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Appraisal of Digital Terrain Elevation Data for Low-Altitude Flight

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Summary

The use of terrain elevation databases in advanced guidance and navigation systems has greatly expanded. However, the limitations and accuracies of these databases must be considered and established prior to safe system flight evaluation. A simple approach to quantify reasonable flight limits is presented and evaluated for a helicopter guidance system dependent on a terrain database. The flight test evaluated involved a helicopter equipped with a Global Positioning System (GPS) receiver and radar altimeter, and a ground station GPS receiver which provided improved helicopter positioning. The precision navigation and radar altimeter data was acquired while flying low-altitude missions in south-central Pennsylvania. The aircraft-determined terrain elevations were compared with the terrain predicted by the Defense Mapping Agency (DMA) Level 1 terrain elevation data for the same area. The results suggest a safe set clearance altitude of 220 ft for flight testing of a DMA-based guidance avionic in the same area.

Introduction

The application of digitized terrain elevation data in guidance and navigation systems is becoming widespread, spurred by the availability of the databases, heightened emphasis on passive, less-detectable guidance, and potential for more cost-effective navigation. Avionic systems that depend on digitized terrain elevation data for guidance generation or navigational reference require accurate absolute and relative distance measurements to the terrain, especially as they fly at lower altitudes. This is particularly exacting in low-altitude helicopter missions, whose aggressive maneuvering and terrain hugging nature create minimal horizontal and vertical clearances and demand precise terrain positioning knowledge. Numerous database-dependent guidance and navigation algorithms have been studied in computer and flight simulations (refs. 1-4), and some have been evaluated in flight (refs. 5 and 6).

The Defense Mapping Agency (DMA) is responsible for compiling and updating a variety of mapping, charting, and geodesy products. One such product is the Digital Terrain Elevation Data (DTED), which consists of a uniform matrix of mean-sea-level (MSL) terrain elevation values set in the World Geodetic System (WGS). Terrain elevation values for Level 1 DTED within 0°-50° N-S latitude are provided every 3 arc sec of latitude and every 3 arc sec of longitude. At higher latitudes, longitudinal resolution remains at 3 arc sec, while latitude resolution decreases. Such DMA DTED Level 1 data is commonly referred to as "100 meter" data

(the approximate length of 3 arc sec in longitude at the equator).

The most frequent use of DMA terrain elevation databases has been in navigational systems. Current terrain referenced navigation algorithms, such as SITAN (Sandia Inertial Terrain-Aided Navigation) or the British TERPROM (TErrain PRofile Matching), utilize radar-altimeter returns, a DMA terrain database, and a Kalman filter to calculate corrections to the aircraft's inertial navigation system (INS). Such systems have been evaluated in flight trials in aircraft as diverse as high-performance fighter aircraft (ref. 7), to light utility helicopters (ref. 8). Some cruise missiles are currently operating with terrain referenced navigation systems. Although these systems have been extended to assist in target acquisition, ground proximity warnings, and in moving map displays, their principal function and capability is navigation. The navigation function is accomplished by comparing a set of radar altimeter terrain profiles with candidate digital map terrain profiles, and selecting the most similar digital map profile to acquire a fix on the aircraft's latitude-longitude in the digital terrain elevation map. Differences between the radar-determined terrain elevation and digital map elevation simply enter the profile selection algorithm's cost functional in evaluating the candidate terrain profiles (and hence aircraft location). Consequently, errors in the digital map's predicted terrain elevation are inherently hidden as the profile selection algorithm chooses the profile of minimum cost. The terrain referenced navigational solution will still usually converge to the proper latitude-longitude values. Such natural insensitivity to digital map terrain elevation error is obviously desired in a latitude-longitude fix, but could lead to a ground collision when accurate *absolute* vertical terrain proximity is required, such as in helicopter low-altitude flight.

Terrain elevation data has been employed in a low-level, maneuvering terrain following/terrain avoidance (TF/TA) guidance algorithm for helicopters that is being developed at NASA Ames Research Center (ref. 9). The algorithm uses mission requirements, aircraft performance capabilities, navigation data, and digitized terrain elevation data to generate a low-altitude, valley-seeking trajectory. This trajectory guidance is presented to the pilot on a helmet-mounted display. The system has been evaluated in several real-time piloted simulations, and has reached sufficient maturity for flight evaluation. A joint NASA/Army program to flight test the system on the Army NUH-60 STAR helicopter is scheduled for the Winter of 1991/1992. A calibration of the DMA DTED database in the proposed flight test area prior to extensive flight testing is warranted, and is the impetus for

this work. The methodology for this appraisal, however, is applicable in the analysis of other digital terrain elevation based avionics.

The paper first provides a description of the methodology and requirements for the appraisal of a terrain elevation database. The procedure is then illustrated for a database-dependent helicopter guidance system: flight test experimental details are described and followed with a results and discussion section. Finally, conclusions of the work are drawn.

Appraisal Methodology

Assessment of a terrain elevation database is accomplished by comparing predicted elevation values based on measured horizontal position with elevation obtained by taking the difference between the measured vertical position and radar attitude. Precision navigation and radar altimeter returns are recorded as a test aircraft flies low-altitude missions. The flight profiles should include overflight of the most rugged as well as plain areas. The test aircraft's radar altimeter returns above-ground-level (AGL) altitude, while its navigation system outputs height above mean-sea-level (MSL) and latitude-longitude. By subtracting the radar-altimeter value from the MSL altitude, one determines the elevation of the terrain at the sampled position. Such a calculation is made for all of the flight data, and stored with the aircraft's latitude-longitude position as provided by the navigation system. The latitude-longitude position is used with the terrain elevation database to obtain the predicted elevation value.

The database prediction of terrain elevation is then found at each sampled aircraft position. The nearest three "posts" of digital terrain data are used to form a triangular terrain plane; the interpolated elevation value of this plane below the aircraft is taken as the database elevation prediction. Note that the DMA DTED database always measures MSL height of the terrain, independent of any foliage. A direct comparison of the aircraft-determined terrain elevation with that given in the digital terrain database may then be performed for the entire flight.

Discrepancies found between the two terrain elevation values will be due to database errors and foliage, as well as to aircraft instrumentation errors, i.e., navigation and radar altimeter errors. The methodology presented is

quite sensitive to vertical navigation error, as this enters directly into the aircraft-based calculation of terrain elevation. Horizontal navigation error will reference database elevation "posts" offset from those desired; this becomes more acute over rugged terrain. Finally, radar altimeter accuracy, which degrades with AGL altitude and has the potential for erroneous early reflection from tree canopy top, will corrupt the terrain elevation computations. Consequently, terrain elevation differences observed are inherently coupled to the test aircraft's instrumentation errors. Isolation of database errors is most readily achieved through increased navigation system accuracy.

The comparison of the database terrain elevations with those of the test aircraft will yield maximum and minimum difference bounds. The maximum difference found will establish a safe set clearance altitude for more extensive flight testing in the same area.

Flight Test Experimental Details

Low-altitude helicopter flights were conducted in a UH-1 (Huey) helicopter. The test data analyzed was collected during the Heli/SITAN flight tests of Hollowell (ref. 8) during Fall 1989. Heli/SITAN is a terrain referenced navigation algorithm developed by Sandia National Laboratories and the U.S. Army Avionics Research and Development Activity (AVRADA).

The test aircraft was equipped with a simultaneous 4-channel, Clear Acquisition (C/A) code GPS receiver (Motorola Eagle Mini-Ranger). The carrier-aided tracking receiver employed an 8-state Kalman filter, providing positional accuracy below 25 m (82 ft) Spherical Error Probable (SEP). Selective availability, the intentional degradation of the GPS signal, was not activated. GPS positional outputs recorded were geodetic latitude, longitude, and MSL altitude in the NAD27 datum. Raw aircraft GPS data was converted from the NAD27 to WGS84 datum to allow comparison with the WGS84 referenced DMA terrain data. The GPS patch antenna was mounted flush on the top of the aircraft, between the cabin overhead windows just forward of the VHF/UHF blade antenna.

The radar altimeter (Honeywell APN-209) fitted to the aircraft was limited to altitudes below 1500 ft and to pitch and roll attitudes of 45°. The fan-type radio-frequency altimeter returned aircraft height above the ground or closest terrain obstacle, depending on the nature of the obstacle. Flight over densely foliaged trees will yield height above the tree tops, while flight over bare (winter) trees will give height above the ground.

Radar altimeter accuracy was specified to be within ±(3 ft + 3% of actual altitude) (refs. 10 and 11).

Airborne GPS and radar-altimeter data were recorded on a SANDAC V avionics computer. GPS receiver outputs were latitude, longitude, MSL altitude, satellite identification numbers, positional dilution of precision (PDOP), GPS system status, and GPS hr/min/sec time. A time stamp was affixed to both the GPS data and the radar altimeter output upon input to the SANDAC V. All flight data was recorded in binary form at a 1 Hz rate.

A ground station in the test area equipped with an identical GPS receiver provided an improved airborne navigation solution. The station location was established using the Transit satellite system (accuracy to ±15 ft). Maximum distance between the ground station and the aircraft during the flight test was 15 n.mi. The ground GPS receiver was forced to track the same four satellites as the airborne system. GPS latitude, longitude, MSL altitude, satellite identification number, PDOP, and GPS hr/min/sec were recorded, allowing positional errors in the ground station GPS solution to be calculated. These errors were then applied to the airborne GPS navigation solution. The positional dilution of precision (PDOP), a measure of the geometrical component of a navigation solution's sensitivity to error, was nearly identical for both the airborne and ground GPS receivers. The two receivers PDOPs varied from 4.2 to 2.6, indicating good satellite geometry throughout the flight.

The terrain data employed was Level 1 DMA DTED in the 1° by 1° cell from −77° to −78° (West) longitude and from 40° to 41° (North) latitude. The DMA accuracy objective for DTED Level 1 data is 130 m (427 ft) at 90% circular error for absolute position, and ±30 m (98 ft) at 90% linear error for absolute vertical elevation. Each 1° latitude by 1° longitude DMA DTED database cell carries individual accuracy information, however, which depends on the data collection method employed in that area. The database used was referenced to the WGS84 datum with stated accuracy levels of 260 m (853 ft) absolute horizontal position and 50 m (164 ft) absolute vertical elevation (both at 90% confidence). The DMA database was slightly modified for use in the NASA Ames low-altitude guidance avionic mentioned in reference 9. The raw 3 arc sec by 3 arc sec terrain elevation values created a rectangular grid pattern longer in latitude than longitude. A square grid pattern (a requirement of the guidance algorithm) was generated by linearly interpolating along the latitude values.

The flight test area was in south-central Pennsylvania, just south of Harrisburg, PA, in moderately rough terrain. The area includes diverse features; flat plain sections as well as South Mountain, running diagonally through the test area (fig. 1). The rougher sections of the terrain contain rather densely populated deciduous trees. The flight profiles flown were all "low-level" missions, i.e., fixed MSL altitudes. Speed was held constant at 90 knots. A rectangular course, followed by a bow-tie diagonal pattern, was flown. After takeoff from Shippensburg airfield, the helicopter flew north to the NW corner of the course, then completed a clockwise course back to the NW corner. A diagonal flight to the SE corner, then northward to the NE corner, and finally a diagonal to the SW corner completed the course (fig. 2, table 1). Interruptions in the ground track flight profile are times of GPS satellite loss or GPS receiver queries for better satellite geometry. Only aircraft GPS results improved by ground-station calibration are presented. The data gathered when the ground and airborne receivers were tracking different satellite constellations, or were switching satellites, have been deleted. During the lower leg of the course (from the SE to SW corners), both GPS receivers were switching satellites.
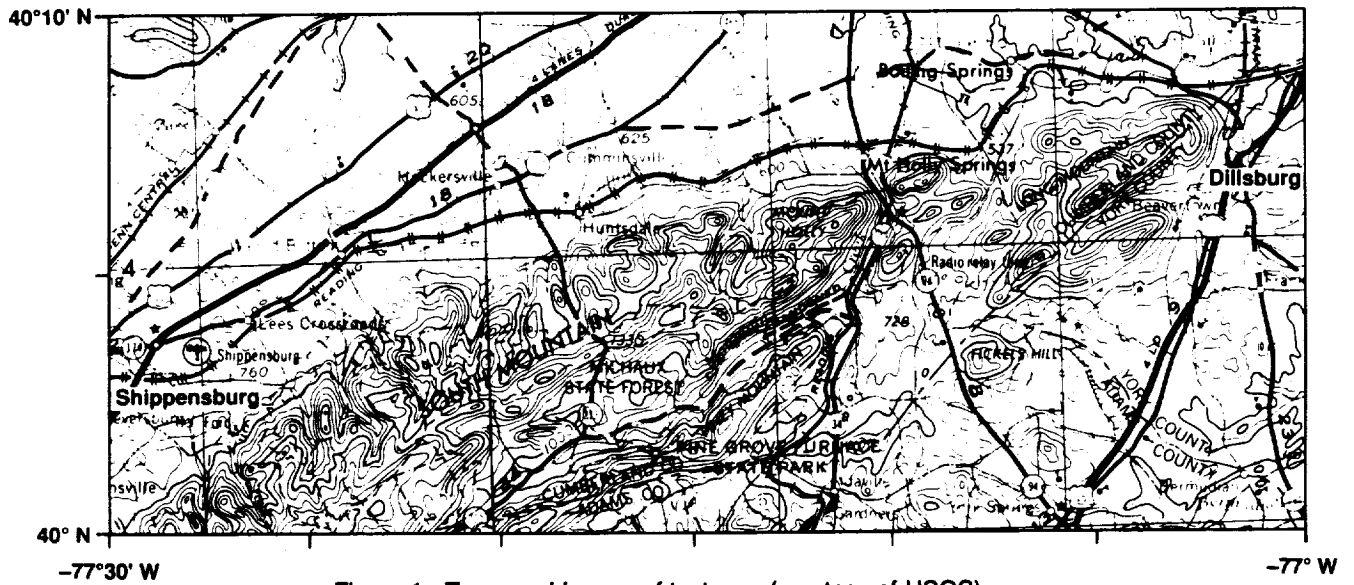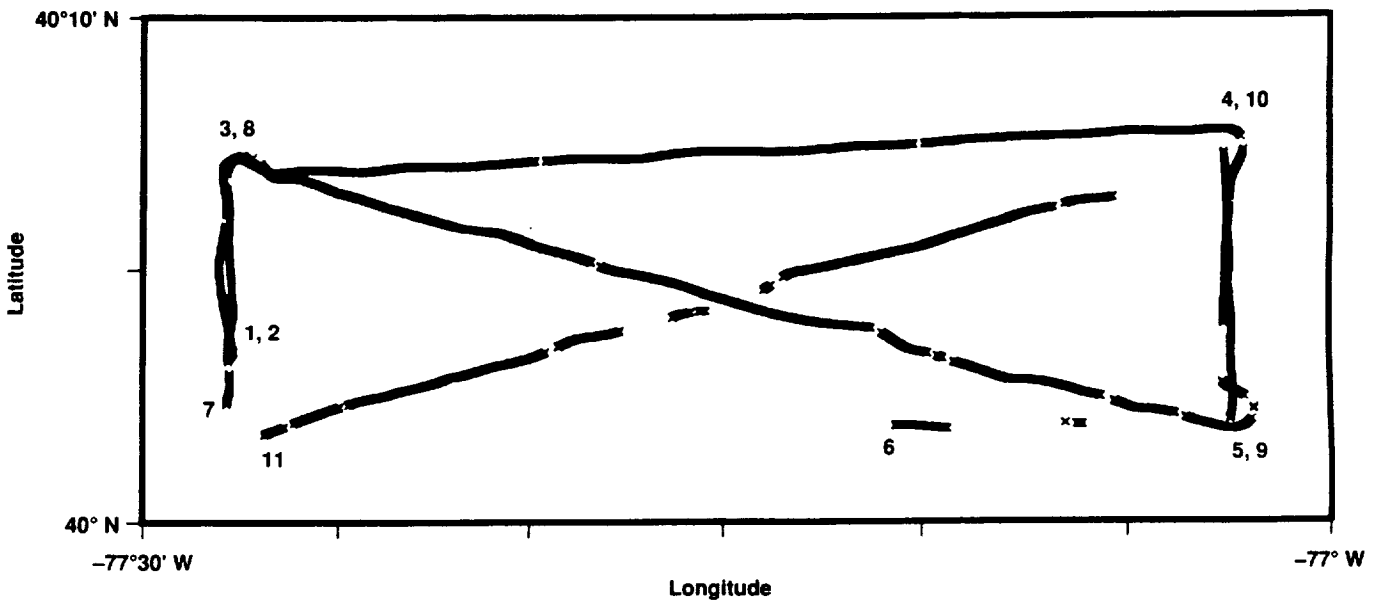
Figure 1. Topographic map of test area (courtesy of USGS).

Note: Numbers refer to flight events identified in Table 1.

Figure 2. Flight test ground track.

Table 1. Flight profile

| Event no.	Event	Relative time (sec)
1	Start of data recording, tracking satellites 3,11,13,14	0
2	Take off from Shippensburg, PA	526
3	At NW corner, turning East to NE corner	697
4	At NE corner, turning South to SE corner	1487
5	At SE corner, turning West to SW corner	1717
6	Data interruption; switching satellites	1990
7	At SW corner, turning North to NW corner (now tracking satellites 3,16,13,14)	2537
8	At NW corner, fly diagonal to SE corner	2692
9	At SE corner, turning North to NE corner	3577
10	At NE corner, fly diagonal to SW corner	3765
11	End of data recording	4651

Results and Discussion

The aircraft-determined terrain elevations calculated for the flight are shown in figure 3(a); table 1 describes the flight events. The aircraft was running up at the Shippensburg airfield until takeoff, labeled as event 2. Because the radar altimeter returns during this period were zero, the positional Differential GPS (DGPS) MSL aircraft altitude is the aircraft-determined terrain elevation. The value realized during this period had an average of 700 ft. The elevation at Shippensburg airfield, according to both the USGS topographic map (fig. 1) and NOAA Aviation Sectional Chart, is 760 ft. The aircraft-determined terrain elevation, based entirely on the DGPS MSL altitude, is 60 ft off from survey. Although some of this difference could be attributed to airfield elevation survey error, or an aircraft run-up area slightly downhill or uphill of the survey site, the majority of this difference must be allotted to navigational error in the DGPS vertical solution. Navigation accuracy of this order for vertical positioning must be assumed for the entire flight data analysis. This critical navigation accuracy limitation is noted and will be addressed again.

After take-off (event 2) from Shippensburg airfield, the aircraft began its rectangular course with a northerly heading to the NW corner (fig. 2, table 1). Low-level (constant MSL) flight proceeds to the NE and then SE corners of the course, with both the airborne and ground GPS receivers tracking the same satellite constellation. Several terrain elevation features evident in the topographic map (fig. 1) can be seen in the aircraft-determined terrain elevation profile of figure 3(a). The first terrain elevation spike between events 3 and 4 corresponds to the terrain near Hockersville (fig. 1), while those just before event 4 (negotiating the NE

course corner) correspond to overflight of Long Mountain, situated in the NE corner of the course. Just after arriving at the SE corner and initiating a westerly heading, the airborne GPS receiver lost reception of a satellite. This is the reason for the break in the terrain elevation values immediately after event 5. The satellite was then recovered briefly and lost again. At this point, the intermittently received GPS satellite was replaced with another in both the ground reference and airborne receivers and data recording resumed. The aircraft kept flying its SE to SW leg during the satellite switching operation.

Continuous data resumed as the aircraft turned north (event 7) towards the NW course corner. The downward sloping terrain along this leg is evident in figure 3(a). The flight then continued (from event 8 to 9) along the southeasterly diagonal to the SE corner. The elevation peak of 1533 ft during this period corresponds to the aircraft's overflight of South Mountain (fig. 1). The second, less-severe climb and descent during this leg of the flight represents the negotiation of Fickels Hill (fig. 1). Event 9 is identified by the helicopter's turn to the north toward the NE course corner. The positive elevation gradient during this course leg is apparent, again reconciled by the terrain of Long Mountain at the NE course corner.

The flight was completed with a southwesterly leg along the course diagonal (event 10 through 11). This flight was over the most aggressive terrain of the area; essentially over the length of South Mountain. After an initial period of satellite masking, aircraft DGPS and radar altimeter data allowed terrain elevation to be calculated. The steep and severe nature of the terrain during this final course leg is apparent in figure 3(a).

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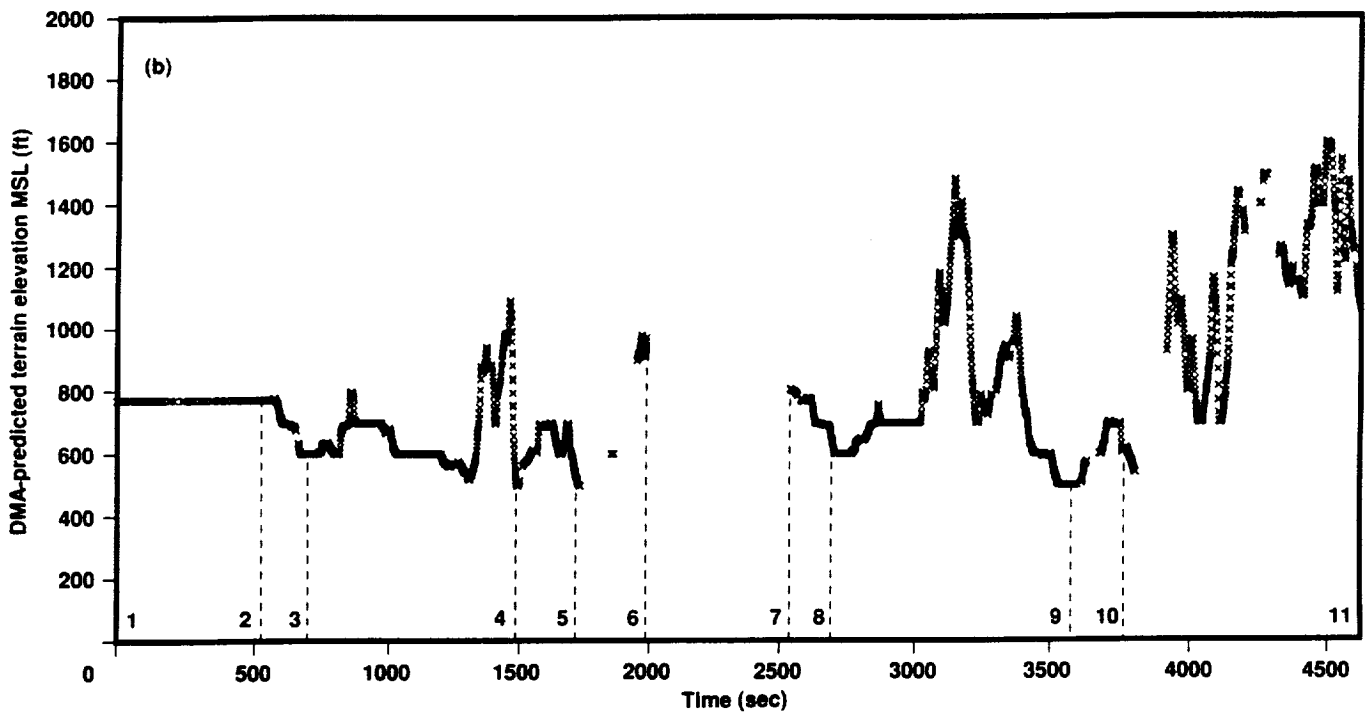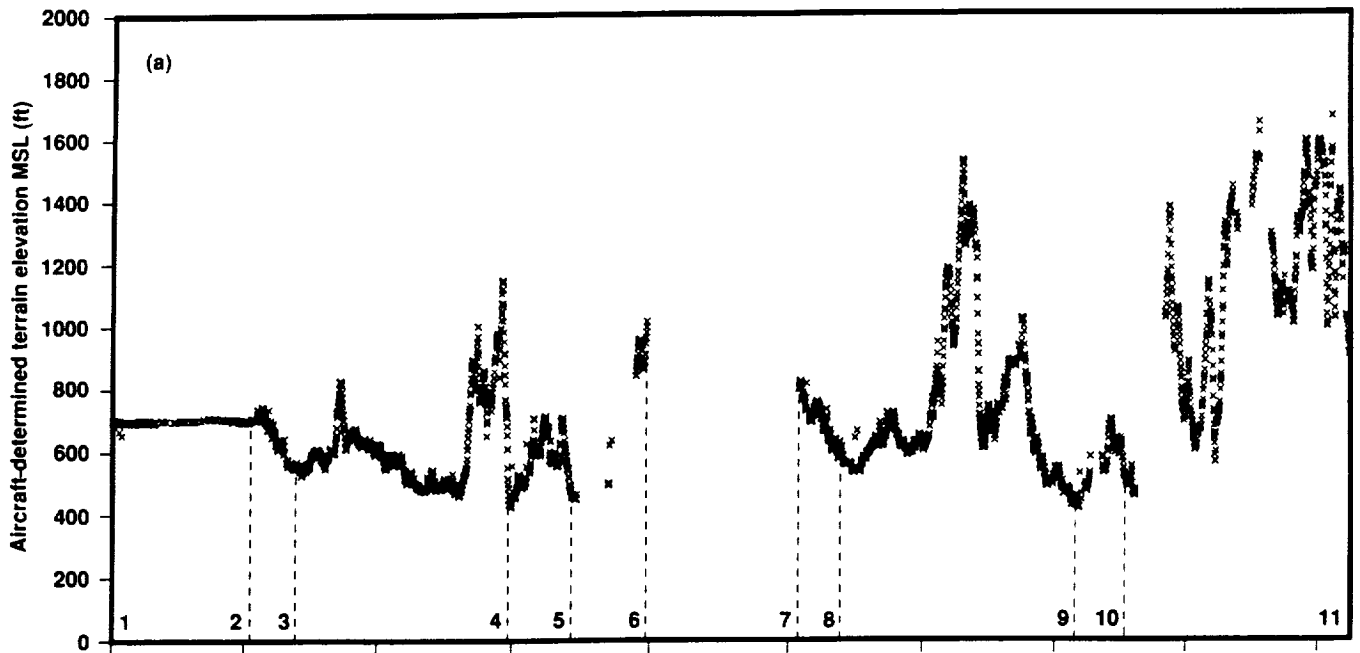
Note: Numbers above abscissa refer to flight events identified in Table 1.

Figure 3. Terrain elevation profile. (a) Aircraft-determined; (b) DMA-predicted.

Figure 3(b) traces the DMA DTED prediction for terrain elevation during the flight. The DMA terrain elevation prediction for the airfield is shown to be 771 ft. This is 11 ft greater than the USGS topographic map (fig. 1) and 11 ft greater than the USGS topographic map (fig. 1) and aviation sectional chart value, and 71 ft greater than the instrumented aircraft calculation. The smoother nature of the DMA terrain profile versus the experimentally determined profile (fig. 3(a)) is apparent. Interruptions

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in the data of figure 3(b) are caused by the GPS receiver discontinuities previously discussed. The general topographic trends of the flight-test course (fig. 1) are also realized in the DMA values, e.g., the crossing of Long Mountain in the NE course corner (just prior to event 4) and over South Mountain during the NW-SE diagonal route (from event 8 to 9).

In order to quantify the disparities between terrain elevations determined by the aircraft and those predicted by the DMA DTED database, their difference was plotted for the length of the flight (fig. 4). Recall that the data through event 2 was acquired during helicopter run-up. The 71 ft difference in airfield terrain elevation between the aircraft calculated value and that of the DMA database is evident. The DMA is overestimating the terrain elevation value with respect to the aircraft DGPS calculation, and continues to predict higher values as the aircraft takes off and flies north to the NW course corner (event 3). The majority of this difference (71 ft) at the airfield is probably due to GPS navigation error, as the field elevation (760 ft) is actually 11 ft below the DMA prediction, but 60 ft above that of the aircraft DGPS solution. Higher DMA terrain values than those found by the aircraft generally continue during the NW-NE course leg (events 3 to 4). Note the terrain difference excursions as the terrain of Long Mountain is encountered just before event 4. During this period the

difference fluctuates to extremes of +150 ft (DMA below aircraft determined terrain elevation value) and −130 ft (DMA above aircraft value). The NE-SE course section (events 4 to 5) again principally presents DMA predictions above those of the aircraft. The limited data acquired during the bottom leg (between events 5 and 6) indicates difference extremes of +42 ft to −107 ft .

After the satellite constellation change, continuous data resumes for the SW-NW course leg (fig. 2). Aircraft-determined terrain elevation minus DMA DTED values vary from +35 ft to −110 ft through the SW-NW leg into the early section of the NW-SE diagonal leg (events 8 to 9). During overflight of South Mountain (approximately midway along this route) the difference plotted reaches extremes of +178 ft to −140 ft. Such large discrepancies between the database and the aircraft "truth" values over South Mountain (the most rugged course terrain, with the greatest terrain elevation gradients) can be attributed to four factors: (1) This area is heavily wooded with assorted species of deciduous trees. The late Fall flight date (30 October) created sections of trees with varying degrees of foliage. As such, the peculiarities of the radar altimeter, i.e., whether it returns AGL values to tree canopy top, ground level, or somewhere in between, will be at issue. (2) The aircraft's positionally corrected DGPS navigation solution
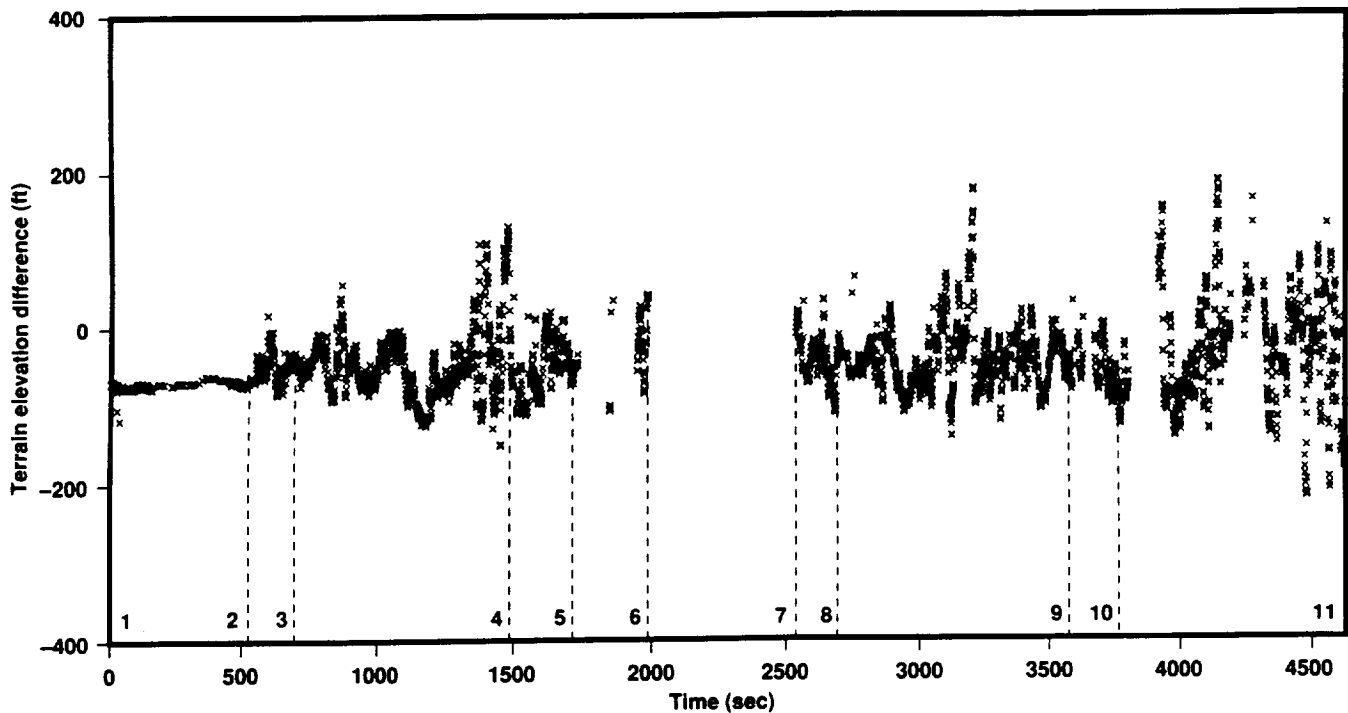
Note: Numbers above abscissa refer to flight events identified in Table 1.

Figure 4. Difference in terrain elevation profiles (aircraft-determined − DMA-predicted).

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contains inaccuracies; hence errors in outputed latitude-longitude values will reference an offset DMA database post as well as yield an imprecise vertical position. (Recall the 60 ft vertical positioning accuracy limitation witnessed during aircraft run-up at Shippensburg airfield.) (3) The distance between the GPS reference station from the aircraft GPS receiver will also create some error in the differential navigation corrections applied. (4) Some errors between the DGPS radar altimeter terrain elevation and DMA will in fact be due to DMA inaccuracy. The comparison of figure 4 is inherently coupled to all of the above errors, although their impact can be reduced. The appraisal methodology is most directly dependent on precision navigation. For this reason, the greatest strides toward isolating terrain database errors can be made through highly accurate navigation positioning.

The remainder of the NW-SE diagonal course leg (event 8 to 9) and the northerly SE-NE course legs generally show DMA terrain elevation predictions greater than those from the aircraft. Note the retracing of the SE-NE course section during the flight test (between events 4 to 5 and 9 to 10). The terrain elevation profiles during these periods were compared in order to address data repeatability. Although the two runs *generally* duplicate one another, a definitive comparison is not justified as the two legs are not near enough to the same course. Their longitude values differed by up to 10 arc sec, translating to a positional difference of over 1000 ft. The greatest extremes in the terrain elevation values between DMA and aircraft "truth" occurred during the final leg of the flight test (from event 10 to 11), which was along South Mountain. Terrain elevation differences of +188 ft to –219 ft were realized. The region's patches of deciduous trees also created the atmosphere for irregular radar altimeter AGL measurements.

The maximum error range realized suggests a minimum set clearance altitude of 220 ft AGL. Recall that the DMA stated accuracy level for the 1° by 1° cell appraised was 164 ft in absolute vertical height (90% confidence). Over the entire flight, the mean difference in terrain elevation (aircraft minus DMA) was –45 ft, with standard deviation of 47 ft. The negative mean difference in terrain elevation denotes overestimation of terrain elevation (on average) in the DMA database.

Conclusions

1. A methodology for the appraisal of a digital terrain elevation database has been developed. The method requires an aircraft equipped with a precision navigation system, radar altimeter, and data recording hardware.

Such an appraisal of terrain data is critical for low-altitude aircraft operations that rely on a terrain elevation database.

2. The methodology presented is limited in its ability to separate digital terrain database error from aircraft instrumentation errors. The analysis is very sensitive to navigation inaccuracies, and radar altimeter idiosyncrasies over forested terrain will yield irregular data. The more sophisticated and accurate the precision navigation system used, the more isolated database errors will become.

3. In the test area evaluated using positional C/A code DGPS precision navigation, the DMA DTED Level 1 ("100 m") database was found to represent the terrain to within 220 ft. The database terrain elevation was generally greater than that found by the test aircraft. Minimum clearance altitude for flight testing of a DMA-based guidance system in this area is suggested to be 220 ft AGL.

Future Work

Based on the results of this work, a radar altimeter is planned to be integrated into the NASA/Army guidance avionics (ref. 9) scheduled for flight test. This is expected to correct for some of the terrain elevation discrepancies, and allow for lower altitude operation. Eventually, a forward-looking sensor will be incorporated as nap-of-the-Earth altitudes are approached.

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