraft is deemed to be landing, i.e., on an ILS approach (Mode 4 below).
B. Aircraft determined to be below the minimum safe altitude (MSA) level for a given geographic area.
C. Excessive closure rate to terrain. This includes when the aircraft is projected to over fly rising terrain in a manner that will violate Mode 1, within a defined period of time, if the aircraft maintains its present flight path.
D. Aircraft determined to be below the glide path on an IFR approach.

Protection by this latter Mode places the greatest burden on the performance of the unit. Figure 2 provides a functional block diagram of the TWAS device showing major interfaces and components contained within the unit.

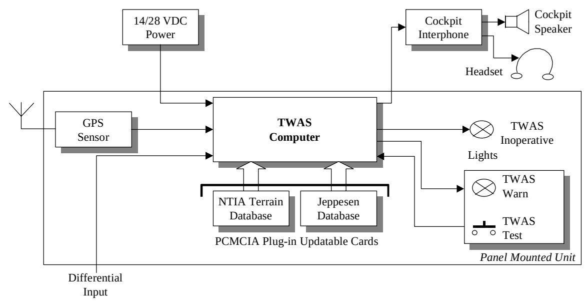

Figure 2. Simplified TWAS Configuration Terrain/Topographic Database

Terrain/Topographic Database

The proposed source of the terrain/topographic database is the National Telecommunications and Information Administration (NTIA) data file containing digitized elevation data for the 48 contiguous states of the U.S., Hawaii, and Puerto Rico. Also included are parts of Canada and Mexico along the U.S. border. The NTIA elevation database was obtained from the Department of Defense Center for Electromagnetic Compatibility Analysis (ECAC), which in turn obtained the data from the Defense Mapping Agency (DMA). The ultimate source of the terrain database is the U.S. Geological Survey 1:250,000 scale series of U.S. maps, and similar maps for the Canada and Mexico border areas.

The elevation data are stored in 1 degree latitude by 1 degree longitude blocks referenced by the coordinates of the extreme southwest corner. The data within each block is in a matrix with 30 seconds of latitude between each row and 30 seconds of longitude between each column, i.e., there are 14,400 elevation points within each block. Thus, the database consists of the elevation at each intersection of a matrix or grid with about 0.5 NM between the rows and columns over the entire U.S. The latitude will range from 17 to 50 degrees North with longitude ranging from 61 to 161 degrees West (these ranges include Hawaii). The database will not return values for every combination of latitude and longitude since some of these blocks are in adjacent countries or are far offshore oceanic areas.

Rannoch's preliminary analysis of the database has indicated that it appears suited for the intended TWAS application. However, the following issues will need to be carefully considered:

- The elevation data does not account for vegetation nor man-made obstructions such as tall buildings. This is not deemed a severe operational drawback but should still be considered.
- The finite accuracy of the elevation data varies according to whether 50-ft. or 200-ft. contour lines were used during the U.S. Geological Survey. Elevation errors up to one half of the contour interval (worst case) are inherent in the data due to the manner chosen in which to construct the database. This gives an elevation accuracy of ± 12.5 ft. for non-mountainous regions and ± 50 ft. for mountainous regions.
- There are likely to be small residual errors in the elevation data due to the manner in which it was recorded and manipulated to form the elevation matrix. These errors are considered much smaller than the resolution error but would need to be quantified more precisely.
- The final consideration is not the accuracy of the elevation data itself, but in the approach taken to extract the data and interpolate when elevations are needed at locations other than at 30-second matrix intersections (which will be most of the time - see Figure 3). In these instances, the choice of the "recovery" routine can select either a "closest point of approximation," which sets the unknown elevation equal to the elevation at the nearest 30-second matrix intersection, or a "four point interpolation," which sets the unknown elevation equal to the average of the nearest four matrix elevations using the relative distances from the intersections as weighting factors. The latter option, or a variation of it, is the most likely choice but the precise recovery algorithm will have to be considered further.

This database can be configured to fit onto a PCMCIA plug-in card with 20 Mbytes of storage capacity. Obviously, higher resolution elevation databases, which do exist for certain parts of the world, would require a greater capacity PCMCIA card with their corresponding access and processing burden.

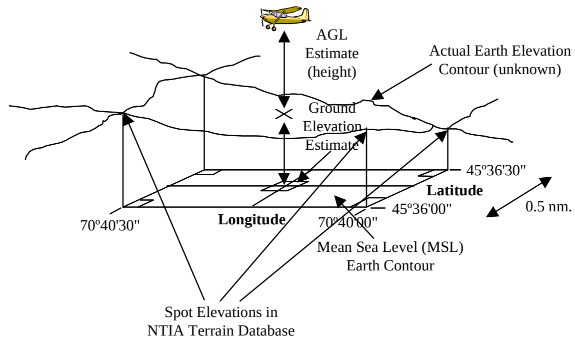

Figure 3. Extraction and Interpolation of Terrain Elevation Data

The GPS Sensor Unit (GPSSU)

The GPS system is intended to provide highly accurate worldwide navigation capability with a high degree of integrity. For the prototype TWAS we would propose to use a fully embedded GPSSU, although the unit could accept data from an external GPS sensor if available. The GPS navigation information is used to provide aircraft a three-dimensional position to the TWAS processor. The latitude/longitude data is used to extract the best estimate of the ground elevation, while the GPS altitude data is used to compute an estimate of height - AGL.

The GPSSU will use the L1 band C/A code transmitted from the GPS satellites and will perform RF processing (including down-conversion of the RF signal), correlation and loop tracking to compute and output position (latitude and longitude), ground speed, ground track angle (wrt to magnetic north), geometric altitude, and UTC time.

Most reference materials, including the Federal Radionavigation Plan (FRP), quote the performance of the GPS standard positioning service (SPS) as being 320 ft./l00 m (2drms) and about 450 ft./140 m (95%) vertical. While the horizontal navigation performance of GPS is adequate for this application, the critical vertical positioning performance is not sufficient for all modes of operation - it may support Mode 1 but not Mode 3. However, considerable improvements can be realized by exploiting the differential navigation performance provided by the Wide Area Augmentation System (WAAS) in conjunction with the SPS service. This will give rise to different performance levels with DGPS than with GPS alone, but the minimum performance will still be sufficient to protect against the majority of CFIT incidents.

In reviewing GPS engines currently or soon to be on the market, there are two candidates for the GPSSU that are expected to meet the price criteria (see Table 1).

Table 1. TWAS Candidate GPS Engines

Manufacturer	**Magellan Systems 960 Overland Ct. San Dimas, CA 91773**	**Canadian Marconi Company 2442 Trenton Avenue Montreal, Quebec H3P 1Y9, Canada**
Model	AIV-10	MicroGPS-2
Channels/Tracking Mode	10 par.	12 par.
Signals Tracked	L1 only, C/A-code	L1 only, C/A-code
Max. No. Of Satellites Tracked	all-in-view	12
Use	suitable for aviation	suitable for aviation
Size (w x h x d)	2.8 x 4.3 x 0.5	2 x 0.5 x 3
Weight (lb.)	0.125 lbs.	<1 oz.
Position (meters SEP) (Single/Differential)	15/5	25/3
Velocity (m/s) (Single/Differential)	0.2/0.2	0.05/<0.05
Update Rate (sec.)	1	1
Time to First Fix (min.)	5 typical	10
Cold Start	50 sec.	2 min.
Reacquisition	2 sec.	0.3 sec.
No. of Ports	2/2	2/1
Type	TTL, CMOS/TTL, CMOS	RS232/422, NMEA0183
Baud Rate	1200-9600/1200-9600	300-4800/300-4800

The most likely final for the TWAS is the MicroGPS-2, since this unit has been designed specifically for low cost [4, 5], has two more channels, and a slight performance advantage.

TWAS Application to the GA Market

GPWS application to the light GA market is completely new since the existing GPWS units sell for well over $10,000 (prohibitively expensive to the average GA owner/operator) and are not designed with the GA market in mind. GA is a low-cost market, and many avionics units retail in the $2,000 to $7,500 range. A desirable cost target for the TWAS is less than $2,000, since improved safety is not necessarily a major selling point to many potential purchasers. Also, ease of installation is a major design goal to accommodate the retrofit market.

There are over 180,000 GA aircraft today in the U.S. with varying levels of avionics equipage. As more GA technology is available at lower prices, and as GA aircraft performance improves, there is a need to present an increasing amount of real-time information to the pilot and to provide systems that improve the pilot's ability to operate his aircraft safely. Over the past 10 years, although there has been a considerable decline in aircraft manufacturing, there have been significant developments in avionics equipment that provide weather, navigation, and surveillance information. For many existing GA aircraft there is a severe lack of panel space to accommodate new avionics and associated displays. One of the biggest concerns of GA pilots in a recent survey regarding a new avionics product was the shortage of panel space to accommodate it.

This means that the final form of TWAS functionality may not be a standalone panel-mounted device, but instead may be integrated into other systems, such as a cockpit display of traffic information (CDTI) system or an FMS-type system. This is conducive to achieving a fully integrated avionics system. This potentially could include:

- Integration of weather, navigation, (moving map), terrain/obstacle database, and traffic situation information into one primary flight display.
- Integration of simplified flight controls with flight guidance displays.

Technical Objectives

Specific objectives are to develop an initial design, simulate the operation of the device, and build a preliminary prototype. The initial design will include physical and functional requirements, paving the way for a full production prototype development. The simulation will use a GPS sensor model, the NTIA terrain database, and the standard Jeppesen database.

Develop Database Configuration

The NTIA database is quite extensive and will be housed in a plug-in Personal Computer Memory Card International Association (PCMCIA) module of 20Mbytes capacity. This requires some well-considered planning with regards to data storage, compression and retrieval to ensure optimum performance. Initial estimates indicate that the database can be programmed into a PCMCIA card using 17Mbytes of storage. The retrieval algorithm would still have to be assessed once this is done to ensure adequate performance. As part of this assessment, refinements to the storage and indexing process may be required to meet the data integrity and retrieval requirements. These refinements may increase the amount of capacity needed.

The preliminary prototype will be the first step in integrating the software (from the simulation) and the hardware (that was evaluated and selected) to arrive at a fully functioning device suitable for more extensive testing.

CONCLUSIONS

This device has potential application to every existing U.S. GA aircraft today - over 150,000 - and assuming availability of suitable databases, also has application to the global market. Our initial impression is that the device, or a functional implementation of its capabilities in a larger, more integrated system, may appeal to the serious IFR pilot because of the improved level of safety achievable.

REFERENCES

1. *Safety Group Highlights CFlT Risk for Regionals,* Aviation Week and Space Technology Special Report, May 9, 1994.
2. *General Aviation Accident Analysis Book for the years 1982-1988,* AOPA Air Safety Foundation, 1991 Edition.
3. *Minimum Performance Standards for Airborne Ground Proximity Warning Equipment*, RTCA SC-128, Document No. DO-161A, May 27, 1976.
4. *Highly Integrated Chipset for GPS Receivers Using RISC,* Bingham, P.M., Fryer, M., GEC Plessey Semiconductors, ION GPS-93, Utah, 1993.
5. *Low Cost Front Ends for GPS Receivers*, Goddard, S.P., Barber, W.L., GEC Plessey Semiconductors, ION GPS-93, Utah, 1993.

For more information on this paper, visit Rannoch Corporation's web site at http://www.rannoch.com, or e-mail us at info@rannoch.com.