A TERRAIN DATABASE INTEGRITY MONITOR FOR SYNTHETIC VISION SYSTEMS

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Abstract

This paper discusses a terrain database integrity monitor for Synthetic Vision Systems (SVS) in Civil Aviation applications. SVS provide the pilots with advanced display technology containing terrain information as well as other information about the external environment such as obstacles and traffic. SVS will improve situational awareness and thereby reduce the likelihood of Controlled Flight Into Terrain (CFIT). Safe utilization of the SVS for strategic and tactical applications may require a terrain database integrity check. The discussed integrity monitor checks the consistency between the sensed terrain profile as computed from DGPS and radar altimeter data and the terrain profile as given by the terrain databases. A case study to verify the integrity monitor's performance is presented based on data collected during flight-testing performed by NASA at Asheville, NC.

Introduction

A Flight Safety Foundation study of 132 accidents that occurred between 1984 and 1993 revealed that 54 (41%) involved Controlled Flight Into Terrain (CFIT) [1]. This study and others like it suggest that CFIT accidents are a significant contributor to the overall accident rate. Both the government and private sectors are pursuing several CFIT mitigation strategies. Further, the Federal Aviation Administration (FAA) has mandated Terrain Awareness and Warning Systems (TAWS) for nearly all aircraft [2]. However, it is important to note that TAWS is purely an advisory system.

Recently, the government has made significant research and development investments to further improve aviation safety including the reduction of CFIT. Three examples are NASA's Aviation Safety Program, the FAA's SafeFlight21 Program, and NIMA's Ron Brown Airfield Initiative.

Within NASA's aviation safety program, the synthetic vision project is working on the development of a system that provides the pilots with advanced display technology containing terrain information as well as other information about the external environment such as obstacles and traffic. Various terrain elevation databases are available and/or being developed by NIMA (Digital Terrain Elevation Data, DTED), NASA, National Geodetic Survey (NGS), and United States Geological Survey (USGS). Each terrain elevation database product has its own coverage area and error characteristics.

When utilizing terrain elevation databases in applications other than advisory systems, it is important to avoid display of misleading terrain information. This paper proposes the addition of a real-time integrity monitor to the terrain elevation database in order to reduce the probability of an undetected database error. Sensor information from DGPS and radar altimeter are used to generate a synthesized, or "sensed", elevation profile. This profile is compared to the elevation profile from the stored database and if there are inconsistencies between the two, an integrity alarm will be generated and presented to the pilot in some fashion.

SVS Integrity Monitoring

The purpose of the integrity monitor for a Synthetic Vision System (SVS) is to provide the user with a warning when the SVS should be used with caution or not to be used at all. Warnings would be provided when an error is detected that results in the display of hazardous misleading terrain information (HMTI) on the SVS display. The integrity is driven by the probability that the system does not detect the occurrence of this type of event. The probability of an undetected SVS failure is dependent on the probabilities of undetected failures in each of the SVS subsystems as depicted in the example fault tree shown in Figure 1. This example assumes that the failure rates are independent. For example, an SVS may consist of various components or subsystems such as the SVS display, the SVS computer, the terrain elevation database to generate the terrain, the obstacle database to generate the man-made objects that require visualization on the SVS display, navigation systems, etc. An undetected failure in each one of these subsystems can lead to a failure of the overall SVS. The SVS undetected failure rate is determined by the sum of the individual undetected failure rates ($P_{display}$, $P_{computer}$, $P_{terrain}$, $P_{obstacle}$, etc.). This is indicated by the "OR" operation in Figure 1.

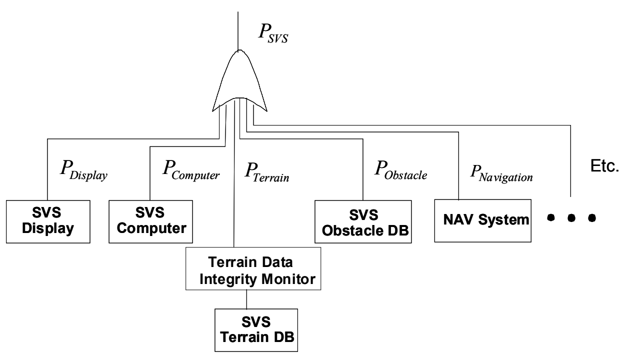

Figure 1. Sample SVS Fault Tree.

This paper focuses on the terrain data integrity monitor block depicted in Figure 1.

The required terrain elevation data integrity level is dependent on the application of the SVS and the importance of the terrain elevation data within this application (i.e. the operational use of the SVS). In general, three categories of SVS applications are envisioned [3]:

1. SVS advisory system applications (nonessential),
2. SVS strategic applications (essential),
3. SVS tactical applications (critical).

The integrity levels required for these three types of applications are determined by their probability of an undetected failure. For advisory system applications, this probability can be greater than 10^{-5}. For strategic essential applications, this probability is expected to be between $10^{-5}$and 10^{-9}. For flight-critical, SVS tactical applications, the level of integrity is expected to be smaller than 10^{-9}.

To avoid presenting HMTI to pilots, the integrity of the elevation database needs to be monitored. HMTI monitoring is based on checking the agreement, or consistency, between the stored digital terrain elevation data and elevation data derived from an independent source (e.g. synthesized terrain). The digital terrain elevation database can be any terrain database (such as DTED I). The synthesized terrain in our case is computed from sensor information from Differential GPS (DGPS) and radar altimeter. Example DGPS implementations that may be used are kinematic GPS (KGPS), the Local Area Augmentation System (LAAS), or the Wide Area Augmentation System (WAAS).

Terrain Database Integrity Monitor

The basic metrics used to express the degree of agreement between the synthesized and database terrains are the absolute and successive disparities [4]. The absolute disparity is given by:

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

where h_{SYNT} is the synthesized height and h_{DTED} is the height as derived from the terrain elevation database. Both elevations are defined at time t_i. In the proposed system the synthesized height is given by the difference between the height above Mean Sea Level (MSL) as derived from DGPS measurements, h_{DGPS}, and the height Above Ground Level (AGL) as obtained from the radar altimeter, h_{RADALT}, according to:

$$h_{SYNT}(t_i) = h_{DGPS}(t_i) - h_{RADALT}(t_i) \quad (2)$$

The successive disparity is given by:

$$s(t_i) = p(t_i) - p(t_{i-1}) \quad (3)$$

Successive disparities have been used extensively in military systems. The main advantage of subtracting the previous absolute disparity from the current absolute disparity is the ability to remove radar altimeter biases. However, for the design of an integrity monitor, this bias removal feature can be undesirable, because it can cause bias-like errors in the terrain elevation database to be missed.

Under error-free and space-continuous terrain database conditions the synthesized height and the height derived from the terrain database should be equal resulting in an absolute disparity equal to zero. However, both the sensors and the terrain elevation databases contain biases and/or noise errors under nominal or fault free conditions (H_0 hypothesis). These errors can be attributed to measurement noise and the band-limited character of terrain databases, which are two-dimensional discrete-space representations of the continuous terrain. [4] estimated the nominal underlying statistics of both sensors and DTED to be normally distributed. As a result the absolute disparity will be distributed normally also. The probability density functions (PDFs) of the absolute disparity and successive disparities are estimated [4] to be $p(t_i) \sim N(0,(18.9)^2)$ and $s(t_i) \sim N(0,(13.0)^2)$, respectively.

For the implementation of an integrity monitor, test statistics are derived based on absolute and successive disparities. Test statistics are indicators or measures of agreement based on the systems' nominal or fault free performance. If this test statistic exceeds a pre-defined detection threshold, an integrity alarm results.

Computation of the detection thresholds requires pre-defined false alarm and missed detection rates, and an understanding of the underlying system fault mechanisms and characterization of the nominal system error performance described by the probability density functions (PDFs) of both the terrain elevation database errors and errors in the sensor(s) used to derive the synthesized elevations.

The test statistics are derived from the absolute and successive disparities according to the Mean Squared Difference (MSD) principle as follows:

$$T = \frac{1}{\sigma^2} \sum_{i=1}^{N} p^2(t_i) \qquad (4)$$

$$Z = \frac{1}{2\sigma^2 (N-1)} \sum_{i=2}^{N} s^2(t_i) \qquad (5)$$

In Equations 4 and 5, N can be interpreted as an integration time. [4] shows the performance of the integrity monitor for a variety of values for N. For the case study presented later in this paper, N is chosen to be 50.

Based on the given underlying normal distributions of the absolute and successive disparities, T is found to be a chi-square distribution with N degrees of freedom and Z is found to be a normal distribution for $N > 20$ [4].

The thresholds, T_D, are calculated from a required probability of fault free detection or false alarm, P_{FFD}, and the parameters that define the underlying error PDFs, such as the variance. Figure 2 (a) shows the PDF under fault free operation or H_0 hypothesis; the gray area represents P_{FFD}. Whenever a fault such as a bias, ∴, is present in either the terrain database or the sensors, the system will operate under faulted conditions or H_1 hypothesis. In that case the missed detection probability requirement (P_{MD}) determines a minimum detectable bias (MDB). Figure 2 (b) shows the PDF under the H_1 hypothesis. The gray area indicates P_{MD}.

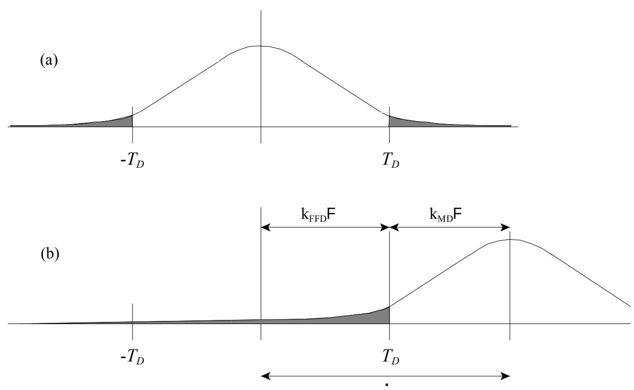

Figure 2. Fault-free (a) and faulted (b) conditions.

The results shown in this paper are based on a P_{FFD} equal to 10^{-4}, and an integration time of 50 seconds or $N = 50$. An integration time of 50 seconds limits the time required to achieve confidence in the database. Based on these values, the threshold for the T was found to be equal to $T_D = 96$ and the threshold for Z was found to be equal to $Z_D = 2.2$ for the case study presented in this paper.

Flight Test Overview

Flight tests were performed in the vicinity of the Asheville, NC, airport (AVL) during the fall of 1999 using an Air Force Convair aircraft known as the Total In-Flight Simulator (TIFS)[1]. The test was part of a research program led by NASA Langley Research Center investigating Synthetic Vision Systems (SVS). Figure 3 shows the TIFS on the ramp at AVL. Because of its forward flight deck, the TIFS aircraft provides a unique environment for flight-testing advanced avionics that drive experimental displays.

Figure 3. TIFS aircraft.

In total, three evaluation pilots flew 53 approaches at AVL using the SVS display for primary tactical guidance cues. The important components with respect to database integrity monitoring are the GPS components, the radar altimeter, and the geospatial data. Ashtech Z-12 GPS receivers were utilized both onboard and at the ground reference site. Post-processing of the recorded GPS data resulted in an accurate estimated flight trajectory ("truth") that has been used in the analysis presented. The nominal accuracy of this position data is 10 cm (RMS). The radar altimeter used during the SVS test, was a Honeywell AN/APN-171(V) unit. Under standard conditions its altitude accuracy is given by:

$$\begin{aligned}\varepsilon_{radalt} &= f(range, range\,rate) \\ &= 5 + 0.03\cdot(range) + 0.05\cdot(range\ rate) \quad ft\end{aligned} \tag{6}$$

Note that the radar altimeter error is a function of the altitude (range) and the rate at which the altitude changes (range rate). This altitude dependency needs to be included in the proposed integrity algorithm or avoided by overbounding the radar altimeter error PDF for all altitudes.

Various terrain databases were available for the Asheville, NC area to support our case study analysis. These include the Airport Safety Modeling Data (ASM100 and ASM12), the Digital Terrain Elevation Data (DTED level I and DTED level II), the United States Geological Survey (USGS) Digital Elevation Model (DEM), and a high resolution National Geodetic Survey (NGS5) DEM created solely for the Asheville airport area.

Flight Test Results

The proposed test statistics were calculated for a number of flight segments flown in October 1999 with the TIFS. The set of flight segments include several Instrument Landing System (ILS) approaches to runway 16 and 34. Figure 4 shows the two-dimensional elevation model of the Asheville area using DTED level I. The runway and runway ends are indicated.

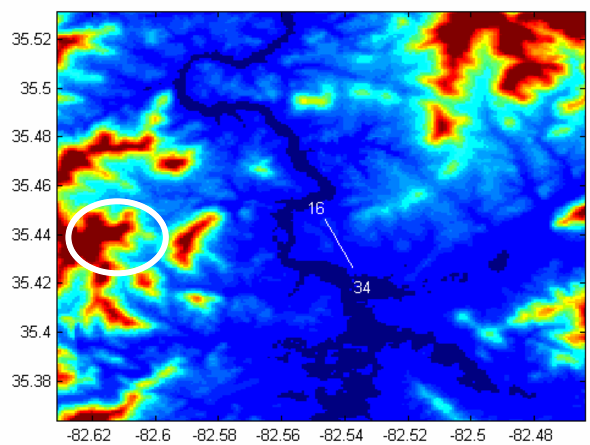

Figure 4. Digital Elevation Database for AVL.

The ILS approach to runway 34 shows 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. Both characteristics can be observed in Figure 4.

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[1] TIFS is operated by Veridian Engineering, Buffalo, NY.

Figures 5 and 6 show the absolute disparity for the approaches to runway 34 and 16, respectively. Significant biases show up in the absolute disparities. When causing an alert such a bias would be blamed on the terrain elevation database. However, during this test un-modeled radar altimeter errors could be causing the bias as well. During the approach on runway 34, the bias is present during flight over the terrain with large variations, and reduces to zero during final approach. The relationship between the low-frequency error component and the variation in the terrain may point to error mechanisms in the radar altimeter. This error mechanism will be discussed in the next section.

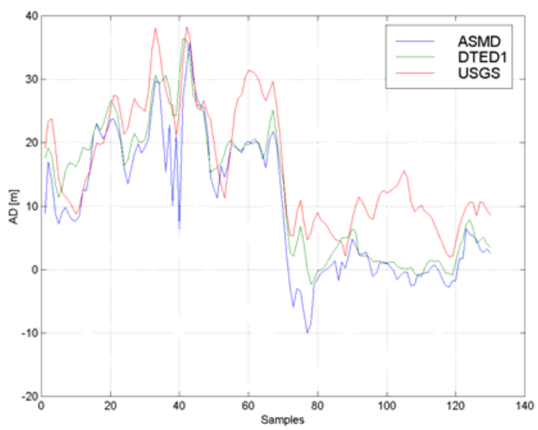

Figure 5. Absolute Disparities (AD) approaching Runway 34 (10/11/99 75047-75176).

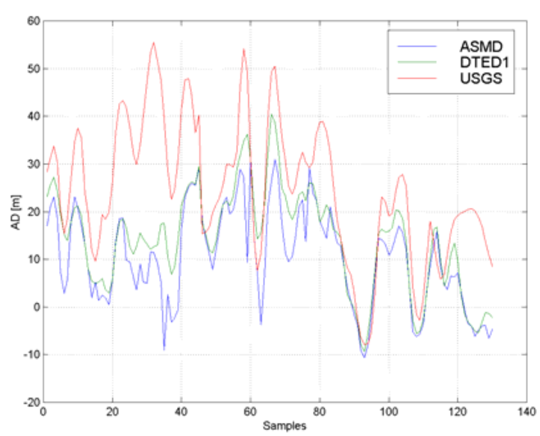

Figure 6. Absolute Disparities (AD) approaching Runway 16 (10/11/99 79040-79169).

Another effect to be noted in Figures 5 and 6 is difference between the absolute disparities computed using the ASM and DTED I and the absolute disparities computed using the USGS. The fact that the ASM was derived from DTED I explains this discrepancy. It will be necessary to investigate the difference between DTED and USGS more closely. Different vertical datums and the use of different sources (remote sensing, photogrammetry, etc.) to derive terrain elevation information is the most likely explanation. To determine the effect on the test statistics, *T* and *Z* were calculated for two approaches to runway 16, one approach to runway 34, and the holding pattern. Figure 7 shows the results for *T* and *Z*, respectively (th = T_D). As can be seen in figure 7, the presence of the bias does not cause the *T* statistic to exceed the threshold for the approach to runway 34. Such a bias is referred to as an undetectable bias. The magnitude of undetectable biases is determined by P_{MD} and underlying statistics. Removal of the bias will improve the performance of the algorithm as is illustrated. Figure 7 also illustrates a violation of the detection threshold for an approach to runway 16.

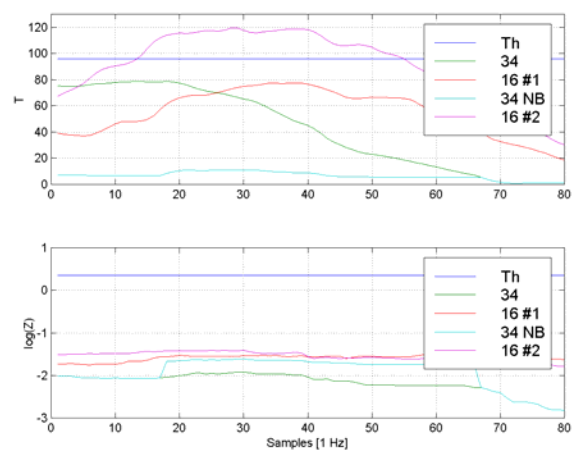

Figure 7. T statistic and Z [log(Z)] Statistic, P_{FFD}= 0.9999, N= 50.

Using the *Z* test statistic (see Figure 7), none of the flight segments caused *Z* to exceed the threshold due to *Z*'s insensitivity to bias-like or low frequency errors. This insensitivity of the *Z* statistic to biases is obvious from equation 3 and is undesirable for an integrity monitor.

For the approach to runway 16 that caused *T* to exceed the threshold, the synthesized and database elevations is given in Figure 8. Although clearly present, the bias is not a constant and shows a strong dependence on the terrain features. Again, this can be caused by both inaccuracies in the radar altimeter measurements and errors in the database.

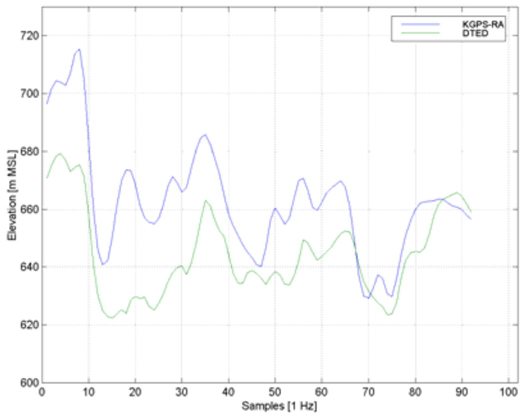

Figure 8. Database Profile to Runway 16 using DTED (10/14/99 67351-67442).

Numerous approaches to runway 16, including straight-and-level approaches, triggered an integrity alert (exceeded the predefined threshold) such as the one shown in Figure 8.

Comparison of the DTED data with more accurate NGS data (4 meter post-spacing, and 1 m vertical accuracy 90%) showed a better agreement with the sensed (synthesized) profile. Figure 9 shows the results.

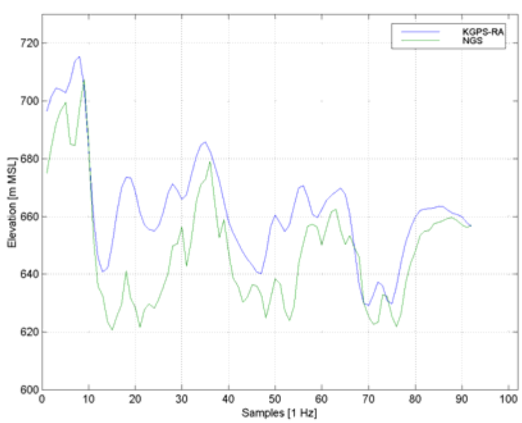

Figure 9. Database Profile to Runway 16 using NGS data (10/14/99 67351-67442).

Other possible causes of the apparent discrepancy between synthesized and database heights is an erroneous understanding of the radar altimeter's behavior, the impact of foliage, such as trees, on radar measurements and possible absence of this information in the terrain databases. Although it is difficult to indicate an exact cause, the terrain underneath these approaches tend to have strong gradients in the terrain and the presence of water (i.e. a river). Since preliminary investigations show a relation between the terrain gradient and the algorithm performance, it is necessary to analyze the radar altimeter's behavior under these conditions and to repeat this type of assessment with other altimeters.

Radar Altimeter Characterization

So far, the test statistics have been based on a radar altimeter measurement of the range to the point directly below the airplane (same x- and y-coordinate). However, the radar altimeter used on board the TIFS has a mode of operation based on tracking the leading edge of the returned pulse. This represents a measure of the range to the nearest reflecting object illuminated by the antenna beams rather than the point directly underneath the airplane. This effect is illustrated in figure 10. Rather than tracking point B, directly underneath the airplane, the radar altimeter will track point A under no-roll conditions and point D under roll-conditions.

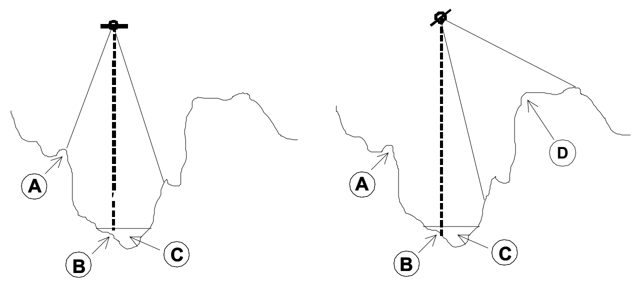

Figure 10. Leading edge tracking.

To account for this effect under roll conditions, attitude information from sensors such as an Inertial Navigation System (INS) is required. In this paper the discussion will be limited to the no-roll case. An improved test statistic could be derived when considering all elevations within a possible illumination zone as illustrated in Figure 10. Next, the range from the aircraft to each one of the illuminated points is calculated, and the smallest range is selected and compared to the radar altimeter measurement. The difference between the calculated ranges and the radar altimeter measurements is the new absolute disparity. For simplicity, this algorithm is referred to as the “spot” algorithm.

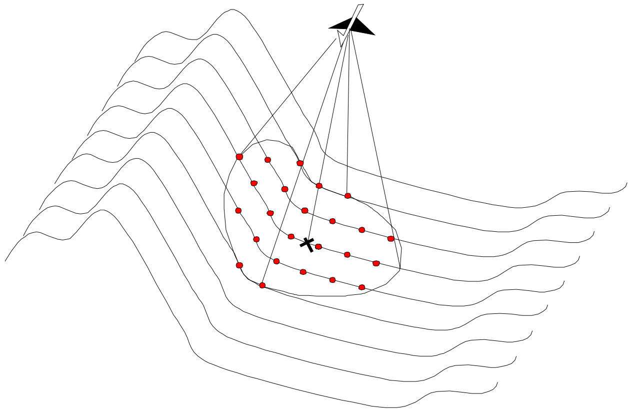

Figure 11 Points illuminated by the radar altimeter.

Application of this new algorithm to DTED terrain data did lead to improvements, although not significant. However, application of the algorithm to NGS terrain data did improve the agreement between synthesized and database terrain significantly as is illustrated in figure 12.

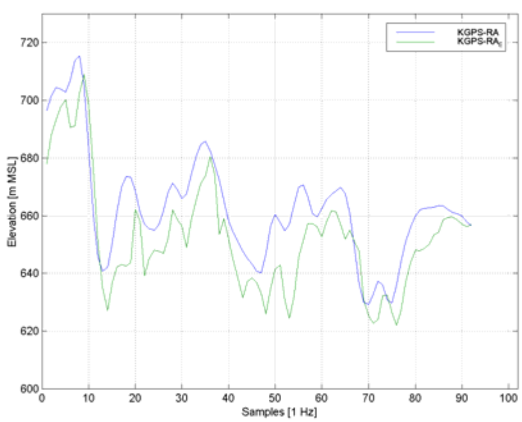

Figure 12. Database Profile to Runway 16 using NGS data and the “spot” algorithm (10/14/99 67351-67442).

Furthermore, the test statistics are significantly improved for all approaches during which the threshold was exceeded. Figure 13 shows the test statistic *T* for the approach to runway 16 used in figures 8, 9 and 12. . Note that a lower T corresponds to a better agreement between measured and database heights.

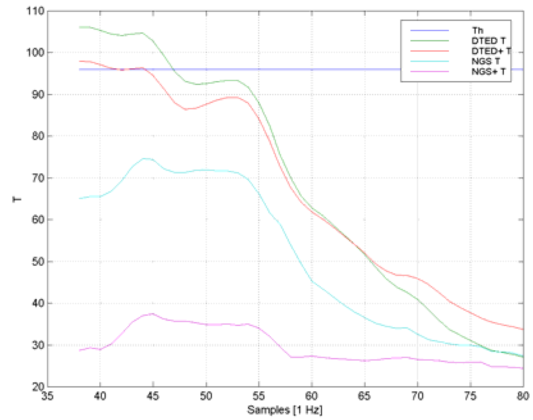

Figure 13. T statistic for approach to runway 16 (10/14/99 67351-67442).

Summary and conclusions

Flight tests were performed in the vicinity of Asheville, NC during which radar altimeter and KGPS data was collected. This data was combined with terrain elevation data originating from DTED I, the USGS DEM, and ASM12. Synthesized elevations were formed from the sensor information. Comparisons of the synthesized elevations with the elevations derived from the terrain databases show the presence of significant biases over terrain that has large variations. These biases may be due to elevation database or radar altimeter characteristics. In the absence of the bias, the variation in the absolute disparity is similar to the one previously shown in [4].

When implementing the test statistics *T* and *Z*, it was shown that *Z* was not sensitive to bias or low frequency errors due to the use of successive differences to compute this test statistic. Although larger than normal, most *T* values did not exceed the thresholds. Removal of the bias, however, showed a significant improvement in algorithm performance.

The *T* threshold was exceeded on various occasions during the approaches to runway 16. This may be due to inaccuracies in the terrain database, but it can also be attributed to error mechanisms of the radar altimeter. This requires a better characterization of the radar altimeter error mechanism. Use of NGS data instead of DTED significantly improved the test statistic. This may point at possible large errors in the DTED. Incorporation of the “spot” algorithm further improved the test statistic for all approaches. The thresholds were no longer exceeded for any of the approaches when utilizing both the NGS data and the “spot” algorithm. A verification of these findings is planned in Asheville, NC using Ohio University’s DC-3 and an alternate radar altimeter.

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