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A Cost-Effective Adverse-Weather Precision Guidance System

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Prepared by
Sandia National Laboratories
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A Cost-Effective Adverse-Weather Precision Guidance System

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Abstract

This SAND report documents the results of an LDRD project undertaken to study the accuracy of terrain-aided navigation coupled with highly accurate topographic maps. A revolutionary new mapping technology, interferometric synthetic aperture radar (IFSAR) has the ability to make terrain maps of extremely high accuracy and spatial resolution, more than an order of magnitude better than currently available DMA map products. Using a laser altimeter and the Sandia Labs Twin Otter Radar Testbed, fix accuracies of less than 3 meters CEP were obtained over urban and natural terrain regions.

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I. Introduction

This paper documents a specific result of the "Adverse Weather Precision Guided Munitions" LDRD, namely the Inertial Terrain-Aided Guidance (ITAG) concept. In addition to the ITAG concept exploration described in this paper, the complete LDRD effort included investigation of a number of technologies related to the precision delivery of conventional munitions, the results of which have been are doumented elsewhere. These include:

"Target location using SAR", Scott M. Burgett, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada, 1994.

"An Investigation of Airborne GPS/INS for High Accuracy Position and Velocity Determination", Todd E. Owen and Mark A. Meindl, ION National Technical Meeting, 1994.

"SAR in a 3-D Target Space for Precision Guided Munitions", Armin W. Doerry, Sandia Laboratories internal memo, 1993. Copies of this memo are available upon request.

The other major focus of the LDRD was the investigation of a low-cost adverse-weather terminal sensor for use on existing munitions and cruise missiles which can deliver terminal accuracy of less than 3 meters CEP. The terminal system incorporates an Inertial Terrain-Aided Guidance (ITAG) system which utilizes a high-accuracy radar altimeter for terrain elevation profile measurement and stored Digital Terrain Elevation Data base (DTED) for terrain elevation profile prediction. The elevation prediction algorithm is a high-altitude extension of Sandia's Inertial Terrain-Aided Navigation (SITAN) algorithm. The SITAN extension executes in an on-board computer to correlate the measured profile to the predicted profile to compute guidance corrections. The ITAG concept incorporates improvements over previous terrain-aided systems as 1) the stored DTED is generated pre-attack by an airborne mapping platform utilizing an interferometric synthetic aperture radar (IFSAR) and 2) utilization of a high-accuracy radar altimeter on the weapon rather than a conventional radar altimeter. The interferometric DTED promises elevation accuracy far greater than previous mapping techniques, and the high-accuracy radar altimeter allows operation at higher altitudes and promises greater accuracy at lower altitudes. Additionally, the interferometric DTED / altimeter combination promises successful operation over urban areas, a feature generally not available with previous terrain-aided systems.

This paper presents an overview of the ITAG concept, a description of the Sandia Inertial Terrain-Aided Navigation (SITAN) Algorithm, a brief description of IFSAR mapping, and the status of Sandia's work in an ITAG performance demonstration.

II. ITAG System Overview

The proposed ITAG terminal guidance system is intended to be a "strap on" guidance upgrade compatible with existing and planned munitions and cruise missiles, as illustrated for in Figure II-1.

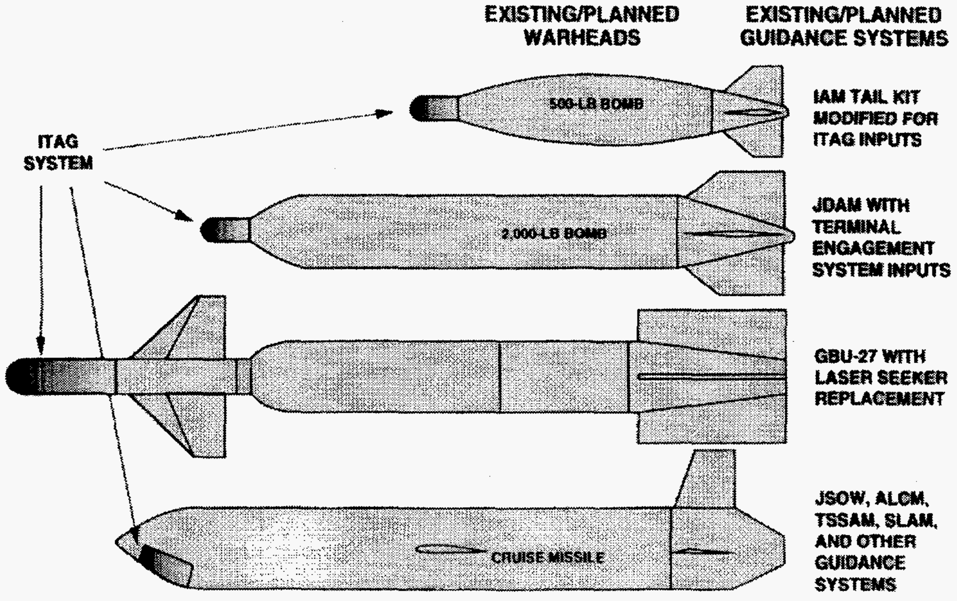


Figure II-1: Potential ITAG Platforms

The required additional guidance components will depend on the platform being upgraded, and may consist of a low quality INS only or an integrated GPS/INS guidance package with 15 meter nominal accuracy. The ITAG terminal system can reduce the 15 meter accuracy to a level of 3 meters or less. The target ITAG unit production cost is $30k or less.

The operational scenarios under consideration are: 1) the high altitude delivery of a guided munition, 2) the loft delivery of a guided munition, and 3) the low altitude delivery of a cruise missile. The high altitude delivery scenario is intended for weapon delivery at 50,000 feet or above, as would be the case for a B-2 delivering a MK-84 or BLU-109 (JDAM). The loft delivery is intended to meet the requirements of the Joint Stand-off Weapon (JSOW) program. The low altitude system would be suitable as an upgrade to existing or future cruise missile systems.

As illustrated in Figure II-2, the TAG concept combines technology advances in the following three areas:

1. IFSAR terrain map production, an area where advances in the last few years have made possible extremely high accuracy (centimeter-level) mapping accuracy with high spatial resolution.
2. High altitude altimetry, where a high altitude, high accuracy altimeter system was developed and flight tested at Sandia in the mid-1980s for maneuvering re-entry vehicle application.
3. Terrain-aided navigation, a technology which was introduced in the 1960s, and currently supplies the mid-course guidance capability for the tomahawk cruise missiles. The SITAN algorithm was introduced by Sandia in the early 1970s and has also been flight tested on a number of systems.

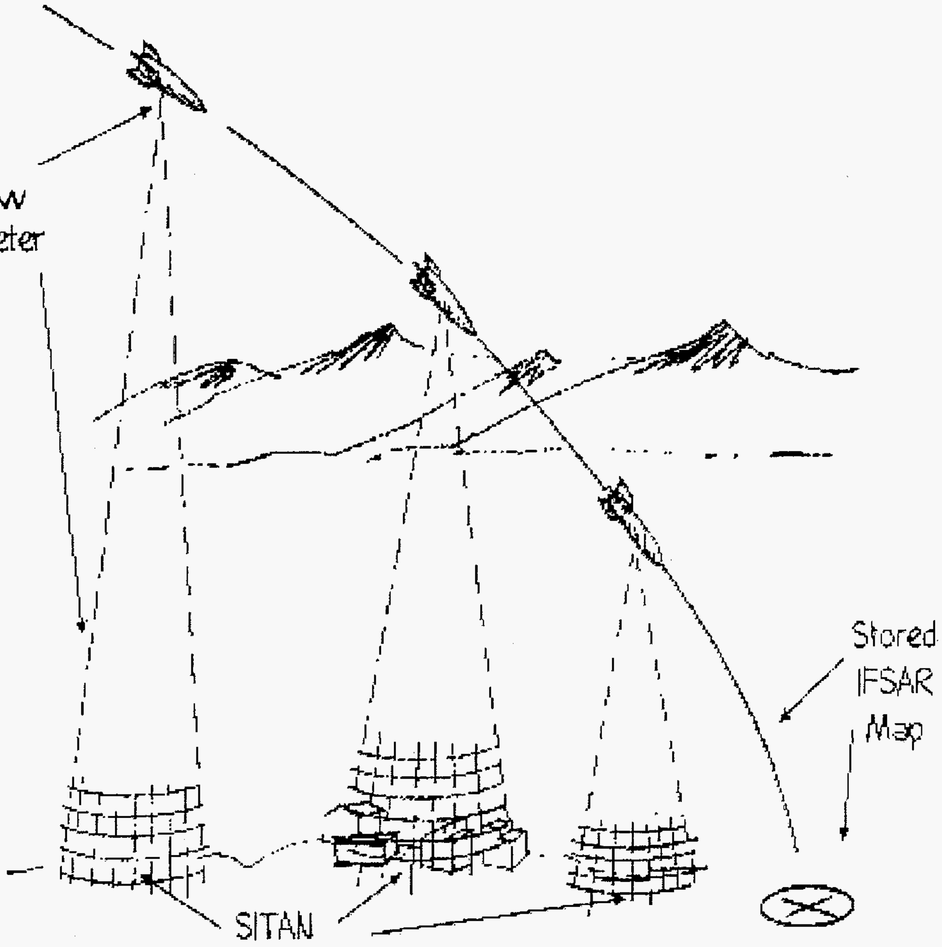


Figure II-2: ITAG Concept

A description of each of these technology areas is contained in the following sections.

II.1. IFSAR Mapping

The digital terrain data required for ITAG operation is produced by an off-board interferometric mapping platform (airborne or spaceborne), and the digital terrain data is pre-loaded into the ITAG weapon. The Interferometric SAR mapping concept [1] illustrated in Figure II-3. The technique requires either 1) two SAR antennas located on the same platform (as illustrated in Figure II-3), or 2) repeat passes of a single SAR platform. When the terrain to be mapped is viewed from slightly different angles, the height of the terrain is a function of the phase difference between the two received signals. This phase difference is very sensitive to the terrain height changes, thus maps of very fine detail and very high accuracy can be produced. Sandia and has successfully demonstrated high accuracy terrain mapping of both natural and urban terrain, with both single-pass and two-pass IFSAR implementations on board its Twin Otter aircraft.

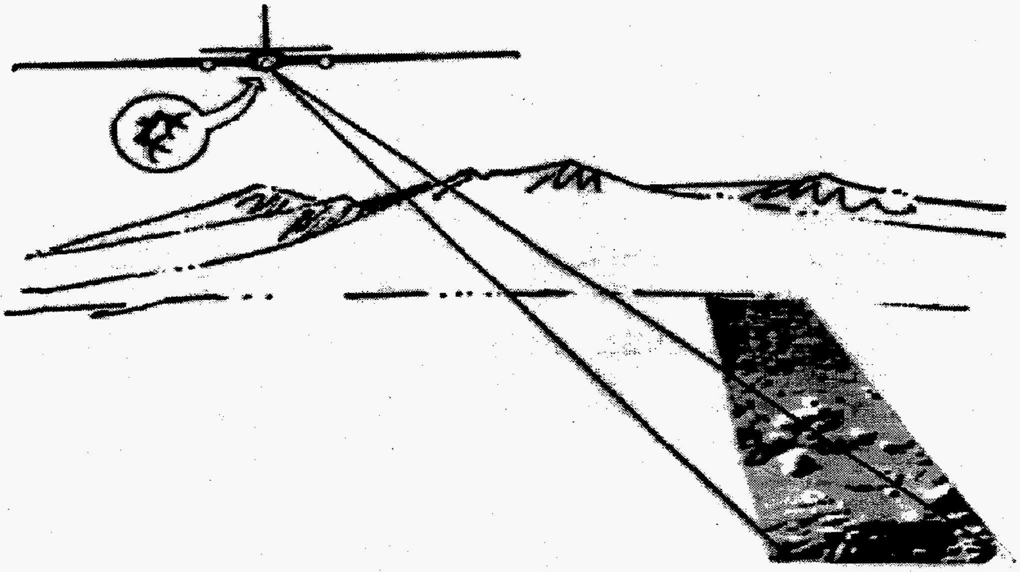


Figure II-3: IFSAR Mapping From a Single Platform

A critical parameter relating to ITAG terminal accuracy is the achievable mapping accuracy which can be obtained via IFSAR mapping techniques. Sandia has been involved with mapping accuracy analysis for some time, and data collections to evaluate mapping accuracy are ongoing. We and others have demonstrated that mapping accuracy well below 1 meter is achievable. Sandia's interferometric SAR efforts utilize a 15 GHz SAR operating aboard a "Twin Otter" aircraft. Both a single-pass and two-pass capability have been demonstrated. An example IFSAR terrain map produced by Sandia's Twin Otter SAR Test bed is illustrated in Figure II-3.

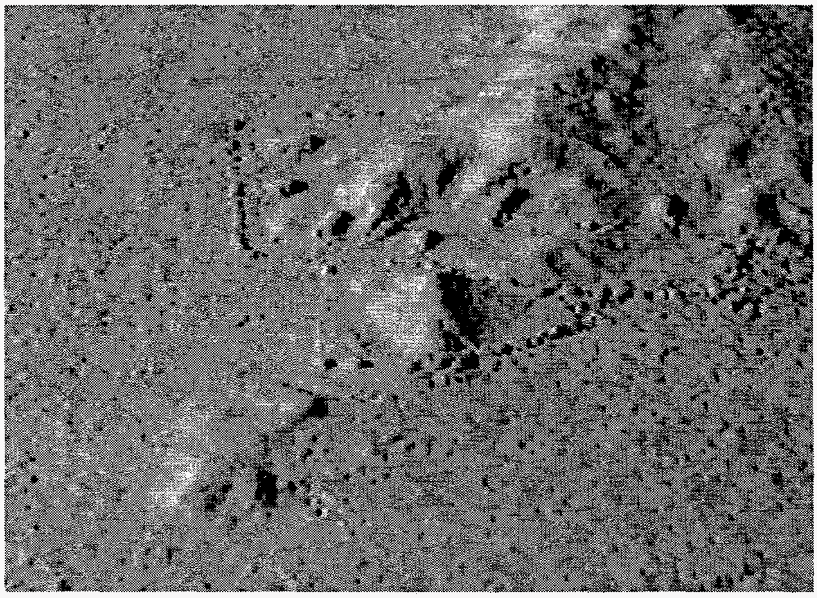
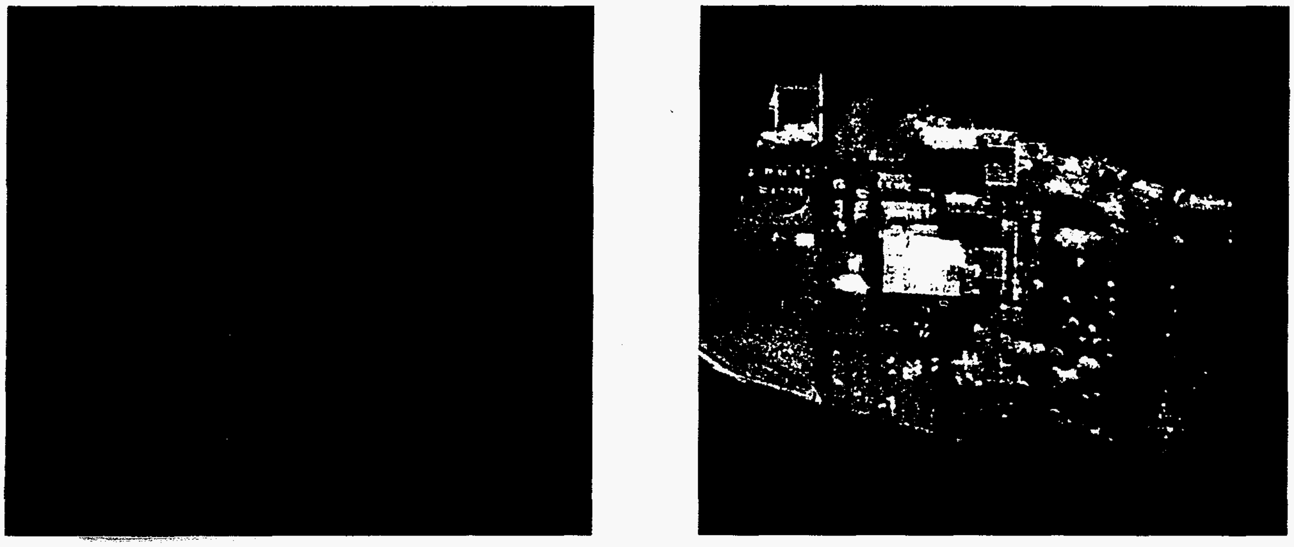


Figure II-4: IFSAR Terrain Map

The topographic map in Figure II-4 contains significant fine terrain detail, including small hills (a few feet high), and an 8-foot high chain-link fence. Sandia has also investigated the mapping of urban areas with IFSAR, and an example urban height map is shown in Figure II-5.

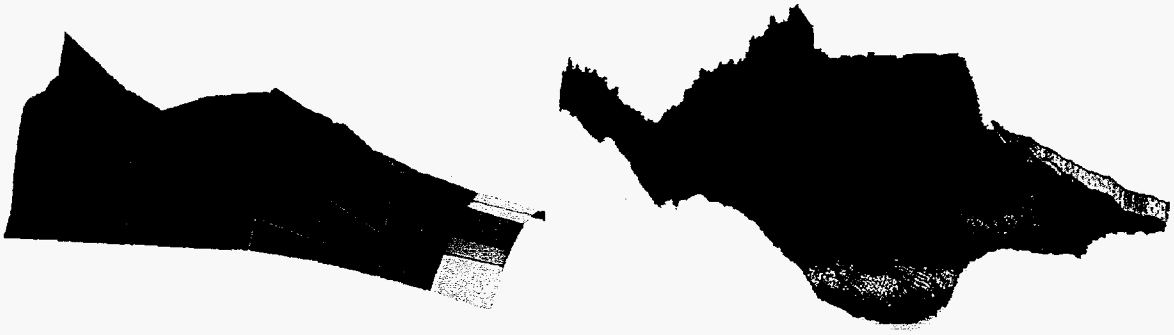


Height Map (Color Denotes Height)

SAR Image

Figure II-5: IFSAR Urban Terrain Map

The mapping accuracy and spatial resolution which can be achieved with IFSAR is significantly better than can be achieved with traditional stereo optical techniques, as illustrated in Figure II-6, which shows an IFSAR-derived map of a hilltop in northern New Mexico, and the corresponding DMA Level 1 DTED for the same area.



DMA Level 1 DTED

IFSAR 3 Meter DEM

Figure II-6: DTED Comparison

II.2. SITAN Algorithm

Sandia has been involved in the design and implementation of terrain-aided guidance systems since 1974, when the Sandia Inertial Terrain Aided Navigation (SITAN) algorithm was first introduced. Since then SITAN has been successfully applied to several platforms, and achieved accuracy ranging from 120 meters to 6 meters. As illustrated in Figure II-7, SITAN accuracy is primarily a function of terrain roughness and mapping accuracy. The 6 meter performance was achieved over moderately rough terrain and very accurate maps. The interferometric SAR mapping technique promises even greater mapping accuracy, and the question arises if 3 meter CEP is a reasonable performance expectation. In addition to the accuracy question, the issues of high-altitude and all-weather operation must be addressed if SITAN is to be a robust guidance system.

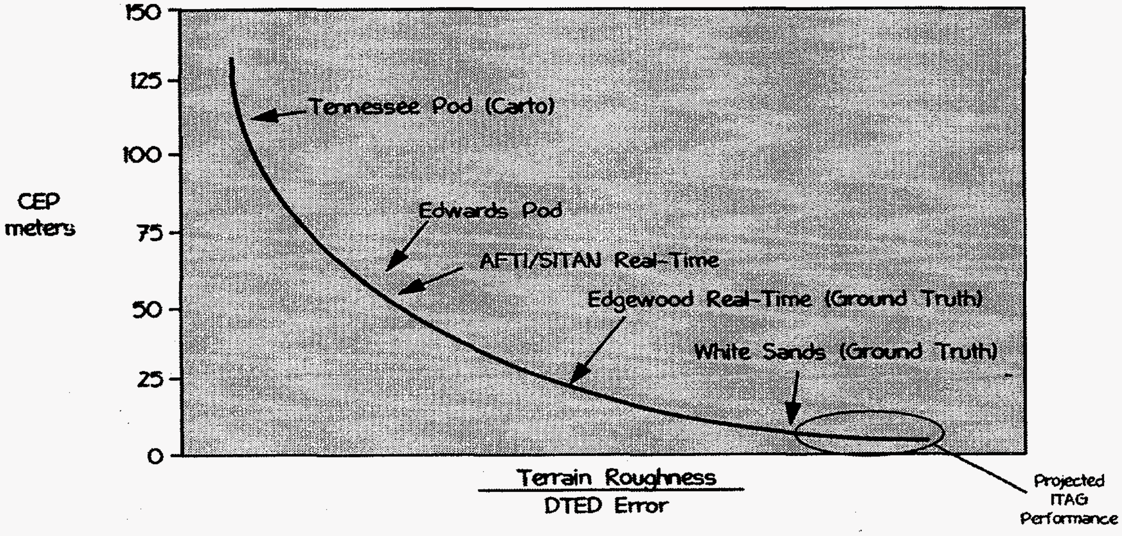


Figure II-7: Historical SITAN Accuracy

The SITAN algorithm CEP model will be utilized to address the question of what mapping accuracy will be required to achieve 3 meter terminal CEP for the ITAG. Recall that this modeling procedure has been performed for the original SITAN formulation (low altitude, standoff missiles or attack aircraft), where three assumptions were maintained: 1) the horizontal distance traveled was large compared to the terrain correlation length, so that adequate "lock on" could be achieved, 2) the radar altimeter measures the range to the nadir point and 3) the altimeter/map updates were not statistically correlated. For this scenario, the achievable CEP was shown to be:

$$CEP_{SS} = 0.57 \cdot \delta V^{1/4} \cdot \left(\Delta d / s\right)^{3/8} \cdot \left(\sigma_n / h\right)^{3/4}$$

where:		Representative ITAG values:
CEP_{SS}	is the steady state circular error probable	3 m
σ_n	is the standard deviation of the profile measurement errors	1.65 m
h	is the local terrain slope	0.02 (2% slopes, fairly smooth terrain)
Δd	is the distance between profile measurements	13 m (HIDRA Resolution)
s	is munition ground speed	175 m / s
δV	is INS / GPS maximum velocity error	0.1 m / s (P - code GPS)

As illustrated, using representative values for the ITAG system and assuming the three assumptions are valid yields a required profile measurement accuracy approximately 1.65 meters 1-sigma. The profile measurement accuracy includes the mapping accuracy plus the HIDRA measurement error. Sandia's altimeter programs have demonstrated that altimeter error below 1 meter can be easily achieved. Thus approximately 1 meter IFSAR map error will be required to achieve 3 meter terminal CEP. IFSAR mapping was discussed in a previous section, and indicated that 1 meter mapping accuracy was easily achievable.

As mentioned earlier, the original SITAN algorithm was designed primarily for use on low-altitude platforms (standoff missiles and attack aircraft), and the assumption that the radar altimeter measures the range to the nadir point was maintained. This assumption holds for altitudes up to approximately 5000 feet AGL. Above 5000 feet AGL the altimeter generally measures range to a non-nadir point. Additionally, radar altimeter measurement accuracy degrades at higher altitudes due to a "terrain smoothing" effect. High altitude SITAN formulations which use a radar altimeter and account for non-nadir ranging and decreased measurement accuracy have been developed, but the algorithm is more complex and achievable navigation accuracy is degraded.

An alternative to this high-altitude SITAN algorithm was developed at Sandia in the early 1980s for use as the mid-course guidance system for re-entry vehicle applications. This system utilized an advanced altimeter as the terrain profile measurement sensor. This sensor is named HIDRA and is discussed in the next section.

II.3. Radar Altimeter Alternative

High Accuracy Radar Altimeter Alternatives

As indicated in the previous sections, ITAG requires a high accuracy radar altimeter to measure the terrain profile during the descent trajectory. Standard radar altimeters do not measure the terrain profile to the accuracy required to achieve the ITAG terminal accuracy goal. As illustrated in Figure II-8, a LASER altimeter and a High Altitude Doppler Radar Altimeter (HIDRA) are both adequate sensors from a terrain profile measurement accuracy standpoint. However, LASER altimeters are altitude and weather limited, but are common off the shelf items. Because of the availability, a LASER altimeter was chosen as the altimeter for the initial ITAG performance demonstration, but a HIDRA would be required if all-weather, high altitude operation is desired.

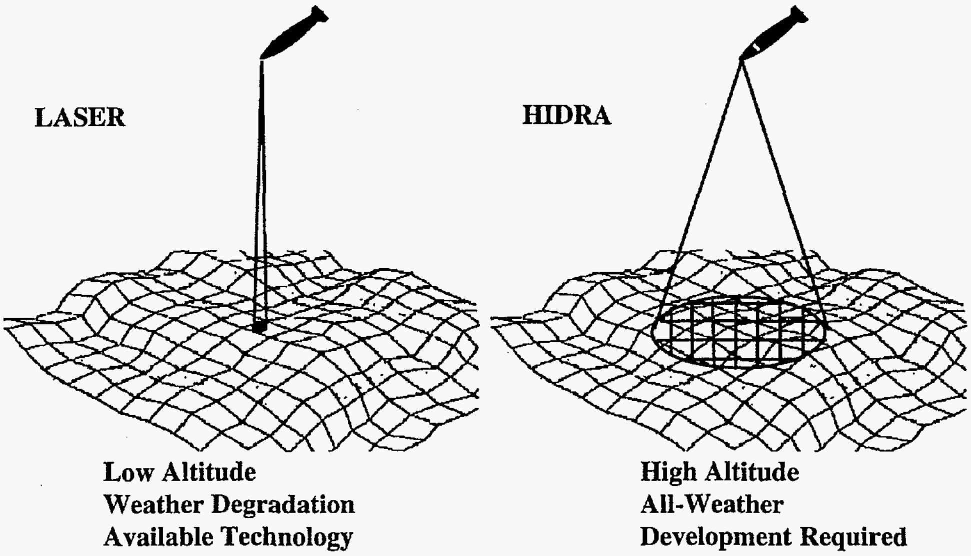


Figure II-8: Radar Altimeter Alternatives

HIDRA (High Altitude Doppler Radar Altimeter) incorporates three improvements over the traditional radar altimeter approach: 1) Doppler processing is exploited to "sharpen" the along-track radar beam, 2) multiple range bins reduce the terrain-smoothing effect of the radar altimeter, and 3) monopulse is utilized to measure the cross-track angle to the non-nadir return point. Examples of HIDRA terrain profiles are shown in Figure II-9, where elevation is vertical, along-track (Doppler) is horizontal, and cross-track (monopulse) is color-coded.

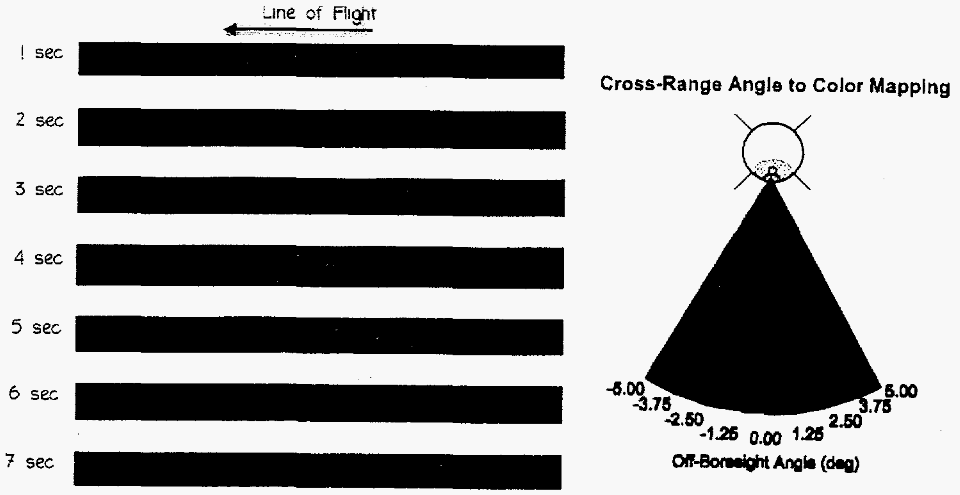


Figure II-9: HIDRA Images

An early prototype HIDRA system was successfully flight tested at Sandia in the late 1980s at altitudes up to 27,000 feet, and the system design will allow operation up to 100,000 feet.

II.4. ITAG Terminal Guidance System

As noted above, the HIDRA or LASER sensor under consideration is less complex than traditional seekers, such as SAR, and the projected unit cost falls within our targeted $30k system cost. Thus the ITAG system, consisting of stored IFSAR terrain maps, HIDRA/LASER, and SITAN, form a precision guidance technique potentially offering:

- 3 meters or less CEP
- Countermeasure resistant
- All-weather (HIDRA)
- Inexpensive
- Use existing Intel-planning infrastructure
- Uses existing aircraft-weapon interface
- High and low altitude delivery (HIDRA)
- Operation over urban and natural terrain
- No target location error

III. LASER ITAG Technology Demonstration

The goal of this study was to validate the feasibility of using high accuracy terrain maps, a high accuracy altimeter, and terrain-aided navigation techniques to achieve fix accuracies of > 3 meters CEP (median). The terrain maps were produced using two methods: traditional optical stereo photogrammetry, and interferometric synthetic aperture radar (IFSAR). The maturation of IFSAR mapping technology is the reason terrain-aided navigation was investigated as a means for terminal guidance of precision guided munitions (PGMs).

This study did not involve any actual terminal guidance maneuvers by a free fall PGM. Rather, all flight data was obtained though captive carry flights of the altimeter on the Sandia Laboratories Twin Otter Radar Testbed. All altimeter, navigation, and scoring data was recorded during flight, then post-processed on the ground to compute fix accuracies. Because the accuracy specification for terminal guidance is often quoted at < 3 meters CEP, it was clear that we needed to have the most accurate maps, altimeter, and flight trajectory scoring system available. These systems are described in detail below.

III.1. Altimeter Description

An altimeter suitable for use in this program had to meet two hard requirements. First, it had to produce a small enough spot size on the ground to sample each map post independently. For example, if the terrain map post spacing is 3 meters, the altimeter spot size must be < 3 meters in order for the maximum amount of map information to be utilized. Second, because the accuracy of the maps used is typically better than 1 meter, the altimeter must have a range resolution of < 1 meter. Currently, there are no commercially available radar altimeters that can meet these specifications. However, laser altimeters do exist that can meet these specifications.

The altimeter selected for use in this program was manufactured by Hughes Danbury Optical Systems in Danbury, Connecticut. Known as the imaging laser radar (ILR), it is a scanning instrument originally developed for use in automatic target recognition applications. It provides two channels of data, reflectivity and range. The range provided is range modulo 10 meters. In order to determine absolute range, the number of ambiguity intervals between the laser aperture and the ground must be determined. Table III-1 lists some of the specifications.

Laser:	Gallium Arsenide diode
Max Power in Exit Beam:	1.0 watt
Wavelength:	850 nm
Minimum Scan Rate:	400 scans/sec (558 scans/sec used in test)
Along Track Aperture:	10.16 cm
Along Track Beam Divergence:	.75 milliradians
Across Track Aperture:	.953 cm
Across Track Beam Divergence:	.5 milliradians
Scan Cycle:	180° (± 90°)
Active Scan:	95° (±47.5°)
Nominal Aircraft Speed:	65 m/s
Pixels per Scan:	2048
Range Quantization:	1.5 inches (8 bits for 10 meter ambiguity interval)
Range Accuracy:	SNR dependent, < 1 foot, typically
Spot Size at 1000' AGL:	25 cm (about 10 inches)

Table III-1: ILR Specifications

The ILR was body mounted in the camera bay of the Twin Otter. Because the mounting fixture was not inertially stable, the pointing angles of the ILR had to be measured very accurately. This was accomplished by mounting a highly accurate ring laser gyroscope inertial measurement unit (IMU) on the same mounting fixture as the ILR. Further, the IMU was aided by GPS position observations at a 1 hertz rate. Figure III-1 is a picture of the Twin Otter aircraft used in the this experiment. Figure III-2 is a picture of the ILR installed in the Twin Otter camera bay. Note the IMU (labeled "Gimbal Reference") mounted aft of the sensor.

Figure III-3 is an example of the high quality output of this sensor. It is a reflectivity image of the Kirtland AFB infirmary, taken at about 1000' AGL. The pixel size is about 11". The range channel is pixel registered with the reflectivity channel and has the same pixel size. This sensor provides range measurements over a ±47.5° swath. To simulate a non-scanning altimeter, only the nadir trace was used in the navigation processing. An operational altimeter would not be nearly so complicated, and most likely would not scan. The ILR was selected because it could provide data similar to a non-scanning altimeter, and was available for use quickly and inexpensively.

Very accurate timing information was needed to accompany the ILR data. Hughes Danbury modified the ILR to provide a real-time clock signal. This reading of this clock was stored at the beginning of each scan line. The resolution of the clock was 500 microseconds.

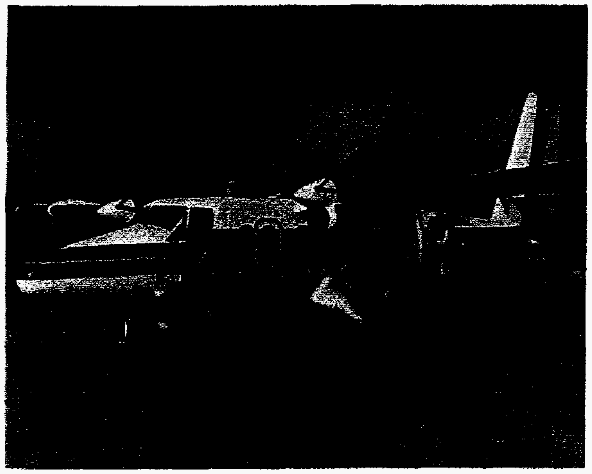


Figure III-1: Twin Otter Aircraft

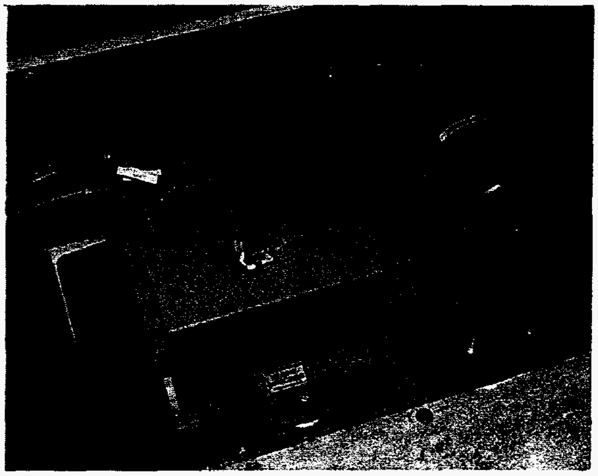


Figure III-2: ILR and IMU Installation

Figure III-3: ILR Reflectivity Image of the KAFB Infirmary (white line is the nadir trace)

III.2. Map Description

Terrain maps derived from two sources were used in this program. Their benefits and drawbacks are discussed below.

Photogrammetric Terrain Maps

Stereo photogrammetry is the traditional way terrain maps are produced. They can be quite accurate if they are constructed with care; however, the process required to achieve this accuracy is quite laborious. A very precise ground survey of reference points in the area to be mapped must be performed. These reference points are marked so that they will show up in the aerial photography. An airplane equipped with a very sensitive camera must then overfly the area at a low level, taking pictures of the terrain. Finally, the pictures are taken back into the lab and very painstakingly processed to produce a terrain map. The method is quite time-consuming and prone to operator error. However, if done correctly, the result can be a very accurate map with height accuracies and post spacings similar to those attainable with IFSAR.

Vexcel Corporation of Boulder, Colorado, was contracted to produce photogrammetric terrain maps of the tests areas - the Sandia Labs Tech Area 1 and surrounding Kirtland AFB, and an area known as the NATO Site, southeast of the Tech Area. In these maps, all cultural features are mapped accurately. All buildings, water towers, bunkers, or other structures were mapped. Trees were not mapped. The specifications for these maps were .5 meter post spacing, and .3 meter rms height error. The maps were registered in Universal Transverse Mercator (UTM) coordinates referenced to the WGS-84 ellipsoid. Figure III-4 is an rendering of a portion of the Vexcel Tech Area 1 map.

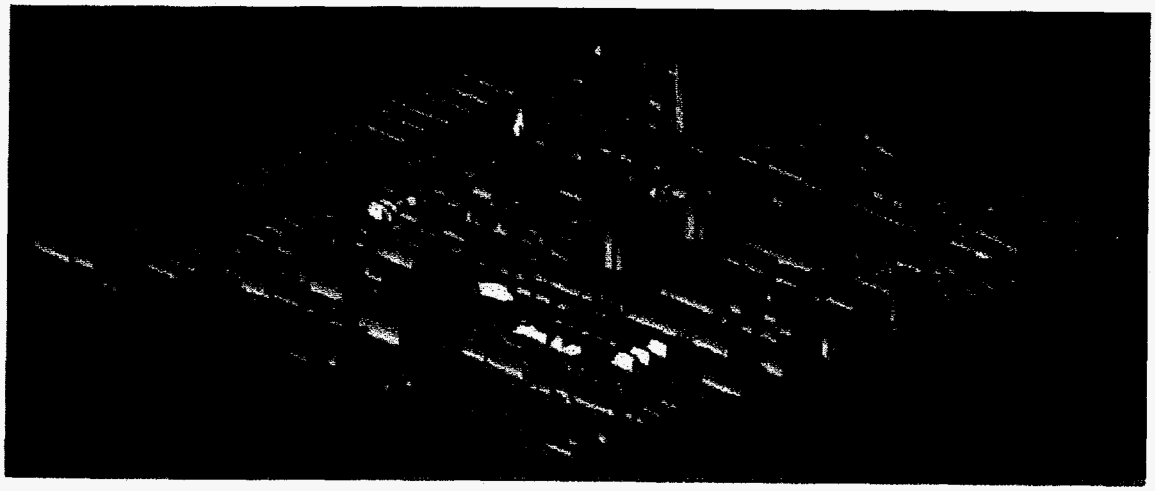


Figure III-4: Vexcel Tech Area 1 Terrain Map

As mentioned earlier, Interferometric Synthetic Aperture Radar (IFSAR) is a technique for producing terrain elevation maps of very high accuracy (< 1 meter) and very fine spatial resolution (meter level). IFSAR requires two pixel registered, coherent SAR images of the target area that were formed from slightly different viewpoints. This can be accomplished by mounting two antennas on the SAR platform, or by flying repeat passes using a one antenna SAR system.

III.3. Scoring System Description

The scoring system utilized in this program had to be very accurate. Until recently, the only aircraft scoring systems with accuracies of < 3 meters were on instrumented test ranges. However, with the advent of the Global Positioning System (GPS) satellite navigation system, GPS scoring techniques capable of this accuracy have been developed. The technique used in this program to score the flight trajectories of the Twin Otter is called SEMIKIN. It is a differential GPS technique where data collected during flight is post-processed to arrive at a scoring solution. SEMIKIN, developed at the University of Calgary, is advertised to have a post-processed accuracy of < 1 meter in airborne applications. SEMIKIN's accuracy on ground vehicles had been validated, but the accuracy for airborne platforms had never been confirmed.

In order to validate SEMIKIN's accuracy, a flight test was conducted on the instrumented test range at Sandia's Tonopah, Nevada facility. The scoring system there is a cine-theodolite system with an accuracy of ~1 meter horizontally and ~1.5 meter vertically. Figure III-5 is a plot of the difference between the SEMIKIN solution and the cine-theodolite trajectory solution in straight and level flight. The results of that test were conclusive: in straight and level flight, the cine-theodolite solution and the SEMIKIN solution agreed to less than 1 meter horizontally and about 3.5 meters vertically (this bias is due to an inconsistency between the cine-theodolite vertical reference and SEMIKIN's vertical reference). In fact, at this level of accuracy, it was not clear who was scoring whom.

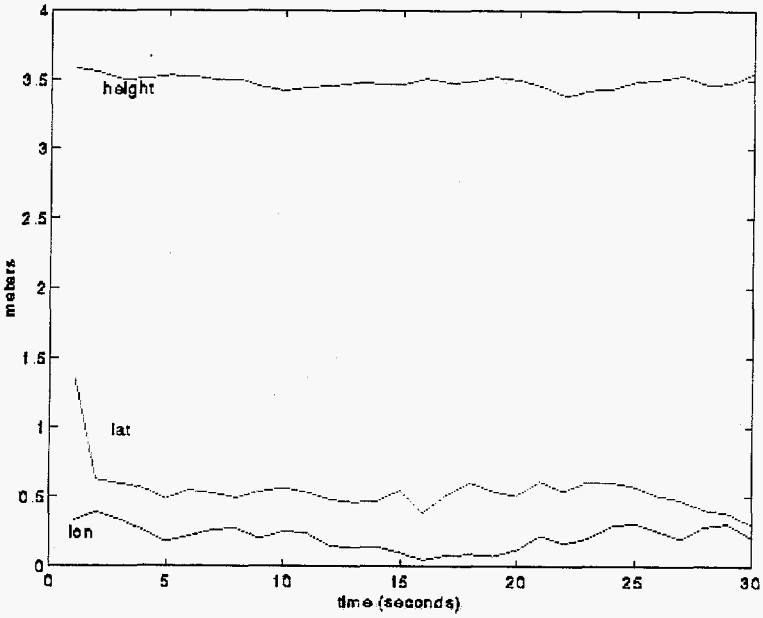


Figure III-5: Comparison of SEMIKIN and Cine-Theodolite Data 1

III.4. Reference Datum

The trajectory scoring information is referenced to the GPS datum, known as WGS-84. Because of difficulties in converting between datums, all the map products, scoring information, and navigation data used in this program is referenced to the WGS-84 datum. None of the errors observed should be due to uncertainties and inaccuracies in coordinate transformations or control.

III.5. Data Collection Description

Flight testing of the ILR and the scoring system was performed on September 13-17, 1993. Data was collected over two areas; the Sandia Labs Tech Area 1 and surrounding Kirtland AFB, and a hilly region southeast of the Tech Area known as the NATO site. ILR data was collected in straight and level passes above the regions of interest. The nominal altitude of the Twin Otter was 1,000 feet AGL. In all, 10 passes were made over Tech Area 1, and 8 passes were made over the NATO site.

During the flights, navigation and attitude data from the IMU mounted on the ILR unit was sampled at 4 Hz, in order to try to capture any high frequency motion. Carrier phase trajectory scoring was nominal for the Tech Area passes. Carrier phase scoring for the NATO site passes only exists for passes 3, 4, 5, 6, and 7.

Figure III-6 shows the ground track of the Twin Otter trajectories used in this study superimposed on the contour plot of the Vexcel terrain map of the Tech Area/Kirtland AFB. Figure III-7 shows the ground track of the Twin Otter trajectories used in this study superimposed over a contour plot of Vexcel terrain map of the NATO site.

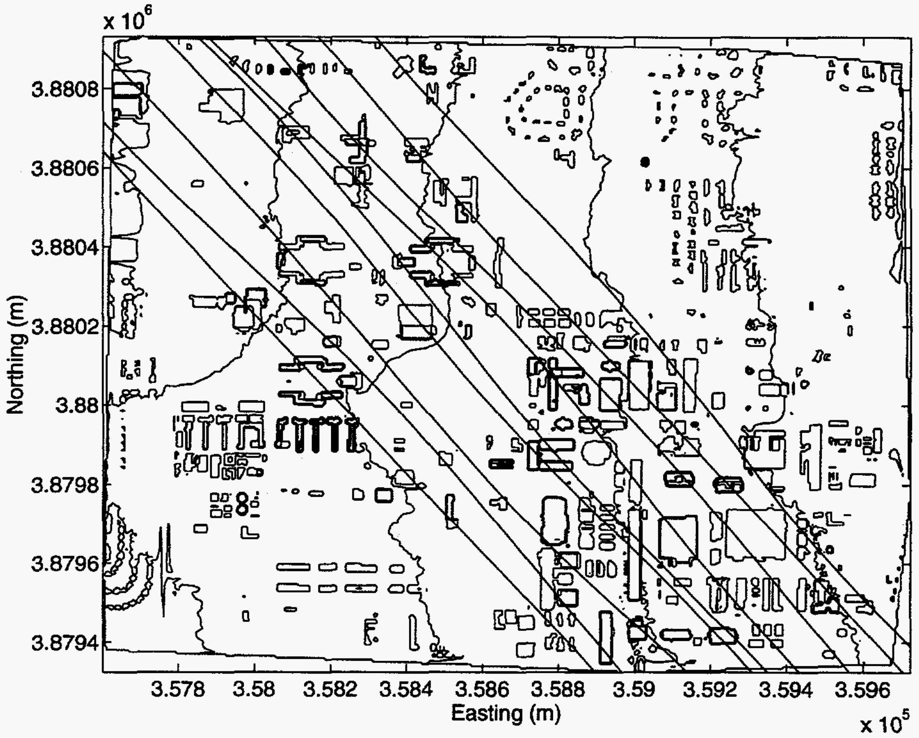


Figure III-6: LASER Tracer Over Urban Map

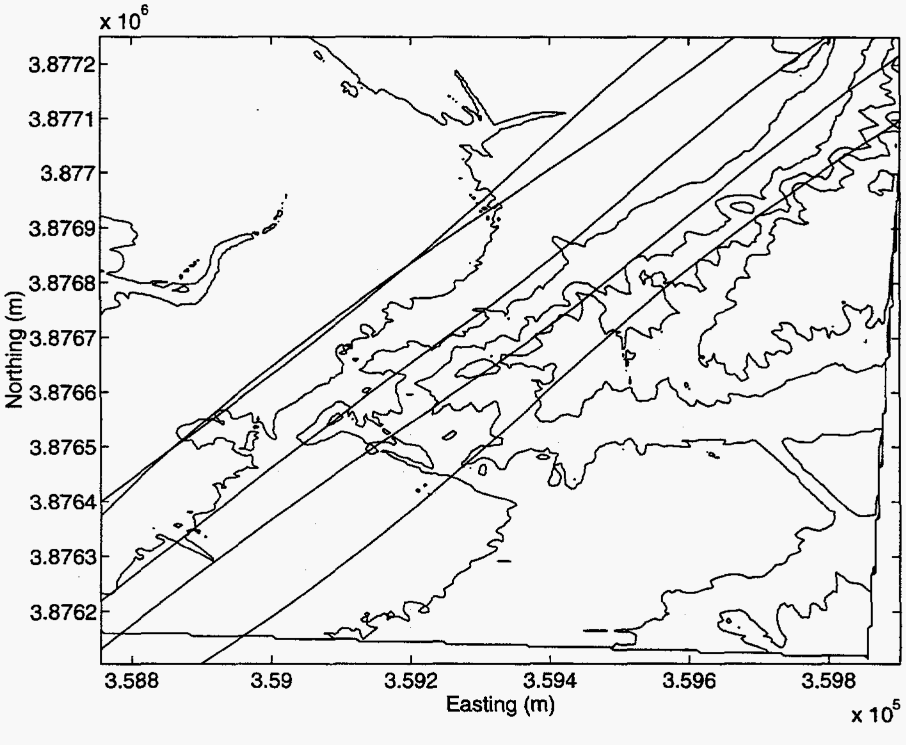


Figure III-7: ILR Passes Over Vexcel NATO Map

IV. Data Reduction Description

The ILR produces data at the staggering rate of 4 Mbytes/second. In order to keep from being swamped by the volume of data collected, significant data reduction was in order. The process used to reduce the data is described below.

Transfer of Data from VLDS to UNIX 8mm Tape

The ILR records its data on high speed VLDS tape. The data must then be converted from VLDS format to UNIX tar format. This is accomplished using a VLDS in the lab that has been interfaced to a UNIX host computer. Mark Heying, Department 9137, wrote the software to accomplish this.

When the data was read from UNIX 8 mm tape into the workstation, one more processing step was performed. To keep the file size manageable, the ILR data resided in 4 Mbyte files (1 second of flight data) on the 8 mm tape. As each file was read from tape, the data was separated into time, range, and reflectivity channels and stored on disk. Further, the 558 scan/second rate causes the ILR to oversample the terrain below by almost exactly two times. Therefore, in order to reduce the size of the data further, every other scan was discarded.

IV.1. Mounting Attitude Calibration

The ILR was body-mounted into the camera bay of the Twin Otter. Any roll or pitch by the Otter moved the position of the nadir pixel in the scan. In addition, the location of the nadir pixel in relation to the ILR aperture changed as of function of roll and pitch. The error budget for knowledge of the pointing angles of the ILR was quite small. To obtain the most accurate angles possible, an attitude-measuring IMU was mounted on the same fixture as the ILR. Due to space considerations, the IMU was rotated 90° counterclockwise. Refer to Figure III-2 for a picture of the installation. Because the IMU was not exactly mounted in the ILR frame, it was necessary to determine the small angular misalignments between the ILR body frame and the IMU frame. No facilities existed to perform this alignment on the ground. Rather, flight data was used to accomplish this calibration. Ron Tucker, Department 9132, wrote the computer code to perform the calibration described below.

During the production of the photogrammetric terrain maps, a very high accuracy control network was surveyed in the WGS-84 frame. Sixteen points comprise this network. During the data collection, laser retro-reflectors were placed on these points. Consequently, these points appeared as bright points in the ILR reflectivity data. Using the trajectory scoring information to obtain the exact ILR aperture position, and the known position of the reference point, a vector in three space was constructed. This "truth" vector was compared to the vector defined by the IMU attitude, ILR position, and range to the target. Using four such observations, an overdetermined solution for roll, pitch, and yaw misalignment was performed. The calibration was quite good, with low standard error residuals, as listed below.

Yaw misalignment:	90.49526°	standard error:	.18518°
Pitch misalignment:	-3.32065°	standard error:	.05981°
Roll misalignment:	5.34576°	standard error:	.05547°

Table IV.1: Attitude Misalignments

In order to determine the pointing angles of the ILR, the attitude data of the IMU must be rotated by the above angles to arrive at the proper ILR attitude.

IV.2. Nadir Range Processing

Since the ILR was body mounted into the Twin Otter camera bay, the nadir trace in general was not the center pixel of the scan. Using the roll information provided by the IMU, the nadir pixel of each scan was determined. At this point, the ambiguous range measurement had to be rectified. As stated previously, the output of the ILR range channel is actual range modulo 10 meters. The unambiguous range to each nadir pixel was determined by comparing the ILR height at the time of scan (using the trajectory scoring information) to the height of the terrain directly below the ILR (using the photogrammetric map). Through use of this a priori knowledge, the number of integer ambiguities between the ILR aperture and the terrain could be computed directly, and an unambiguous range measurement were computed.

Once the nadir range had been rectified, the flight data was segmented into three-second segments for navigation fix accuracy processing. Three seconds represents about 200 meters of ground track extent. Each segment represents an independent terrain profile, or transect. The choice of three-second segments was totally arbitrary. In an operational system, many kilometers of ground track terrain profile would be available for use by the terrain-aided navigation processor. All terrain-aided navigation systems obtain their position estimates by correlating these sensed transects with transects computed from terrain maps. As with any correlation, in general, the longer the correlation sequence, the more accurate the correlation. Using a longer transect length in this study would certainly have improved the fix accuracies.

IV.3. Navigation Accuracy Results

Description of Correlation Method

The minimum absolute difference (MAD) terrain-aided navigation metric was used to judge the fix accuracies that were obtainable from this data [2]. MAD was selected rather than Heli-SITAN because MAD is essentially a non-recursive form of Heli-SITAN, and MAD has a much more straightforward implementation [3]. The fix accuracies obtainable by the MAD method should be quite close to the fix accuracies obtainable through use of Heli-SITAN.

The scope of this study was not to develop a closed loop navigation system, but rather to study the kinds of fix accuracies that might be available by using very high accuracy maps and altimeters. Therefore, all the data processing was performed off-line.

Fix Accuracy over Urban Areas Using Vexcel Photogrammetric Terrain Maps

In all, 21 transects of urban terrain were processed. The transects are adjacent 3 second segments of flight data where the Twin Otter trajectory intersected the map data. They are independent in that they do not overlap in any way. Each transect was required to contain at least one man-made structure.

To begin, the scored trajectory was used as the reference trajectory. A map-derived transect, h_i, was generated by determining the elevation values of the points that would have lain beneath the reference trajectory. Then the map-derived transect was correlated against the laser sampled transect, r_i, according the MAD metric:

$$MAD(x_m,y_n) = \frac{1}{N}\sum_{i=1}^{N}\left| r_i - h_i(x_m,y_n) - \frac{1}{N}\sum_{j=1}^{N}\left[r_j - h_j(x_m,y_n) \right] \right|$$

where
x_m - x position of the center of the transect
y_n - y position of the center of the transect
N - the number of samples in the transect
r_i - i^{th} altimeter measurement
h_i - i^{th} map terrain profile measurement

Figure IV-1 is a plot of the map derived transect, h_i, and the laser derived transect, r_i, at the fix position for the KAFB Infirmary transect (see Figure III-3 for the ground trace). An error surface was generated by varying the position of the center of the transect, (x_m,y_n), recomputing h_i, and calculating the MAD value at that position. The position of (x_m,y_n) was varied by ±25 meters in .5 meter increments in both the x and y dimensions. The result was an error surface containing the MAD values. Figure IV-2 is a plot of the error surface generated using the KAFB Infirmary transect. The location of the global minimum of the error surface was declared the fix location. The Euclidean distance between the global minimum and the scored location was computed and declared to be the fix accuracy. Note that no analysis of the steepness of the error bowl was performed in any quantitative way.

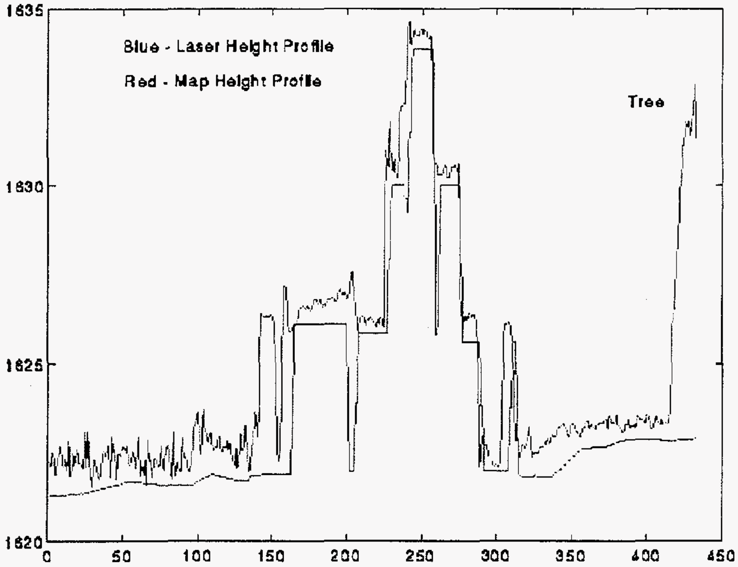


Figure IV-1: Laser Sensed Height and Map Computed Height Profile, KAFB Infirmary

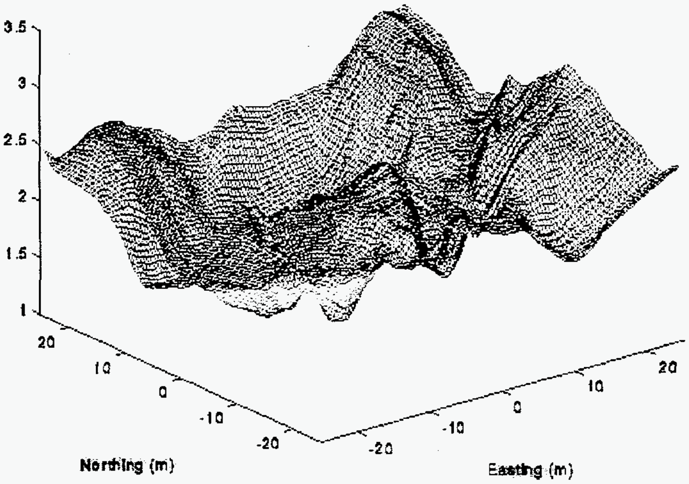


Figure IV-2: Error Surface, KAFB Infirmary Transect

The results were extremely good. The median value (CEP) of fix accuracies was 2.54 meters. The 95th percentile accuracy figure is 5.0 meters. Figure IV-3 is a plot of fix accuracies.

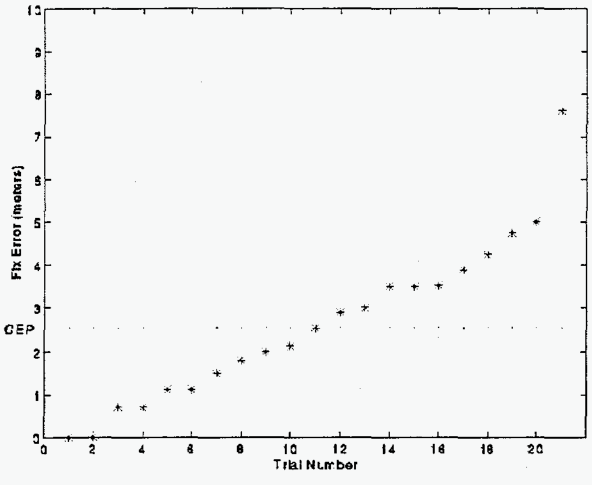


Figure IV-3: Fix Accuracies Over Urban Terrain,
Vexcel Terrain Map

Effect of Heading Error

In the preceding analysis, the heading was known exactly. The same data set was processed again, this time with a 1° heading error introduced into the reference trajectory. In this case, a significant degradation in CEP occurred, the CEP dropping to 4.24 meters. More importantly, two false fixes occurred. A false fix is somewhat arbitrarily defined as a fix with an error of more than 20 meters. Also important was the nature of the error surfaces changed. In general, they became much more broad, and competing local minima were much closer in value to the global minimum. In an airborne, real-time system, where heading error must be taken into account, it would seem prudent to produce reference trajectories at less than 1° heading increments.

Fix Accuracy Over Natural Terrain Using Vexcel Photogrammetric Map

The NATO site was chosen for the natural terrain test site because it has areas of both very flat and very hilly terrain. Again, 21 transects were identified over the NATO site. They represent a random sampling of the terrain types there. Again, the transects are independent of one another. The results were somewhat less accurate than the urban terrain tests. The CEP was 3.16 meters, with the 95th percentile number being 9.2 meters. Figure IV-4 is a plot of fix accuracies at the NATO site using the Vexcel terrain map. These results are to be expected, as natural terrain has much less terrain signature than urban terrain (the exception being very mountainous natural terrain). It is logical that fix accuracies would be lower. However, as stated before, the arbitrary selection of 3 seconds (~200 meters) of flight data as a transect was not the best choice for natural terrain. A transect of a kilometer or longer is much more representative of an operational scenario. Certainly, the fix accuracies would have improved over regions of small terrain signature if a longer transect had been used.

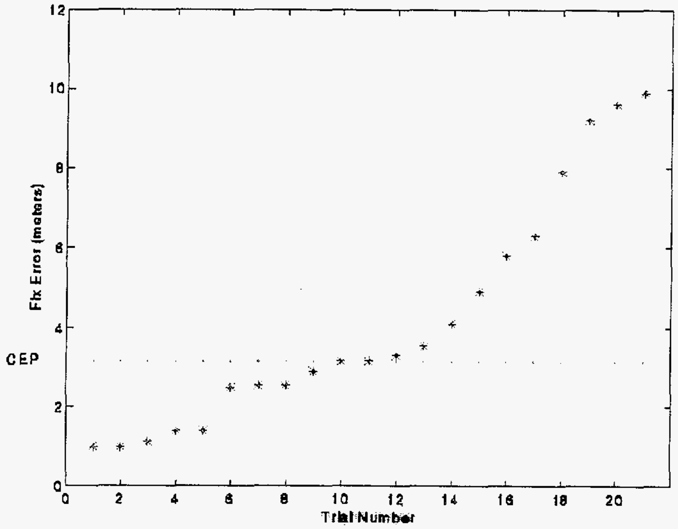


Figure IV-4: Fix Accuracies Over Natural Terrain, Vexcel Terrain Map

Figure IV-5 illustrates the map transect and the laser transect for a fairly representative sample from the natural terrain data set. Note the outstanding (2.5 meter) fix accuracy even though the terrain varies ~ 3 meters over the length of the transect.

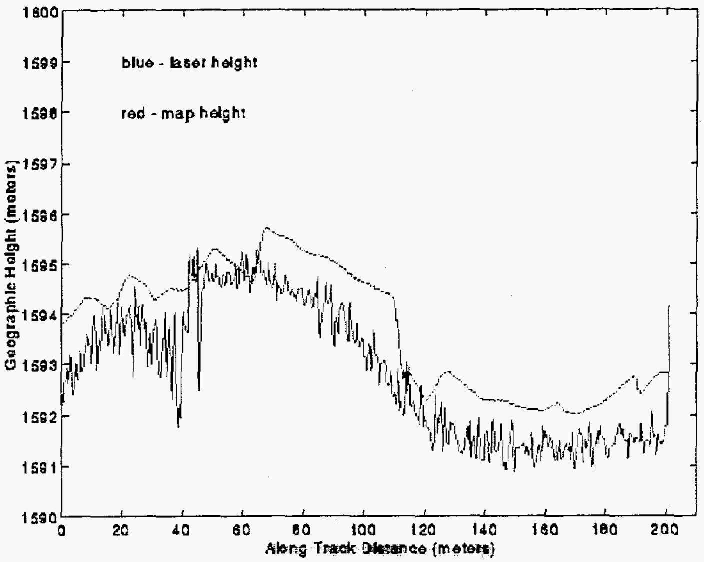


Figure IV-5: Laser Sensed Height and Map Computed Height Profile, NATO Site

Fix Accuracy Over IFSAR Urban Terrain Map

The Twin Otter IFSAR imaged the same regions that were mapped using photogrammetric methods. As a result, an IFSAR terrain map was produced of the Kirtland AFB infirmary (Figure IV-6). One of the ILR transects includes the infirmary. This transect was processed against the IFSAR map.

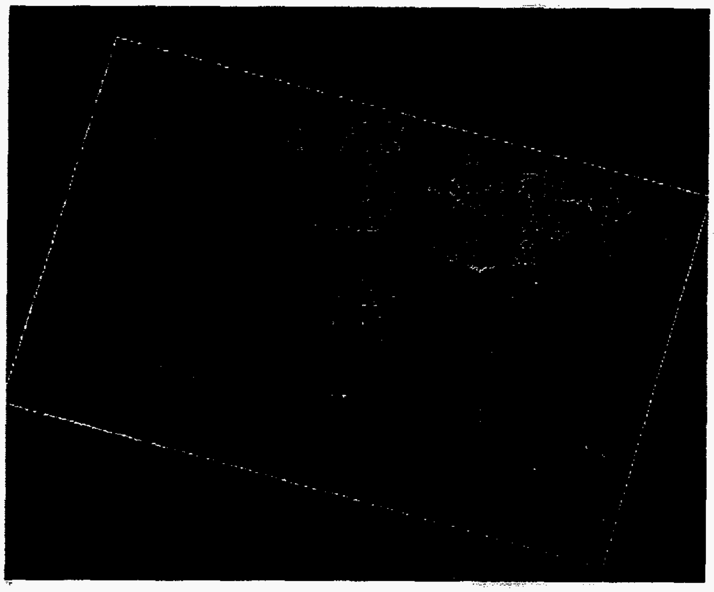


Figure IV-6: Kirtland Air Force Base Infirmary IFSAR Map

The infirmary IFSAR map had an effective resolution of 3 meters. The map was processed and registered in WGS-84 coordinates using the photogrammetric map as the control. The height accuracy of IFSAR maps is driven by many factors: antenna baseline, calibration, transmitter power, and radar cross-section, to name a few. Given that the baseline, calibration, and transmitter power remain constant throughout an image pair, the variations in radar cross-section across an image will determine the height accuracy. For example, in areas of radar shadow (zero RCS) or low RCS (asphalt, for example), the height accuracy will be poor. This information is known a priori. It seems logical to only use map data of adequate height accuracy in the MAD correlation.

In navigation over urban areas, the information in the map is contained in the transitions, the edges between ground level and the first floor, between the first floor and the second floor, or between the ground and the top of a tree, for example. The IFSAR map of the infirmary was fairly noisy, although the transitions were apparent. In order to emphasize the transitions, some extra processing on the map was performed. A filtering operation was needed that would average out small scale, noise-like variations, yet leave long-term trends and transitions unfiltered. Morphological operations met these requirements.

The morphological processing was performed using the Khoros image processing environment and the gray scale morphology toolbox written at Sao Paulo State University. The map data was cast from floating point representation into unsigned byte representation (the quantization was .25 meter) and was processed using a close-open filter with a 3x3 rectangular kernel. The resulting map maintained the long-term terrain character, as well as preserving the transitions.

The filtered map still had areas where the height error was unacceptable, typically shadow areas due to the building and trees. These points were marked when they occurred in map transects. The MAD algorithm was modified to process these map transects by essentially not correlating against a map transect sample if it was marked bad.

When the morphologically filtered map was processed against the ILR transect, the result was outstanding. The fix error was 2.2 meters. Figure IV-7 illustrates the radar transect and the map transect. A 2.2 meter fix using a laser altimeter and an IFSAR terrain map is indeed a remarkable result. It demonstrates that an IFSAR map of an urban area is suitable for use in a terrain-aided terminal guidance system. Certainly, IFSAR processing has some maturation to do before IFSAR terrain maps are widely available. Nevertheless, when properly done, an IFSAR map of an urban area, paired with an accurate altimeter, could be used as a terminal guidance system.

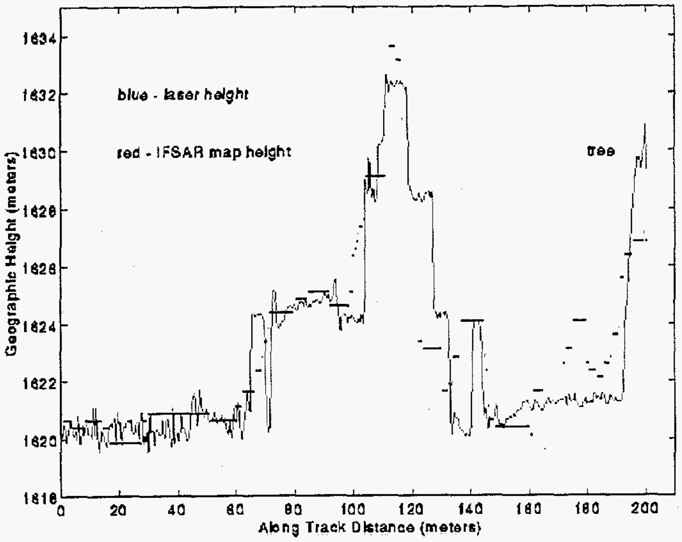


Figure IV-7: Laser Sensed Height and IFSAR Terrain Map Height, KAFB Infirmary

IV.4. Other IFSAR Advantages

It is important to note one significant advantage that IFSAR maps have over photogrammetric maps. A single pass interferometer operating at 15 GHz center frequency or higher will most likely map trees provided they are in leaf. This phenomenon was observed in the infirmary map. In Figure IV-7, the feature at the right end of the transect is a lone tree in a meadow. While this tree was not mapped in the photogrammetric map, it was mapped by the IFSAR. This tree is an important feature for use in navigation, and greatly improves the sensitivity of the MAD algorithm in this instance. Without the tree, the fix accuracy would have been poorer.

Although all the scoring and mapping used in this study was registered in a global frame of reference, terrain-aided navigation over terrain maps is essentially a relative navigation scheme, and is not subject to target location errors, since the target location is known exactly in the map coordinate frame. The map itself may not be properly located in a global (i.e., GPS) frame. The ramifications of poor map registration mainly lie in the initial fix probabilities. It is necessary for the map to be registered and a munition to be delivered with enough accuracy that the munition can locate itself in the local mapping coordinates, then guide itself to a target. The size and sensitivities of the initial delivery error basket has not been studied here, but is worthy of further study.

Conclusions

Previously, terrain-aided navigation has been relegated to a mid-course guidance role since real-time accuracies have not been at 3 meter CEP specification necessary for terminal guidance applications. The limiting factor in terrain-aided navigation has traditionally been the terrain map accuracy and post spacing. The advent of a new mapping technology, IFSAR, prompted another look to be taken at terrain-aided navigation.

A very accurate laser altimeter and an attitude measuring device were installed on a Twin Otter aircraft, and captive carry flight data was taken over both urban and natural terrain. Urban and natural terrain maps derived from photogrammetric techniques but indicative of the IFSAR mapping accuracies were procured, and an IFSAR terrain map of an urban scene was produced. This data, along with very accurate trajectory scoring data was post-processed on the ground. Three meter CEP terrain-aided navigation performance was achieved over both natural and urban terrain using the photogrammetric maps, and a 2.2 meter fix was achieved over the IFSAR terrain map.

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