# LIDAR and IFSAR:
# Pitfalls And Opportunities For Our Future

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## ABSTRACT

Light Detection and Ranging (LIDAR) and Interferometric Synthetic Aperture Radar (IFSAR) have recently become the technologies of choice in mass production of Digital Elevation Models (DEMs), Digital Terrain Models (DTMs), and Triangulated Irregular Networks (TINs), referred to generically hereafter as DEMs. This paper presents lessons learned from LIDAR projects to date in various states. It addresses opportunities presented by LIDAR and IFSAR for generating DEMs as articulated by various user groups in the *National Height Modernization Study*. Finally, it summarizes actions required by the remote sensing community to establish LIDAR and IFSAR as standard tools, with established standards, for generating digital elevation data for the new millennium.

## INTRODUCTION

The mapping community has known for years that its users have unsatisfied requirements for high-accuracy, high-resolution DEMs. U.S. Geological Survey (USGS) Level 1 DEMs typically have 30-meter post spacing, and the advertised root mean square error (RMSE) is 7 meters. In the limited areas where they exist, USGS Level 2 DEMs typically have 10-meter post spacing, and their advertised accuracy (at the 90% confidence level) is equal to one-half the contour interval of the quad maps used to digitize the contours and generate the Level 2 DEMs. For example, if a USGS 7.5-minute quad map with 20-foot contour interval is used to generate a Level 2 DEM, 90% of the DEM data points should be accurate within ±10 feet. Both Level 1 and Level 2 DEMs utilize the National Geodetic Vertical Datum of 1929 (NGVD 29) which is obsolete for many applications.

The *National Height Modernization Study*, conducted in early 1998 by the National Geodetic Survey (NGS), documented user needs for DEMs, preferably in the North American Vertical Datum of 1988 (NAVD 88). User categories with DEM needs that could be satisfied with Interferometric Synthetic Aperture Radar (IFSAR) technology, advertised in the vertical accuracy range of 1-3 meters, included: Disaster Preparedness and Response; Seismic Monitoring; Air Navigation and Safety; and Forestry. User categories with DEM needs that could be satisfied with Light Detection and Ranging (LIDAR) technology, advertised in the vertical accuracy range of 15-30 centimeters (6-12 inches), included: Flood Mitigation; Coastal Stewardship; Marine Navigation and Safety; Vehicle Positioning and Safety; Train Positioning and Safety; Water Supply and Quality; Stormwater and Utility Management; Infrastructure Construction; Mining and Earth Moving; Pipeline Construction; Precision Farming; Recreation; and Environmental Protection. Only one user category, Subsidence Monitoring, had DEM needs that could not be satisfied by remote sensing technologies; this user group identified DEM accuracy needs at the 2-cm level, and this accuracy can only be achieved by ground surveys.

## IFSAR AND LIDAR BASELINE STUDY (1995)

Conducted in cooperation with the Federal Emergency Management Agency (FEMA), National Aeronautics and Space Administration (NASA) and U.S. Army Corps of Engineers (USACE), the U.S. Geological Survey (USGS) conducted a baseline evaluation of IFSAR and LIDAR DEMs of an area near Glasgow, Missouri. The Method, Accuracy, Reliability, and Applications Test (MARAT), documented in USGS Open-File Report 96-401 available from the Internet, resulted from recommendations of General Gerald Galloway, U.S. Army, who chaired the Interagency Floodplain Management Review Committee (IFMRC) following major flooding in the mid-west in 1993. Neither the IFSAR nor LIDAR sensors were nearly as capable as they are today, but their results provide baseline data for comparing the rapid progress that has resulted in subsequent years, as summarized in case studies that follow.

For the USGS test site, DEMs from IFSAR and LIDAR sensors were compared with extensive mass points and breaklines determined to be the most accurate that could be produced photogrammetrically from aerial photography flown at 3,000 feet above mean terrain. This was the bare-earth "standard" against which IFSAR and LIDAR DEMs were compared.

- Flown at 480 miles/hour, 40,000 feet above mean terrain with a swath width of 10,000 meters and 10-meter nominal point spacing, the IFSAR DEM had a mean error of 3.4 to 4.6 feet with a standard deviation of 6.2 to 10.5 feet for relatively unobstructed views of the ground. The test report indicated: "This sensor did not demonstrate an ability to penetrate leafless trees." The IFSAR industry has subsequently worked to utilize different frequency bands designed to penetrate foliage to some degree, but results are currently unknown.
- Flown at 175 miles/hour, 3,000 feet above mean terrain with a swath width of 1,500 feet and 10-foot nominal point spacing, the LIDAR DEM had a mean error of 1.5 to 3.4 feet and a standard deviation of 1.4 to 8.7 feet for relatively unobstructed views of the ground, i.e., categories of open ground, low cover, and scrub. The test report indicated, "The LIDAR sensor demonstrated an exceptional ability to penetrate relatively leafless tree cover." This was a single return LIDAR sensor. Since 1995, the LIDAR industry has developed sensors that collect multiple returns, and the "last-returns" are now commonly used to generate bare-earth DEMs; this is the major reason why modern LIDAR sensors have vastly improved in recent years.

The major opportunities offered by both technologies was their rapid generation of high density DEMs, presumably at lower cost than photogrammetric DEMs The major pitfalls for both were uncertainty of elevations in vegetated areas and inability to check the horizontal accuracy of IFSAR or LIDAR data points.

## DEM ACCURACY

In 1998, the Federal Geographic Data Committee (FGDC) published the National Standard for Spatial Data Accuracy (NSSDA) which supersedes the National Map Accuracy Standard (NMAS) of 1947 for digital products. The NSSDA replaces the NMAS for softcopy (digital) spatial products (which includes DEMs and digital contours), but the NMAS remains in effect for hardcopy maps (which includes contours on published paper maps). The NSSDA states in FGDC-STD-007.1-1998, paragraph 1.2, Accuracy Standard, "The reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95-percent of the time." Note that the NSSDA defines accuracy at the 95% confidence level and assumes errors have a normal distribution, whereas the NMAS defines accuracy at the 90% confidence level and does not assume errors have a normal distribution. Thus, the 10% of points that fall outside the NMAS 90% standard could have errors of any magnitude, whereas the 5% of points that fall outside the NSSDA 95% standard should normally have errors only slightly larger than that standard, or otherwise those "outliers" would greatly magnify when squared as part of the RMSE computations. Whereas 90% and 95% appear to be similar, the former allows two "outliers" from 20 check points, but the latter allows only one "outlier" from 20 check points. Note also that the NMAS allows apparent vertical errors to be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale; whereas the NSSDA does not make such allowances. Many NMAS assumptions become meaningless with digital spatial data.

Most DEM users have what they consider to be a clear concept of the meaning of vertical accuracy, or accuracy of ±1-foot, for example, but such terms mean different things to different people. Few users realize that a Vertical Root Mean Square Error ($RMSE_z$) of 1-foot nearly equates to Vertical Accuracy ($Accuracy_z$) of 2 feet at the 95% confidence level. According to FGDC-STD-007.3-1998, Accuracy Statistics, NSSDA, $Accuracy_z = 1.9600 \times RMSE_z$. It further states: "Accuracy of new or revised spatial data will be reported according to the NSSDA."

One pitfall to be avoided in evaluating LIDAR and IFSAR data is to ensure that everyone understands and uses the correct NSSDA terminology regarding accuracy of digital elevation data, including DEMs. Stating that something is "accurate to ±6 inches" may or may not mean the same thing to others as it means to you. With either $RMSE_z$ or $Accuracy_z$, all should be able to understand their true meanings.

## PROJECT LESSONS LEARNED

In reviewing the following projects pertaining to IFSAR and/or LIDAR, readers can see how these technologies have matured and improved in the short period of time between 1996 and 2000. The names of specific IFSAR/LIDAR projects and vendors are deliberately excluded from this document so that readers can focus on the strengths and limitations of the technologies and avoid unfair comparisons between different remote sensing vendors, all of whom are continuously improving their sensors and data processing procedures.

## PROJECT 1 – COUNTYWIDE LIDAR DEM (1996)

This project summary is extracted from an *Earth Observation Magazine* (EOM) article that can be downloaded from the web. See http://www.eomonline.com/stone.htm.

### Summary of Opportunities

- At relatively low cost, added high-density, high-accuracy DEM and contour information to the county's GIS that previously had included only planimetric information, e.g., digital orthophotos; road centerlines; tax parcels; address, zoning, census, and soils data; and utility system data.
- Proved "last return" LIDAR pulses generally penetrated the vegetation to provide ground elevations.
- Proved ability to survey without setting foot on the ground. This allows surveying of dangerous or difficult access areas and properties for which right-of-entry is unavailable.
- Saved survey crews from traffic hazards; operations or traffic flows are uninterrupted.
- Provided accurate topographic data for design of new construction projects, including drainage improvements.
- Hydraulic modeling used to update obsolete Flood Insurance Rate Maps (FIRMs); actual flood-prone areas proved to be smaller than shown on FEMA's current FIRMs, opening new areas to development without endangering future buildings and property.
- Lowered estimated cost of construction for drainage improvements on a major canal by $7 million by using LIDAR DEMs for hydraulic modeling.
- LIDAR DEM was ideal tool for comprehensive countywide land use analysis.
- First to develop countywide 1-foot contour map using LIDAR technology.

### Summary of Pitfalls

- The county recognized the potential foliage penetration pitfall by stating: "If you can't see the sky when walking in the forest, the LIDAR can't see through the forest to survey the ground." The county also recognized that some features (e.g., pipelines, manholes, culverts) must still be obtained by ground surveys; and the county supplements its LIDAR topographic data with ground surveys and transects.

- Although contours were mapped with 1-foot contours, Dewberry & Davis (D&D) considers it doubtful that these contours satisfied the NMAS for maps with 1-foot contours. D&D was informed that the LIDAR data were believed to have an $RMSE_z$ of 15-cm. This equates to $Accuracy_z$ of 30-cm (1-foot) at the 95% confidence level per the NSSDA. The more-familiar NMAS requires 90% of the points to be accurate within the Vertical Map Accuracy Standard (VMAS) of one-half contour interval (6 inches), not the full contour interval (12 inches). According to the NSSDA (FGDC-STD-007.3-1998, section 2.2), the NMAS' VMAS (one-half contour interval) = 1.6449 x $RMSE_z$. In other words, the contour interval (CI) = 3.2898 x $RMSE_z$. Therefore, an $RMSE_z$ of 15-cm equates to a contour interval of 1.619 feet. To be fair to all involved, this accuracy calculation is widely misunderstood by the mapping community, and the NSSDA did not clearly define the relationship between RMSE (horizontal and vertical) calculations and the NMAS until publishing the NSSDA in mid-1998, three years after this pioneering LIDAR project.
- Even today, the conversion of LIDAR or IFSAR $RMSE_z$ values into equivalent contour intervals (defined by the NMAS) is only relevant when assuming that elevation errors have a normal distribution. This is not necessarily true since LIDAR elevation errors depend largely on the post-processing of LIDAR data to remove unwanted vegetation or man-made structures for which automated or manual procedures may not yield errors with a normal distribution. For example, human failure to remove a LIDAR point that falls on a treetop or rooftop could disproportionately devastate an $RMSE_z$ calculation that squares all errors between ground truth elevations and elevations interpolated from surrounding DEM points. The NMAS typically allowed the worst 10% of the points to be rejected regardless of error magnitude, whereas the NSSDA methodology (including $RMSE_z$ calculations) squares such errors as part of the $RMSE_z$ and $Accuracy_z$ calculations.

## PROJECT 2 – LIDAR DEM FOR FLOOD INSURANCE STUDY #1 (1998)

This was the first project known to D&D that was designed to demonstrate the utility in using high-resolution, high-accuracy LIDAR DEMs for automated/semi-automated hydrologic and hydraulic (H&H) modeling for updating of Flood Insurance Rate Maps (FIRMs) published by the Federal Emergency Management Agency (FEMA). This was also the first known project for which the recently published NSSDA standards were applied to DEMs.

### Summary of Opportunities

- Prior to detailed independent evaluation by FEMA, the LIDAR DEM was initially believed suitable for automated H&H modeling for efficient and effective FIRM updating

### Summary of Pitfalls

- FEMA's independent DEM accuracy assessment demonstrated that the bare-earth DEM (following post-processing for removal of vegetation and man-made structures) had $RMSE_z$ values considerably greater than the 15-cm $RMSE_z$ required by FEMA for H&H modeling. The accuracy assessment was controversial because of uncertainty as to whether errors that were squared in the RMSE calculations resulted from LIDAR errors or post-processing errors. It is possible that the pitfall described in the third bullet of Project 1 was relevant in this example, but errors were on the order of 1-meter, and not 5-20 meters as might be expected from a failure to delete LIDAR data points that fell on treetops. Furthermore, the errors appeared to have a normal distribution, and the size and number of negative (below ground) errors were comparable to the size and number of positive (above ground) errors. All checkpoints were supposed to be selected on terrain with uniform slopes within 5-meters of the surveyed check points in all directions, but it is possible that some check points were marginal in this regard, making it more difficult to objectively quantify the DEM vertical accuracy.
- Perhaps more important than vertical accuracy, FEMA's DEM assessment identified a pitfall caused by data voids. Some data voids were caused by the fact that LIDAR does not normally receive returns from water which absorbs the laser pulses. Other data voids were deliberately caused by automated or manual post-processing to remove data points on buildings and vegetation where it was believed the LIDAR had not penetrated to the ground. As shown in Figure 1, the large data voids near the stream channels made it impossible to generate 3-D breaklines at the tops and bottoms of stream banks or otherwise generate cross sections as needed for hydraulic modeling.


Figure 1
This figure shows three things wrong with the LIDAR data acquired for hydraulic modeling:

1. The "removal" of LIDAR data points on trees near the river make it impossible to generate accurate breaklines or cross sections needed for hydraulic modeling of the stream channel.
2. The LIDAR was acquired during high-water rather than low-water. Check point 132, shown in the middle of the stream, was "high and dry" when check point surveys were conducted, with a small stream only near the shore on the east. Here, the majority of the stream channel is under water and was not sensed by the LIDAR pulses. Critical stream channel topography was missed because the LIDAR was not flown during low water conditions.
3. The LIDAR points were not completely removed from the bridge. The hydraulic model would show an artificial dam across the river, depicting stream blockage so that water could not pass through the area.

None of these deficiencies were obvious until D&D displayed the DEM points over digital orthophotos obtained independently.

- The above deficiencies caused additional ground surveys to be required to supplement the LIDAR data. Some hydrographic surveys were required in any event because of the LIDAR's inability to penetrate water to map the bathymetry.

## PROJECT 3 – FEMA LIDAR GUIDELINES AND SPECIFICATIONS (1999-2000)

Project 2 caused FEMA to prepare draft guidelines and specifications for LIDAR surveys used by FEMA Study Contractors in preparation and/or update of FIRMs. See http://www.fema.gov/mit/tsd/MM_LIDAR.htm.

### Summary of Opportunities

- By publishing Appendix 4B, Airborne Light Detection and Ranging Systems, to FEMA 37, *Flood Insurance Study, Guidelines and Specifications for Study Contractors*, FEMA acted to publish guidelines and specifications that must be used for the application of LIDAR systems for gathering the data necessary to create DEMs and other products of the National Flood Insurance Program (NFIP).

- Section A4B-6 states, for example: "For hydraulic modeling, the contractor must provide high-resolution, high-accuracy, 'bare-earth' ground elevation data. To restrict data to ground elevations only, the contractor must remove elevation points on bridges, buildings, and other structures and on vegetation from the LIDAR-derived data. In addition to randomly spaced LIDAR points, before and after removal of data associated with structures and vegetation, the contractor must produce a bare-earth DEM, with the minimum regular point spacing, no greater than 5 meters, allowed by the data in eastings and northings … In addition to DEMs, the contractor shall produce breaklines for stream centerlines, drainage ditches, tops and bottoms of streambanks, ridge lines, road crowns, levees, bulkheads, road/highway embankments, and selected man-made features that constrict or control the flow of water (e.g., curb lines). The contractor shall specify the sources and accuracy of breakline data."
- Section A4B-7 states: "DEMs should have a maximum RMSE of 15 centimeters, which is roughly equivalent to 1-foot accuracy (at the 95% confidence level). The contractor must field verify the vertical accuracy of this DEM to ensure that the 15-centimeter RMSE requirement is satisfied for all major vegetation categories that predominate within the floodplain being studied. The main categories of ground cover that the contractor must separately evaluate and report on the DEM accuracy for shall be: a) Bare-earth and low grass (plowed fields, lawns, golf courses); b) High grass and crops (hay fields, corn fields, wheat fields); c) Brush lands and low trees (chaparrals, mesquite, swamps); d) Fully covered by trees (deciduous, coniferous, mixed forests); and e) Urban areas (high, dense man-made structures)."

### Summary of Pitfalls

- When this document was first published, no LIDAR vendor had yet demonstrated that $RMSE_z$ of 15-centimeters could be achieved for all major vegetation categories within floodplains being studied. Thus, the $RMSE_z$ standard might be unachievable unless certain provisions are waived.
- The breakline requirements are currently considered to be unachievable by LIDAR vendors unless supplemented with alternative technologies that will significantly increase project costs.
- FEMA recognizes that the document is incomplete. FEMA plans to update this Appendix to provide guidelines and specifications for (1) data voids, (2) artifacts, and (3) sidelap merges/overlays.

## PROJECT 4 – LIDAR CAPABILITY STUDY (1999)

The USACE is assisting FEMA in developing guidelines and sample statements of work (SOW) for LIDAR data collection and post processing. Numerous LIDAR sensors acquired LIDAR data of a residential test area in Lakewood, Calif. and post-processed the data with various proprietary techniques. Each participating company was required to deliver a 3-meter resolution DEM for comparison with ground truth surveys. LIDAR offers the opportunity to achieve significantly lower cost, faster turnaround times, and increased accuracy in the production of elevation information. This particular element of terrain information is one of the most important to support responsive flood hazard mapping and is also often critical of other FEMA and USACE needs.

### Summary of Opportunities

- Provide USACE and FEMA with a current assessment of the state of the art as pertains to LIDAR technology. This in turn will enable USACE and FEMA to publish realistic SOWs for upcoming projects that require high-accuracy DEMs. See Figures 2.a and 3.a.
- This study demonstrated that vertical accuracy of 7-15 cm (1-sigma) is realistically achievable when compared to ground control points in open areas with no vegetation obstructions.
- To qualitatively measure the random distribution of raw data points generated by each LIDAR sensor, a Void Map technique was created. The Void Map algorithm plots a gray scale range based on the distance to the nearest neighbor. For this study, data points at least 12 meters apart were assigned the color black; data points within 1-meter and less would be assigned the color white. See Figures 2.b and 3.b.

### Summary of Pitfalls

- Each LIDAR data set that was delivered used a different datum.
- The performance of the various LIDAR sensors within different types of vegetation was not taken into consideration in the initial study design.

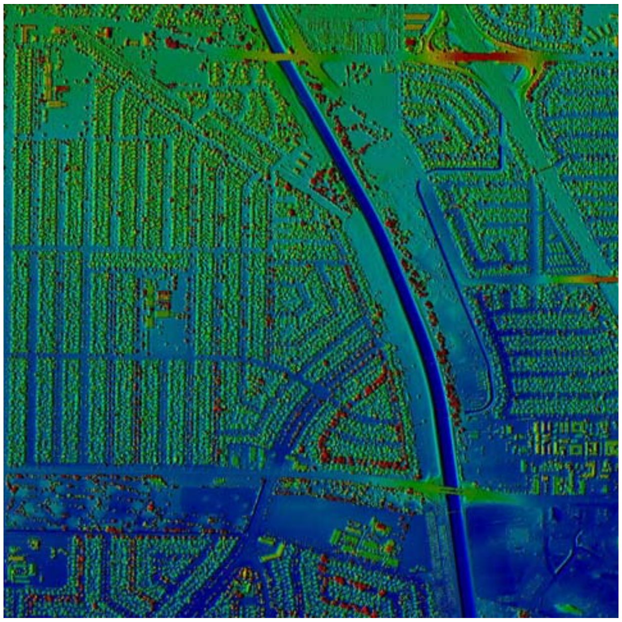

Figure 2.a
Unprocessed Last-Return LIDAR DEM – prior to removal of man-made features and vegetation. Such digital images can be viewed in 3-D with ChromaDepth™ 3-D glasses.

Figure 2.b
Unprocessed LIDAR Void Map

- Black: nearest neighbor >12 meters away.
- White: nearest neighbor < 1-meter away.
- Gray: varies between 1 and 12 meters apart.

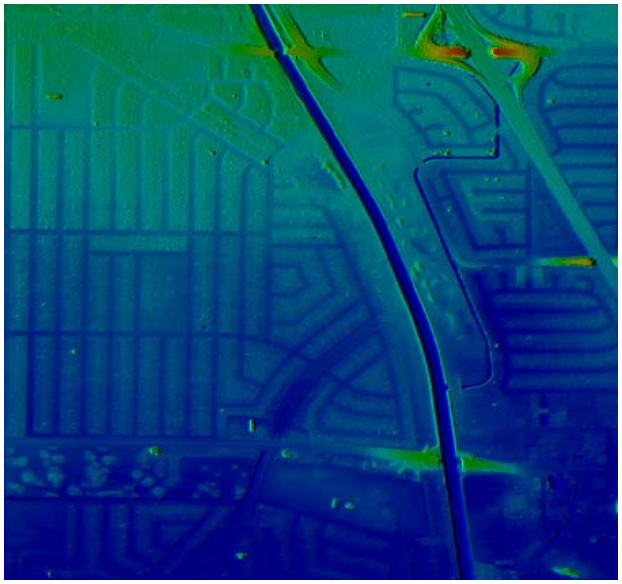

Figure 3.a
Post-Processed LIDAR Bare-Earth DEM. Elevations to the north are slightly higher than elevations to the south. Streets are also lower.

Figure 3.b
Post-Processed LIDAR Bare-Earth Void Map. Black speckles are data voids caused by removal of data points from buildings and vegetation

## PROJECT 5 – LIDAR DEM FOR FLOOD INSURANCE STUDY #2 (1999)

For a county in Florida, this was the second project known to D&D that was designed to demonstrate the utility in using high-resolution, high-accuracy LIDAR DEMs for automated or semi-automated H&H modeling for updating of FIRMs. Using guidance from D&D, the County Surveyor conducted independent checkpoint surveys in five major vegetation categories representative of the County floodplains: 1) woods or under individual trees (158 check points); 2) tall weeds or agricultural fields (100 check points); 3) short grass or weeds, or on bare earth, sand, or rocks (191 check points); 4) mangrove (105 check points); and 5) sawgrass (123 check points). The County Surveyor provided the results of his check point surveys to FEMA and D&D.

### Summary of Opportunities

- D&D determined that all errors in the $RMSE_z$ calculations for the first three vegetation categories had a normal distribution. The number and size of negative (below ground) errors were approximately equal to the number and size of positive (above ground) errors. The County Surveyor's $RMSE_z$ calculations of 25.3-cm, 14.0-cm, and 10.6-cm for vegetation categories 1, 2 and 3, respectively, were considered to be valid.
- D&D determined that all errors in the $RMSE_z$ calculations for the last two vegetation categories did not have a normal distribution. All errors were positive, indicating that the LIDAR had surveyed the tops of the dense mangrove and sawgrass areas, and had not penetrated to the bare-earth ground beneath. After computing the average errors for 4) mangrove and 5) sawgrass, and subtracting those average errors from all LIDAR elevations for those vegetation categories, then the errors had a normal distribution, and the $RMSE_z$ for mangrove was recalculated to be 20.3-cm, and the $RMSE_z$ for sawgrass was recalculated to be 20.0-cm.
- FEMA concluded that the LIDAR-generated DEMs, when corrected for systematic errors in mangrove and sawgrass, were acceptable for hydraulic modeling in County floodplains. In all vegetation categories, the LIDAR data clearly exceeded FEMA's traditional FEMA 37 requirement for 4-foot contours. The LIDAR data exceeded FEMA's new 15-cm LIDAR standard in only two of the five vegetation categories (tall weeds or agricultural fields; and short grass or weeds, bare earth, sand, or rocks), but these were the categories that were most representative of key areas where hydraulic modeling was most critical. Only where dense vegetation prevented the laser pulses from reaching the ground (woods, mangrove, sawgrass) did the LIDAR fail to meet FEMA's 15-cm LIDAR standard, but it was doubtful that traditional photogrammetry would have done any better in dense vegetation. Therefore, FEMA concluded that the LIDAR had met all realistic expectations for hydraulic modeling.

### Summary of Pitfalls

- The County still needs to delineate the boundaries of mangrove and sawgrass fields in order to apply the systematic corrections to all DEMs in those vegetation categories.
- Minor data voids and artifacts still needed to be addressed.
- Procedures for developing breaklines and cross sections still needed to be developed.

## PROJECT 6 – FEMA/USACE IFSAR/LIDAR DEM COMPARISON (1999)

The 1997 Red River flood resulted in catastrophic damages to residential, commercial, industrial, agricultural, and public properties in large portions of the Red River Valley in the States of Minnesota and North Dakota and in the Province of Manitoba. In the aftermath of the flood, the governments of the U.S. and Canada asked the International Joint Commission (IJC) to analyze the cause and effects and to recommend ways to reduce the impact of future floods. In support of the IJC study, the Saint Paul District of USACE requested assistance from the U.S. Army Topographic Engineering Center to evaluate emerging airborne remote sensing technologies for application to crisis management support. A pilot study was conducted utilizing both IFSAR and LIDAR collection systems to determine the correct mix of technologies required. A major objective of the study was to develop and implement a data fusion technique to merge IFSAR and LIDAR DEMs.

### Summary of Opportunities

- The IFSAR DEM was found to have an $RMSE_z$ of 82-centimeters for approximately 500 check points that were within the area overlapping the LIDAR DEM and not under vegetation canopy. This was the best independently-verified accuracy achieved to date by an IFSAR solution.

- The LIDAR DEM was found to have an $RMSE_z$ of 32-centimeters for approximately 500 check points. GPS data was collected along the major routes of transportation for the area.
- Data fusion or merging of the LIDAR and IFSAR DEM was accomplished and a corrected IFSAR DEM surface was merged with the LIDAR DEM. Final analysis is still pending. See Figure 4.

**Summary of Pitfalls**

- Recognizing that IFSAR does not penetrate vegetation, the accuracy of the IFSAR DEM was not evaluated under vegetation canopies.
- The study is still a draft, pending redelivery of the LIDAR DEM due to a systematic error found in the LIDAR DEM.

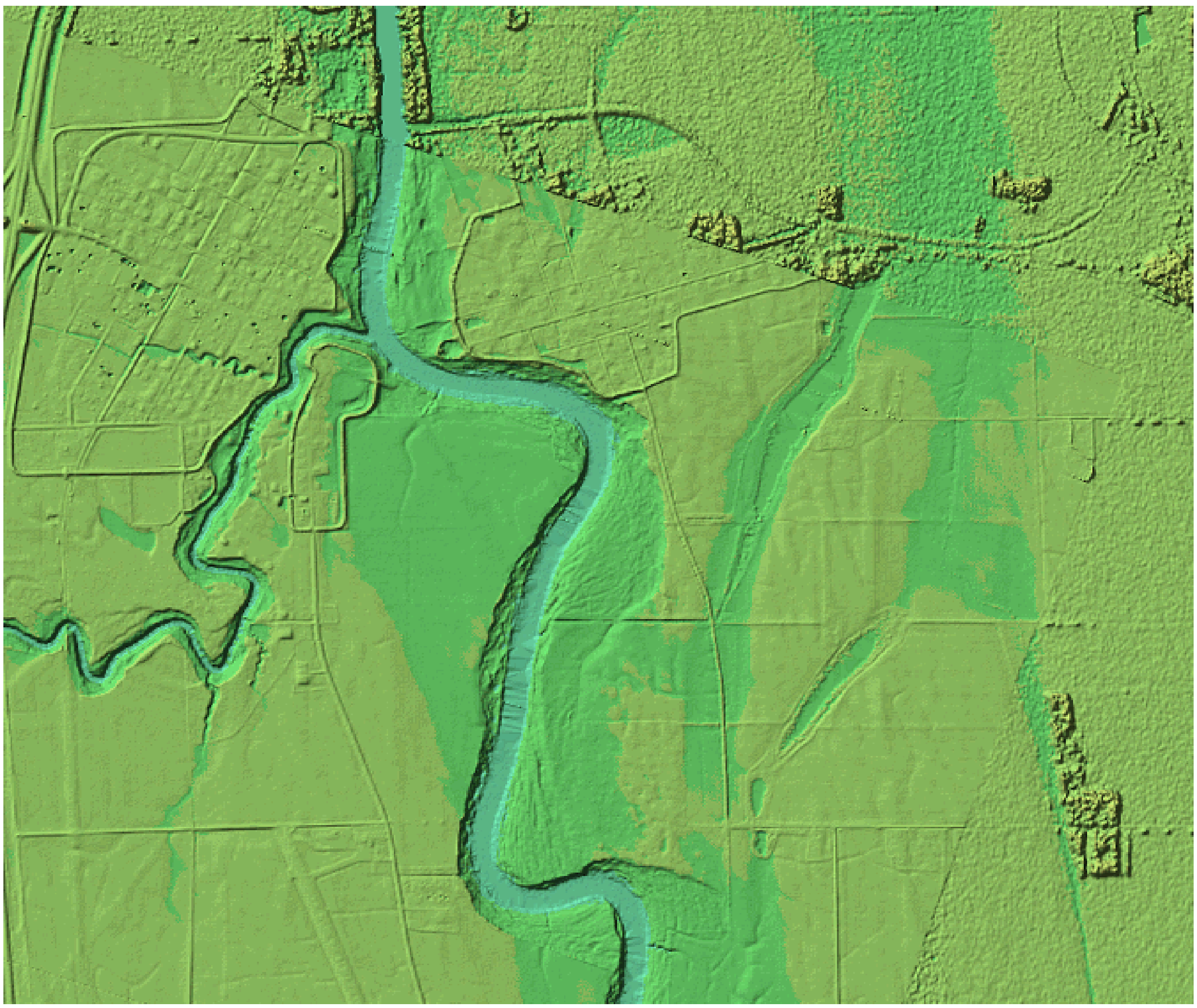

Figure 4

Merger of LIDAR and IFSAR DEMs. Less expensive IFSAR DEMs could be acquired of broad areas for hydrologic modeling and other applications where sub-meter level accuracy is acceptable; the areas to the northeast in this image show IFSAR first-return (tree top) DEMs. More expensive LIDAR DEMs could be acquired of limited areas for hydraulic modeling and other applications where decimeter-level accuracy is required; the areas in the center and to the southwest in this image are LIDAR last-return DEMs that approximate bare-earth. The LIDAR data can also be used to improve the accuracy of the IFSAR data.

## PROJECT 7 – USGS IFSAR/LIDAR DEM COMPARISON (1999)

This project was funded by USGS to compare the IFSAR and LIDAR DEMs of the area covered by a USGS 7.5-minute quad map for which extensive ground survey control data are available.

### Summary of Opportunities

- The IFSAR DEMs accurately represented the elevations of the tree canopies but should not be used for bare-earth DEMs.
- Upon completion of post-processing to remove buildings and residual vegetation, the "last return" LIDAR bare-earth DEMs were estimated to have $RMSE_z$ within the 15-cm accuracy range predicted for this project.
- Subtracting the LIDAR elevations from the IFSAR elevations yielded a product that could be used for biomass determination of forested areas.

### Summary of Pitfalls

- Errors tend to increase in IFSAR data from near to far edge owing to the decrease in signal to noise ratio. Similarly, LIDAR vertical errors are minimal near the nadir and increase at wider scan angles.
- LIDAR acquired during leaf-off conditions produce more accurate bare-earth DEMs than when LIDAR data are acquired during leaf-on conditions.
- Minor "corn row" effects, within the LIDAR's 15-cm accuracy band, were found to exist in the sidelap areas.

## PROJECT 8 – LIDAR DEM OF EVERGLADES (1999)

This project was funded by USGS to rapidly acquire LIDAR DEMs of a large portion (nearly 183,000 acres) of the Everglades for which ground elevations were not available from conventional photogrammetry because of cover with sawgrass and other dense vegetation. When large areas of vegetation were burned off with wildfires in May, 1999, USGS contracted quickly with D&D to survey the area with LIDAR so that the bare-earth DEM could be acquired prior to regrowth of vegetation.

### Summary of Opportunities

- Photogrammetry cannot generate accurate topographic data of sawgrass areas because clearly defined points on the ground can not be seen from two perspectives as required for stereo photogrammetry. Even when sawgrass is burned off, photogrammetry would have great difficulty identifying photo-identifiable features on the stereo imagery.
- LIDAR doesn't need to "see" in stereo in order to survey topographic data, and LIDAR doesn't even need daylight to survey the terrain. All LIDAR data for this project (millions of data points) was acquired at night, avoiding periodic rainclouds and other obscurations that primarily occurred during daylight hours. The data was acquired from a flying height of 8,000 feet above mean terrain.

### Summary of Pitfalls

- USGS identified what appeared to be tilt in some of the flight lines in the original data set, revealing a tilt range from 20 to 45 cm across the flight lines. After determining that this was apparently caused by an encoder slip equivalent to a rotation offset in the roll angle of the LIDAR system's inertial measuring unit (IMU), the DEM was reprocessed and the apparent tilt errors were successfully corrected.
- Although LIDAR does work at night, LIDAR is still limited by lingering smoke from the wildfires, and by clouds, either of which would be easily penetrated by IFSAR. The LIDAR team needed to cleverly dodge such conditions in order to acquire a successful data set.

## PROJECT 9 – CONCURRENT LIDAR AND NAPP PHOTOGRAPHY (1999)

Two projects were funded by USGS to demonstrate potential benefits of integrating aerial photography, acquired to satisfy National Aerial Photography Program (NAPP) standards, with LIDAR data (simultaneously acquired from an altitude of 20,000 feet above mean terrain) to satisfy USGS DEM standards. The simultaneous acquisition of NAPP photography and DEM (from 20,000 feet, using an aircraft with twin camera ports) could simplify the production of digital orthophotos for the National Digital Orthophoto Program (NDOP).

**Summary of Opportunities**

- Integrated data sets were successfully acquired for multiple quad maps in two states.
- NAPP photography, digital orthophoto quarter-quads (DOQs), and DEMs were delivered to USGS for evaluation.
- With this process, stereo photogrammetry is not required to generate digital orthophotos.

**Summary of Pitfalls**

- None to date. Benefit/cost analyses of such integrated data acquisitions has not been determined.

## PROJECT 10 – LIDAR DEM WITH INTENSITY RETURNS

At least one LIDAR system manufacturer is currently selling LIDAR sensors that measure and record the intensity of the LIDAR first and/or last returns.

**Summary of Opportunities**

- As shown in Figure 5, the resulting LIDAR intensity image is similar to an IFSAR image which also enables the user to see the terrain being scanned by the sensor.
- This capability should greatly facilitate the post-processing procedures to remove LIDAR data points that fall on buildings and trees not penetrated to the bare-earth by the laser pulses. This is especially helpful on highways where moving vehicles would otherwise cause unexplained DEM "bumps" that need to be moved. Periodic images from video or other cameras are less useful for this purpose.

**Summary of Pitfalls**

- None known

Normally, IFSAR clearly delineates water areas, but LIDAR does not, as shown here.

Baltimore Inner Harbor

**Note:**
Since water absorbs the laser pulses from LIDAR sensors, elevations in water areas are always suspect and are normally deleted within water polygons.

Figure 5
Baltimore, Maryland, showing LIDAR intensity returns that appear similar to a photograph

## SUMMARY OF OPPORTUNITIES AND PITFALLS

The first pitfall to be avoided is to ensure that everyone involved with an IFSAR or LIDAR project understands the meaning of vertical accuracy as defined by the NSSDA. Currently, most users do not understand the official definitions of $RMSE_z$ and $Accuracy_z$.

IFSAR DEMs are less expensive but also less accurate than LIDAR DEMs. IFSAR DEMs are satisfactory for some applications, but users must remember that $RMSE_z$ values, as good as 60 cm, pertain to rooftops and treetops, and not bare-earth DEMs. This value is expected to improve to 30 cm within the next year or two, but such accuracies are only theoretical at this date.

LIDAR DEMs are more expensive but also more accurate than IFSAR DEMs. Last-return LIDAR data can yield bare-earth DEMs with $RMSE_z$ values of 15-cm or better (after post-processing to remove data points that fall on buildings and vegetation not penetrated by the LIDAR). When bare-earth DEMs are required, LIDAR data should be acquired during leaf-off conditions, and also during low-water conditions when used for floodplain modeling. Natural data voids over water (and some asphalt), and man-made data voids caused by post-processing, may seriously degrade the utility of LIDAR data.

LIDAR TINs (with non-uniform point spacing) are generally more accurate than DEMs (with uniform point spacing), making TINs superior to DEMs for hydraulic modeling, for example. The post-processing of LIDAR data causes the "removal" of LIDAR points that hit rooftops or treetops and did not penetrate to the ground. This causes data voids that need to be filled in by an interpolation process necessary to generate DEMs. This interpolation process causes the DEM points to be artificially generated from surrounding data that may inaccurately depict the shape of the terrain in the area that previously contained data voids.

The effects of terrain slope on LIDAR and IFSAR are not fully understood. Some researchers have reported an increase in LIDAR vertical error that is proportional to the slope of the terrain; this could be caused by systematic horizontal errors translating into vertical errors at steeper slopes. Effects with IFSAR are reportedly similar, though less pronounced.

Both IFSAR and LIDAR provide the U.S. with the opportunity to generate new DEMs on the NAVD 88 vertical datum at costs significantly less than photogrammetrically compiled DEMs. However, neither IFSAR nor LIDAR are as good as photogrammetry in generating breaklines. Unwanted artifacts and "corn rowing" can occur with either IFSAR or LIDAR data.

The remote sensing community needs DEM standards that address not just vertical accuracy, but also data voids, artifacts, "corn-rowing" and other effects of sidelap merges and overlays. This will be a critical challenge for ASPRS in the immediate future as LIDAR and IFSAR emerge as the hottest new technologies as we begin the new millennium.

Most importantly for IFSAR and LIDAR data alike, it is important that tests are independently performed and reported by disinterested third parties to ensure that accuracy claims are not overstated.

With the use of IFSAR, large data sets can be collected and processed very quickly and less expensively than LIDAR. However, for small areas, the situation is reversed in that LIDAR can collect and process the data quickly and less expensively than IFSAR. As an example, during the February 2000 mission, the Space Shuttle collected IFSAR data for approximately 80% of the earth's land surface. Although the vertical accuracy is estimated at +/- 4 meters at the 95% confidence level, the actual processing of the massive data sets will require years. A project of this magnitude is not considered feasible for LIDAR at this time. However, both of the technologies are being improved so rapidly that many of the limitations will be overcome within the decade. Researchers are beginning to envision the total opportunities available with these technologies which will become more widely used as they are enhanced.