Prepared in cooperation with the Lancaster County Assessor and the City of Lincoln

Collection and analysis of high-resolution elevation data for the Lincoln Lidar Project, Lincoln, Nebraska, 2004

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Preface

The Lincoln Lidar Project was a partnership developed between the U.S. Geological Survey National Center for Earth Resources Observations and Science (EROS), Lancaster County and the city of Lincoln, Nebraska. This project demonstrated a successful planning, collection, analysis and integration of high-resolution elevation information using Light Detection and Ranging, (Lidar) data. This report describes the partnership developed to collect local Lidar data and transform the data into information useable at local to national levels. This report specifically describes project planning, quality assurance, processing, transforming raw Lidar points to useable data layers, and visualizing and disseminating the raw and final products.

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Abbreviations and Acronyms Used

Acronym or Abbreviation	Definition
cm	Centimeter
m	Meter
ft	Feet
3-D	Three-dimensional
DEM	Digital Elevation Model
DFIRM	Digital Flood Insurance Rate Map
DOQQ	Digital Orthophoto Quarter Quadrangle
DNR	Department of Natural Resources
EDC	EROS Data Center
EROS	Earth Resources Observations and Science
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FGDC	Federal Geographic Data Committee
GIS	Geographic Information System
GPS	Global Positioning System
HARN	High Accuracy Reference Network
HME	Height Modernization Effort
IMU	Inertial Measurement Unit
Lidar	Light Detection and Ranging
LLC	Lincoln and Lancaster County
LOMR	Letters of Map Revision
MCMC	Mid-Continent Mapping Center
MSL	Mean Sea Level
NAD83	North American Datum 1983
NAVD88	North American Vertical Datum 1988
NED	National Elevation Dataset
PDOP	Positional Dilution of Precision
QA/QC	Quality Assurance/Quality Control
RMSE	Root Mean Square Error
TIN	Triangulated Irregular Network
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

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Introduction

Light detection and ranging, or Lidar, data are becoming a proven, effective remote sensing technology capable of delivering highly accurate, fine-resolution elevation information. The use of three-dimensional (3-D) data is rapidly becoming important in the visualization and analysis of geographic information. The generation of 3-D bare earth, forest, and urban models has become a major focus of photogrammetric research in the past few years. Photogrammetry involves using stereo pairs of overlapping images to identify 3-D points, whereas Lidar is an active sensor that can directly measure elevation features. The basic measurement by a Lidar system is the distance between the sensor and a target. This is calculated by determining the time it takes for a short-duration laser pulse to be emitted, reflected by the target surface, and received by the sensor. Multiplying this time interval by the speed of light results in the round-trip distance, and dividing by two provides the distance between the sensor and the target (Lefsky and others, 2002). These reflections generally are called returns or postings. Today's Lidar systems can record multiple returns from a single pulse, or even digitize the entire return waveform.

The complete Lidar system contains several components that work together to provide precise and accurate return locations. These components include the laser, a global positioning system (GPS), an inertial measurement unit (IMU), and an on-board computer. Commercial Lidar systems also include a scanning mirror, which allows for recorded Lidar returns from a swath based on the angle of the scan across the track of the flight path. The laser emits pulses and a sensor receives the laser pulse returned and records the time of each emitted and received pulse. The GPS allows for high-precision locational knowledge of the platform with a very high accuracy. The IMU records the roll, pitch, yaw, and speed of the aircraft several times per second. The on-board computer records the information collected by these separate components and converts this information into x, y, and z coordinates (Ackermann, 1999). These coordinates then are converted into 3-D “clouds” of data, and these clouds are traditionally converted into surfaces for analysis and visualization.

No standard methods have been created for processing Lidar data due to different Lidar sensor configurations, desired applications, improvements in the sensor technology, and computer processing power and memory. Key differences among Lidar sensor configurations include wavelength, power, pulse duration, repetition rate, beam size and divergence, angle, scanning mechanics, and information recorded for each reflected pulse (Lefsky and others, 2002). New techniques and methods continue to become available as computer power and Lidar system capabilities increase. As a result of these capabilities, new applications using Lidar data also have become available in the past few years. The three main categories of research using Lidar data involve bare earth analyses, vegetation analyses, and feature extraction, such as buildings.

Mapping bare earth is the largest and fastest growing application using Lidar remote sensing because of its use in commercial land-use surveys (Flood and Gutelis, 1997). With proper quality control, the accuracy of Lidar points can achieve root mean square errors (RMSE) of 50 centimeters (cm) in the horizontal planes and 15 to 20 cm in the vertical plane. Raw Lidar data can consist of many different features other than the bare earth, including human made objects (such as buildings), clouds, vegetation, or even birds. To extract a topographic surface from these raw points, a series of filters must be used to remove Lidar points that are not associated with the ground surface. Numerous filtering methods exist, but generally they combine automated processes with some manual correction (Kilian and others, 1996; Kraus and Pfeifer, 1998). Most commercial vendors have developed their own proprietary methods for extracting bare earth from Lidar data, which unfortunately means that bare earth outputs for the same area can differ between vendors. Examples of bare earth applications include mapping of polar ice sheets (Krabill and others, 1999), topography under forested areas for geomorphic analyses and hydrologic modeling (Harding and Berghoff, 2000), and beaches (Krabill and others, 2000). To obtain higher resolution elevation data, the U.S. Geological Survey (USGS) is incorporating bare earth Lidar data into the National Elevation Dataset (Gesch and others, 2002) in selected areas.

Highly accurate models of urban surfaces are becoming widely used in applications such as digital orthophoto production, 3-D modeling for urban and regional planning, and 3-D building reconstruction (Haala and Brenner, 1997). Lidar is recognized as an accurate data source for digital surface model generation in urban areas (Haala and others, 1997). Research has shown that Lidar data have the potential to support 3-D feature extraction, especially when combined with other types of data such as imagery and/or two-dimensional geographic information system (GIS) ground plans (Maas, 1999; Brenner and Haala, 1999; Weidner and Förstner, 1995). Detecting buildings directly from the raw Lidar data is a challenging problem, and as a result, data fusion can be helpful (i.e., combining spectral information with elevational information). The importance in using data fusion of Lidar and imagery has to do with the fact that Lidar acquires samples in a regular pattern. This pattern, however, often is inadequate to identify breaklines such as building edges. Without building breaklines, the Lidar-derived buildings often “taper” down to the ground, and will not accurately represent the building. Edge detection in urban areas has been shown as a quick way to create breaklines for buildings (Zhou and others, 2002). However, combining the elevational data with high-resolution spectral information allows for easier separation and better delineation of building footprints. A variety of methods for extracting buildings can be found in Tao and Hu (2001). Once buildings are identified, they can be reconstructed and represented using the Lidar data and a host of modeling and visualization techniques (Maas, 1999).

Advances in computer hardware in recent years (such as faster, larger and cheaper memories) have allowed for revolutionary approaches in computer graphics. Visualization of 3-D data has become an effective way for scientists and managers to view data and answer questions that require a topographic context (Haala and Brenner, 1997). The most popular methods for 3-D visualization in the geography field today are the creation of surfaces using raster grids (Mark, 1978) and triangulated irregular networks (TINs) (Peuker and others, 1978). Other 3-D representations such as voxels are being assessed as a way to represent Lidar point clouds (Stoker, 2004).

Lancaster County, Nebraska often is assumed to be relatively flat; however the regional elevation changes from about 1520 feet (ft) in the southwest to 1040 ft in the northeast. Localized drainage takes place within the Salt Creek Basin, which flows to the Platte River. A 1997 orthophoto project produced a 2-ft contour data set that encompassed more than 250 square miles.

In the 7 years since that image acquisition, Lincoln has grown substantially, with its property parcels increasing from 80,000 to more than 100,000. New subdivisions and developments have reshaped the land surface, increasing the amount of impervious surfaces and expanding construction into new drainage sub-basins.

Elevational information at a very high resolution and accuracy for both bare earth and structures was needed in the Lincoln / Lancaster County area in Nebraska for improve flood mapping, improved feature extraction, and to demonstrate the potential of Lidar data in various simulation and visualization activities for ***The National Map***. As a result, the USGS, the city of Lincoln, and Lancaster County cooperated in the Lincoln Lidar Project to meet these needs. The purpose of this report is to describe the collection and analysis of high-resolution Lidar data for the Lincoln Lidar Project.

Introduction

The Lancaster County Engineering Department began developing a GIS in 1989. By 1993, four city and county departments were collaborating on various GIS projects. In 1997, this group funded an ortho-image and contour project for Lincoln that has proven to be very useful. The city of Lincoln and Lancaster County (LLC) coordinated with the Nebraska Department of Natural Resources (DNR) on two different USGS digital orthophoto quarter-quadrangle (DOQQ) projects. In December 2001, EROS staff visited Lincoln to meet with the various departments about data sharing. This meeting set the groundwork for a shared vision between the local government entities in Nebraska and the USGS.

LLC has a collaborative enterprise GIS in place with more than 250 users in 20 departments accessing a central server. All of the framework data sets identified by the Federal Geographic Data Committee (FGDC) have been created and are maintained at the local level. LLC has cooperated with State and Federal agencies on the development of new and innovative projects. In 1994, the National Geodetic Survey (NGS) conducted an Eastern Strain GPS project to help study crustal deformation. This established the first A-order and B-order GPS points in Nebraska. In 1996, LLC again participated with NGS in the creation of the Nebraska High Accuracy Reference Network (HARN). A subsequent re-observation of the HARN in 1999 validated the precision obtained during the 1996 survey. LLC collaborated with the Nebraska DNR in the development of a 1993 and 1999 DOQQ project for the entire state of Nebraska. Lancaster County was selected as the pilot area in each project and incorporated the data immediately upon receipt. In 2002, LLC participated with NGS and the Nebraska Department of Roads in conducting a Height Modernization Effort (HME). During this GPS project, more than 80 stations were surveyed in an attempt to obtain highly accurate horizontal and vertical positions.

In 2001, the Federal Emergency Management Agency (FEMA) provided LLC with its latest Digital Flood Insurance Rate Map (DFIRM) product. Prior to that time, they had been using a table-digitized version that the Planning Department had digitized from the paper Flood Insurance Rate Map (FIRM) products. Both versions helped illustrate that substantial development had filled in many drainage ways. Additional properties were subject to potential flooding and flood basin pools appeared to have expanded. The City Council authorized the creation of a taskforce to update development codes and form policy on new developments within the flood plain.

A strong need exists to update the FEMA DFIRM product for this area. Many Letters of Map Revision (LOMR) have been approved by FEMA allowing construction within the floodplain. These new construction sites are built upon fill dirt that appears to displace the overall floodplain pool. When one compares the Lidar-derived shaded relief with the existing polygon boundaries of the DFIRM, it appears that the DFIRM boundary could be adjusted in multiple areas. Obviously, FEMA has a specific process by which DFIRM updates have to take place but the Lidar results could provide reliable data to aid in any future update.

By February 2002 discussions began between LLC, EROS, and the USGS Mid-Continent Mapping Center (MCMC) on a 0.3-meter (m) color ortho-imagery project to be conducted in cooperation with the National Geospatial Agency (NGA) as part of *The National Map* Urban Areas program. An attempt was made to incorporate a Lidar project with the acquisition of the imagery but the project timeline and the expanded costs prevented that attempt. Instead, LLC provided MCMC with their 1997 digital elevation model (DEM) and breakline information for use with the ortho rectification process. Nine quadrangles covering Lincoln and much of Lancaster County were flown on April 17, 2002.

Several days before the USGS/NGA aerials were flown LLC coordinated with the Nebraska Department of Roads and placed 6-ft canvas panels on 44 NGS stations that were within the coverage area. These NGS points had been surveyed with GPS as part of an HME conducted by NGS and Lancaster County Engineering Department. These visible panels have proven to be an excellent resource to help assess the horizontal spatial component of the USGS/NGA color ortho-imagery.

In 2003, the Lidar project once again became a possibility, and a partnership of local and federal agencies was formed. The Lidar flights took place in November and December of 2003. The coverage area was identical to the nine quadrangles flown in 2002 for the color ortho-imagery project, with an area of higher resolution around downtown Lincoln (fig. 1). The color imagery, the visible panels, and the elevation data from the NGS stations were used to assess the accuracy of the Lidar results.

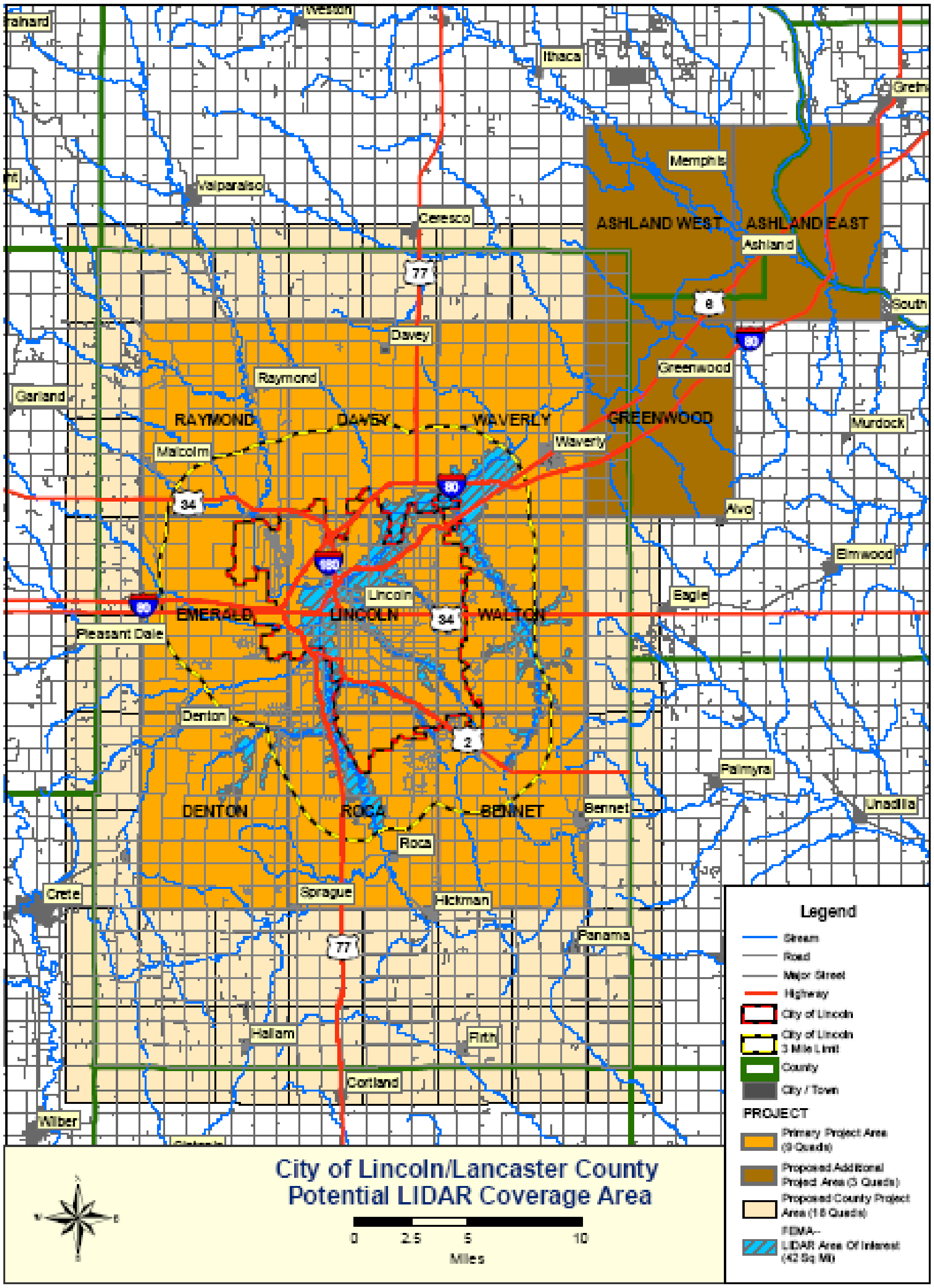

Figure 1. Lincoln Lidar Project area (area in brown not flown) (Courtesy of City of Lincoln and Lancaster County)

Lidar Data Acquisition

Lidar data was provided by Photo Science Inc. for the project area with a 3-m ground sample distance (not bare earth) for the nine quadrangles, and a 1-m ground sample distance “precision” area consisting of approximately 3.6 mi^2 centered in the downtown Lincoln area. All data were delivered as “last return”, and one quarter-quad of data was required to be bare-earth processed. The Lincoln International Airport was the base of operations for the contract aircraft. The crews consisted of one or two pilots, two sensor technicians, with one technician also operating one of the base stations required for the larger area, and one person on the ground. Flights were accomplished primarily during daylight hours, with some evening work. The flights were completed in seven missions on the following days:

November 16, 2003 (3 missions)

December 7, 2003 (3 missions)

December 27, 2003 (1 mission)

Weather considerations caused an average of 3 days delay per mission.

Two base stations were utilized during the flights. These stations were running before, during, and after each mission. Static starts were utilized, which required that the aircraft sit on the ground running while all IMU and GPS systems were allowed to acquire satellites and stabilize. This assured that the aircraft and base stations were reading the same satellites. Once airborne, the aircraft made shallow bank turns of 15-18 degrees or less to ensure satellite lock. LIDAR data were not collected in turns or in areas that were not part of the project unless used for quality control (QC) purposes.

As part of the data capture routine, calibration flights were performed over the airport. Each calibration consisted of three flight lines flown twice each in opposite directions. The calibration flights were scheduled to begin immediately before the first mission, and every other day thereafter, and as the last mission before leaving the project area. Calibration flights are used to calibrate a day’s flight in case data anomalies occur within the subsequent processing. Typically these data are not processed unless there is a problem, and these data are saved as part of the project archive. The calibration data were not used for this project.

All data captured, including ground data, were downloaded and processed to ensure that there were no slivers or gaps in the raw LIDAR data. Each operator was responsible for reviewing the data and planning re-flights as needed. A third flight (December 27th) was needed to re-capture data that were identified as corrupted after the initial flights.

Quality-control ground points were used to check the vertical accuracy of the data and help determine the RMSE. Forty-four points were captured. The vertical guidelines of the digital elevation data required that points not exceed an RMSE or 18.5 cm in open terrain. The horizontal requirements of the digital elevation data points were not to exceed an RMSE or 2m.

The data were divided into 36 quarter-quadrangles, due to file sizes and the number of points produced per quadrangle. The primary area encompassed approximately 509.5 mi^2 and covered the following quarter-quadrangles:

Bennett NE	Bennett NW	Bennett SE	Bennett SW
Davey NE	Davey NW	Davey SE	Davey SW
Denton NE	Denton NW	Denton SE	Denton SW
Emerald NE	Emerald NW	Emerald SE	Emerald SW
Lincoln NE	Lincoln NW	Lincoln SE	Lincoln SW
Raymond NE	Raymond NW	Raymond SE	Raymond SW
Roca NE	Roca NW	Roca SE	Roca SW
Walton NE	Walton NW	Walton SE	Walton SW
Waverly NE	Waverly NW	Waverly SE	Waverly SW

The precision area covered approximately 3.6 square miles and encompassed the core of downtown Lincoln, Nebraska. The following bounding coordinates defined the precision area:

NW Corner:	40.83225083 degrees latitude /	-96.72046611 degrees longitude
SE Corner:	40.80480083 degrees latitude /	-96.68434555 degrees longitude

The entire area was flown at the 3-m posting, and the precision area (1-m posting) was flown and developed separately. The precision area also was used as a quality control (QC) check of the 3-m posting area.

Flight Specifications

All flights were flown from north to south. The 3-m posting density flights were flown at an elevation of 8,020 ft above Mean Sea Level (MSL) and at a speed of 130 knots, with an alternative set of parameters that allowed a flight speed of 110 knots at 7,980 ft MSL. There were 27 flight lines, which averaged 26 miles in length each.

The 1-m posting density flights were flown at an elevation of 3,430 ft MSL. There were 16 flight lines for the low-level flights, which were flown at 90 knots.

At the beginning of each flight, the aircraft crew performed a static initialization for the Lidar unit to orient the IMU and lock on to GPS satellites. This static initialization also was performed after every flight while the aircraft was running. These initializations were critical to the accuracy of the data being collected. Because a static initialization was performed, it was not necessary to fly directly over the ground points for initialization.

Shallow bank turns were observed during all flights. Banking in excess of 15 degrees can lose satellite lock, which can render subsequent data worthless. This is a critical element of the flights and lasts from startup to shutdown.

Ground speed and elevation also are critical in collecting accurate data. Calculations are made for specific elevations and speeds to generate a certain pattern of evenly spaced returns on the ground. If the ground speed is either too fast or slow, then the returns will not be evenly spaced, and the accuracy of the data could be questionable. Elevation also affects the spacing of the points and the swath width of data being collected. Generally, Photo Science Inc. has an elevation tolerance of 100-300 ft; anything outside of this tolerance can affect the spacing and accuracy, as well as create data voids between flight lines. For this project, Photo Science Inc. over-sampled the area to provide denser point spacing than required in the contract.

Base Stations

Two base stations were used for this project, and they were operated during the entire time the flights were in progress (figs. 2 and 3). After each day's flights the base station data were downloaded, and two copies of the data written to DVD along with all the position, navigation, and Lidar data. Data also were left on the Lidar hard drive in the aircraft until the project was completed and it was confirmed that all data were accounted for.

The base stations were located as follows:

Base Station 1 Position:

North American Datum of 1983 (NAD83), Universal Transverse Mercator (UTM) zone 14, northing = 4510963.305 m, easting = 694411.777 m, elevation = 361.370 m

Figure 2. Base station 1 (Courtesy of Photo Science Inc.)

Base Station 2 Position:

North American Datum of 1983 (NAD83), Universal Transverse Mercator (UTM) zone 14, northing = 4528784.134 m, easting = 694364.555 m, elevation = 373.905 m

Figure 3. Base station 2 (Courtesy of Photo Science Inc.)

Lidar Operation

All flights were flown using T-NAV for navigation, and the operator turned the laser on and off based on indications from T-NAV. The flights were logged on the Lidar log sheet at the end of each operator's daily session. The operator was responsible for downloading the Lidar, GPS, and IMU/Position data to ensure completion and that no data gaps or other problems existed. Before every flight, the operator checked all equipment to ensure that the sensor lens was clean and that the belly of the aircraft from the engine to the sensor opening was oil free. Photo Science Inc. generated GPS Positional Dilution of Precision (PDOP) charts for each day to check if there were times when flights might not be appropriate (for example, if the constellation was weak, or if a satellite became unhealthy).

Data Development

Photo Science Inc. delivered all elevation data points in the UTM coordinate system (zone 14), NAD83, North American Vertical Datum of 1988 (NAVD88) in meters to the nearest centimeter. Each data position was in ASCII x, y, z files organized by individual USGS 7.5-minute quarter-quadrangle. Only locations inside the project area contained data. Any areas included outside the project area contained null data.

All data were variably spaced and clipped to the identified quarter-quadrangle boundaries. The ASCII files contained the x, y, z triplets with one record per line. All records were comma delimited with the x and y values containing a precision to hundredths of meters.

All files were named using the following file naming format. Spaces are provided in the example for clarity, (the actual names did not have spaces).

qdnm xx typ .ext

where*:*

qdnm - The first four characters of the quadrangle name.

xx - The quarter-quadrangle of the quadrangle name, where:

ne – northeast quarter-quadrangle

nw – northwest quarter-quadrangle

se – southeast quarter-quadrangle

sw – southwest quarter-quadrangle

typ - Identifies this file contents as:

lst - mass points file (last return),

pts - mass points file (bare earth); and

.ext - File extension, where:

.txt - Geo-referenced ASCII x, y, z file.

.mta - Metadata header file for each ASCII x, y, z file.

Photo Science Inc. processed the data to bare-earth samples from the “last return” data for the Lincoln NW quarter-quadrangle. The data were reported to accurately represent the bare-earth surface, with all trees, buildings, bridges, and other structures effectively removed. Digital orthophotography available from the county were used to verify the accuracy of the surface model. The following methods were used:

- Points were edited at bridges and overpasses to represent a true earth surface beneath the span of each structure;
- Rivers and major tributaries were mathematically modeled to ensure continuous downstream flow of accurate slope within the channel;
- Water bodies were represented as flattened surfaces containing consistent elevation points; and
- Bare earth data set(s) were free of data voids or “holidays” except where removed to represent bare earth.

Project level metadata were produced and included on each CD-ROM. File level metadata was produced and conformed to the FGDC metadata standard. In addition to the FGDC required fields, the following additional metadata information were provided by the vendor:

nposts - number of x, y, z triplets in the data set;

xmin - minimum x value in data set;

xmax - maximum x value in data set;

ymin - minimum y value in data set; and

ymax - maximum y value in data set.

Quality Assurance/Quality Control

The quality assurance / quality control (QA/QC) method preferred by LLC consisted of using a preliminary adjustment of the NGS HME results. This joint Federal/State/Local HME was intended to produce a highly accurate horizontal and vertical control set at 88 stations within and surrounding Lancaster County. Forty-two of these HME points reside within the nine-quadrangle coverage area of both the 2002 color ortho-imagery project and the 2004 Lidar project (fig. 4). The 6-ft canvas panels were placed on 42 points and are visible on the color orthophotos. The HME project attempted to meet the NGS specifications of an RMSE of 2-5 cm for orthometric heights. These specifications were not met because additional geometry was needed to strengthen the GPS vectors. The preliminary adjustment of the vertical component yielded an RMSE of 7-9 cm for the project.

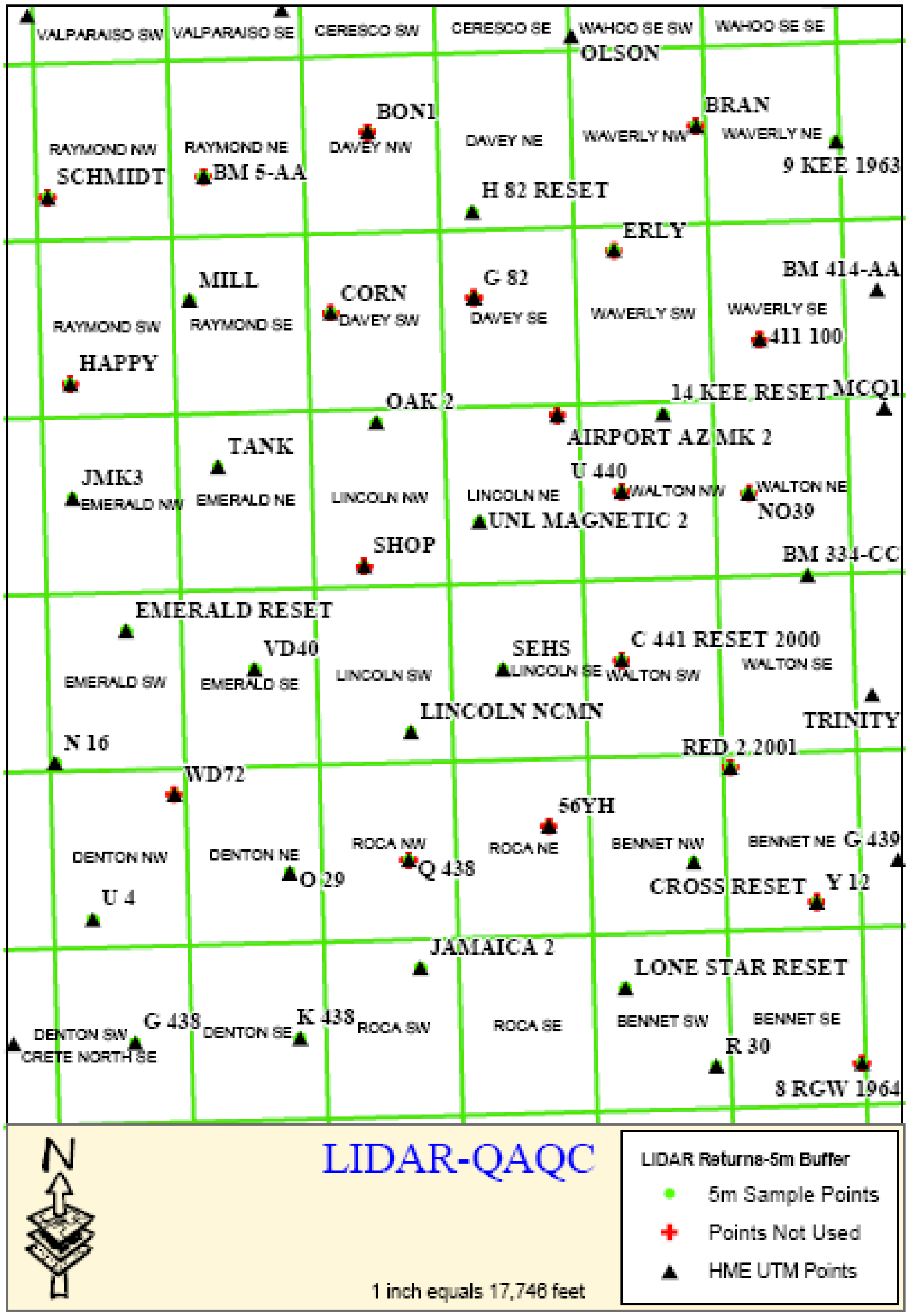

Figure 4. Location of points used in the height modernization effort (HME)

The preliminary adjustment of the HME points produced a set of data containing latitude, longitude and ellipsoid height. These data were projected to UTM coordinate system to overlay the

2002 color orthophotos. Each point matched remarkably well with the visible panels on the orthoimage and provided further assessment of the horizontal component of the orthoimagery. All 42 points were visible on top of 6-ft canvas panels and are within 1 m from the center of the target (in other words the 2002 color orthophotos are within 1 m of true or absolute spatial positioning).

Assessing the accuracy of the Lidar return vertical component involved extracting a 5-m buffer of Lidar measurements surrounding all 42 points. This was accomplished by creating a circular polygon with a radius of 2.5 meters from the center of a single HME point, and then clipping the corresponding Lidar returns out of this circular polygon. Because the Lidar returns were not bare earth filtered, the elevation readings for this buffered set were manually scrutinized to filter erroneous values. One example of this shows automobiles that were in a parking lot next to the canvas panel for panel SHOP (fig. 5). The height difference between those (elevated) points from the automobiles and the surrounding surface points were clearly identifiable. As a result, Lidar returns from the cars were not used in the calculation of the bare ground inside the 5-m buffer from the HME point.

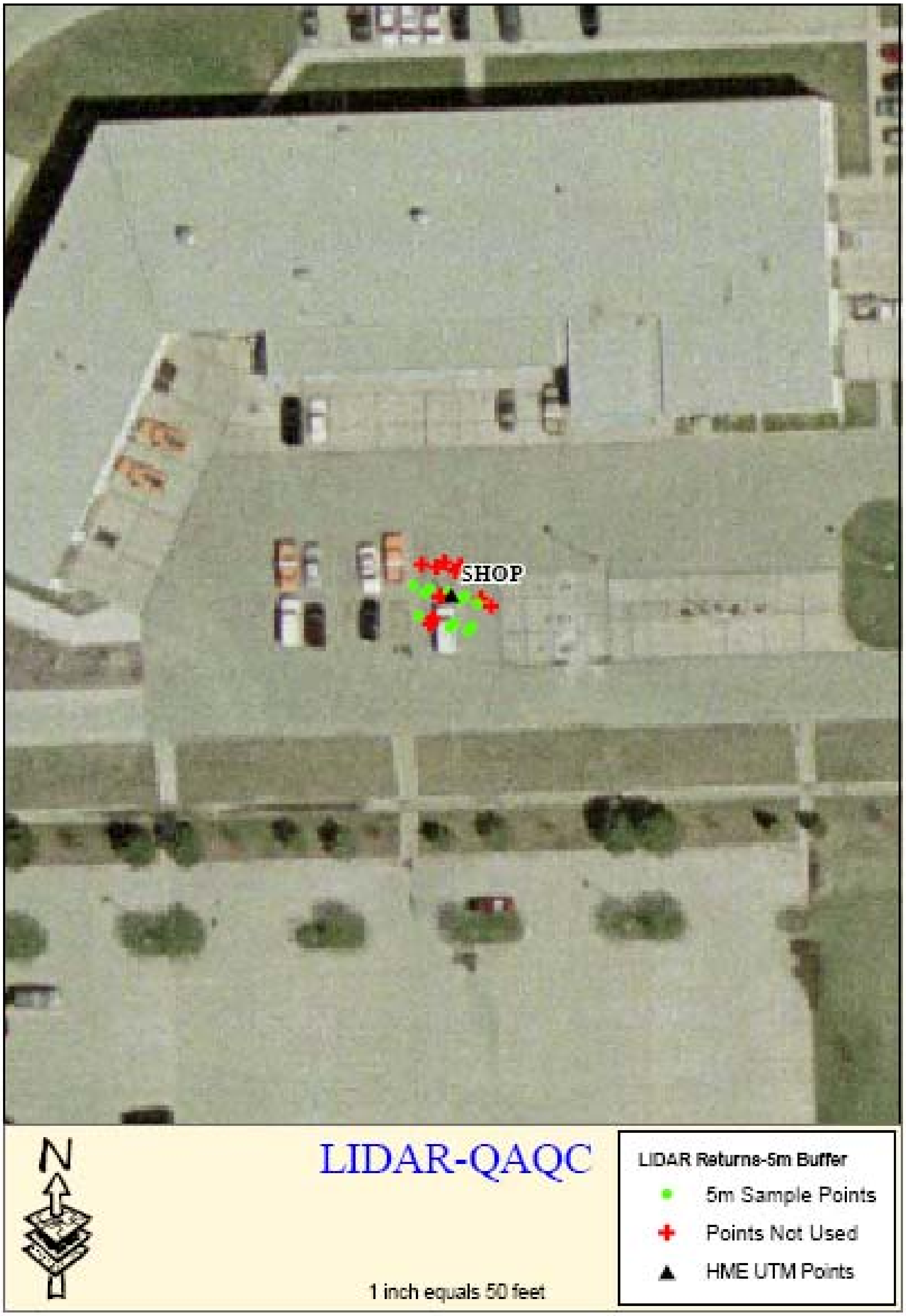

Figure 5. Lidar and height modernization effort points (HME) on orthophotos

Next, the geoid separation of the 42 HME points were derived and added to the ellipsoid values. This produced a corresponding orthometric height that could be compared to an average of the buffered and selected Lidar measurements.

Three of the 42 test areas were outside the RMSE of 18.5 cm stipulated in the Lidar contract. This could be due to the preliminary nature of the HME processing. Another possibility is that those three measurement locations were very close to utility poles or fence posts that may have interfered with the GPS signals. The remaining test areas were all within the RMSE of 18.5 cm with the average RMSE of all points of 8.8 cm. This corresponds to 1 sigma. A spreadsheet has been created to summarize these 42 test areas (Appendix B).

Although the HME data are preliminary, they provide ancillary evidence to support the accuracy of the Lidar project.

Processing

Once the accuracy of the Lidar returns were independently assessed and verified, bare-earth processing of the raw Lidar point data began. The nine quadrangles were originally partitioned into 36 quarter-quadrangle files, with each file requiring approximately 300-400 megabytes (Mb) for the 3-m data. Only the Lincoln NW quarter quadrangle was processed to bare earth by Photo Science Inc. The other 35 quarter-quadrangles were processed to bare earth at EDC using the TerraScan (TerraSolid, 2002). The ground classification routine in TerraScan classifies ground points iteratively by building a triangulated surface model. The first step in this process was to classify all “low” points, defined as points that are more than a specified distance below neighboring points. These points can sometimes be errors inherent in the Lidar system, and must be first classified so that they are not erroneously introduced as the starting ground points for the model. The ground routine begins selecting local low points that are assumed to be clear ground returns. The routine then builds an initial model from selected low points. Triangles in this initial model are mostly below the ground with only the vertices touching the ground. The routine then starts iterating the model upward by adding new points to it. Each added point allows the model to follow the ground surface more quickly as it iterates. Iteration parameters, such as iteration angle and iteration distance, determine how close a point must be to a triangle plane in order to be accepted into the surface model. Iteration angle is the maximum angle between the surface and selected point, and iteration distance ensures that the iteration does not make excessive jumps upwards when triangles are large. The smaller the iteration angle, the less likely the routine is to follow changes in the point cloud (TerraSolid, 2002).

The automated ground classification routine was run at EROS for the Lincoln NW quarter-quadrangle. Although this routine did an excellent job of automatically classifying ground and non-ground points, several buildings were left in the bare earth model. This was because these buildings were larger than the window size being analyzed, and as a result all points seemed to be on the same "ground" level. Also, some areas, including gradual-sloping buildings and parts of a large stadium, were left because the iteration angle was less than the slope of these areas.

The USGS automated bare-earth classification of the Lincoln NW quarter-quadrangle was then compared to the bare earth provided by Photo Science Inc. to check for consistency. Although the vast majority of classified points matched one another, some differed. This was checked by creating a raster grid of the bare earth points from both data sets, and then differencing the resultant grids (fig. 6). Qualitative analysis showed that the main differences were in areas near water and bridges, which could be attributed to Photo Science Inc. using different rules for using points around water and bridges than EROS. Quantitative analysis showed that 8852 cells processed by EROS were lower than the error bounds of -0.3 m, and 34,466 processed by EROS were higher than the error bounds of 0.3 m (out of a total of 3,860,877 cells).

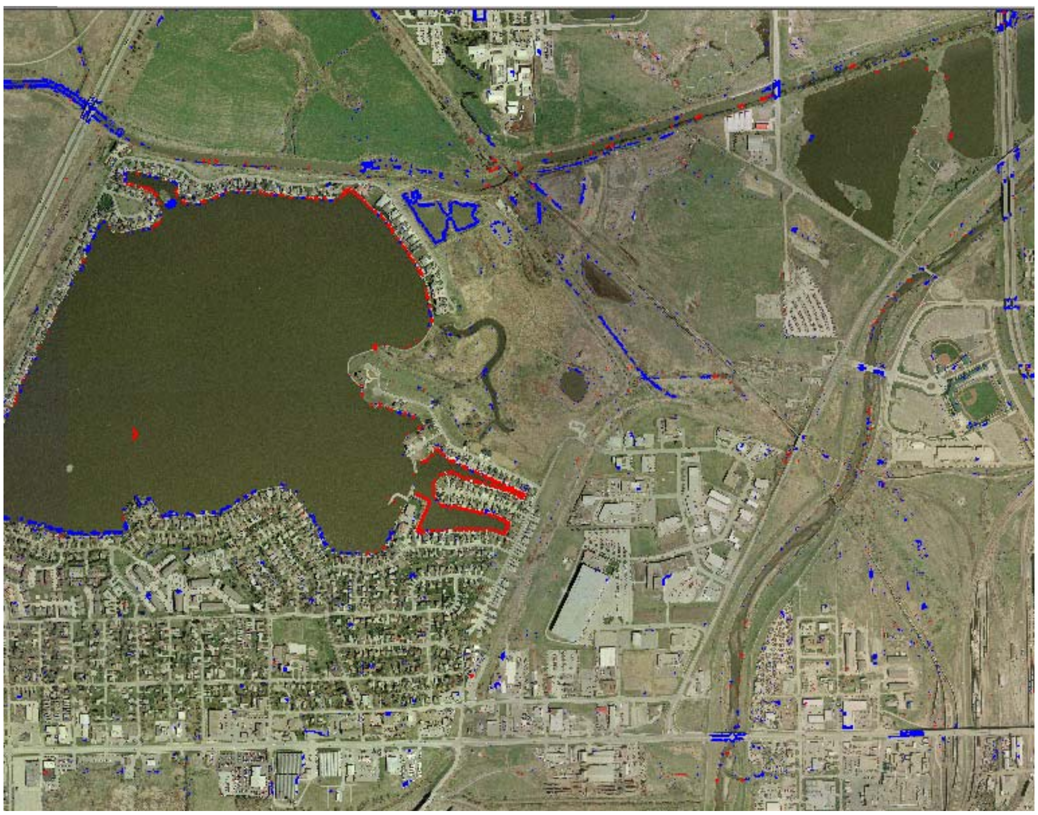

Figure 6. Comparison of first-run bare-earth processing

The next step involved manual classification of the points in order to remove the misclassified points. Data were evaluated manually by observing relationships between points in the cloud and by using the high-resolution orthophotography to provide reference (fig. 7).

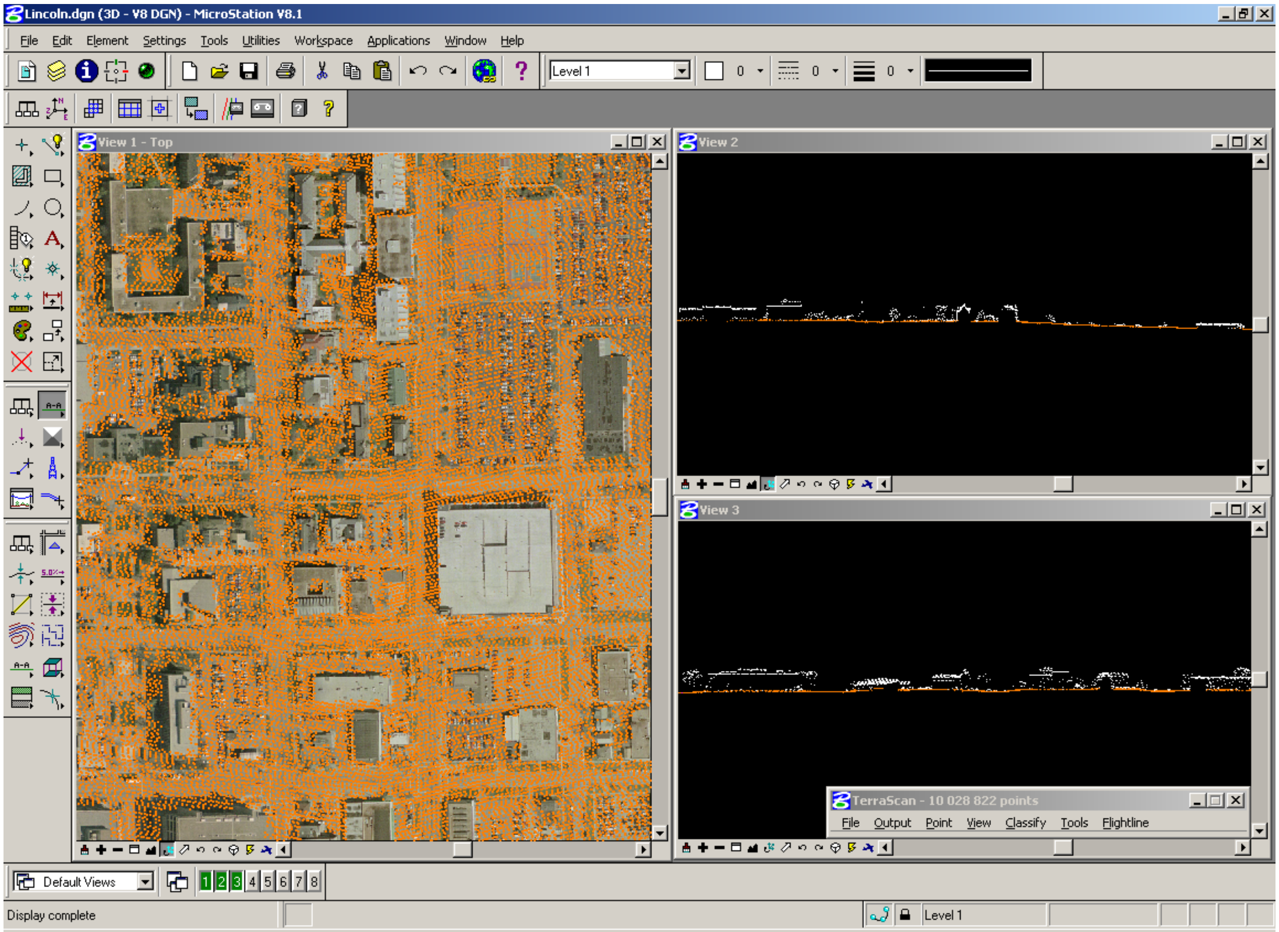

Figure 7. Manual bare-earth processing

This process of automated bare-earth filtering and manual post-processing was repeated for all 36-quarter quadrangles. Then the results were submitted to LLC, who looked over the points and identified any errors in classification based upon their ground knowledge of the areas. EROS corrected those errors and returned the quarter quadrangle data sets to LLC. This process was repeated until a satisfactory bare-earth model was created.

Transformation

Once the bare-earth processing was completed, the raw x, y, z points were transformed into useable files for GIS applications. The desired file format for the USGS for the bare-earth data was an Arc/Info GRID (raster) format because the National Elevation Dataset (NED) is stored and delivered in this raster format (Gesch and others, 2002).

The conversion from x, y, z points into Arc/Info raster formats involved several steps. The first step was to convert the points into a surface (fig. 8). This step was performed using TerraScan and TerraModeler.

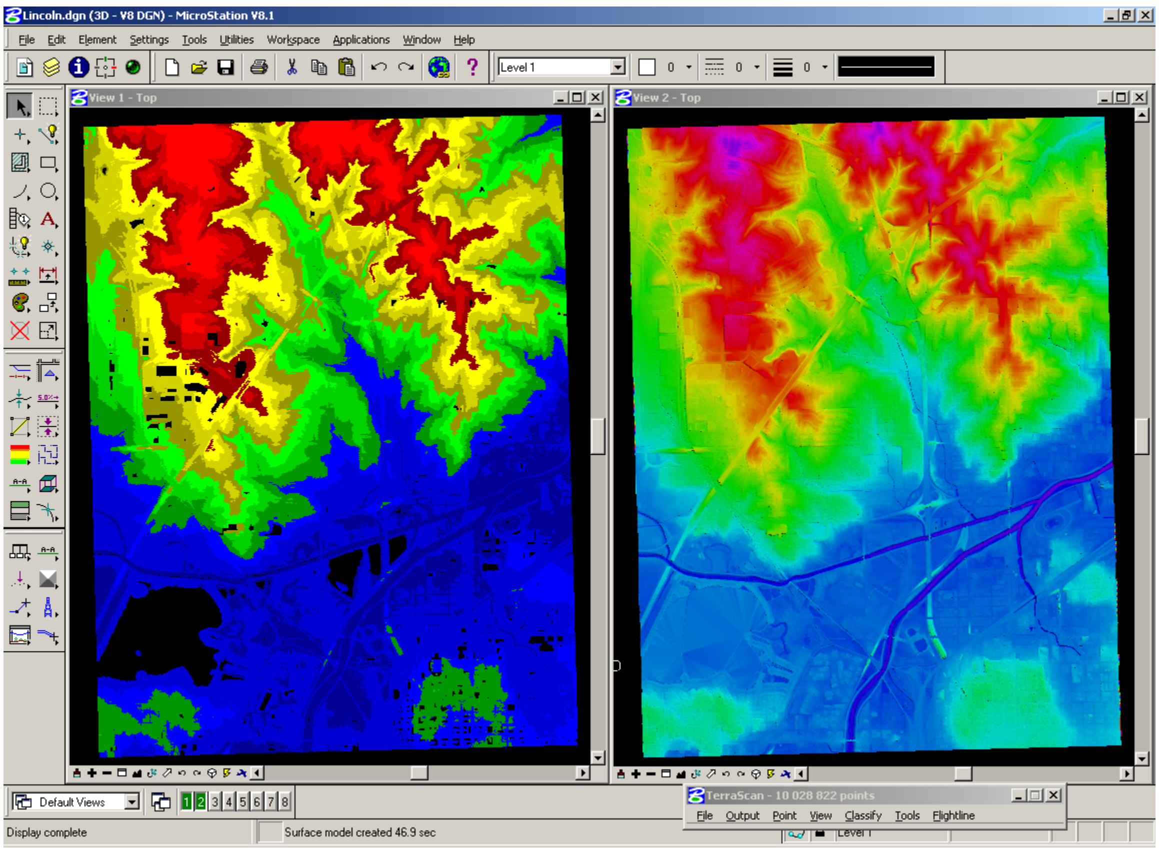

Figure 8. Bare-earth points (left) and derived surface (right)

The next step involved creating a lattice point file from the generated surface. This placed a point value at a regularly spaced interval along the created surface. The point spacing was defined by the resolution of the raster grid desired. For the Lincoln Lidar project, a lattice point spacing of 3 m was defined because the average point density of the collection was at this spacing and the desired grid resolution for the one-ninth arc-second NED was 3 m. This step also was performed using TerraModeler (fig. 9).

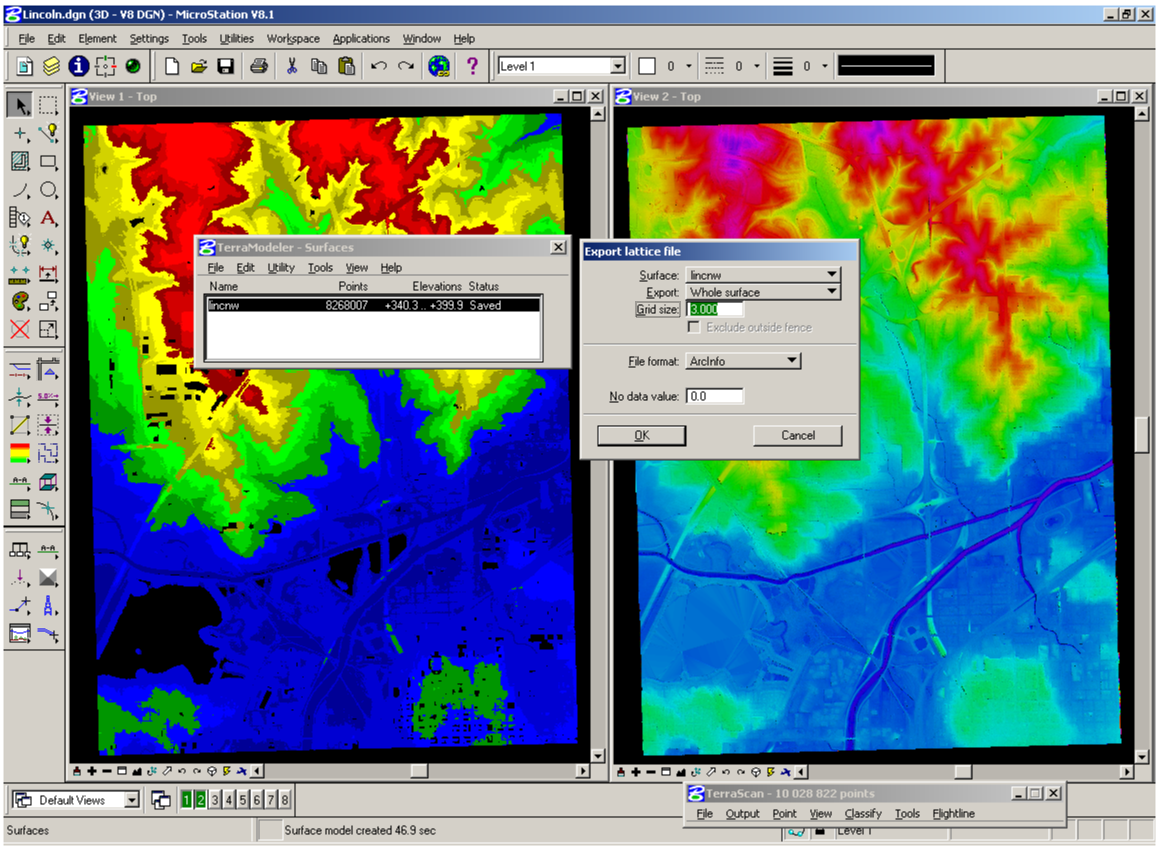

Figure 9. Defining the lattice point spacing from a surface

Once the lattice point file was created, the points were converted into a grid in ArcGIS using the Asciigrid command. This command used the header information from the lattice point file and created a grid based on that information and the corresponding elevation values. This grid was then useable as input into NED, and for 3-D viewing using ArcScene.

Visualization

With the Lidar data in point, triangulated irregular network (TIN), and raster file formats, the data can be visualized as point clouds, TIN surfaces, or 3-D raster grids. Each visualization technique has advantages and disadvantages. It is important to understand exactly what information needs to be conveyed to the viewer, as each type of visualization technique conveys information differently.

Point cloud data contain all of the information collected by the Lidar instrument, and out of the three visualization techniques is the best way to visualize the “raw” data. A point cloud can be viewed as a cluster of x, y, z points that float in 3-D space. Attributes, such as elevation, can be assigned to each point and represented as a color, or ancillary information can be added to each point, such as RGB colors from associated orthoimagery (fig. 10).

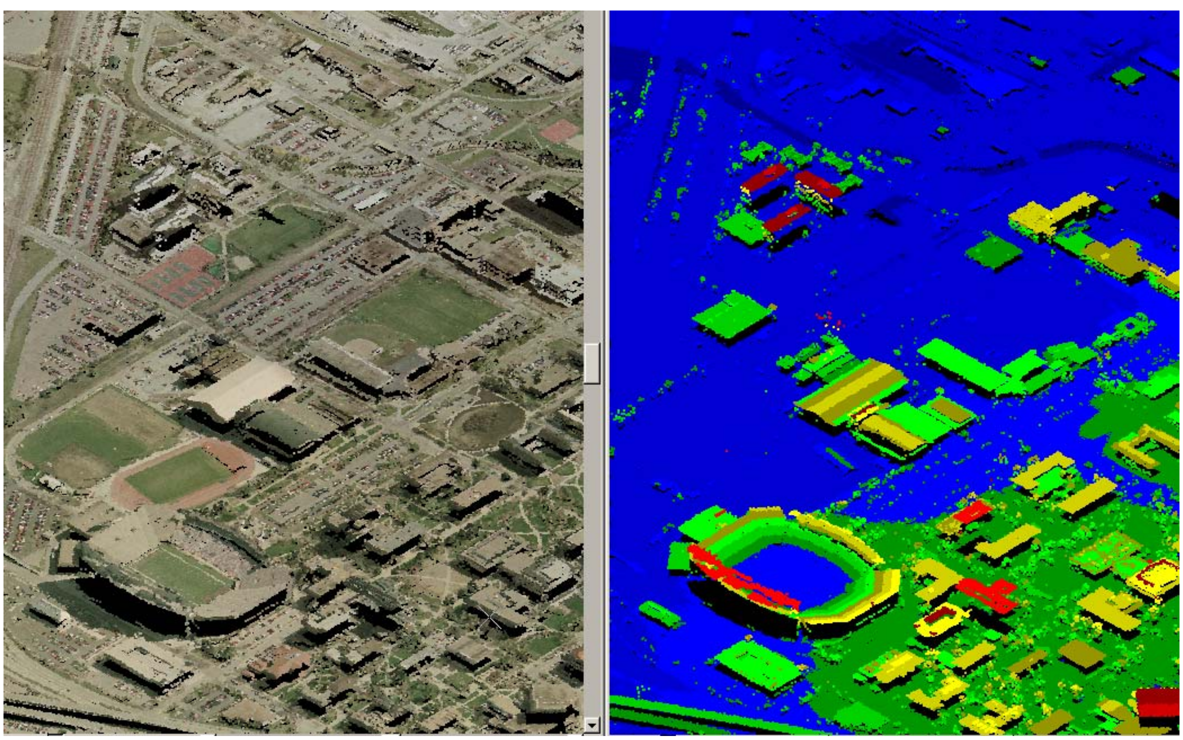

Figure 10. Point clouds displaying RGB imagery information (left) or elevation (right)

The advantage of using the raw point clouds to visualize the Lidar data is that all of the data can be represented. This is especially true in multiple-return Lidar systems where there may be multiple z values for the same x, y. The data are viewed as “clouds” of points, which allows complete representation of elevational information, and can be viewed very well using a system that allows for stereo viewing. Disadvantages include difficulties in modeling or viewing the cloud of points. Few software programs can handle the massive amount of data inherent in a point cloud due to the topology needed for each x, y, z point. As a result, only small portions of the data can typically be viewed at a time to fit the memory requirements available on most systems. Also, connectivity between individual points is difficult to define, especially in multiple-return Lidar data. This limits the ability to model the data.

The most common way to represent Lidar data is to convert the data into a surface, either a TIN or grid. TINs are popular surface representations because they use all the points and do not need the data to be regularized. A TIN representation creates triangles by connecting the nearest three points, and these triangular facets make up the slope and aspect of the surface (Peuker and others, 1978). Lighting effects are employed in order to shade triangles based on slope and aspect conditions that can be viewed in 3-D (fig. 11).

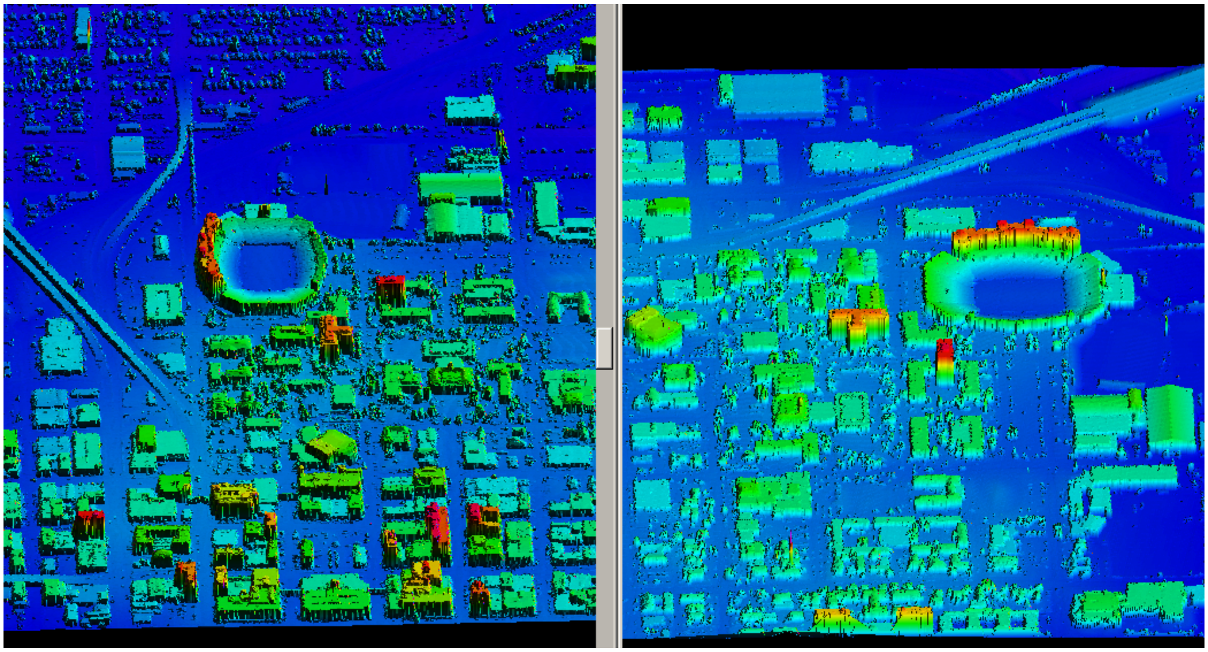

Figure 11. Triangulated irregular network of Lidar returns

A raster grid also is a popular way to represent Lidar data, mainly because the raster format is not as memory intensive. Also, modeling is easier to perform with raster grids than the other visualization techniques because raster grids make use of the regular cell spacing (fig. 12). Standard DEMs traditionally have been in a raster grid format (Mark, 1978). Disadvantages of raster representations are the fact that raster is a 2-D representation of 3-D data. Each cell can contain a value, such as elevation in the case of representing Lidar data. Multiple z values cannot be represented in a raster cell.

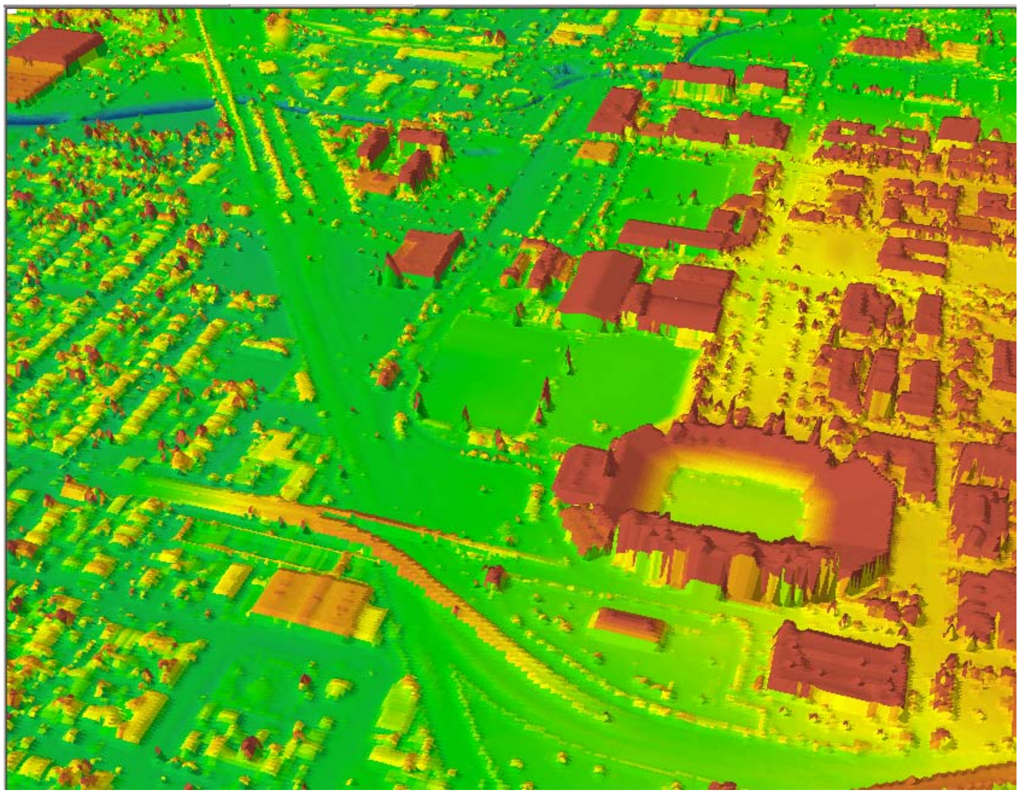

Figure 12. Raster grid representation of elevation data

A potential solution to the difficulties inherent in raster grids and TINs for representing multiple-return Lidar data is the use of volumetric pixels, or voxels, as the atomic representation of this kind of information derived from Lidar. A voxel is the cubic unit of volume centered at an integral grid point (fig. 13).

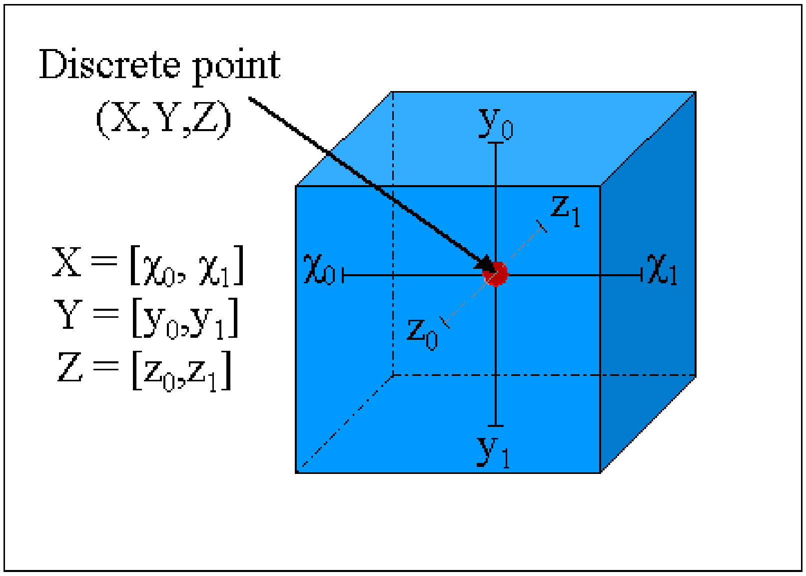

Figure 13. Voxel description

Representing a unit of volume, the voxel is the 3-D counterpart of the 2-D pixel, which represents a unit of area (Kaufman and others, 1993). Each voxel can have associated attributes which represent measurable properties or independent variables (such as color, opacity, density, material, intensity, return number, and elevation). An example is a voxel matrix for Lidar data that contains a binary attribute showing presence or absence of a Lidar return. The advantages of using voxels instead of surfaces include insensitivity to scene and object complexity, viewpoint independence, ability to represent sampled and simulated data sets, ability to represent interior information and amorphous phenomena such as clouds and smoke, and ability to support various block operations. Disadvantages include the fact that voxels store data in discrete rather than continuous form, the loss of geometric information, and the large memory and processing power traditionally required. Recent developments in volumetric visualization have reduced the memory and computing power needed to render a scene; in fact, some software can render scenes more efficiently than surface representations. To date, voxels have not been widely used in the analysis and visualization of commercial Lidar data but often are used in medical imaging and computer gaming applications. Research on utilizing volume visualization(fig. 14) has begun at EROS with very promising results.

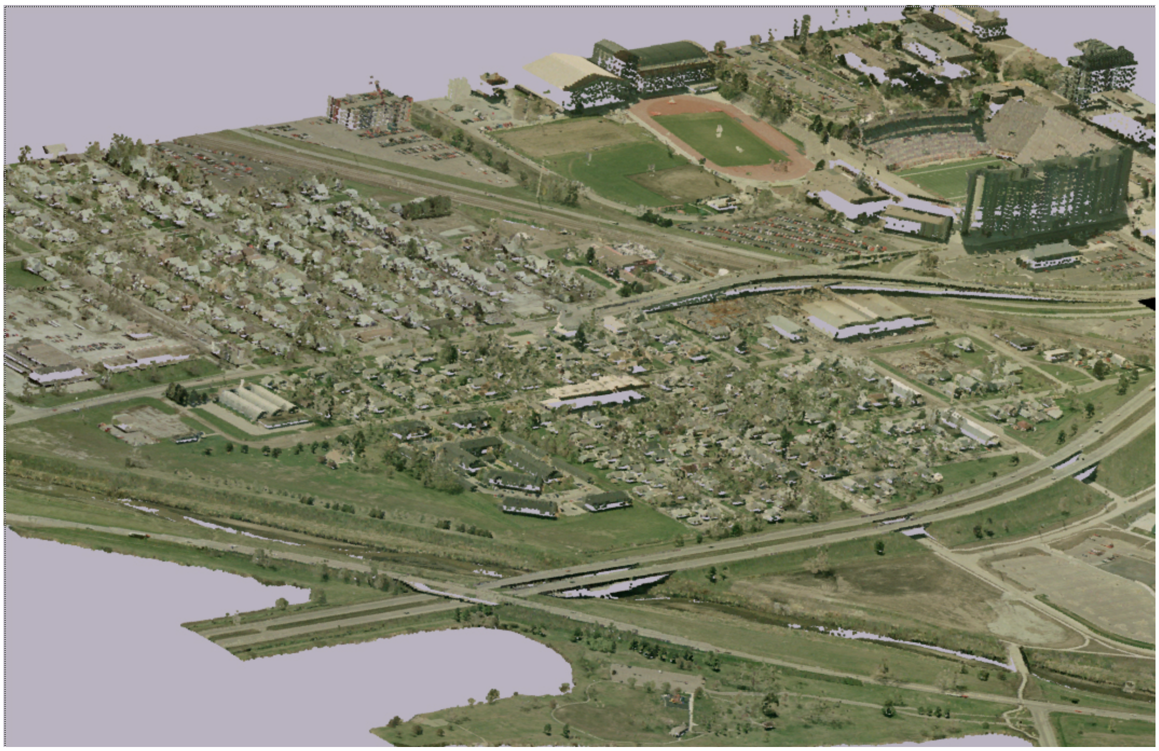

Figure 14. Volume visualization

Conclusions

The rich detail of Lidar data may be able to help various local departments in many and sometimes unexpected ways. The original purpose of the Lincoln Lidar Project was to provide an updated (2004) elevation layer to supplement the 2-ft contour layer developed in 1997. Since 1997, numerous land changes have taken place in and near Lincoln, Nebraska as new urban developments have altered the land by adding residential and commercial subdivisions. Multiple road projects involving widening, cutting, filling, and relocating have occurred. Urban growth into new drainage basins has occurred and is expected to continue. The 2004 Lidar data indicated a substantial elevation difference when compared to the 1997 2-foot contours for that area.

The partnership between the U.S. Geological Survey EROS Data Center (EROS), and Lincoln and Lancaster County (LLC) for this project was based upon cooperation, coordination and collaboration. EROS, LLC, and users of the information derived will benefit from the collection, processing and analysis of this Lidar data. During the Lincoln Lidar project, extremely valuable high-resolution elevation data were effectively collected, processed, analyzed, visualized, and made available to others.

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