NASA Earth Science Enterprise
Commercial Remote Sensing Program
Affiliated Research Center
University of South Carolina

Final Report:

Evaluation of the Utility and Accuracy of LIDAR and IFSAR Derived Digital Elevation Models for Flood Plain Mapping

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March 30, 2001

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Executive Summary

In September 1999, Hurricane Floyd caused one of the worst natural disasters in U.S. history. The torrential rains that followed Floyd's path dumped 20 inches of rain that washed mountains of sediment and waste into North Carolina's water system and displaced tens of thousands of people in the wake of the floods. These floods killed 48 people in the state and destroyed nearly 3,700 homes. Floyd was the costliest natural disaster in U.S. history, effecting a total of 66 eastern U.S. counties. Flood is the costliest natural hazard in the world and accounts for approximately 30% of the economic losses resulting from natural catastrophes (Galy and Sanders, 2000). The insurance industry is becoming increasingly concerned of the financial cost of flooding and would like to develop new methods to accurately quantify flood-damaged areas.

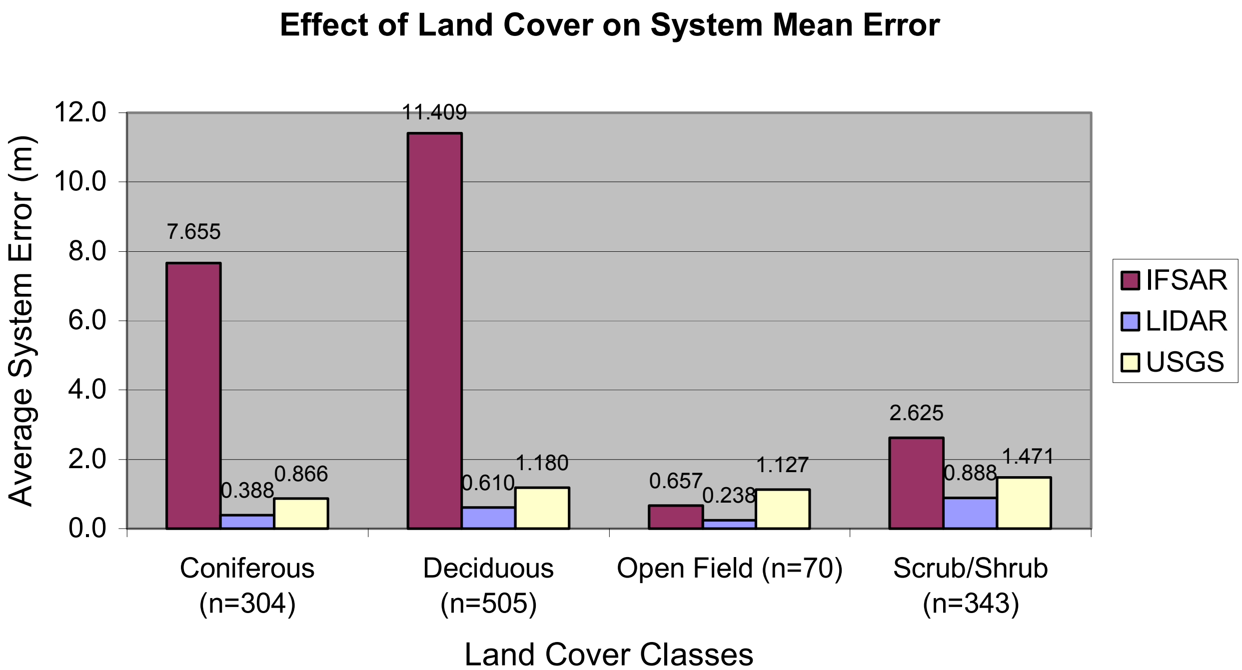
In order to assess flood-damaged areas in a quick and efficient manner, the acquisition of accurate terrain elevation is essential. Accurate terrain elevation is often the costliest geographic information to acquire and is difficult to obtain in a timely manner. Recent developments in new technologies such as LIDAR and IFSAR possess ideal characteristics to capture accurate digital elevation information quickly and efficiently. Few studies exist that compare and contrast these two technologies in their elevation accuracy and utility in flood plain mapping. In addition, many agencies desire to know and understand the advantages and disadvantages that are associated with each of these technologies in order to make better and more informed decisions.

The NCCGIA ARC project tested the efficacy of LIDAR and IFSAR for accurate floodplain mapping. The state of North Carolina desired an unbiased assessment and comparison of LIDAR and IFSAR accuracy. This research illustrated the significant advantage in accuracy provided by the LIDAR system. However, cost differences between the two systems must be considered, and the advantage of LIDAR is reduced. The table below summarizes the accuracy and costs that were determined from this project:

System	Accuracy (RMSE)	Cost /km^2
LIDAR Aeroscan	0.93 m	$500
IFSAR Star-3i	10.63 m	$35
USGS Level 2 DEM	1.64 m	Not available

The LIDAR accuracy is impressive, but at this time does not meet the FEMA standards for LIDAR-derived DEMs used for floodplain mapping. As this data was acquired during leaf-on conditions, it is expected that a leaf-off product will produce acceptable results.

Analysis of each system's performance in varying land covers was beneficial for future decision-making. Each system demonstrated significant weaknesses and strengths in different categories as listed in the graph below:



1.0 Introduction

EarthData International is a mapping and GIS firm with offices in California, Maryland, North Carolina, and Florida. The company provides data acquisition, custom mapping, and GIS services using a variety of sensors including the Aeroscan LIDAR (light detection and ranging) sensor. **Intermap Technologies** is a Canadian-based mapping company with offices in Ottawa, Canada, and Denver, Colorado. The company provides digital elevation models from data acquired by the Star-3*i* interferometric synthetic aperture radar system.

This study involved the comparison of two relatively new remote sensing technologies. The state of North Carolina desired a thorough assessment of each company's product for future floodplain mapping. Each company provided the data and post-processing necessary to perform a complete accuracy assessment. Both companies have extensive mapping experience and are continuously refining their methods. In addition, each company to provided the best product possible to the state of North Carolina in the interest of future mapping contracts.

This NASA sponsored Affiliated Research Center ARC project with the state of North Carolina examined recent developments in remote sensing technology to assess and compare the accuracy of two new systems capable of floodplain mapping. In September 1999, Hurricane Floyd caused one of the worst natural disasters in U.S. history. The torrential rains that followed Floyd's path dumped 20 inches of rain that washed mountains of sediment and waste into North Carolina's water system and displaced tens of thousands of people in the wake of the floods. These floods killed 48 people in the state and destroyed nearly 3,700 homes. Floyd was the costliest natural disaster in U.S. history, affecting a total of 66 eastern U.S. counties. Flood is the costliest natural hazard in the world and accounts for approximately 30% of the economic losses resulting from natural catastrophes (Galy and Sanders, 2000). The insurance industry is becoming increasingly concerned of the financial cost of flooding and would like to develop new methods to accurately quantify flood-damaged areas.

In order to map flood zones in a quick and efficient manner, the acquisition of accurate terrain elevation is essential. This information is often the costliest geographic information to acquire and is difficult to obtain in a timely manner. Recent developments in new technologies such as LIDAR and IFSAR possess ideal characteristics to capture accurate digital elevation information quickly and efficiently. Few existing studies compare and contrast these two technologies in their elevation accuracy and utility in flood plain mapping. In addition, many agencies desire to know and understand the advantages and disadvantages that are associated with each of these technologies in order to make better and more informed decisions.

The North Carolina CGIA NASA ARC focused mapping efforts on a small portion of the Swift Creek watershed in eastern North Carolina. Two pilot study areas were identified based on their topography and land use. The Centerville Pilot Study Area is mainly rural with gently sloping topography. The Princeville Pilot Study Area is predominately urban and has relatively little vertical relief. These areas suffered from severe and unexpected flooding during Hurricane Floyd. The FEMA flood maps for this area are out of date and inaccurate.

The goal of this NASA sponsored ARC was to assess the accuracy and landcover limitations of each product and compare the results to USGS products formerly used for floodplain mapping. This data was acquired during leaf-on conditions, so the capabilities of each system were tested. The knowledge gained in this assessment will assist government agencies in future mapping projects. This study hoped to identify the more accurate system, as well as identify limitations experienced in various landcover.

2.0 Project Background

2.1 Study Area

The Swift Creek watershed is located in eastern North Carolina extends west to Henderson, NC, and east to Tarboro, NC. Swift Creek is a tributary of the Tar River and meets the main stream at Tarboro (Figure 1). The Centerville Pilot Study Area is situated between Rocky Mount and Henderson, NC. The terrain is gently rolling with elevations ranging from 45 to 120 meters. The vegetation is primarily pine plantations and upland hardwoods. Much of the area is cleared for agricultural purposes including tobacco and soybean. The Princeville Pilot Study Area encompasses 46 km^2 of mostly flat terrain. The boundary of the study area includes Princeville and a portion of Tarboro. Princeville is a small, undeveloped town, while Tarboro has a small urbanized downtown. This area includes sidewalks, wide streets, parking lots, and several large buildings. Each study area presents unique challenges for both IFSAR and .LIDAR.

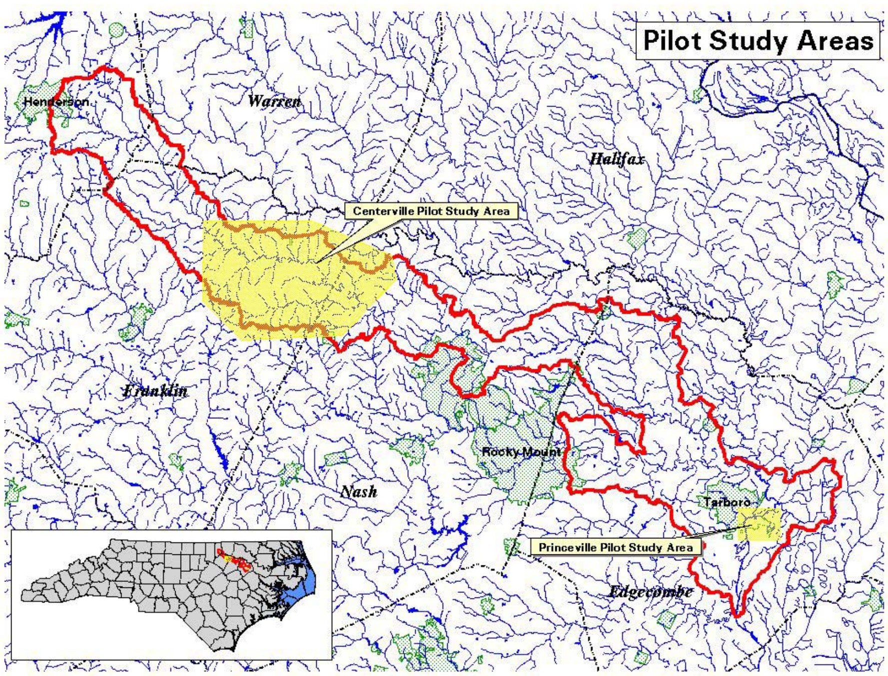


Figure 1 Swift Creek Watershed, the study site in eastern North Carolina

2.2 Previous Studies

The derivation of accurate digital elevation models from data acquired by LIDAR and IFSAR is dependent upon sufficient ground strikes by the laser pulses and radar. The transmission of light and energy through vegetation is related to the degree of canopy closure. Therefore, it is expected that LIDAR and IFSAR will both perform best in areas with little vegetation.

When a LIDAR laser pulse reaches the ground, highly accurate elevation data may be obtained. However, in densely vegetated areas, nearly 60% of the data points will be reflected from the canopy rather than the ground. The role of vegetation removal algorithms is to filter the millions of points to remove those representing strikes on vegetation and man-made objects. Currently, these algorithms are proprietary, and the process is successful in removing most of the erroneous points. The high pulse frequency of most LIDAR systems leaves enough ground points for the true surface to be interpolated. Most laser scanners are reportedly accurate within $\pm$15cm (Ackermann, 1999). Understanding the interaction between the laser pulse and the canopy is the key to a successful vegetation-removal algorithm.

Many studies (Means et al., 1999; Nelson et al., 1984; Lefsky et al., 1999) focus on the determination of canopy characteristics using LIDAR returns, rather than using canopy information to predict the effectiveness of LIDAR. However, the purpose of this research is to allow future LIDAR mission plans to predict the accuracy of the final DEM based on knowledge of the vegetation in the desired site. This evaluation was performed on a filtered, interpolated DEM. The accuracy assessment reflects the success of the LIDAR system in vegetation with a vegetation-removal algorithm.

Hendrix (1999) examined the relationship between canopy closure and error in a LIDAR-derived DEM. He discovered that in areas of dense canopy, there is a decrease in the number of ground points recorded by the LIDAR. It would be expected that the DEM error would therefore increase with increasing canopy closure. However, Hendrix found a weak relationship between canopy closure and DEM error. He hypothesized that this could have been the result of the field sampling method used to obtain the canopy closure measurements. The sampling occurred between the areas of largest DEM error, so Hendrix felt that the relationship was not representative (1999). Nelson et al. (1984) employed a laser profiling system in an area of varying canopy density. The area included foliated and defoliated canopies. Defoliated canopies resulted in a significant increase in pulse penetration and ground hits by the laser. The focus of this study was the ability of the profiling system to characterize the canopy. The study did not assess the accuracy of the ground hits or the effect of the canopy on the accuracy.

Though IFSAR is an excellent tool for gathering topographic information quickly, it does have limitations. The widely used STAR-3*i* system typically records data in 2.5-meter postings, but inaccuracies increase dramatically at densities higher than 5 meters. For this reason, IFSAR is more cost-effective for large study areas with low-density postings. In fact, Mercer (1998) recommends areas that are several kilometers long. Star-3*i* is also limited by X-band radar (2.4 – 3.8cm), which cannot penetrate vegetation (Mercer and Schnick, 1999). Vegetation is expected to produce the most extreme error in the IFSAR-derived DEM.

A study by the US Army Topographic Engineering Center (TEC) assessed the accuracy of a Star-3*i* IFSAR-derived DEM compared to a photogrammetric DEM. Vegetation had such a significant impact on the performance of the IFSAR system that vegetated areas were entirely masked out of the analysis. (Mercer, 1998).

IFSAR flights in forested regions of Connecticut resulted in higher recorded elevations. The average tree height was approximately 15 meters, resulting in an elevation bias of 3 to 5 meters for deciduous forests and 6 to 7 meters for coniferous (Orwig et al., 1995).

Xiao et al. (1998) dealt with vegetation interference through the development of a neural network. A bare-earth ground truth data set provides a target during the training process. The neural network uses backscatter magnitudes and the IFSAR elevations as inputs. Tree heights are estimated by the neural network and subtracted from the IFSAR elevations. The result is a bare-earth DEM, though more post-processing is needed for smoother results.

Given the difficulty IFSAR experiences with vegetation, it is expected that denser vegetation such as deciduous or coniferous forests, would cause greater error in the IFSAR DEM. The X-band radar has the ability to filter through the canopy in much the same way as the laser pulse on a LIDAR system. The elevation recorded by IFSAR is a combination of reflectance from treetops and some volume scattering within the canopy (Tennant et al., 1999). Volume scattering makes it more difficult to derive a bare-earth elevation during post-processing. This study will provide greater detail for understanding the effect of vegetation on the accuracy of IFSAR-derived DEMs.

3.0 Project Implementation

3.1 Project Initiation

This ARC project was developed through a series of meetings with Bruce Davis of Stennis Space Center, the North Carolina Center for Geographic Information and Analysis, and representatives from the University of South Carolina. The milestones of this project are found in Table 1.

Table 1 Chronology of the NC CGIA NASA Affiliated Research Center (ARC) Project.

Event	**Date**
Kick of Meeting	March 14, 2000
NCCGIA Proposal approved by NASA	April 26, 2000
Memorandum of Understanding processed	June 21, 2000
Target area and transects identified	May 5, 2000
In situ data collection	May 24-25, 2000
IFSAR data acquired	May 30, 2000
IFSAR/LIDAR data acquired	June 5, 2000
Processing and analysis of data completed	Jan. 15, 2000
Presentation of project at NASA Stennis Space Center	Feb. 14, 2001
Final Report delivered to NASA Stennis Space Center	April 21, 2001

3.2 Objectives

The main objectives of this study were to assess the accuracy and landcover limitations of each product. This study hoped to identify the more accurate system, as well as identify limitations experienced in various landcover. To complete this ARC project, close cooperation between the USC-ARC staff and the data collectors was required.

The State of North Carolina's responsibilities were to:

1. Provide watershed boundaries and 1:40,000 scale NAPP data for the entire watershed.
2. Assist in identifying optimal transects within the watershed that represent various land cover classes and elevation variation.
3. Acquire LIDAR data for the study area. LIDAR was collected at a 6-meter posting and vertical accuracy of ± 20cm RMSE (typical project specifications).
4. Acquire IFSAR data for the study area. IFSAR was collected at a 6-meter posting and vertical accuracy of 2 meter RMSE (typical project specifications).

5. Acquire survey-grade (±4cm horizontal; ±8cm vertical) elevation ground control within the identified transects study area to be used in the accuracy comparison.
6. Assist in producing the final report documenting the results of the study.

The USC-ARC staff was expected to:

1. Collect the needed *in situ* canopy characteristics which will identify land cover classes within the pre-defined transects.
2. Identify land cover classes within the study area and correlate these areas with the associated terrain elevation accuracy.
3. Document the approximate production costs for the creation of the bare-earth surface models.
4. Perform appropriate statistical analysis of the LIDAR, IFSAR, and USGS bare-earth surfaces and compute a statistically derived elevation error evaluation based on reference data.
5. Assist in producing the final report documenting the results of the study.

3.3 Methodology

3.3.1 Remote Sensor Data Acquisition

All data collected for this study were provided or projected in State Plane – North Carolina. The units were in meters, and the datum was NAD83 and NAVD88. The LIDAR system used in this study is the AeroScan sensor, developed and operated by EarthData International. AeroScan is mounted on a deHavilland Twin Otter and can fly at altitudes up to 6,000 meters. The expected vertical accuracy is 15 cm, but the accuracy of a bare-earth surface model has not previously been validated with precise reference data.

The Star-*3i* system operated by Intermap Technologies is mounted on a LearJet36 and consists of two X-band radar antennae. This system is typically flown at 12,000 m, and the vertical accuracy is <3 m (Intermap Technologies, 2000). Table 1 lists the chosen LIDAR parameters for this study, compared to the parameters of the IFSAR system

The overflights were conducted in May 2000. The tree canopy was fully vegetated at this time and provided an opportunity to test the capability of the LIDAR vegetation removal algorithms. The X-band used in the STAR-3*i* system cannot fully penetrate a vegetated canopy, so collection at this point in the forest's phenological cycle also provided a challenge for the IFSAR system. Table 2 presents typical data collection parameters for both systems.

Table 2. Comparison of systems with mission-specific parameters (Schill, 2000).

	Star-3i	AeroScan
Flying Height	12,000 m	2,400 m
Pulse Rate	15,000 Hz	15,000 Hz
Swath Width	8 km	1.8 km
Point Density	6 meter posting	6 meter posting
Advantages	• <2m vertical accuracy • ideal for large level terrain • $60/km^2 • faster, less processing	• vegetation penetration • ±15cm vertical accuracy • ideal for small areas
Disadvantages	• error from vegetation and slope	• $500/km^2 • slower, more processing

The AeroScan system collected data at 6-meter postings to decrease flight and processing time for this large study area. The data were processed using vegetation removal algorithms to extract the most accurate bare-earth surface model possible. EarthData provided a file of points containing x, y, and z information. The nominal post-spacing for this project was 6 m. The IFSAR data was collected by the STAR-3i system at 6-meter postings. Intermap Technologies provided a standard digital elevation model in a 6x6 meter grid format.

3.3.2 In Situ Data Collection

Highly accurate elevation reference data were needed to perform the accuracy assessment of the surface models. Transects desirable for hydrologic modeling in future studies were selected in the Centerville study area prior to the overflights. The North Carolina Geodetic Survey obtained 1570 survey-grade (±2cm horizontal; ±5cm vertical) elevation data along these transects and at random points throughout the Centerville study area (Figure 2).

In Princeville, a total of 158 random reference points were collected by the NCGS (Figure 2).This area is primarily developed land, and vegetation does not play a significant role in data acquisition. Hydrologic modeling was not performed in this area, so the data were not collected as transects.

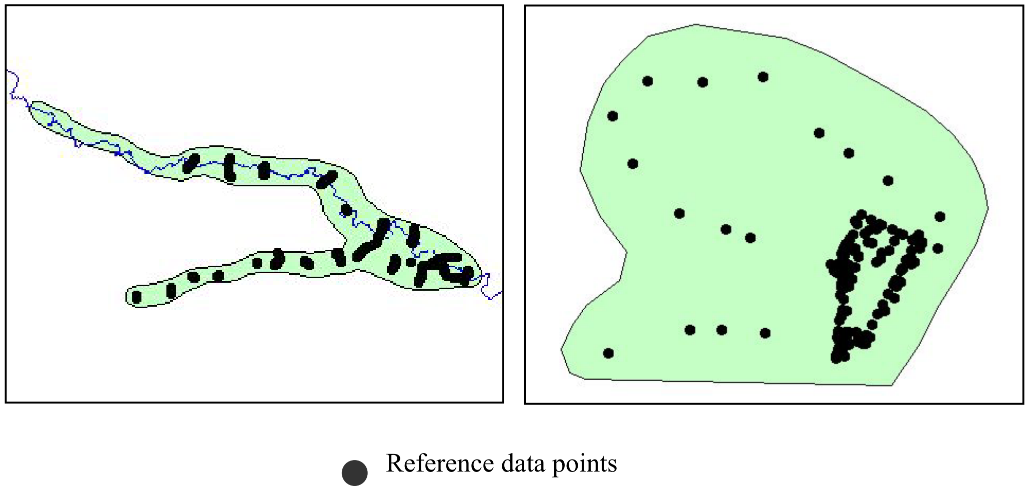


Figure 2 In situ data collection sites in Centerville (left) and Princeville (right) study areas

3.3.3 Data Analysis

3.3.3.1 Accuracy Assessment

The LIDAR and IFSAR DEM, as well as the USGS Level 1 and 2 DEMs were compared to reference data collected by the North Carolina Geodetic Survey to assess the accuracy. The USGS Level 2 DEM was not available for the Princeville study area. Therefore, the comparison in that area was limited to the Level 1 DEM. To perform this analysis, the three data sets were first converted to TINs (triangulated irregular network) using ESRI's Arc/Info 8.0 (Environmental Systems Research Institute) on a PC workstation (Figure 3). The Createtin function derives a TIN from point, line or polygon coverage. The operation allows the user to specify the boundary of the area to be interpolated as well as a proximal tolerance. This allows the user to eliminate points below the specified threshold from inclusion in the interpolation. **Cite ESRI users guide.** The FEMA standards support the use of TINs as a method for LIDAR accuracy assessment. As stated in Appendix 4B, "the contractor must use Triangular Irregular Network (TIN) linear interpolation procedures, including breaklines, when validating the vertical accuracy of the DEM" (FEMAa, 2000).

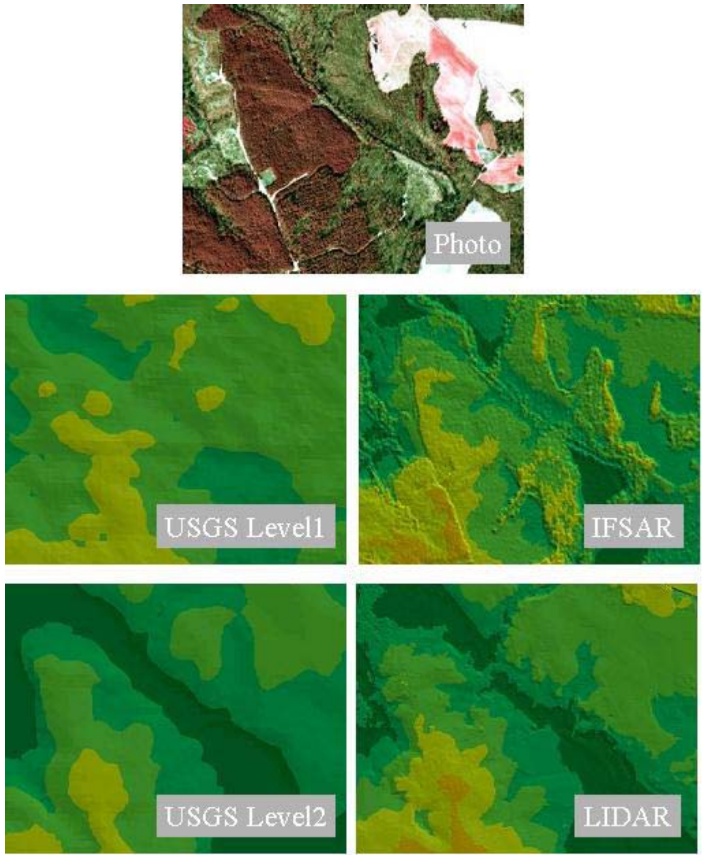


Figure 3 Subset of Centerville TINs created from original point files with DOQ for reference.

The accuracy assessment required elevations from the TINs at the exact location of the reference data. The Arc/Info Tinspot procedure extracts elevation values from the TIN at each reference point and places those values in the point attribute table of the point coverage (Figure 4). **Cite ESRI users guide.**

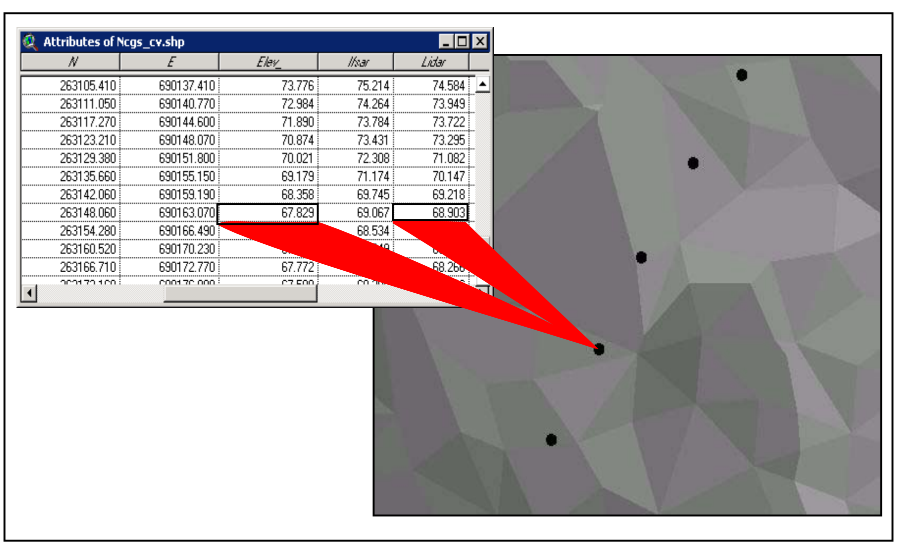


Figure 4. TINSPOT procedure extracts TIN elevation at reference point location.

The vertical error for each DEM was computed as:

Error (m) = TIN Elevation (m) – Reference Elevation (m)

Therefore, negative error values indicate surface model underestimates, and positive values indicate surface model overestimates. An ANOVA was used to verify the significance of mean error differences. A Student-Newman-Kleus test compared the mean error values of each DEM.

3.3.3.2 Land cover Analysis

A second analysis evaluated land cover as a main effect in determining vertical error. Current color-infrared photography for the study area could only be obtained for a portion of the Centerville study area and all of the Princeville area. The photography was used to assign land cover classes to a subset of the Centerville reference points and all of the Princeville reference points. Vertical error was averaged for each land cover class and a two-way ANOVA was used to evaluate the effect of land cover on the accuracy of each DEM.

4.0 Results

4.1 Accuracy Assessment

The vertical error analysis of the Centerville study area indicates that the LIDAR DEM is the most accurate surface model. The mean absolute error of the LIDAR DEM was 0.599 m, significantly more accurate than all other DEMs (F=1128.9,Pr>F=0.000). The SNK test indicates that the mean absolute error of each DEM is statistically unique. The root mean square error and the error at the 95% confidence level were calculated for all DEMs (Table 3). The Federal Geographic Data Committee requires DEM accuracy to be stated at the 95% confidence level (RMSE * 1.96) (FGDC,2000).

The Princeville study area yielded similar results (Table 4). The error is not as high for any of the DEMs in the Princeville area as the Centerville area. The effect of vegetation in the Centerville area is evident. The superior accuracy of the LIDAR DEM is significant (F=42.1, Pr>F<0.001).

Table 3. Vertical error of each DEM of the Centerville Study Area.

Source	LIDAR	IFSAR	USGS L1	USGS L2
Mean abs (m)	*0.599*	7.852	6.021	1.192
RMSE (m)	*0.931*	10.625	7.368	1.638
FGDC (m)	*1.825*	20.825	14.441	3.210

Table 4. Vertical error of each DEM of the Princeville Study Area.

Source	LIDAR	IFSAR	USGS L1
Mean abs (m)	*0.308*	2.124	1.169
RMSE (m)	*0.377*	3.568	1.488
FGDC (m)	*0.739*	6.993	2.916

4.2 Land Cover Analysis

The land cover classes identified from the 1998 photography were coniferous vegetation, deciduous vegetation, scrub/shrub, and open field. Each DEM experienced difficulty in certain land covers while excelling in others (Figure 5).

The effect of land cover on the vertical error of the surface model was significant for all DEMs (Pr>F=<0.0001 for all). Landcover explained 30% of the variance in the vertical error of the IFSAR DEM, but only 8% in the LIDAR DEM. The error in each land cover class was significantly different for all DEMs except the USGS DEMs. In the USGS Level 1 DEM error in deciduous and scrub/shrub environments was not significantly different, and error in open field and coniferous environments was not different. Land cover explained 12% of the variance in the USGS Level 1DEM. In the Centerville study area alone, the error in the USGS Level 2 DEM did not vary significantly between deciduous and open field environments. Land cover explained only 4% of the error variance.

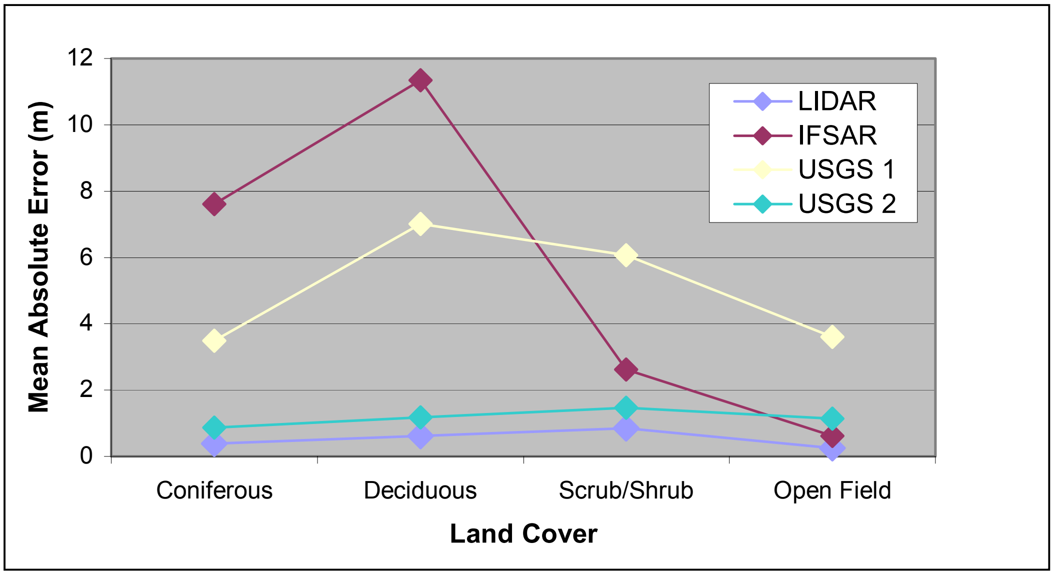


Figure 5. Graph of mean absolute error in each land cover class for all DEMs.

5.0 Conclusion

For this project, remote sensing and geographic information system (GIS) technology, coupled with highly accurate reference data, were used to evaluate the accuracy and utility of two new remote sensing technologies for elevation data acquisition. Hurricane Floyd emphasized the need for more accurate floodplain maps. Previous studies have evaluated the accuracy of the LIDAR and IFSAR systems, but the evaluation was limited to flat, open terrain. The ARC program involved the acquisition of elevation data through application of innovative remote sensing technologies. This study evaluated the IFSAR and LIDAR elevation models to an unprecedented extent. As a result of this study, the state of North Carolina is pursuing a state-wide mapping program using LIDAR technology. This mapping effort will reduce the damage incurred during flood events, and improve the quality of elevation data available for other studies in the state.

The LIDAR system in this study far outperformed the IFSAR system in absolute accuracy. This system is more accurate than the USGS product currently used to create floodplain maps. The Aeroscan sensor had problems in vegetated land cover, particularly deciduous and scrub/shrub environments. The dense deciduous canopy is most likely the limiting factor in acquiring accurate information. It is hypothesized that the scrub/shrub environment is challenging for the LIDAR vegetation removal algorithm. The vegetation in both environments is significantly reduced during the winter. It is expected that a leaf-off mapping effort would result in far more accurate elevation data in these areas, and an improvement in overall accuracy.

LIDAR technology is advancing rapidly and will increase in prominence as a major tool for mapping in the coming years. Limitations in the sensor caused by vegetation and cost are decreasing steadily. More accurate elevation data is essential for the development of safe and current floodplain maps. This data is also vital for many other hydrologic and environmental studies. This study has demonstrated the superiority of LIDAR technology in urban and rural environments. This project should be the foundation of a continued effort to introduce and encourage new technologies for acquiring elevation data.

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