Flight Test Results of a Synthetic Vision Elevation Database Integrity Monitor

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ABSTRACT

This paper discusses the flight test results of a real-time Digital Elevation Model (DEM) integrity monitor for Civil Aviation applications. Providing pilots with Synthetic Vision (SV) displays containing terrain information has the potential to improve flight safety by improving situational awareness and thereby reducing the likelihood of Controlled Flight Into Terrain (CFIT). Utilization of DEMs, such as the digital terrain elevation data (DTED), requires a DEM integrity check and timely integrity alerts to the pilots when used for flight-critical terrain-displays, otherwise the DEM may provide hazardous misleading terrain information. The discussed integrity monitor checks the consistency between a terrain elevation profile synthesized from sensor information, and the profile given in the DEM. The synthesized profile is derived from DGPS and radar altimeter measurements. DEMs of various spatial resolutions are used to illustrate the dependency of the integrity monitor's performance on the DEMs spatial resolution. The paper will give a description of proposed integrity algorithms, the flight test setup, and the results of a flight test performed at the Ohio University airport and in the vicinity of Asheville, NC.

Keywords: Synthetic vision systems, terrain database, integrity, spatial resolution.

1. INTRODUCTION

Synthetic Vision Systems (SVS) are intended to provide pilots with an advanced display that depicts terrain information as well as other information about the external environment such as obstacles and traffic. NASA's aviation safety program is investigating SVS as an enabling technology for a wide variety of applications such as reduction of Controlled Flight Into Terrain (CFIT), low-visibility surface operations, advanced precision approach procedures, and low-visibility loss-of-control scenarios. This range of applications is discussed in NASA's "Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems" [1]. The focus in this paper is the use of SVS for CFIT-reduction. To mitigate CFIT, several strategies have been, and are being, pursued by the government and private sectors, such as Terrain Awareness and Warning Systems (TAWS). TAWS is currently being mandated by the FAA for use on all turbine-powered U.S.-registered airplanes type certified to have six or more passenger seats [2]. It is important to note that TAWS is purely an advisory system.

In an SVS, CFIT reduction is achieved by increasing pilot awareness of nearby terrain by displaying it on either a head up display (HUD) or head down display (HDD). Especially in flight-critical SVS applications, display of misleading terrain information must be avoided. The ad-hoc integration of terrain elevation data into the cockpit may conceivably create scenarios that lead to accidents because of the high level of realism provided by SVS displays. The compelling nature of an SVS underlines the mandate for integrity assurance.

This paper describes the implementation of a real-time DEM integrity monitor in order to reduce the probability of an undetected DEM error and thus reduce the potential for presenting hazardous misleading terrain information. Sensor information from DGPS and radar altimeter are used to generate a synthesized, or "sensed", terrain elevation profile. This profile is compared to the terrain elevation profile derived from the DEM and if there are statistically significant inconsistencies between the two, an integrity alarm will be generated and presented to the pilot in some fashion (to be determined). A prototype SVS DEM integrity monitor was developed based on the availability of radar altimeter and augmented GPS. The augmented GPS was provided by a prototype of the Local Area Augmentation System (LAAS). The prototype integrity monitor was installed on Ohio University's DC-3 and flight test data was collected at two locations: the vicinity of the Ohio University airport (UNI) and the vicinity of the Asheville, NC, airport (AVL). Various test statistics were compared for a number of flight segments flown at UNI and AVL. To evaluate the dependency of the integrity monitor performance on the DEM resolution and accuracy, the test statistics were computed for DTED level 0 and level 1 DEMs.

Techniques similar to the one proposed for terrain database integrity monitoring have been used for terrain-based navigation. Examples are Terrain Contour Matching (TERCOM) [3,4], the Sandia Inertial Terrain-aided Navigation (SITAN) [3,4], and

Terrain Profile Matching, TERPROM [5]. These systems utilize a radar altimeter combined with another positioning source to derive synthesized terrain elevations. The Autonomous Precision Approach and Landing System (APALS) utilizes a modified weather radar in combination with GPS and an Inertial Measurement Unit (IMU) to enable precision approach. It is important to note that these systems were designed to enable position "fixing" in support of autonomous navigation, not as integrity monitors for a display suite such as SVS.

2. SYNTHETIC VISION SYSTEM PERFORMANCE

Figure 1 shows a conceptual block diagram of an SVS. The strategic display, the tactical display, and the HUD are the visual components of the SVS and form the interface between the SVS processor and the pilot [6]. The SVS processor takes the required inputs to generate the information that is being depicted on the displays. Furthermore, the SVS processor is connected to a database server: an onboard unit that stores and manages the data that supports the SVS [7]. This paper concentrates on the terrain data that is being stored and managed in this server. Digitally stored terrain elevation data is referred to as a Digital Elevation Model or DEM. A DEM integrity function would be located within this database server and would require database server inputs such as external sensor information for independent verification of the DEM in real-time.
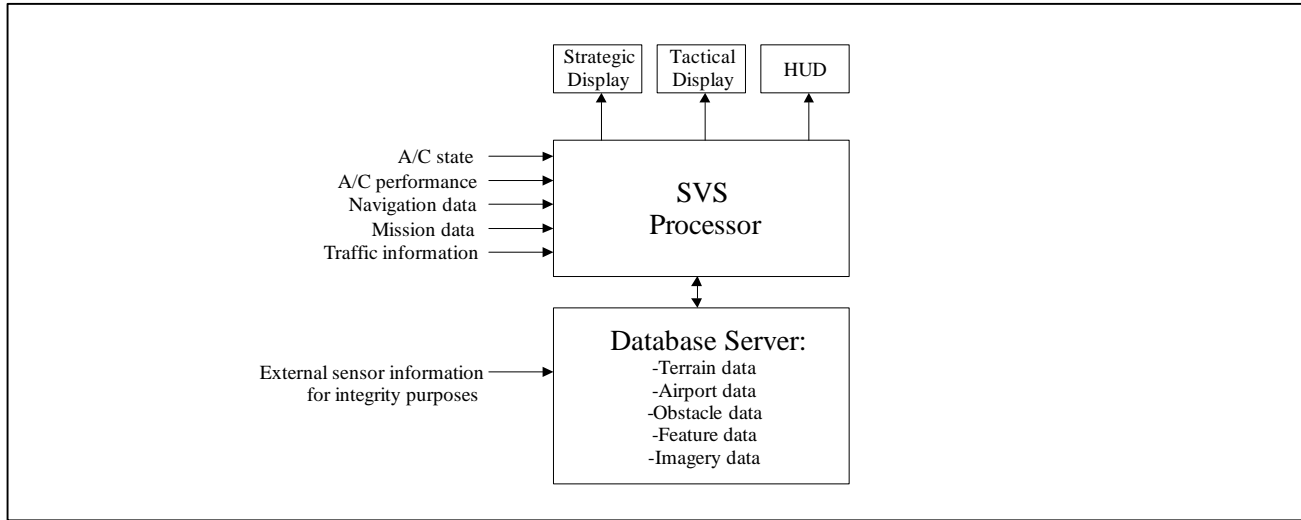

Figure 1. Conceptual SVS system

Subsequent to the identification of the SVS target operations, the development of operational requirements, and the functional analysis, SVS system performance requirements must be developed. SVS system performance can be specified in terms of a set of system performance parameters: accuracy, integrity, availability, and continuity-of-service. This paper will focus strictly on the integrity parameters of the terrain database. SVS-required integrity is dependent on how the SVS is being used; Non-essential use (e.g. clear-day, long-term flight planning); Strategic essential use (e.g. near-term flight planning in low visibility); or Tactical critical use (e.g. low visibility navigation near airports, autopilot).

3. DATABASE INTEGRITY MONITORING

Integrity monitoring of DEM information is accomplished by a consistency check between the information stored in the databases and the information derived from external sensors. Based on the sensor technology that is being used to monitor the DEM integrity, three categories of integrity monitors can be considered: (1) integrity monitors based on downward looking (DWL) sensor information; (2) integrity monitors based on forward looking (FWL) sensor information; and (3) integrity monitors based on both DWL and FWL sensor information (see Figure 2).

In the proposed DWL integrity scheme, sensor information from a Differential Global Positioning System (DGPS) and radar altimeter are used to generate a synthesized, or "sensed", terrain elevation profile. This profile is compared to the terrain elevation profile stored in the database server and if there are statistically significant inconsistencies between the two profiles,

an integrity alarm will be generated and presented to the pilot in some fashion. The difference between the synthesized and stored profiles is referred to as the absolute disparity, whereas the difference between two successive absolute disparities is referred as a successive disparity. Based on the underlying and/or specified error characteristics of the sensors and the DEMs, probability density functions can be derived for the absolute and successive disparities. Test statistics such as the mean square difference, the mean absolute difference, and the cross-correlation, are derived from these metrics and statistically assessed to obtain integrity thresholds and minimum detectable biases.

Integrity algorithms based on FWL sensors would statistically assess the correlation (in time and space) between terrain features observed by FWL sensors and the terrain features derived from the DEM. This paper does not discuss these techniques. Examples of FWL sensors that may be utilized for such an integrity monitor are weather radars, millimeter wave radars, or modified (forward-looking) radar altimeters.

The metrics used to express the degree of agreement or consistency between the synthesized and DEM profiles in a DWL sensor integrity scheme, are the absolute and successive disparities [7]. In this paper the discussion is limited to the use of absolute disparity because of the insensitivity of the successive disparities to biases and low-frequency errors [13]. The absolute disparity is given by:

$$p(t_i) = h_{SYNT}(t_i) - h_{DTED}(t_i) \tag{1}$$

where h_{SYNT} is the synthesized height and h_{DTED} is the height as derived from the DEM. Both elevations are defined at time t_i.
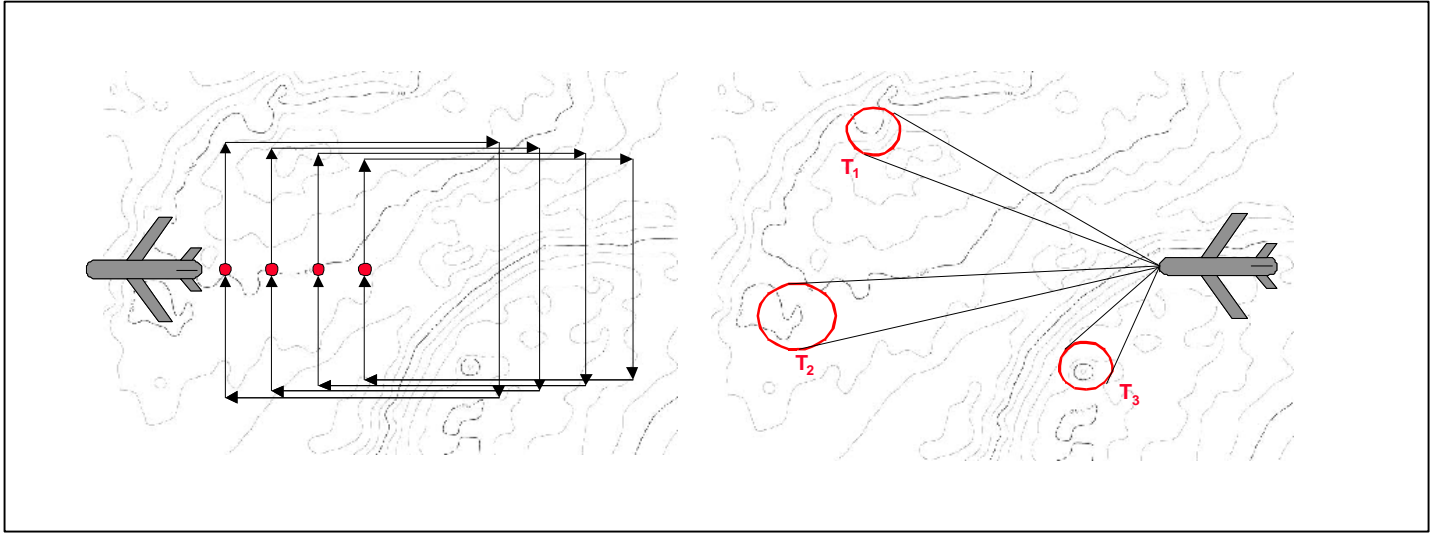

Figure 2. Integrity monitors based on downward- and forward-looking sensors

Ideally, the difference between the stored and synthesized elevation would be zero. However, nominal errors in the sensor performance and stored entries in the DEM cause the absolute disparity to have a nominal error distribution [8]. Overbounding the bias and random error components of both the sensor and the DEM yields a probability density function (PDF) for the absolute disparity under the fault-free condition. This leads to the following null hypothesis H_0:

$$H_0 : p \sim N(0, \sigma_p^2) \tag{2}$$

where $N(0, \Phi_p^2)$ is a normal distribution with a standard deviation of Φ_p. The standard deviation Φ_p can be derived from the individual standard deviations of the sensor error PDFs and specified error characteristic of the DEM.

When a fault in the form of a bias-error occurs the PDF of the absolute disparity will contain a bias component also. Hence, the following expression for an alternative hypothesis H_1:

$$H_1 : p \sim N(\mu_B, \sigma_p^2) \tag{3}$$

where μ_B is the bias-error or fault. Alternative hypotheses can be generated based on other expected error classes or faults. However, this discussion will be restricted to the analysis of bias-like errors (or faults).

For the implementation of an integrity monitor a test statistic must be derived. Examples are the Mean Absolute Difference (MAD) and Mean Square Difference (MSD). The MSD slightly outperforms the MAD [9] and is therefore chosen as the test statistic, T, for proposed integrity monitor:

$$T = \frac{N}{s_p^2} MSD_{AD} = \frac{1}{s_p^2} \sum_{i=1}^{N} p^2(t_i) \tag{4}$$

Under H_0, the PDF of T is found to be a chi-square distribution with N degrees of freedom. Under H_1, the PDF of T is found to be a non-central chi-square distribution with N degrees of freedom and non-centrality parameter δ. The non-centrality parameter is related to the bias-error or fault as follows [10]:

$$\lambda = \frac{N}{s_p^2} m^2 \tag{5}$$

SVS system requirements must specify a probability of detection under fault-free conditions, P_{FFD}, a probability of missed detection, P_{MD}, and the integration time N. Fault-free conditions are those conditions in which errors behave only as expected (or as specified for either the sensor or the DEM). Given the value for P_{FFD}, a threshold can be calculated from H_0. This is illustrated by the solid area underneath the curve in Figure 3. P_{FFD} can also be thought of as the probability of false alarm. For the real-time integrity monitor used during the flight-tests, an integration time of 50 seconds ($N=50$) and a $P_{FFD}=10^{-4}$ were chosen. These parameter values result in a threshold value of $T_D = 96$. The probability of missed detection, P_{MD}, or a continuation of operation under the alternative hypothesis, results in a minimum detectable bias (MDB): that bias for which the probability of a missed detection is equal to P_{MD}. The MDB can be derived from T_D and P_{MD} by identifying that non-central chi-squared distribution for which the gray area in Figure 3 equals P_{MD}. The MDB can then be obtained from the non-centrality parameter in equation 5. For example, for $P_{MD}=10^{-7}$ a MDB value of 33.96 meters results. Note that this value is quite significant.
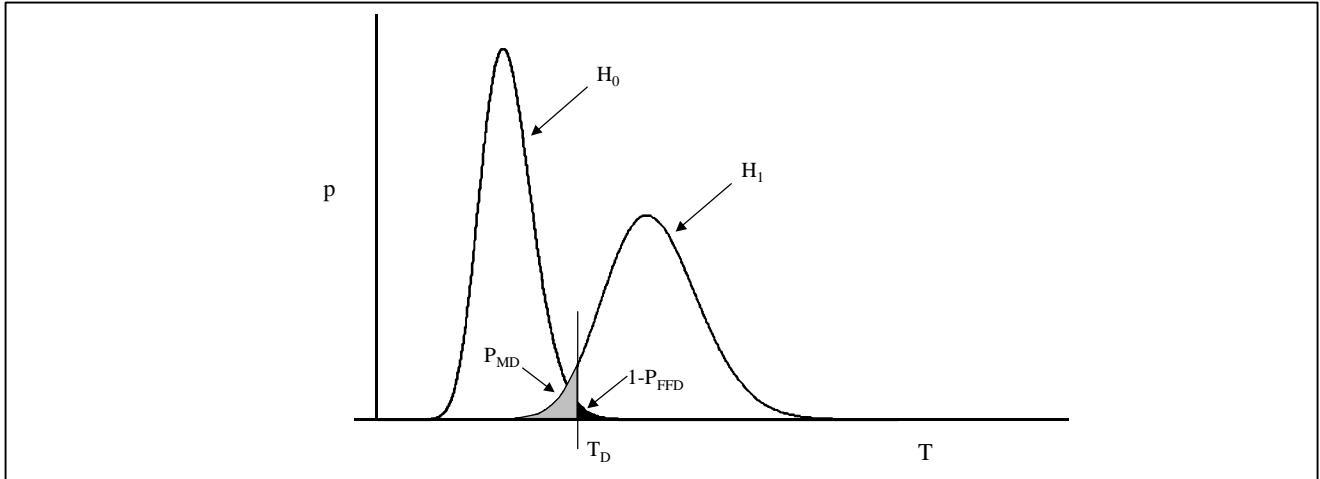

Figure 3. H_0 and H_1 hypotheses for the mean square difference test statistic.

Note that lower values of P_{MD} result in lower values of the MDB [11]. Furthermore, a shorter integration time results in higher values for the MDB.

4. TERRAIN DATABASE ELEVATION MEASUREMENTS

Elevation databases stored digitally and defined at discrete spatial points are often referred to as digital elevation models or DEMs. A variety of sources provide DEMs specified by a number of parameters, such as the post-spacing or spatial resolution, the horizontal and vertical references or datums, and the circular and linear errors. The circular error probability (CEP) represents the horizontal accuracy specification on the post-position, whereas the linear error probability (LEP) or vertical error specifies the accuracy in the vertical direction (height). Various DEMs were available for the Asheville, NC and Athens, OH areas to support the flight-test analyses and real-time implementation. The DEMs used in this paper are the Digital Elevation Terrain Data (DTED) levels 0 and 1 provided by the National Imaging & Mapping Agency (NIMA). For the geographic areas of interest both databases have a similar horizontal and vertical accuracy specification: CEP < 50m, 90% (Φ_{hor} = 30.4 m), LEP < 30m, 90% (Φ_{ver} = 18.2 m). The major difference between DTED Level 0 and 1 lies in their spatial resolutions; whereas DTED level 1 has a post-spacing of 3 arc-seconds, DTED level 0 has a post-spacing of 30 arc-seconds. A limited spatial resolution may result in significant interpolation errors because the terrain is truly under-sampled. In geographic areas with a large terrain standard deviation ("rough" terrain) [9], large interpolation errors may be expected! However, it is in these geographic areas that misleading terrain information is most likely to be hazardous. The effects of the limited resolution and their impact on the nominal performance will be illustrated in the flight test result section of this paper.

5. SYNTHESIZED ELEVATION MEASUREMENTS

The synthesized elevation measurements are obtained by subtracting the height above ground level measured by the radar altimeter from the altitude above mean sea level computed by the Differential Global Positioning System (DGPS). Examples of DGPS that may be utilized in the real-time integrity monitor implementation are the Wide Area Augmentation System (WAAS) [12] or Local Area Augmentation Systems (LAAS) [12]. In this paper, high-precision Kinematic GPS was used for post-processing purposes. The radar altimeter measures the height above ground level (AGL) of the radar altimeter receiving antenna (mounted on the bottom of the aircraft). However, it is important to realize that the radar altimeter measurement accuracy is a function of the altitude and the rate at which the altitude changes. Furthermore, banking of the aircraft may cause the radar altimeter beam to measure a "slant-range" instead of a "plumb bob" range [13].

Given the accuracies specified in [9,11], values for Φ_p can be computed. Table 1 gives an overview of the values for various combinations of DGPS and DEMs. Note that this table includes Φ_p values obtained when using DTED as well as the Shuttle Radar Topography Mission (SRTM)-derived elevation database. The SRTM is a joint project of NIMA and NASA to record radar data that will be used to generate of a digital topographic map of 80% of the Earth's land surface [14].

	DTED 0 / KGPS	DTED 1 / KGPS	SRTM / KGPS	DTED 0 / LAAS	DTED 1 / LAAS	SRTM / LAAS	DTED 0 / WAAS	DTED 1 / WAAS	SRTM / WAAS
Φ_p	18.86	18.86	10.89	18.87	18.87	10.91	18.92	18.92	10.99

Table 1. Standard deviation of the absolute disparity under fault-free conditions.

6. FLIGHT TEST SETUP AND RESULTS

Data from two flight tests was used to evaluate the integrity monitor's behavior as a function of various DEMs and sensor packages; one in the vicinity of Asheville, NC and one in the vicinity of Ohio University in Athens, OH. In both cases Ohio University's real-time synthetic vision prototype was also tested. Figure 4 shows a block diagram of the prototype hardware. A Commercial-Off-The-Shelf (COTS) Honeywell Inertial Navigation System (INS) provides the aircraft attitude, heading, and airspeed information. The aircraft LAAS unit relays the airborne position and altitude above mean sea level to the Central Processing Unit (CPU). The LAAS differential corrections are received from a prototype LAAS ground station that makes use of spread-spectrum radios as short-range low-power datalink. A COTS Honeywell radar altimeter unit is connected to the CPU via a Microcontroller interface unit. The prototype provides A/C state and terrain information graphically to the pilot on a flat panel liquid crystal display that functions as HDD. The HDD software was developed by Delft University of Technology and is used through a memorandum of agreement.
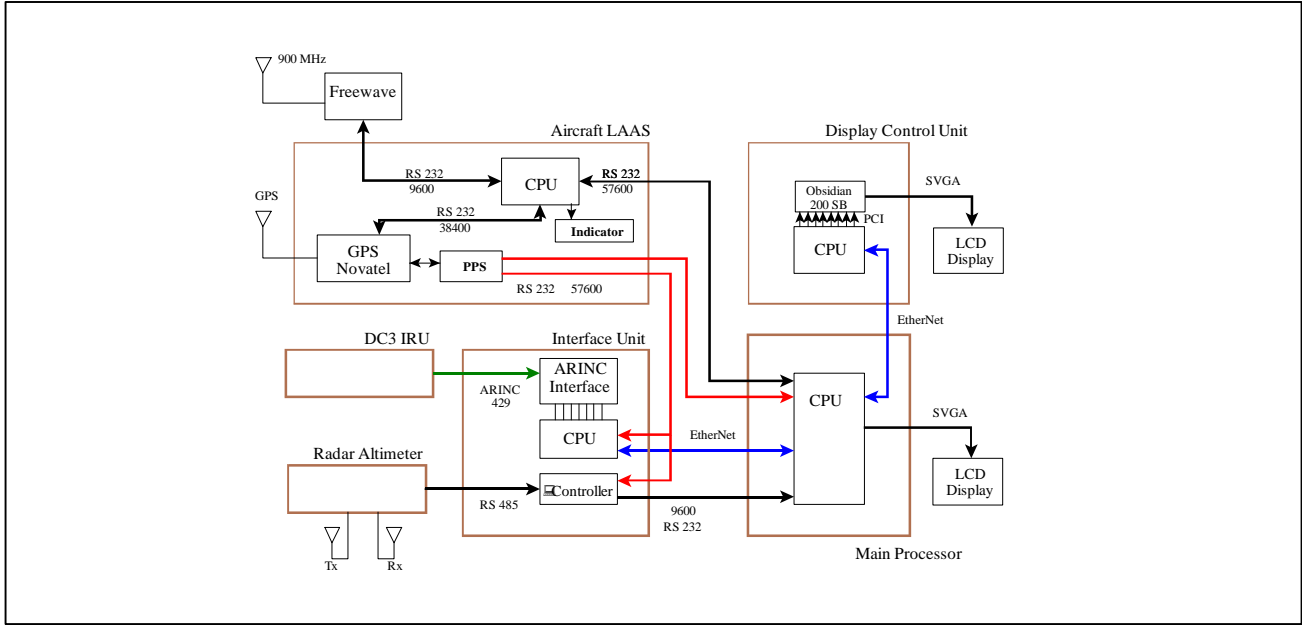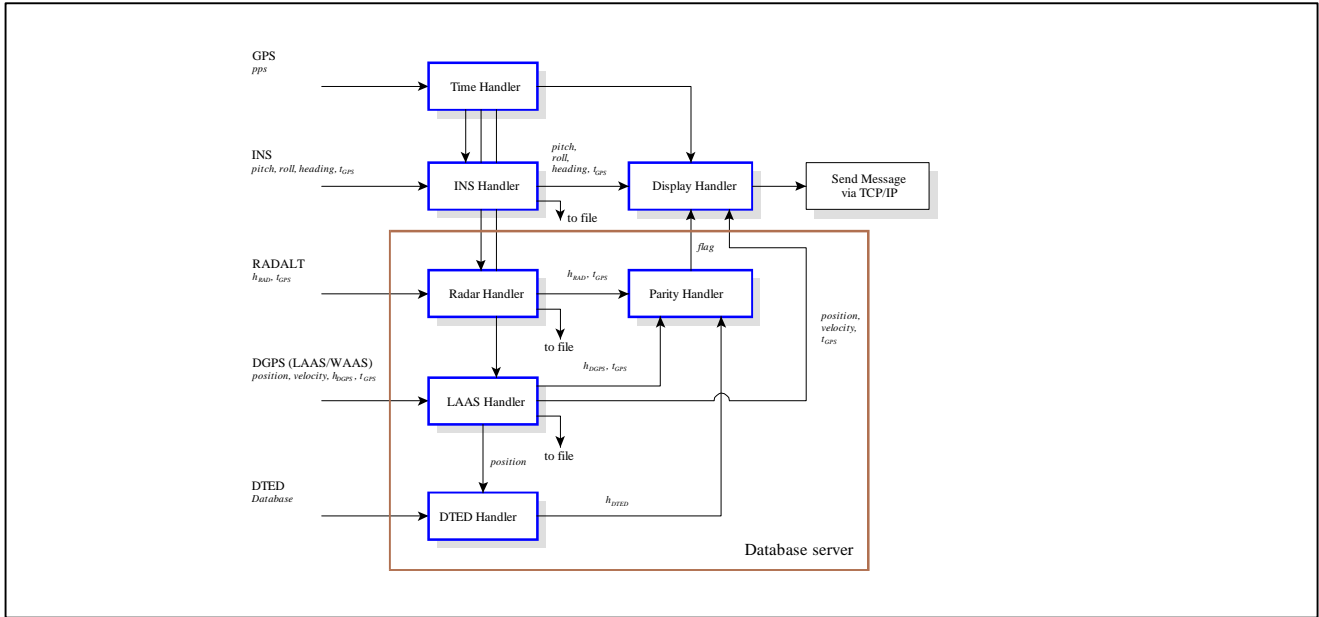
Figure 4. SVS prototype hardware

Figure 5. Software flowchart for SVS prototype

The CPU runs the real-time Integrity Monitor software under the QNX real-time operating system (RTOS). A high-level flowchart of the software is shown in Figure 5. DGPS, radar altimeter, and DTED data are retrieved by their respective handlers and sent to the parity handler. The parity handler computes the absolute disparities and test statistic. Based on the computed test statistic and the integrity threshold T_D, which has been computed a priori, the parity-handler determines if there is an integrity violation and sets an output flag accordingly. The display handler generates the information required by the HDD and sends it via a TCP/IP connection to the dedicated HDD computer. Synchronization of the messages is required to enable a fair consistency check among measurements taken at approximately the same reference time. This function is implemented by the time-handler.

6.1 Ohio University airport (UNI) flight test

The first set of data was collected during a flight test with Ohio University's DC -3 in the vicinity of Ohio University airport (UNI) in August 2000. The data shown here was derived in post -flight to enable a direct performance comparison between the integrity monitor's performance with LAAS / KGPS and DTED level 0 / DTED level 1. Figure 6 sho ws the ground-tracks for the 14 approaches (2 to runway number 7, 12 to runway number 25). Note the curvature of the approaches to runway number 7. The resultant bank angles introduce errors due to the measurement mechanism of the radar altimeter [13].
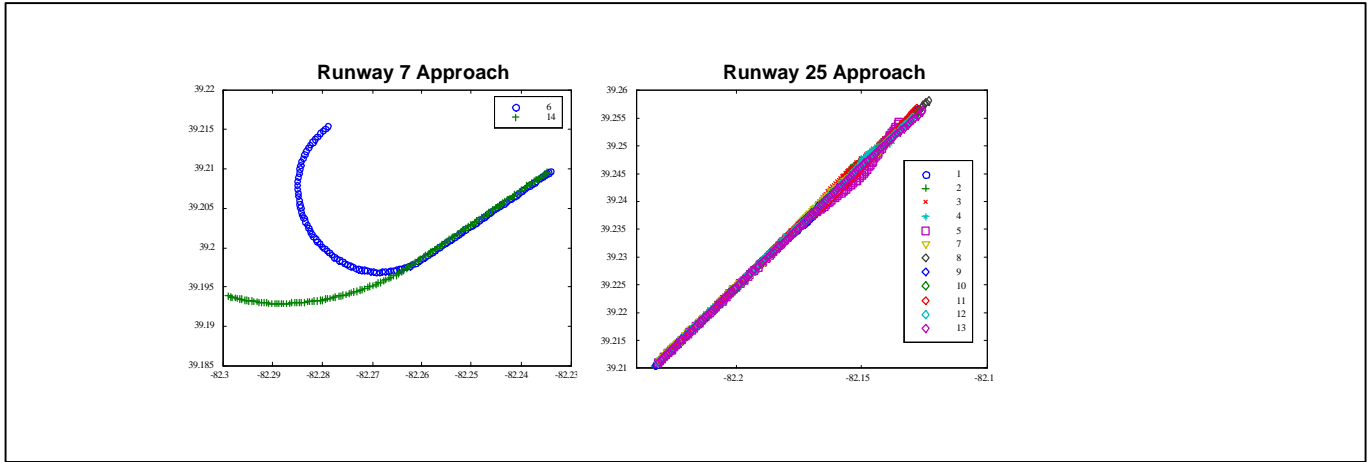
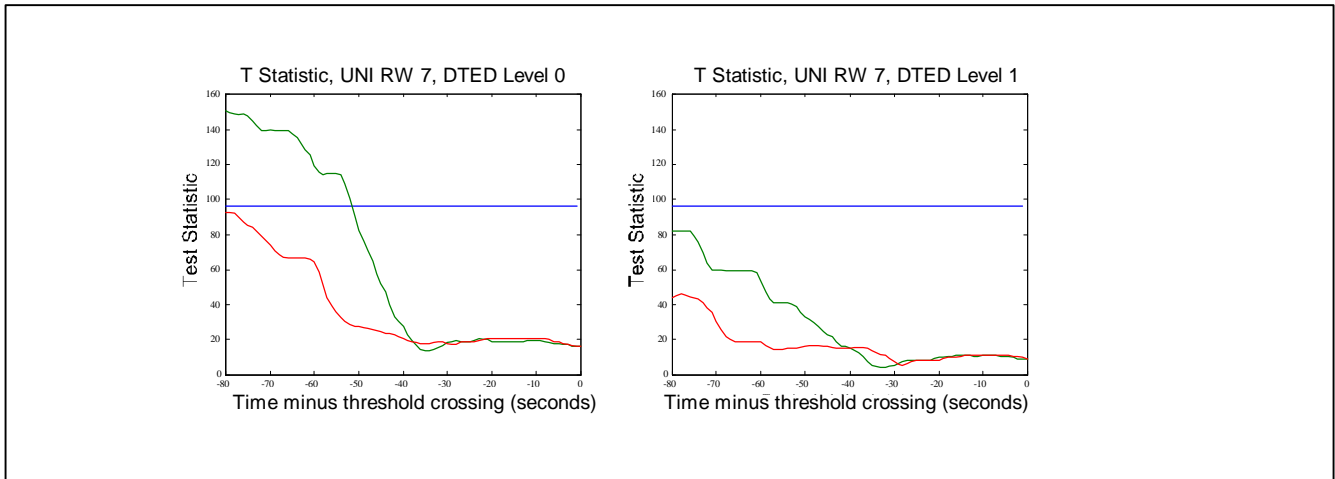Figure 6. Approaches to UNI runway 7 and 25 during the August 2000 flight test.

Figure 7. T -statistic and threshold for the approach to UNI runway 7 utilizing DTED level 0 and 1

The T-statistic results for the approaches towards runway 7 and 25 are shown in Figures 7 and 8, respectively. The graph on the left shows the monitor's behavior when utilizing DTED level 0, whereas the graph on the right shows the monitor's behavior when utilizing DTED Level 1. One can observe an obvious difference in int egrity monitor performance: using DTED level 0 causes the integrity threshold to be exceeded. In other words the interpolation error introduced by the large spatial resolution of DTED level 0 causes the actual fault -free error characteristic to deviate f rom the specified fault-free error characteristic. This will then result in the occurrence of false alarms. It is important to remember that the horizontal and vertical DEM accuracies are defined for one point in space, the post -space, not for the interpolated position.
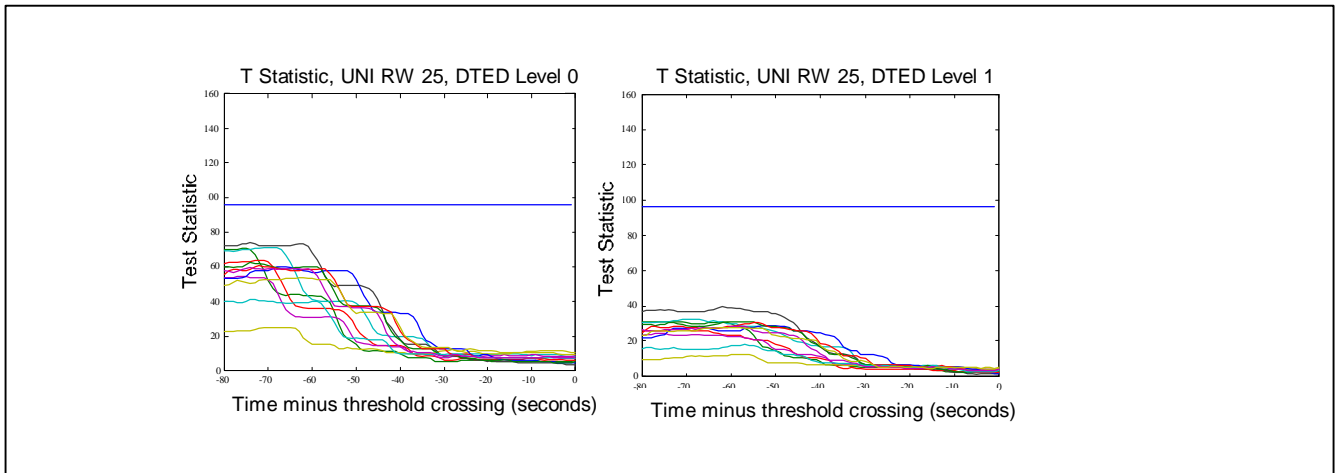
Figure 8. T-statistic and threshold for the approach to UNI runway 25 utilizing DTED level 0 and 1.

Furthermore, it can be seen in figure 7 that the test statistics during the approaches to runway 7 are much larger than the test statistics during the approaches to runway 25. The reason for this is error is twofold: first the terrain underneath the approach to runway 7 has a higher terrain standard deviation than the terrain underneath the approach to runway 25 and secondly, the large bank angles cause a mismatch between the radar altimeter measurements and the interpolated DEM elevation [13].

6.2 Asheville, NC (AVL)

Flight tests were performed in the vicinity of the Asheville, NC, airport (AVL) in September 2000. Figure 9 shows the ground tracks for these approaches. Asheville, NC was chosen for its relative high terrain standard deviation and the availability of multiple alternative terrain databases including photogrammetry data. In 1999, NASA flight tested their SVS prototype on the Total In-Flight Simulator (TIFS) at this same airport.
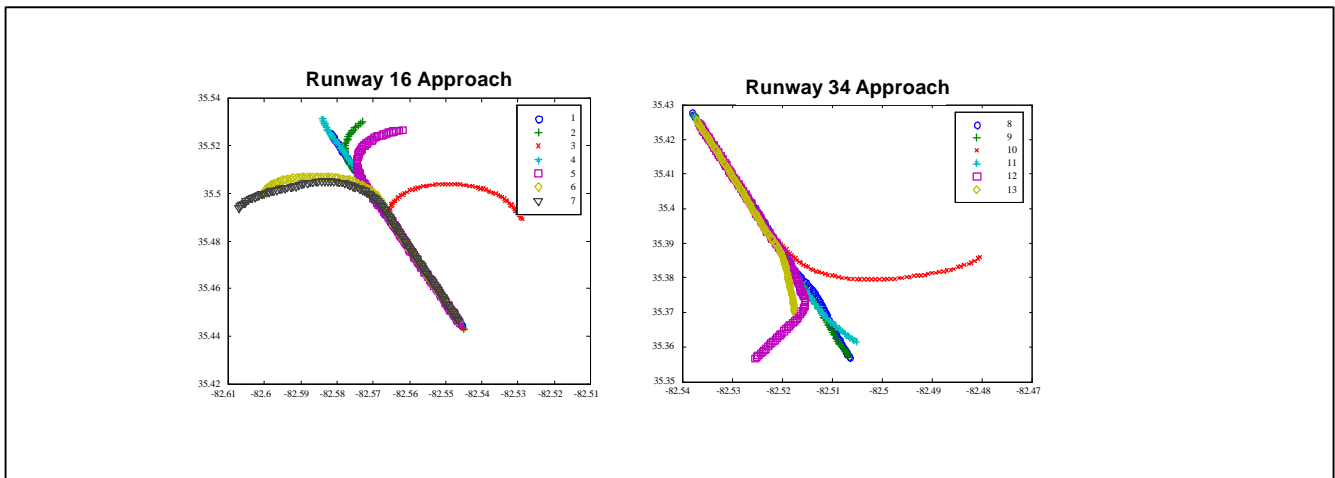

Figure 9. Ground-tracks for the approaches to runway 16 and runway 34 at AVL

The proposed test statistics were calculated for the 14 flight segments flown. The set of flight segments consisted of Instrument Landing System (ILS) approaches to runway 16 and 34. The test statistics for these approaches are given in figures 10 and 11, respectively. The ILS approach to runway 34 has a different terrain profile than the approach to runway 16. During the initial approach to runway 34, the terrain is characterized by large variations, but during final approach the terrain variations become significantly smaller. During the approach to runway 16, the frequency of undulations in the terrain remains significant until the aircraft reaches the runway. Again, when using DTED level 1, no integrity violations were detected. However, when using DTED level 0, the thresholds are exceeded for approaches to both runways. Again,

interpolation errors due to a li mited spatial resolution are the cause of these false alarms. In [11,13] the AVL DTED segment was compared to high-accuracy photogrammetry data and no faults were identified.
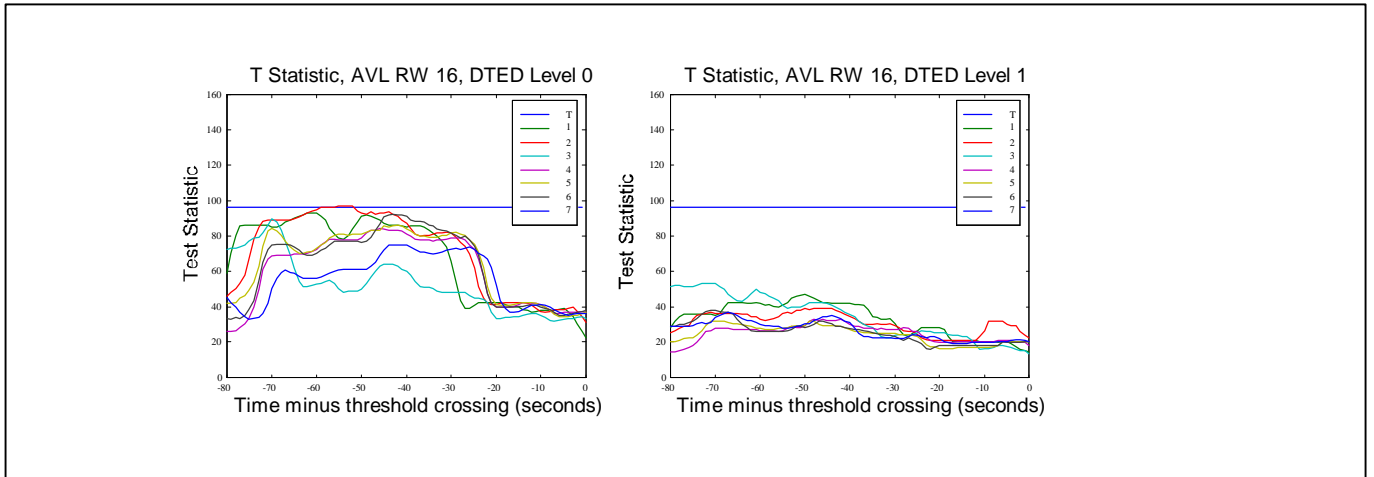

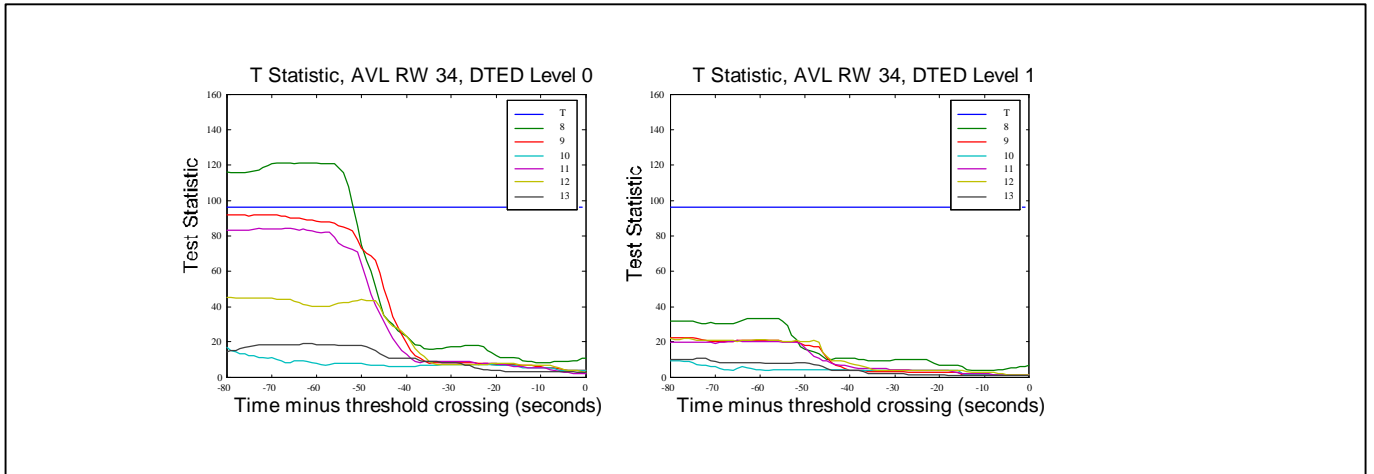Figure 10. T -statistic and threshold for the approach to AVL runway 16 util izing DTED level 0 and 1.

Figure 11. T -statistic and threshold for the approach to AVL runway 34 utilizing DTED level 0 and 1.

The data shown in figures 10 and 11 was generated using LAAS positions and altitudes. A very similar integrity monitor performance is found when using post-flight KPGS. This is to be expected because the standard deviation of the PDF of the absolute disparity is dominated by the vertical standard deviation of the DEM.

7. SUMMARY AND CONCLUSIONS

A prototype SVS with real-time DEM integrity monitor was flight -tested at UNI and AVL. The test statistic values for both geographic areas were consistent and below the threshold for all approaches using DTED level 1. Use of DTED level 0 in the real-time integrity monitor caused the int egrity threshold to be exceeded on various occasions. Each one of these cases corresponded to flight over terrain with a large terrain standard deviation. It is concluded that the limited spatial resolution of DTED level 0 causes the PDF that underlies t he test statistic to be off-nominal, resulting in false alarms and possibly missed detections. DTED level 1 was shown to be sufficient. However, degraded performance of DGPS or radar altimeter may necessitate even higher quality terrain databases.

Comparing the results in this paper with the results in [13] indicate a degraded performance. This can be attributed to the use of different radar altimeters in both test aircraft. Additional flight -tests using a variety of radar altimeters will be necessary to validate the general performance of the DEM integrity monitor.

Even though the integrity monitor performance looks promising, it must be determined during the system requirements development if the resulting MDBs are acceptable. Higher accuracy data bases such as the SRTM, longer integration times, or augmentation with FWL integrity schemes may be necessary to guarantee DEM integrity during all operational scenarios.

ACKNOWLEDGEMENTS

REFERENCES

1. Williams, D., et al., "Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems – Version 1.0," NASA Langley Research Center, January 2001.
2. "Terrain Awareness and Warning Systems", Federal Register - Rules and Regulations, FR Doc 00-7595, Vol. 65, No. 61, pp. 16735-16756, March 27, 2000.
3. Baird, C. A. and M. R. Abramson, "A Comparison of Several Digital Map -Aided Navigation techniques," IEEE PLANS, 1984, pp. 286 -293.
4. Siouris, G. M., *Aerospace Avionics Systems – A Modern Synthesis*, Academic Press, Inc., 1993.
5. Dieffenbach, O., "APALS^{TM} Autonomous Precision Approach and Landing System," Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), Orlando, FL, Apr. 18, 19, 1995.
6. Etherington, T. J., et al., "Synthetic Vision Informat ion System," Proceedings of the Digital Avionics Systems Conference, Philadelphia, 7 -13 October 2000.
7. Zellers, S., "Description of a Database Server Architecture for Synthetic Vision System Applications," Proceedings of the Digital Avionics Systems Conference, Philadelphia, 7 -13 October 2000.
8. Gray, R. A., "In -flight Detection of Errors for Enhanced Aircraft Flight Safety and Vertical Accuracy Improvement Using Digital Terrain Elevation Data with an Inertial Navigation System, Global Positioning System and Radar Altimeter," Ph.D. Dissertation, Ohio University, Athens, Ohio, June 1999.
9. Hinrichs, P.R., "Advanced Terrain Correlation Techniques," IEEE PLANS, San Diego, CA, 1989, pp. 89 -96.
10. Kay, S. M., *Fundamentals of Statistical Signal Processing, Volume II: Detection Theory*, Prentice -Hall, 1998,
11. Uijt de Haag, M, J. Sayre, and J. Campbell, "A DTED Terrain Avoidance System using GPS and Radar Altimeter Monitoring," Ohio University Preliminary Design Review at NASA Langley, November 28, 2000
12. *1999 Federal Radionavigation Plan*, U.S. Department of Transportation and U.S. Department of Defense, 1996
13. Uijt de Haag, M., J. Campbell, R. Gray, "A Terrain Database Integrity Monitor for Synthetic Vision Systems," Proceedings of the Digital Avionics Systems Conference, Philadelphia, 7-13 October 2000.
14. http://www.jpl.nasa.gov/srtm