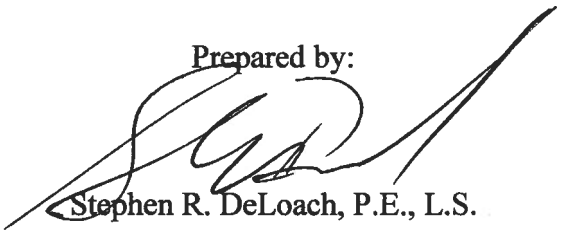
Expert Report

Prepared for

U.S. Department of Justice

Robinson v. United States

Prepared by:



Stephen R. DeLoach, P.E., L.S.

18 December, 2008

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EXECUTIVE SUMMARY

Three (3) mapping projects were conducted in the vicinity of southeast Louisiana that serve as the bases for topographic and structure elevation data for hydraulic model studies supporting the case *Robinson v. United States*. These projects are:

1) The Louisiana Statewide LIDAR Project;

2) The US Army Corps of Engineers (USACE) aerial survey of Lake Pontchartrain Vicinity and Chalmette Loop Levee Systems, flown in the year 2000;

3) The USACE aerial survey of all the levee systems in the New Orleans area flown in 2005 immediately following Hurricane Katrina.

I have performed an analysis of the relative accuracy of these project data following the guidelines provided by the American Society for Photogrammetry and Remote Sensing. My principle findings to a reasonable degree of scientific and engineering certainty are:

1) The best available data for determination of the top of structure heights is the LIDAR point cloud data from the levee mapping project flown in 2000. The estimated accuracy of top of structure elevation determination from this data is two and three tenths (2.3) feet. The United States' experts considered this data in developing levee heights for their analysis.

2) An elevation model with a grid cell size of one (1) foot was derived from the point cloud data from the levee mapping project flown in 2000. The data smoothing process that was used to develop the grid adds an additional uncertainty to the estimated accuracy of top of structure elevation determination of one (1) foot, for a total estimated accuracy of three and three tenths (3.3) feet. The Plaintiffs' experts used this data.

3) In areas of clear open ground, the topographic elevation data from the Louisiana Statewide mapping project, in the vicinity of the MRGO and New Orleans East levee systems, has an accuracy of one and three tenths (1.3) feet as compared to the levee mapping data. The data was not sampled in other terrain, vegetative land cover, or at the land water interface. However, it is known that these land cover types would increase the error.

Additional opinions expressed in this report are to a reasonable degree of scientific and engineering certainty.

1. BACKGROUND

I was retained by the United States as an expert in *Robinson v. United States* in November 2007 to assist the United States' attorneys in analyzing and understanding LIDAR and other mapping models, as well as the data any such models have produced regarding flooding in the Greater New Orleans area. I have reviewed the LIDAR data of the New Orleans hurricane protection system in St. Bernard Parish, New Orleans East, and the Lower Ninth Ward, as well as the statewide LIDAR mapping project in these areas. Additionally, I have reviewed Plaintiffs' expert Chad Morris's opinions on the accuracy of the LIDAR data.

In general, the reports Mr. Morris provided present LIDAR based topographic elevation data collected from several sources for the Plaintiffs' experts to use in subsequent hydraulic model development. I observed that there was limited description of the accuracy of the LIDAR data, or of the data's ability to provide elevations for the subsequent hydraulic model efforts of the plaintiff team. Subsequently, I was asked to provide a review and description of the LIDAR topographic elevation data related to *Robinson v. United States*, and to offer an opinion on the accuracy of derived products from the data, such as terrain elevation and top of levee structure elevation determination. I am compensated for these services at the rate of $175 per hour, and $305 per hour for court testimony.

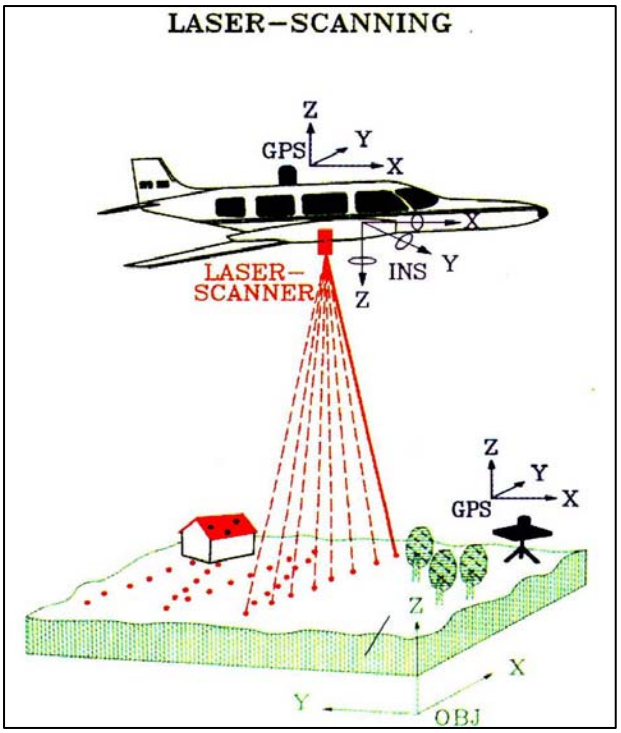


Figure 1 LIDAR System

2. LIDAR DESCRIPTION

LIDAR, or **LI**ght **D**etection **A**nd **R**anging, as discussed in this report and depicted in figure 1, is an aircraft mounted laser scanning system designed to measure the three

dimensional (3D) coordinates of a passive target. A laser ranging device is combined with a scanning device and positioning and orientation measurements. The scanning device points the laser toward the ground in a scanning motion across the flight path of the aircraft. The laser measures the range to a passive target (ground surface, vegetation, or man-made feature) and, when combined with the position and orientation of the sensor, computes a 3D position of the target. The resulting data may be presented in various forms, such as the view in figure 2.

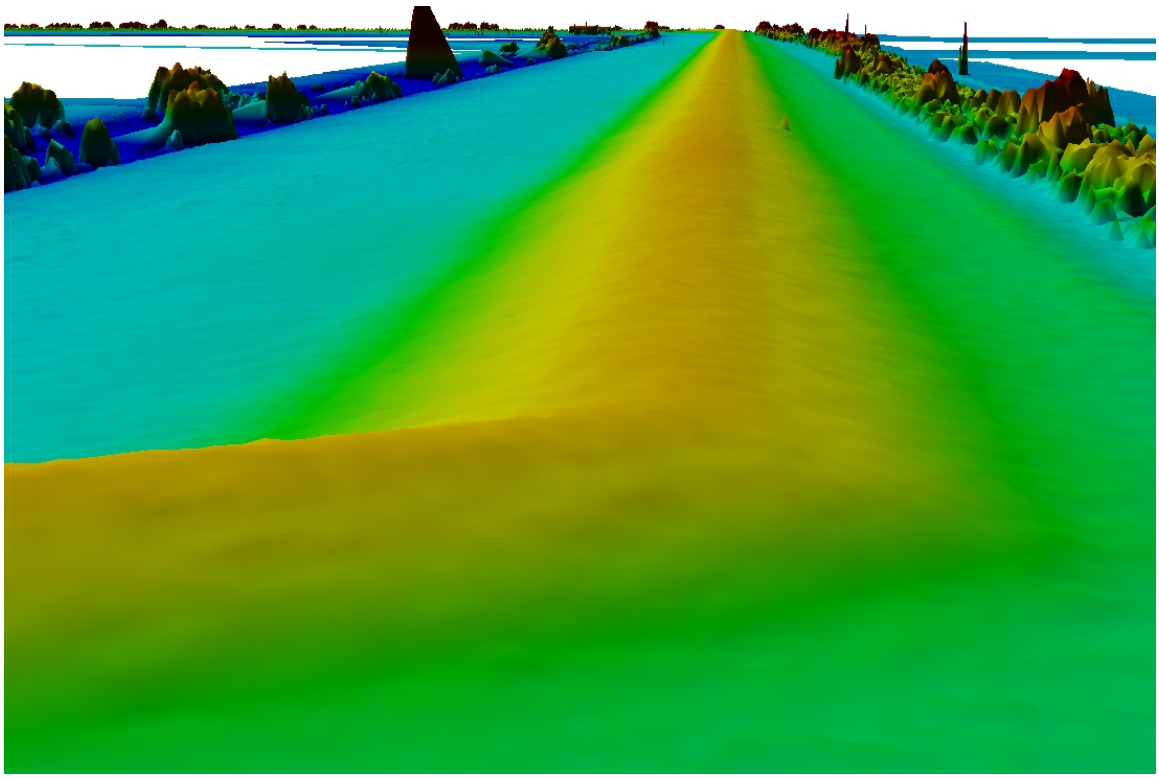


Figure 2 LIDAR data along New Orleans East levee system

2.1. LIDAR System Components

An airborne LIDAR mapping system is composed of a laser sub-system consisting of the laser source, scanning assembly, and timing electronics; a positioning and orientation sub-system consisting of the differential global positioning system (GPS) and inertial measuring unit (IMU); a data storage device, and data handling and processing software.

The lasers selected for LIDAR mapping typically operate near one of two frequencies: 1064 nanometers (nm) and 532 nm (infrared and green wavelengths). The infrared band (1064 nm) provides an excellent return signal from vegetation and is generally selected for topographic systems. Because of its ability to penetrate the water column, the green wavelength (532 nm) is used for bathymetric applications. The laser generates the range to a passive target (the ground, vegetation, structure) by measuring the time of flight for a single pulse to make the round trip from the laser source to the target and return to the laser receiver. The accuracy of the timing circuits is a direct limitation on the range accuracy of the laser. The ability to measure the return pulse is a function of the pulse width and the "steepness" of the rising and falling edges of the pulse. The ability to detect a return signal from targets with weak reflective signatures, or from targets at a great distance is a function of the laser power. The number of laser spots hitting the ground, hence the density of the resulting elevation model, is a function of the pulse rate of the laser. Unfortunately, these three characteristics (pulse width, laser power and pulse rate) work against each other in the selection of the best laser for a particular mapping system. As the pulse rate increases, to produce an elevation model with greater density, the power decreases, and the pulse width increases. The lower power results in fewer target returns and the increased width results in a lower range resolution. To compensate for these laser issues, the mapping systems are designed to fly under specific operational parameters, such as altitude, aircraft speed, and maximum scan width.

An example of the error introduced by the return pulse width, and trigger to the timing circuit is seen in Figure 3. In this case, the reflectivity of the coating on the airport runway caused the laser timing circuit to trigger early, creating a false range (and subsequent false height) of the coated area of the runway. As the LIDAR system only measures 3D coordinates, the coated surface should have been invisible (i.e. at the same elevation) to the system. Changing target material changes the shape of the return pulse, subsequently changing the range accuracy of the laser pulse. Thus, height measurement errors are introduced.

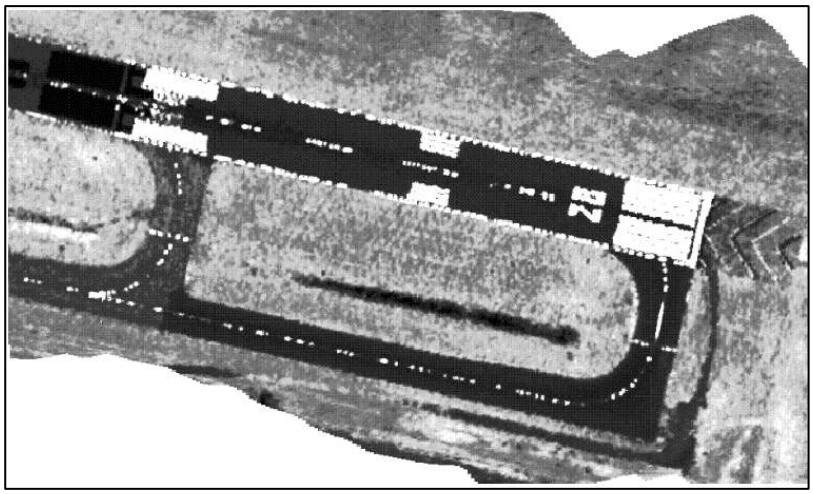


Figure 3 Timing circuit error over airport runway

In this airport runway example, the laser ranging system incorrectly measured the return pulse from the changing surface material on the runway, resulting in an elevation change. When converted to a gray scale raster image as in Figure 3, the LIDAR system appears to create a map of the numbers and painted areas on the runway. The LIDAR only measures elevation; as the painted areas and numbers are the same elevation as the runway, this image clearly shows an error in the LIDAR measurement. This type of error would occur as the LIDAR system scans across multiple materials such as from a grass covered levee to a concrete floodwall. This error is most significant at the boundary between land and water. If the water has a smooth surface, such as in a swamp or wetland area, the laser signal is reflected away from the LIDAR instrument. Thus there is no return signal. When the laser then hits the land surface, a strong signal results, and the timing circuits do not react as quickly as the laser makes measurements, resulting in a series (thousands) of measurements with vertical errors of 1 to 2 feet. This type of error is often referred to as a hedgerow, where one scan line is obviously higher than the adjacent lines. This anomalous data exists in the topographic LIDAR data pertinent to *Robinson*.

Early LIDAR systems simply shot the laser downward, normal to the aircraft, in a profile along the flight path. To develop systems for mapping applications, a scanning mechanism is added to scan a path, side to side, beneath the aircraft, yielding a pattern of points on the ground. After a minimal amount of processing these points become the

basis for an elevation model. Scanning systems vary from rotating mirrors, to counter rotating prisms, holographic optical elements, faceted mirrors and galvanometers. They all share an optical / mechanical tolerance in their manufacture and component wear. Each, however, has its own design advantage for development of an aircraft based mapping system for specific applications. To date most systems, including the systems used for collecting the topographic data pertinent to this case, employ a faceted rotating mirror or a galvanometer.

Positioning of the final point on the ground is derived by adding the laser range to the scan angle and the positioning and orientation information from the aircraft positioning system. This is typically achieved through the use of kinematic differential carrier phase GPS and an inertial measuring unit. Some systems use multiple GPS antennae for orientation computations and/or have included the positions of ground targets to aid the orientation process due to limited accuracy of the low cost inertial units, and to help solve the GPS ambiguity problem. While the GPS and inertial technologies are relatively mature, they each have inherent limitations. For example, kinematic GPS was never intended to operate beyond 25 km from a base station, and the GPS observables are based on the World Geodetic System of 1984 (WGS 84) ellipsoid, a global mathematical surface, and not a local vertical datum. Current technology requires careful consideration of these limitations, especially the horizontal and vertical datums.

2.2 Vertical Datums Related to LIDAR Mapping

The Interagency Performance Evaluation Task Force (IPET) Report, Volume II – Geodetic Vertical and Water Level Datums (2007) explained vertical datums in Southeastern Louisiana in great detail. There are several considerations with regard to the LIDAR data used in this case. These are:

1) The GPS systems used for LIDAR mapping do not directly measure height. The GPS technique used measures the three dimensional change in position between an antenna located at a base station and the antenna mounted on the aircraft. The three dimensional change in position can be broken into three primary components, for example, north, east and height. These ellipsoidal position differences, with height as one component, are based on a mathematical surface of

the earth. This mathematical surface is known as an ellipsoid, and is defined as the World Geodetic System of 1984 (WGS 84).

2) The flow of water, or the heights of interest to support flood models, are based on either the equipotential surface of the Earth, known as the "geoid", or in the case of inundation from the sea, heights based on sea level. The geoid is that surface whose gravity potential is everywhere constant (equipotential) and that most closely fits global mean sea level. In practical terms, the geoid surface is further defined with a series of benchmarks, with surveyed elevations, all mathematically adjusted and established by the Federal Geodetic Control Committee as the North American Vertical Datum of 1988 (NAVD 88). It is important to note that many factors such as currents and bottom friction cause sea level to vary in height with respect to the geoid. Therefore sea level is actually a site specific phenomenon. The IPET report shows variations between the geoid and sea level of eight tenths (0.8) feet across the geographic area pertinent to *Robinson*.
3) The three height systems, ellipsoidal used by GPS, the geoid surface, and the sea surface, all vary with respect to each other both spatially and temporally. All three height systems have a direct effect on the elevation data and the hydraulic models in this case.
4) Within the area of southern Louisiana, these measurement surfaces were not well defined at the time of Hurricane Katrina. Examples given in the IPET (2007) report show recently computed variations on the elevation of a single point of three tenths (0.3) feet related to updating tide epochs (sea level) and four tenths (0.4) feet related to updates in the establishment of geoid based heights. Older, more diverse height values are evident on the geodetic marks throughout the region.
5) The errors between these measurement surfaces would transfer to the LIDAR measurements, and would be promulgated throughout the mapped area. Figure 4 illustrates the relationship of these three surfaces, and the positioning of the LIDAR aircraft.

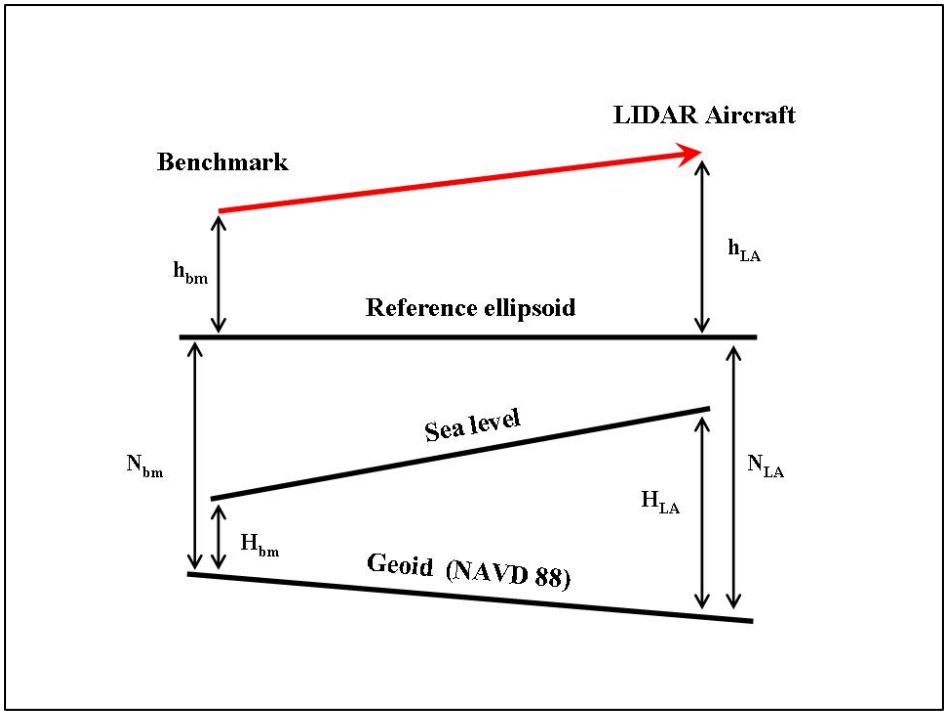


Figure 4 The geoid, ellipsoid and sea level

During the development of the IPET reports, the IPET Team chose to implement the North American Vertical Datum of 1988 local adjustment of 2004. These height values are typically shown with the following nomenclature, *NAVD 88 (2004.65)*. This regional adjustment of the geodetic control points was to help support a single uniform datum of reference for all studies, reports or other works in the region.

The variation in local and regional datums is not unique to southeast Louisiana. The multiplicity of datums used near the coastal boundaries to define sea level and land based heights is a phenomena throughout coastal areas world wide (Sinclair 2008).

2.3 LIDAR Data Smoothing

Conceptually, LIDAR data processing is straightforward. Once GPS positions are determined, the scanner position and sensor orientation are used to compute the position of the laser spot on the ground. The resulting LIDAR "image" is sometimes referred to as a "point cloud", that is not at any regular grid spacing. Most applications for

subsequent map development or input to a mathematical model, require feature removal and conversion to a regular grid spacing. This is accomplished through any number of commercial software packages. This data cleaning and grid development process always involves some form of data interpolation or data smoothing. A paper authored by Robert Cunningham (2004) of Louisiana State University, David Gisclair of the Louisiana Oil Spill Coordinators Office and John Craig, Director of Remote Sensing and R&D with 3001, Inc., described the specific techniques used for the statewide mapping project. The process used for the USACE project data was described in that project's metadata files. These groups used distinctly different approaches to the methodology, both appropriate for their intended use.

The most direct application of LIDAR technology is the creation of a digital elevation model for mapping applications. The LIDAR technique is much faster than previously used photogrammetric techniques, and is easily combined through many commercial software products to numerous mapping and modeling applications. As an active imaging device, the LIDAR is less susceptible to shadows and sun light. The timing and recording units may record multiple laser returns from a single pulse indicating vegetative canopy height and density. For topographic applications, the data is easily contoured. Because each data point is georeferenced, the data is easily merged with other feature data or image sources. Relative to the photogrammetrically-derived data and map products in the past, LIDAR data tends to be more dense, and of a higher accuracy. Thus, LIDAR provides for more accurate elevation models and derived map products.

2.4. National Standards of LIDAR Mapping

The primary LIDAR data collections that serve as the basis for elevation models supporting this case were flown before the development and acceptance of national standards of LIDAR mapping. While LIDAR mapping has been in existence for several decades as a research and development tool, the commercial acceptance of this technology blossomed in the late 1990s and early 2000s. The two primary standards discussed here will include general mapping accuracies suggested for specific types of projects, and the methods suggested for LIDAR accuracy assessment. Both the State of

Louisiana and the New Orleans District, US Army Corps of Engineers (USACE) chose to implement the relatively new LIDAR mapping technology, and to work with professional service providers, supporting the burgeoning, and improving, technology.

2.4.1. ASCE Technical Engineering and Design Guides, No. 14, Photogrametric Mapping

In 1996, the American Society of Civil Engineers (ASCE) adopted the USACE Engineering Manual, EM 1110-1-1000, Photogrammatric Mapping, as ASCE Technical Engineering and Design Guide, No. 14. This manual was unique in that it took established national mapping procedures and accuracy standards and applied these to the support of planning, engineering, design, construction, operations and maintenance of large civil works projects and programs. While this manual does not address LIDAR technology, it does clearly denote the mapping and elevation model accuracies required for specific engineering applications. Elevation accuracies in the categories of interest to *Robinson* are noted in Table 1:

Table 1 Typical Project Requirement (ASCE, 1996)

Project Type	Allowable Error (RMSE)	Contour Interval
Design Memoranda Flood Control Structures	0.5 feet	1 foot
Floodplain Mapping Project Planning	2.0 feet	5 feet

2.4.2. American Society of Photogrammetry and Remote Sensing (ASPRS) Guidelines; Vertical Accuracy Reporting for LIDAR Data

Version 1.0 of this document was released on May 24, 2004. Although published after the collection of the LIDAR data used to create the primary elevation models in this case, the techniques were already in use by the year 2000, and the reference serves as a guide in the development of an opinion of the data accuracies. The ASPRS document references, and includes, their recommendations as a component of the National Standard for Spatial Data Accuracy (NSSDA) promulgated under the Federal Geographic Data Committee (FGGC).

The fundamental accuracy test for LIDAR data is to compare the LIDAR measured elevations with elevations developed from an independent data source where the independent, or reference data, is of a higher accuracy. A minimum of 20 checkpoints are to be tested, distributed to reflect both the geographic area of interest and the distribution of error within the dataset. The vertical accuracy is then defined as the root mean square error (RMSE) at the 95% confidence level, where:

$$RMSE_{95\%} = 1.96 \left(\left(\sum (Z_{data(i)} - Z_{check\ point(i)})^2 \right) / n \right)^{1/2} ;$$

i is the number of check points from 1 to n ;

Z_{data} is the elevation from the LIDAR dataset ; and

$Z_{check\ point}$ is the elevation from the independent check survey.

Further, ASPRS (2004) recognizes that testing of LIDAR-derived elevation data over various ground cover categories has revealed that the magnitude of errors varies between ground cover types, as previously shown in section 2.1 of this report. Therefore the fundamental accuracy of a data set should be tested in open, flat, terrain, with a homogeneous ground cover. The minimum number of checkpoints should also be tested in the various types of ground cover within the data set, and the final elevation model given an accuracy statement for each ground cover type. Products that are derived from the original data, such as a gridded data set or contour data should be tested separately. These derived products generally exhibit an error distribution different from the fundamental data source, due to the interpolation schemes and data smoothing employed to generate these derivative products.

The primary data accuracy requirements for this study were chosen from the ASCE Design Guide as stated in section 2.2.1. The corresponding check point accuracy from the ASPRS LIDAR guidelines is given in table 2. The structure heights along the MRGO and New Orleans East levees result in two primary ground cover types, open ground and the levee wall or sheet pile.

Table 2 Check Point Accuracy Related to Project Requirements

	ASCE guidelines Accuracy of map product		ASPRS Guide Check point accuracy
Project Type	Allowable Error (RMSE)	Contour Interval	Reference Data Accuracy
Design Memoranda Flood Control Structures	0.5 feet	1 foot	0.2 feet
Floodplain Mapping Project Planning	2.0 feet	5 feet	1.0 foot

3. LIDAR DATA USED

There are three independent LIDAR data collection projects that have been used to support the hydraulic model work in this case. Subsequent to the data collection, derivative products were created from these data sets. These data sets are identified as:

1) The Louisiana Statewide LIDAR Project: the derived product used from this project was the digital elevation model based on a 15-foot grid spacing.
2) The USACE aerial survey of Lake Pontchartrain Vicinity and Chalmette Loop Levee Systems, flown in the year 2000 by the Fli-Map system under contract to John Chance Land Surveys. The products used from this work are the original point cloud data, and a derived elevation model on a 1 foot grid. These products are referred to as the "pre Katrina point cloud" and the "pre Katrina 1' data".
3) The USACE aerial survey of all the levee systems in the New Orleans area flown in 2005 immediately following Katrina by the Fli-Map system under contract to John Chance Land Surveys. The products used from this work are the original point cloud data, and a derived elevation model on a 2 foot grid. These products are referred to as the "post Katrina point cloud" and the "post Katrina 2' data".

3.1. The Louisiana Statewide LIDAR Mapping Project

Cunningham (2004) provides a description of the Louisiana Statewide LIDAR Mapping Project. A portion of this data in the region of interest to *Robinson* is shown in figure 5. The mapping began in 2000 under the FEMA National Flood Insurance

Program and is jointly funded by FEMA and the State of Louisiana. The project is designed to develop an accuracy of 15 to 30 cm (0.5 to 1.0 feet) RMSE (allowable error), depending on land cover, to support 1 foot to 2 foot contour intervals. These accuracies are designed to meet FEMA standards for floodplain reevaluation studies and map modernization programs to update Flood Insurance Rate Maps. This designed accuracy exceeds the project criteria for floodplain mapping as designated in the ASCE design guidance as shown in Table 1 and 2. The project was designed to be completed in six years with project data delivered through the Louisiana State University (LSU) Atlas website.

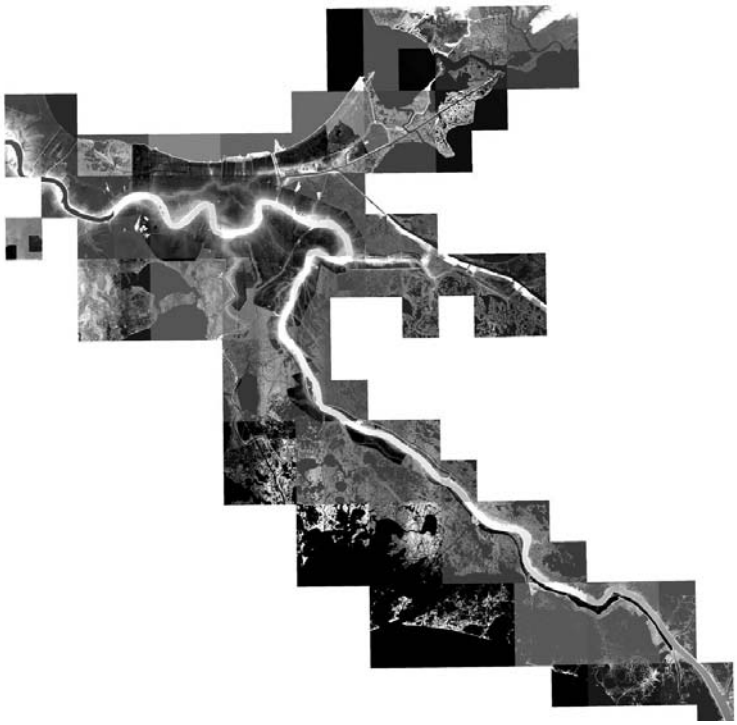


Figure 5 Portion of Statewide LIDAR data

The system used for this project was designed specifically to gather data in support of statewide mapping programs. It was originally designed to fly at an altitude of 20,000 feet above mean terrain with ground coverage equal to a conventional aerial mapping camera. For the Louisiana program, the system was flown at 8,000 feet above mean terrain, with a resulting point spacing of about 10 to 12 feet. The data were then re-sampled and smoothed to a rectangular grid of 15 feet (Cunningham 2004). The vertical datum of reference was the NAVD 88.

Cunningham (2004) further describes the data collection and product development processes and the quality control and accuracy assessment. Although begun in 2000, the description of accuracy assessment is in line with the ASPRS guidelines (ASPRS 2004). Cunningham states that the RMSE of all check points processed thru the preparation of his report is 11.51cm (0.4 feet).

3.2. USACE Project Data

The USACE conducted two LIDAR surveys along the New Orleans levee system. These were conducted in the spring of 2000, and following Katrina in 2005. The objective of these surveys was to measure the levee elevations, to derive surface profiles and cross section data, and to provide information on encroachments along the levee right of way. The report of survey from 2000 noted that *the LIDAR survey will replace traditional ground surveys for the collection of elevation data and will initiate the use of a new technology for topographic monitoring on the New Orleans Levee System*. The designed accuracy of the 2000 survey could not be located. The Statement of Work for the 2005 survey stated the data should be *sufficient to develop 2 foot contours and shall cover the levee from toe to toe, and additional coverage as required to document levee damage*. This 2 foot contour accuracy does not meet the accuracy specified under the ASCE guidance for design memoranda and flood control structures as shown in tables 1 and 2. The datum of reference for both projects was NAVD 88.

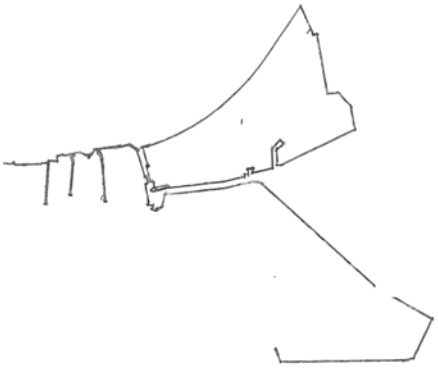


Figure 6 pre-Katrina levee mapping project data

The professional services provider conducting these surveys was John Chance Land Surveys. John Chance used their Fli-Map LIDAR system for both surveys. This system is designed to fly at very low altitudes and to collect a very dense set of data points. For these projects the system was flown at altitudes in the range of 150 to 250 feet, and provided ground point densities in excess of one point per square foot. The data provided to the USACE was:

	Point cloud	1 foot grid	2 foot grid	3 foot grid
2000 survey	yes	yes	no	yes
2005 survey	yes	no	yes	no

John Chance provided a list of accuracy checks of a single point, the differential GPS ground based antenna. The RMSE of these checks was 0.25 feet. Neither John Chance nor the USACE provided an accuracy assessment of the data.

4. ACCURACY ASSESSMENT

The primary objective of this report is to review the LIDAR data that the expert teams considered in this case and to provide an opinion on its accuracy. The data is from three projects; the FEMA / State of Louisiana statewide project, and two USACE levee mapping projects. The accuracy assessment developed for this report is based on the approach given in section 2.4.2 ASPRS Guidelines Vertical Accuracy Reporting for LIDAR Data.

4.1. IPET and State of Louisiana Report Statements

The IPET report, Volume II, states (page II-147):

> *Various older LIDAR mapping projects covering the region that were used for IPET model input were not independently quality assured or ground-truthed for absolute accuracy. Large anomalies and biases were found in this uncalibrated data. The original contract scopes for this mapping did not include adequate assurance checks. In addition, the LIDAR data were thinned to a DEM* (Digital Elevation Model) *post-spacing that was too large to adequately define the terrain or floodwalls.*

In the case of the FEMA / Statewide project, the quality assurance description Cunningham (2004) provides addresses the accuracy assessment criteria found in the ASPRS guidance of 2004 – even though the project was planned and much of it executed prior to the ASPRS guidance. The two USACE levee mapping projects do not provide this level of quality assurance.

4.2 Vertical Datum Rectification

All three of the mapping projects were conducted on the NAVD 88. However, as described in the IPET Volume II report, there was significant variation in the controlling

elevations of benchmarks throughout the region. Further, I found no evidence that the USACE projects and the Statewide project were placed on the same vertical datum adjustment, specifically, NAVD 88 (2004.85). The only method capable of determining the relationship of the varying datums across the region requires a comprehensive geodetic survey be performed including all of the points used as ground control for the LIDAR mapping projects. This updated data would then be used to perform ground based 'calibration" surveys to support improvements to the LIDAR data and its derived elevation products. In this regard the IPET report, Volume II, states (page II-2):

> *The impact of spatially or temporally varying vertical datums and subsidence on hurricane protection levees in St. Bernard and Plaquemines Parishes was not directly evaluated…*

Based on my investigations I concur with this IPET finding. Therefore the ability to reconcile the three LIDAR mapping projects to a single datum within the area of interest for this case is extremely limited, and not fully supported by any direct measurement or geodetic observation.

To develop a best fit of the various datums, the USACE adopted a datum rectification procedure to model the differences throughout the areas mapped during the levee mapping projects of 2000 and 2005. This procedure is given in the metadata files associated with the LIDAR data on the IPET website. It is:

> *Original data was obtained and adjusted to older (2000) published NAVD88 vertical elevation datum values. The elevations in this dataset were adjusted to the NAVD88 (2004.65) vertical datum in Feb-2006. Control points were selected for those National Geodetic Survey (NGS) control locations where 2004.65 elevations were known. The "new" values and the "old" values were used to create a deviation surface for the entire spatial extents of the data using an IDW interpolation scheme. Elevations were then adjusted to the 2004.65 vertical datum using a simple arithmetic procedure.*
>
> *1. The LiDAR data points from each survey line were separated into 1.875 arc minute tiles according to the tiling system described previously in this document. This tile interval was chosen in response to the need for 1ft spatial resolution in the final surface DEM's. Because of this resolution requirement, standard quadrangle (7.5 arc minute) or quarter quadrangle (3.25 arc minute) tiles created resulting raster files with greater than 20,000 x 20,000 grid cells.*
>
> *2. The XYZ points contained in each file were processed by the ESRI ArcInfo software using an Inverse Distance Weighted (IDW) algorithm. The following ArcInfo command was used to develop these DEM surfaces.*

gridData = idw(pointData.gen, #, #, 2, SAMPLE, 5, 03, 01)
This command generates a raster surface with 1 ft horizontal resolution by searching the five closest LiDAR points within a 3 ft radius of the cell center.

Three primary, yet competing, factors influenced the selection of the processing algorithm used to convert the LiDAR XYZ points into a continuous surface representation:
1. Small errors in the vertical resolution of LiDAR XYZ points from subsequent passes over the same geospatial area. This can cause a developed surface to exhibit hedgerows that are problematic for hydrologic modeling software.
2. Sharp elevation changes over a short distance. Such situations occur at the edges of buildings or along the top of levee walls.
3. Small errors in the horizontal resolution of the LiDAR XYZ points that produce near but not exact representations of a vertical surface.

In order to eliminate the effects of the first error, an algorithm that smooths these irregularities is preferred. The Inverse Distance Weighted (IDW) algorithm is one example. IDW samples a number of points from the area surrounding the raster cell being interpolated to compute the elevation at that cell. This reduces the impact of small vertical errors and eliminates the "hedgerow" effect caused by such errors. However, because IDW utilizes surrounding points, it cannot identify areas where sharp elevation changes occur and is not well suited to solve the problems exhibited by the second problem.

One algorithm that can incorporate these sharp changes is a Triangulated Irregular Network (TIN). TIN's can represent sharp changes in elevation over a short distance. However, they do not resolve the hedgerow effect directly. Furthermore, because of factor three above, the points representing the vertical feature may produce spikes in the resulting TIN or DTM surface. Therefore, a TIN representation may not be able to resolve any of the three factors described above.

Based on these factors, it was determined that the IDW interpolation methodology produced the best surface for a majority of areas. However, due to the problems described previously, caution is advised when using the elevations from derived surfaces in areas where levee flood walls are present.

3. The elevations of the IDW derived surfaces were then adjusted to conform to the NAVD88 (2004.65) elevation by first splitting the deviation surface into 1.875 arc minute tiles to match the tiling of the LiDAR data.

4. The spatial resolution of the deviation surface was adjusted to match the 1' horizontal spacing of the elevation data.

The differences between the elevation of the control points from the "old" NAVD height to the "new" NAVD 88 (2004.65) height has an average difference of 0.6 feet with a root

mean square error (95%) (RMSE) of 1.2 feet. The possible error introduced into the LIDAR data is 1.2 feet RMSE from this datum issue alone. This error is dependant on the reference control point used for a LIDAR flight. Each mapping project contained multiple flights over several days of data collection, further confusing the datum issue.

The USACE Engineer Research and Development Center (ERDC) converted all of the levee mapping data John Chance, Inc. collected (point cloud, 1' grid and 2' grid) to the NAVD 88 (2004.65). This procedure was not performed for the Statewide LIDAR mapping data. Therefore the mapping data used by the experts in this case was actually on separate adjustments and not on a single datum.

4.3. Accuracy Assessment Method

To best understand the LIDAR data, and the relationship between the three independent mapping projects, requires a systematic comparison between the data sets themselves. To accomplish this, sixty (60) sample stations were selected in areas of clear open ground at geographic locations throughout the study area. Another sixty (60) sample stations were selected on top of the levee wall structure geographically dispersed throughout the study area. At each of these stations the elevations were read from the following data sources;

1) 15 foot grid (FEMA project)
2) pre-Katrina point cloud (USACE 2000 survey)
3) pre-Katrina 1 foot grid (USACE 2000 survey)
4) post-Katrina point cloud (USACE 2005 survey)
5) post-Katrina 2 foot grid (USACE 2005 survey)

These sample readings were used to develop the RMSE (95% confidence) between the data as prescribed in the ASPRS guidelines (2004). The difference between the ASPRS Guidelines and this method is the absence of a set of ground based check data that is at a superior accuracy level. The value of the approach taken is that it yields a system wide review of the relationship between all of the data sets. This systematic approach includes all sources of error, including GPS measurement, laser measurement and datum discrepancies. Figure 7 depicts the locations of the sample stations used in this analysis.

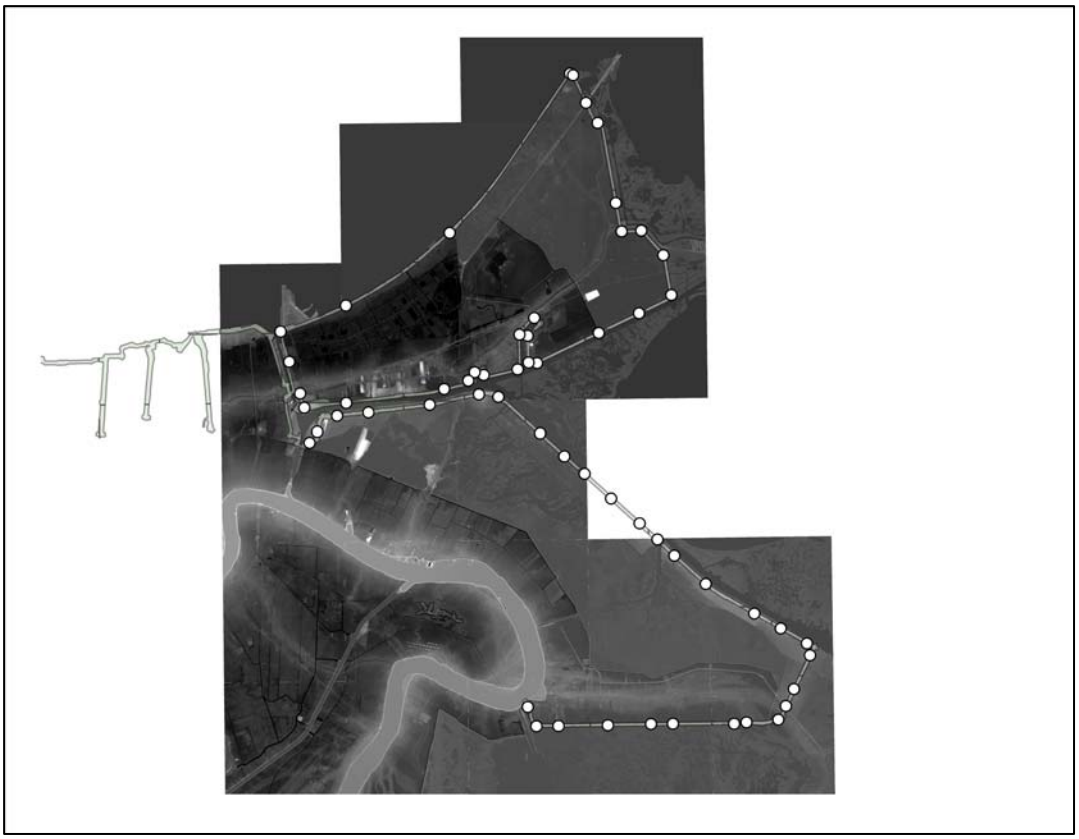


Figure 7 Location of Sample Stations

4.4. Summary of Accuracy

The accuracy of these five (5) data sets is first presented as an assessment of the error due solely to development of a grid based elevation model versus the point cloud data, over areas of open ground and on top of structure (levee wall). Second, all projects are related to each other, assessing the relationship between the surfaces developed from the three mapping projects.

4.4.1 Effect of Data Smoothing

Table 3 shows the results of developing the uniform grid from a non-uniform point cloud, in effect comparing a dataset to itself, only examining the data smoothing process and the relationship between the ability to detect clear open ground versus derivation of structure heights. These results are a function of data smoothing only, and do not consider numerous error sources inherent in the LIDAR data acquisition process. The ability to accurately define an elevation is given by the root mean square error. For

the pre-Katrina data, the gridding process results in a RMSE of 1.5 feet on the top of structure versus 0.4 feet on areas of clear open ground. Smoothing the data to a 2-foot grid spacing increases the RMSE on the top of structures to 2.4 feet. This is logical if you consider the top of structure is a combination of materials and structure types including a predominance of 1-foot wide concrete wall and thin sheet pile. Increasingly larger grid spacing would logically result in loss of ability of the data to accurately describe the structure.

Table 3 Effect of data smoothing (values in feet)

	Open Ground		Top of Structure	
	Mean difference	RMSE	Mean difference	RMSE
Pre Katrina point cloud minus 1 foot grid	0.0	0.4	0.0	1.5
Post Katrina point cloud minus 2 foot grid	0.5	1.0	0.2	2.4

The figures 8, 9, 10 and 11 on the following page are all of the same location south of the Bayou Bienvenue control structure. They show more detail of the effect of data smoothing. The difference in height of the wall structure is more than 1.5 feet between the point cloud data and the 1 foot grid. The Statewide data set misses the wall entirely, and is 1 foot higher on the MRGO side of the levee.

In support of the IPET studies the USACE originally developed structure heights from the pre-Katrina 1 foot gridded data set. Over time, the USACE team performing the hydraulic model efforts recognized the weakness in the gridded data, and reverted to the superior point cloud data set to derive top of structure heights. Using the point cloud data, versus the smoothed 1 foot grid improved the accuracy of the structure heights by approximately 1 foot. The plaintiffs' reports indicate that the plaintiff team used the smoothed 1 foot grid data for the basis of structure elevations.

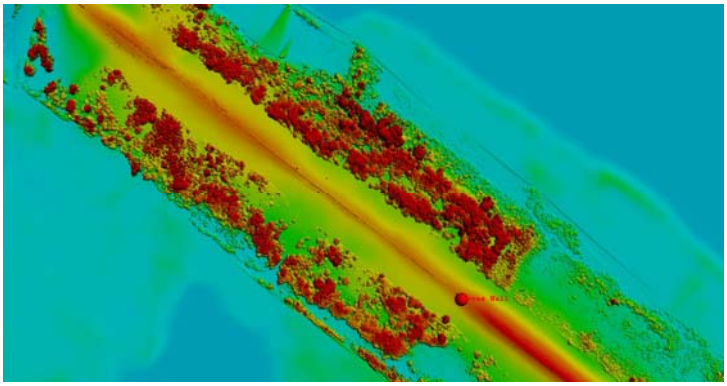


Figure 8 Pre Katrina 1 foot grid data south of Bayou Bienvenue control structure

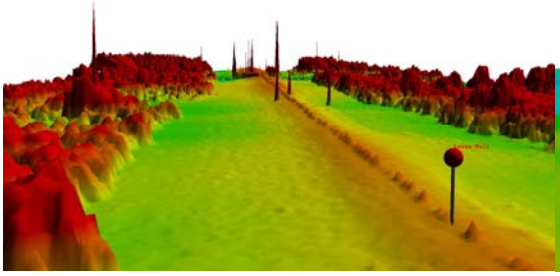


Figure 9 View of 1 foot grid

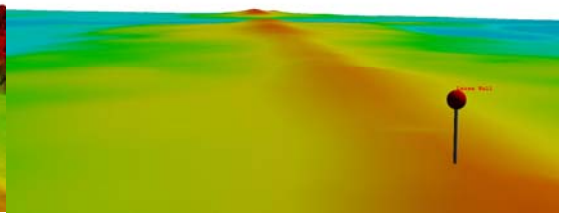


Figure 10 View of 15 foot grid

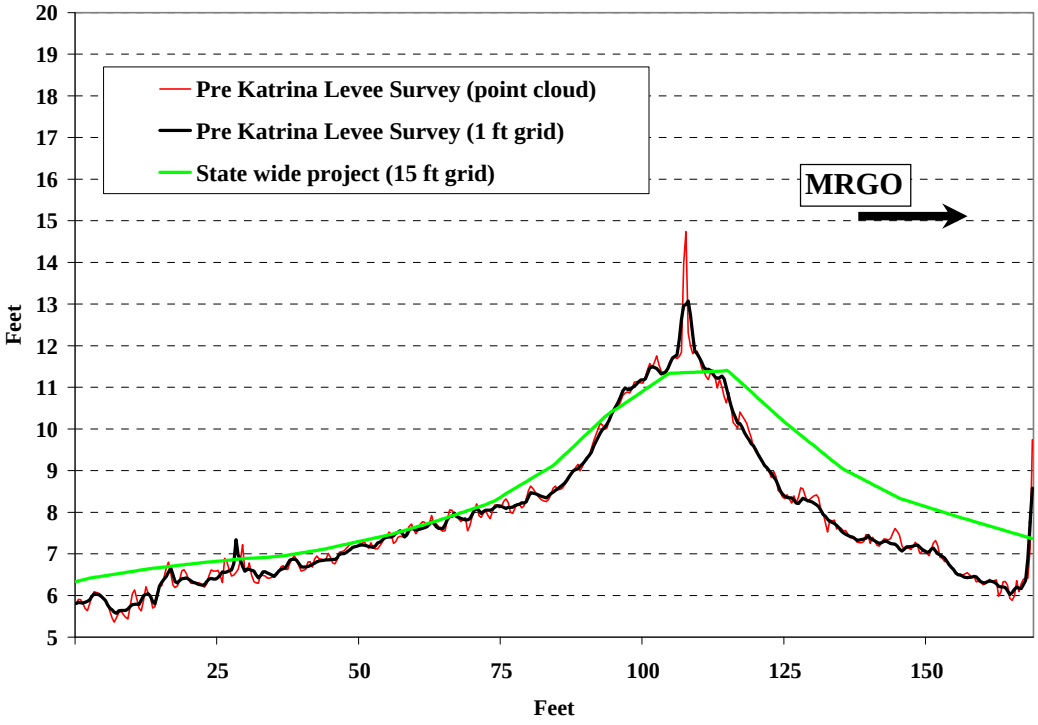


Figure 11 Cross section taken at station shown above

4.4.2 Relationship of Mapping Projects

To assess the overall accuracy of the LIDAR data, I computed the statistical difference between the three LIDAR mapping projects using the ASPRS guidelines (2004). These results are shown in Table 4.

Based on system design and flight characteristics, the Fli-Map system flown by John Chance for the two USACE levee mapping projects should be more accurate than the system used by 3001, Inc., for the Statewide mapping project. The best theoretical accuracy from these data sets would be expected from the point cloud data over an area of clear open ground. A direct comparison of these is shown in Table 4. The mean difference of 0.25 feet indicates a datum error between the two projects, while the RMSE of 0.9 feet indicates the estimated accuracy of any data point. Assuming the accuracy is the same for each project, the accuracy of one project would be assumed to be half, or 0.45 feet. This accuracy meets the allowable error for map products supporting the design of flood control structures as given by ASCE (1996).

I was not able to locate independently surveyed and defensible check points as recommended by the ASPRS Guidelines. Further, I did not find any conclusive data to determine which project is more accurate than the other. This lack of check data is further supported by the IPET Volume II findings. Consequently, this direct comparison of data is the best alternative to assess accuracy of the derived elevation product. Table 4 shows that the accuracy of top of structure heights between the two levee surveys is 4.7 feet. If each survey contains one half (1/2) the error, then the accuracy of levee structure height is estimated to be 2.3 feet. The concept of an increase in error from top of structure measurement versus open ground is supported in the ASPRS Guideline (2004),

Table 4 Mean difference and accuracy estimate (values in feet)

	Open Ground		Top of Structure	
	Mean Difference	RMSE	Mean Difference	RMSE
Pre Katrina point cloud minus Post Katrina point cloud	- 0.25	0.9	0.4	4.7
Pre Katrina point cloud minus 15 foot grid	0.1	1.8	1.9	6.3
Post Katrina point cloud minus 15 foot grid	0.25	1.8	1.7	7.5

the plaintiffs' expert (Morris 2007, 2008) and the metadata from the levee project data found on the IPET website.

The data collected by the state-wide mapping project is presented in a 15 foot grid, or digital elevation model. This data was predominantly used as a basis of the hydraulic models of the larger region, including the polders, and would include the area of the MRGO channel and marsh areas. Table 4 also shows the relationship between the levee data from both the pre- and post-Katrina surveys and the Statewide project data. The best possible accuracy would be expected over clear open ground. The comparison of the three data sets shows an RMSE between each levee project and the Statewide project of about 1.8 feet. The accuracy of the levee project data has already been assessed at 0.45 feet. Therefore the accuracy of the Statewide project would be 1.8 – 0.45 or 1.35 feet. In my opinion, the accuracy of the Statewide data over clear open ground, in the vicinity of the MRGO and New Orleans East levee systems is 1.35 feet. This meets the allowable error (2 feet) for floodplain mapping as given by ASCE (1996) and shown in Table 2. It does not meet the design accuracy for the Statewide project as discussed by Cunningham (2004). The differences between the pre-Katrina levee data and the Statewide project data is further shown in the appendix, charts 17 and 18.

The mean difference between the three data sets is within a range of -0.1 to +0.25 feet (Table 4). However, a more detailed review of the sample points collected in the open ground throughout the study area shows a step of nine tenths (0.9) feet in the heights from the Statewide project data in the vicinity of the MRGO and those heights in the vicinity of New Orleans East as compared to the elevation data from the two (2) levee mapping projects, Table 5.

Table 5 Mean height difference MRGO reaches vs New Orleans East (values in feet)

	MRGO		New Orleans East	
	Mean Difference	RMSE	Mean Difference	RMSE
Pre Katrina point cloud minus Post Katrina point cloud	- 0.2	1.0	- 0.4	1.0
Pre Katrina point cloud minus 15 foot grid	- 0.3	1.4	0.6	2.2
Post Katrina point cloud minus 15 foot grid	- 0.1	1.0	0.8	2.5

Figure 12 and Appendix, charts 11 through 16 show further evidence of this anomaly. This systematic height difference in the Statewide data is likely the result of the various datum errors within the region as described in the IPET report, Volume II (2007). Regardless of the source of error, the two levee mapping projects each exhibit the same magnitude of error with respect to the Statewide project data. This error would directly, and adversely, contribute to error in the hydraulic models used in this case.

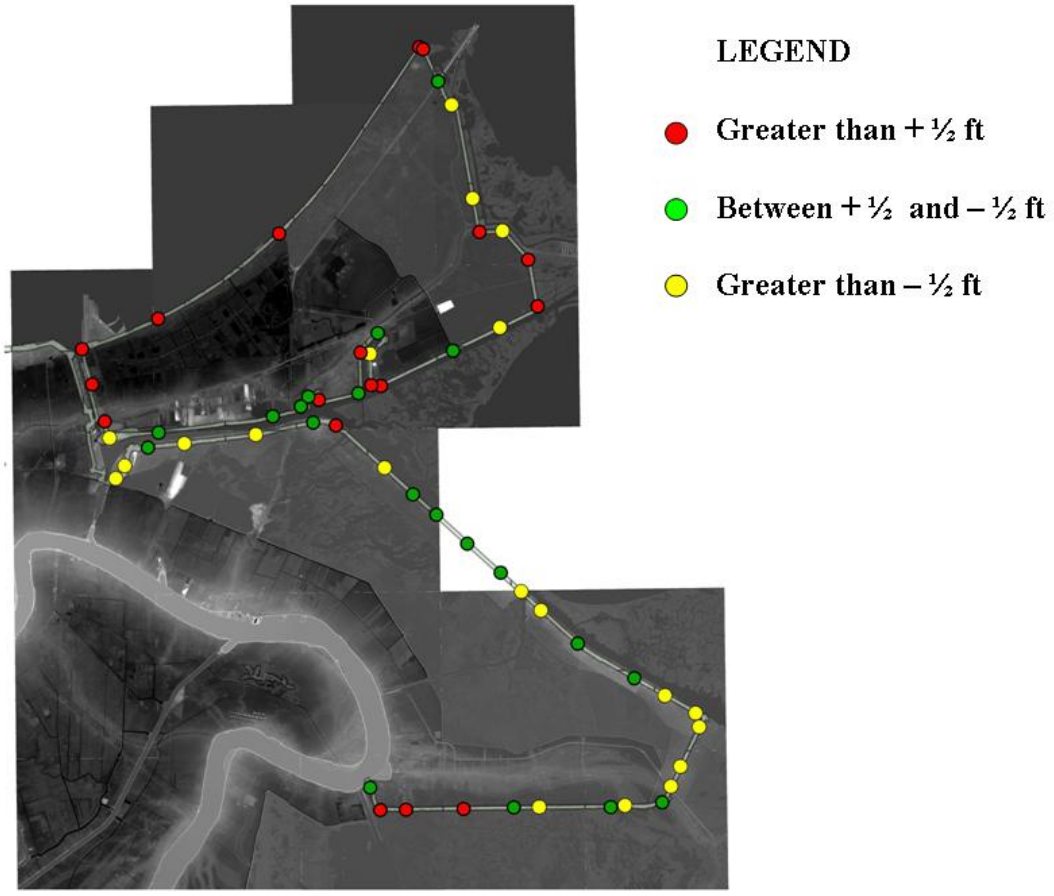


Figure 12 Height differences, Pre-Katrina levee data minus Statewide LIDAR data

5. CONCLUSION

LIDAR systems have been adopted as the standard tool for collecting elevation data covering large geographic regions. In this context, they are typically more accurate than previously used mapping systems. LIDAR, however, is far from perfect. Many error sources are inherent in these systems.

In my opinion to a reasonable degree of scientific and engineering certainty, the accuracy of the three LIDAR mapping projects the expert teams use in *Robinson v. United States* are summarized as follows:

1) The levee mapping project data collected in 2000 and 2005 met the intended accuracy to support 2 foot contours found in the contract scope of work (2005) and met the accuracy specified by ASCE (1996) for flood control structures.

2) The best available data for determination of the top of structure heights is the LIDAR point cloud data from the levee mapping project flown in 2000. The estimated accuracy of top of structure elevation determination from this data is two and three tenths (2.3) feet. The United States' experts considered this data in developing levee heights for their analysis.

3) An elevation model with a grid cell size of one (1) foot was derived from the point cloud data from the levee mapping project flown in 2000. The data smoothing process that was used to develop the grid adds an additional uncertainty to the estimated accuracy of top of structure elevation determination of one (1) foot for a total estimated accuracy of three and three tenths (3.3) feet. The Plaintiffs' experts used this data.

4) In areas of clear open ground, the topographic elevation data from the Louisiana Statewide mapping project, in the vicinity of the MRGO and New Orleans East levee systems, has an accuracy of one and three tenths (1.3) feet as compared to the levee mapping data. The data was not sampled in other terrain, vegetative land cover, or at the land water interface. However, it is known that these land cover types increase the error. This accuracy does not meet the intended accuracy as specified by Cunningham (2004), however, it does meet the accuracy specified by ASCE (1996) for floodplain mapping.

5) The elevations of the Louisiana Statewide mapping project appear to have a systematic shift between the New Orleans East area and the MRGO reaches as compared to the levee mapping elevation data. The elevations in the New Orleans East area appear to be nine tenths (0.9) feet lower than those in the vicinity of the MRGO reaches.

The accuracy estimates discussed are within the bounds of empirical evidence and statistical findings from other projects within my experience. The errors are predominantly associated with three issues. First are the general limitations of the LIDAR technology itself. The second is the ability of the data to support derivation of the elevation of the top of a thin structure such as a concrete flood wall or thin sheet pile. The third is the result of the datum errors in southeast Louisiana. A complete accuracy analysis of any mapping data should always be performed and utilized for regional studies such as the hydraulic and flood modeling the experts performed in this case. Plaintiffs' expert reports make no indication that these inherent limitations of LIDAR data were taken into account. Therefore, any hydraulic or flood modeling reliant on this data is likely to have additional uncertainty. I have not had the benefit of final depositions of the plaintiffs' experts and may be required to address issues based therein. I also am prepared to address issues regarding LIDAR and mapping that are raised at trial.

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Chart 1

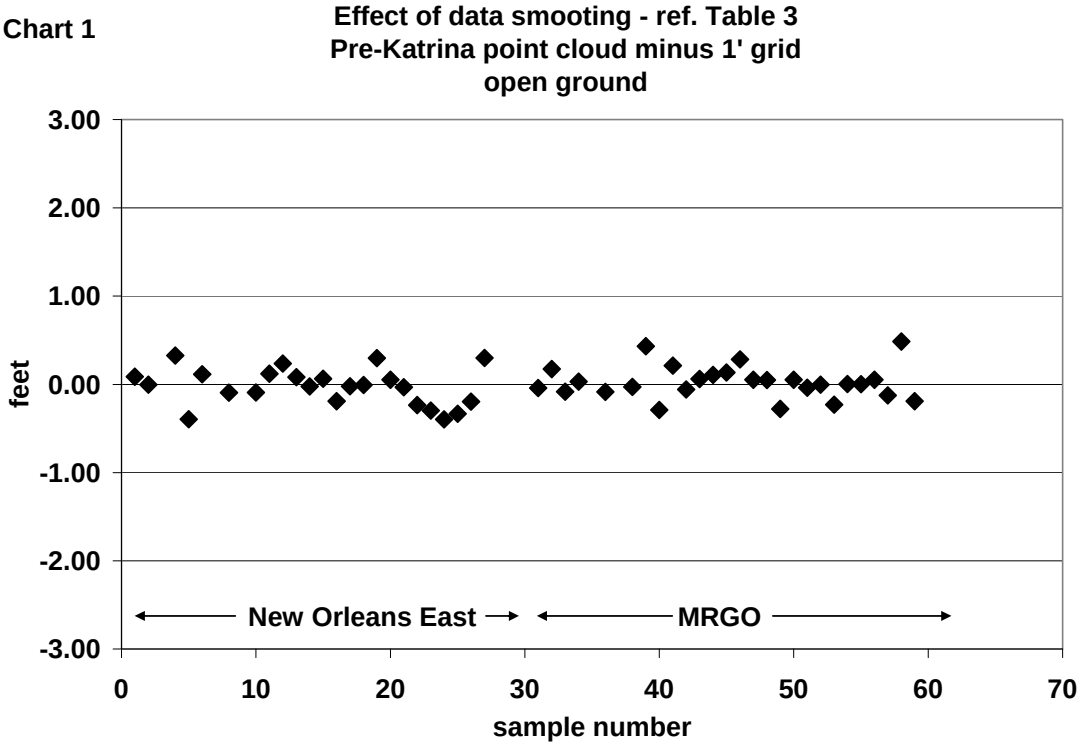
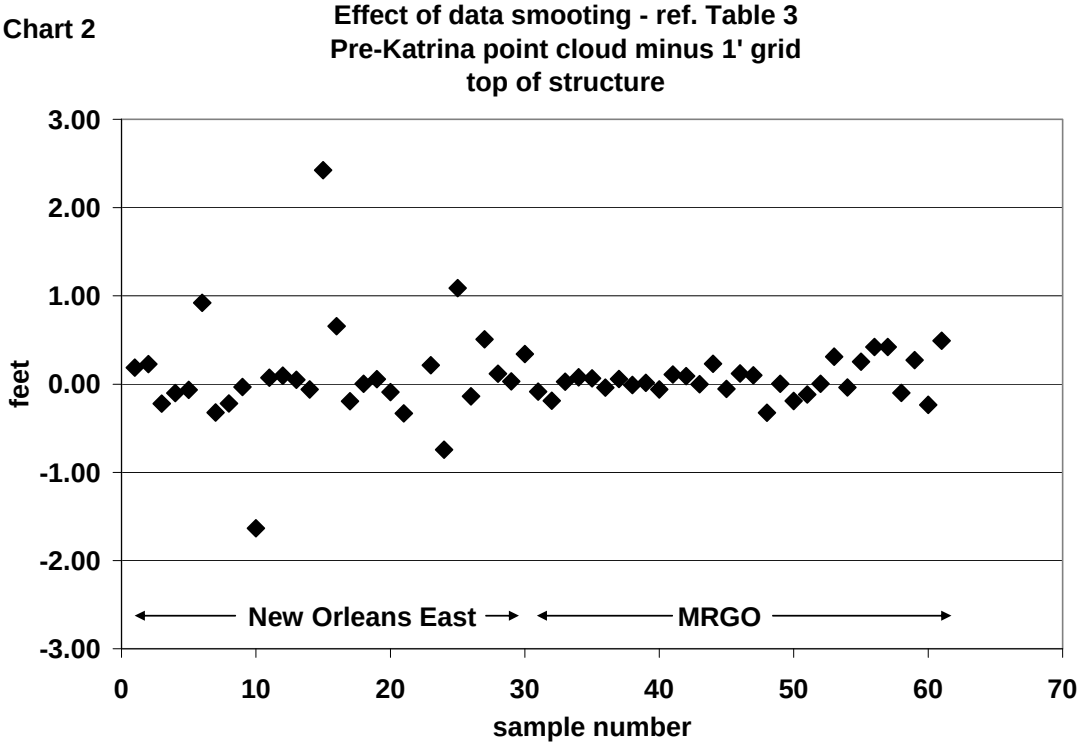


Chart 2



APPENDIX: Error Estimation Charts

Chart 3

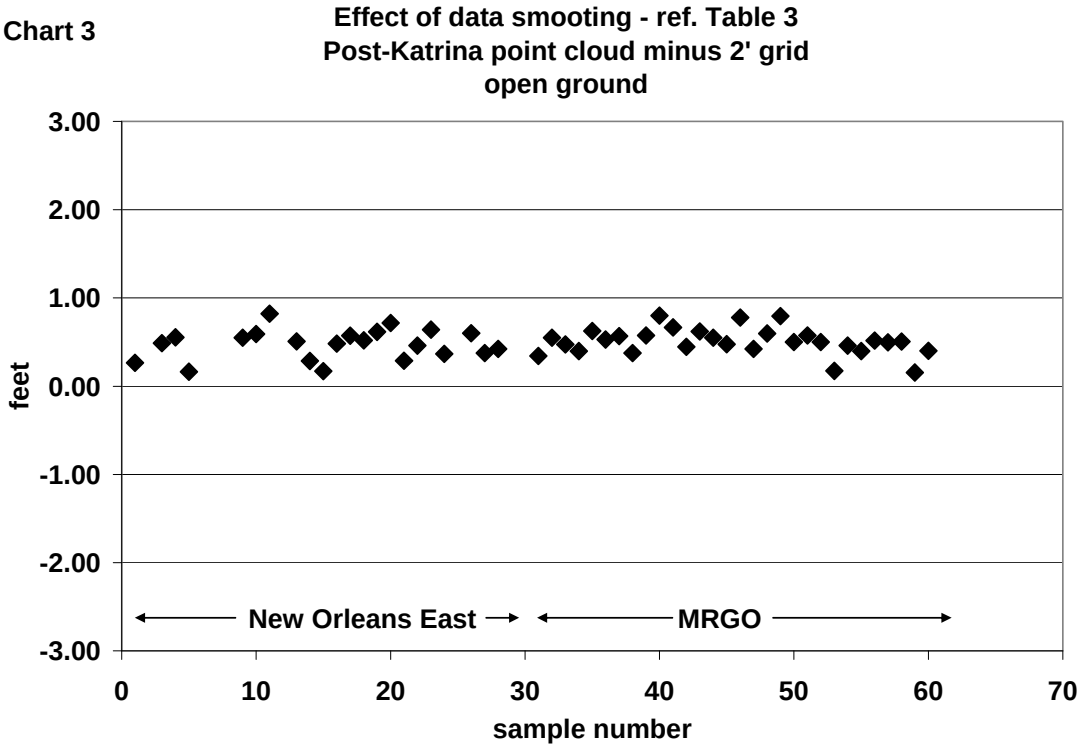
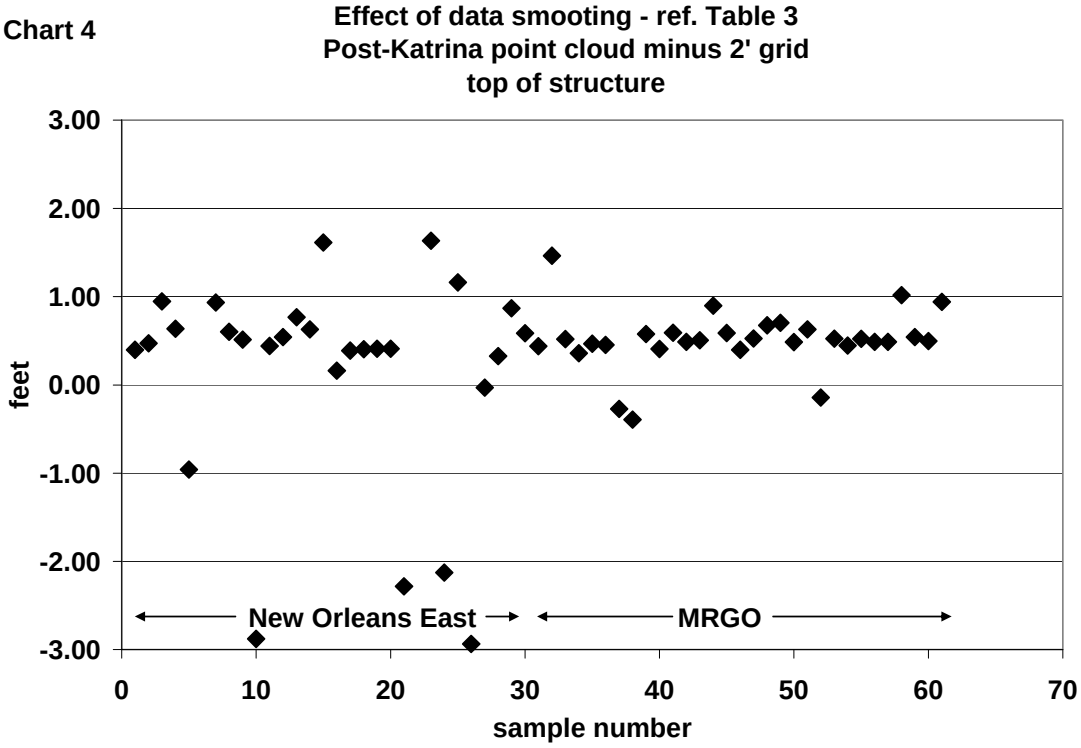


Chart 4



APPENDIX: Error Estimation Charts

Chart 5

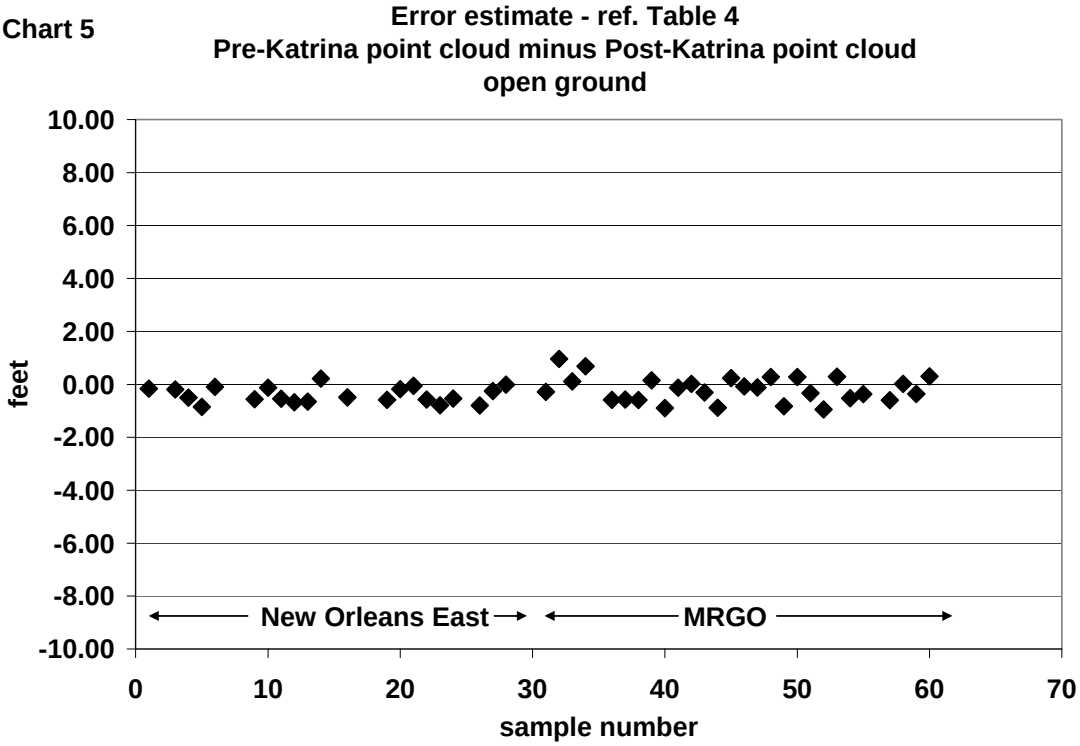


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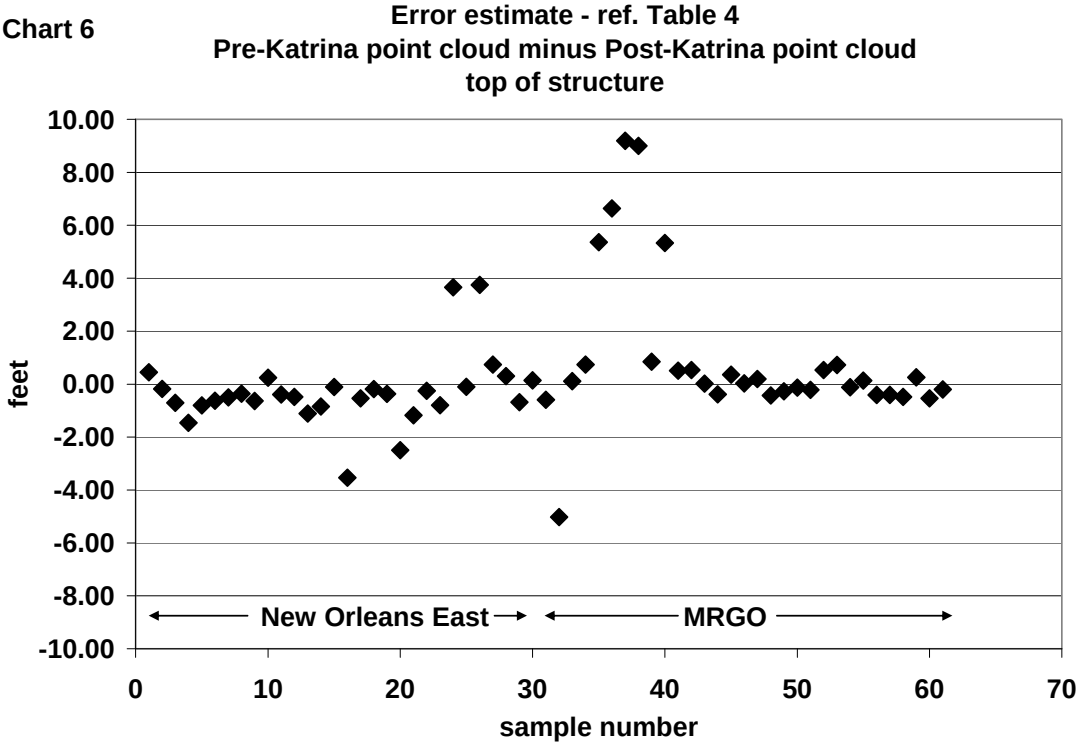


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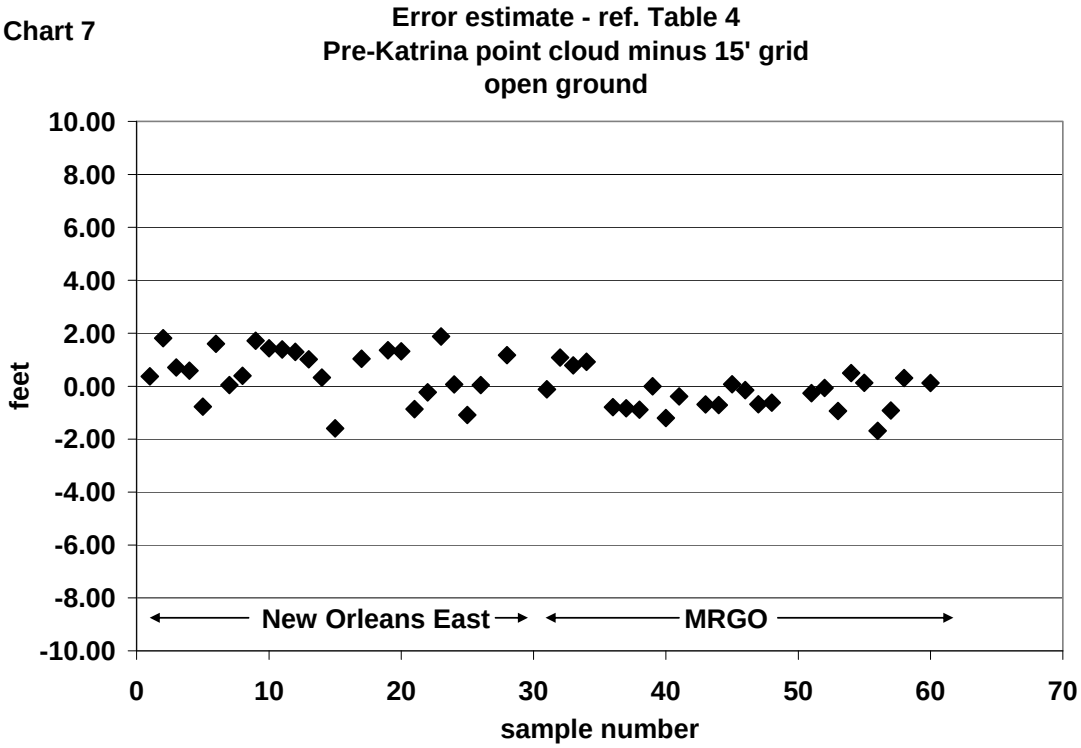
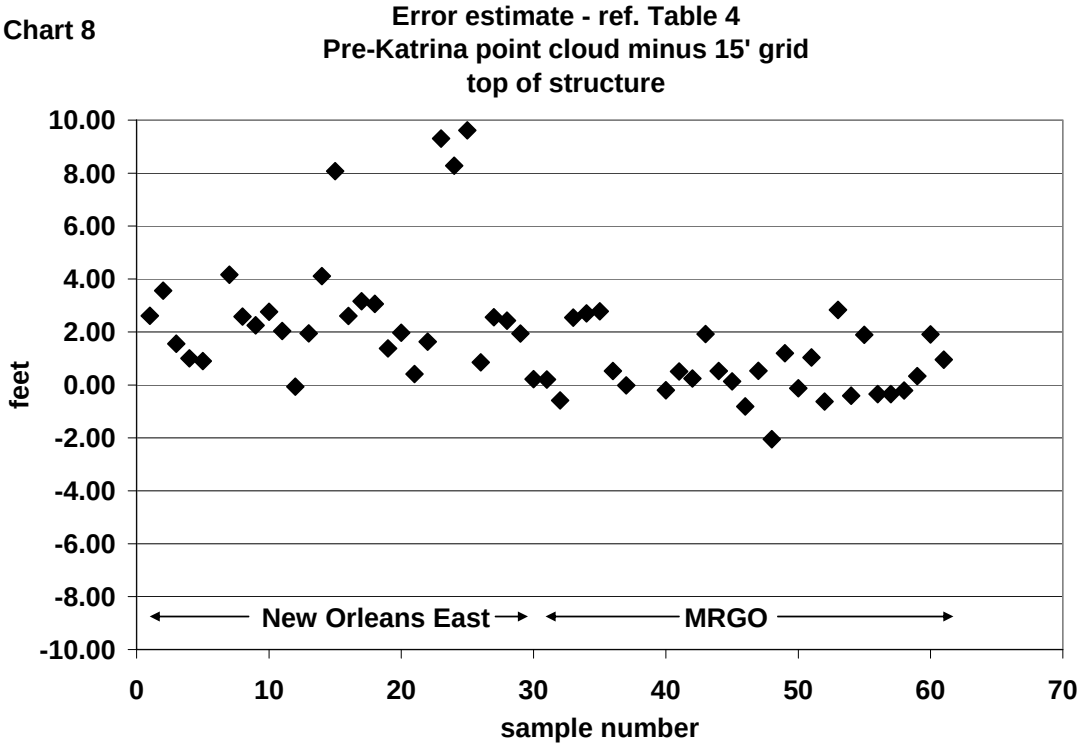


Chart 8



APPENDIX: Error Estimation Charts

Chart 9

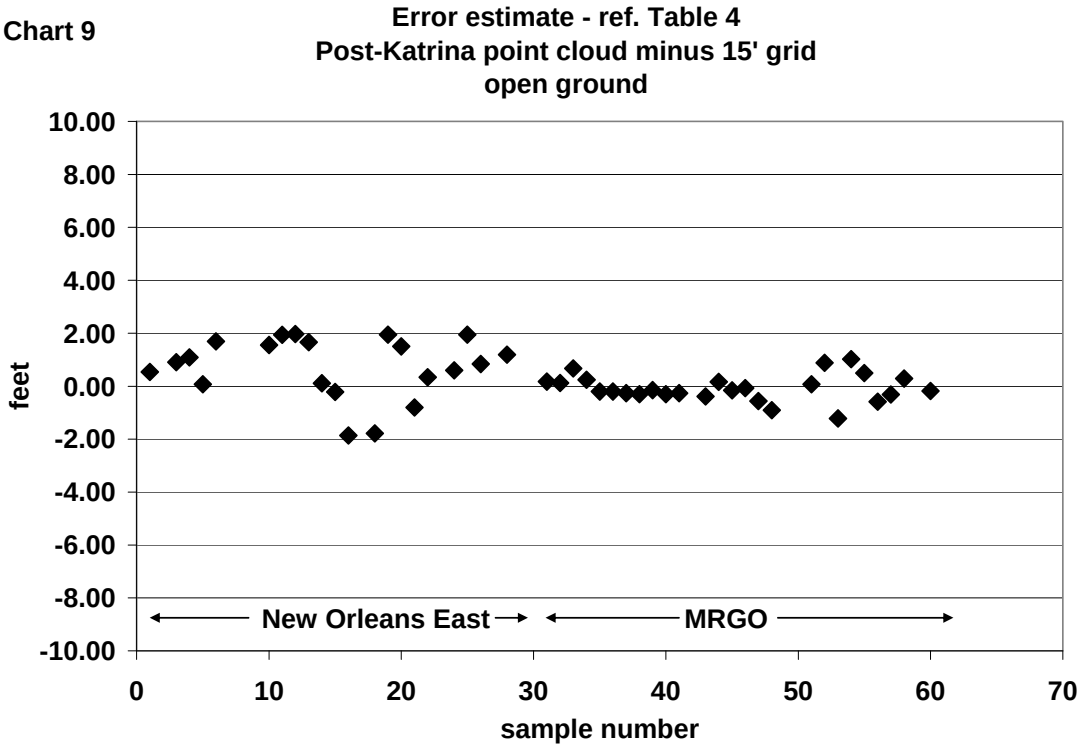
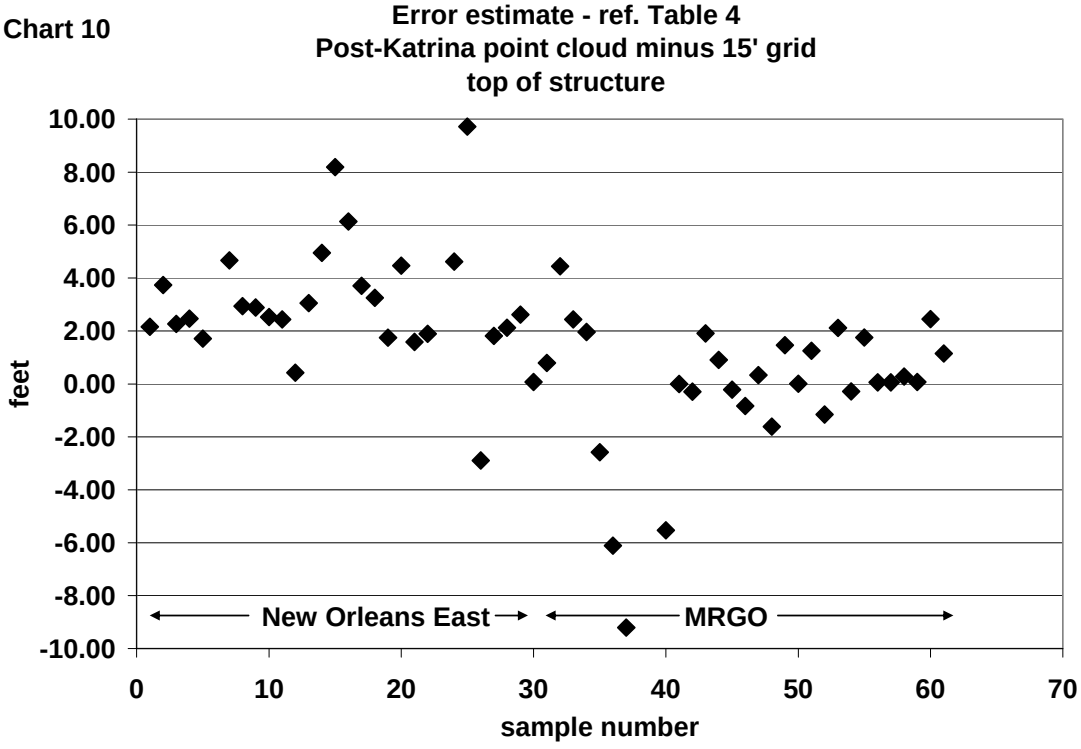


Chart 10



8. APPENDIX: Height difference MRGO reaches vs. New Orleans East

Chart 11

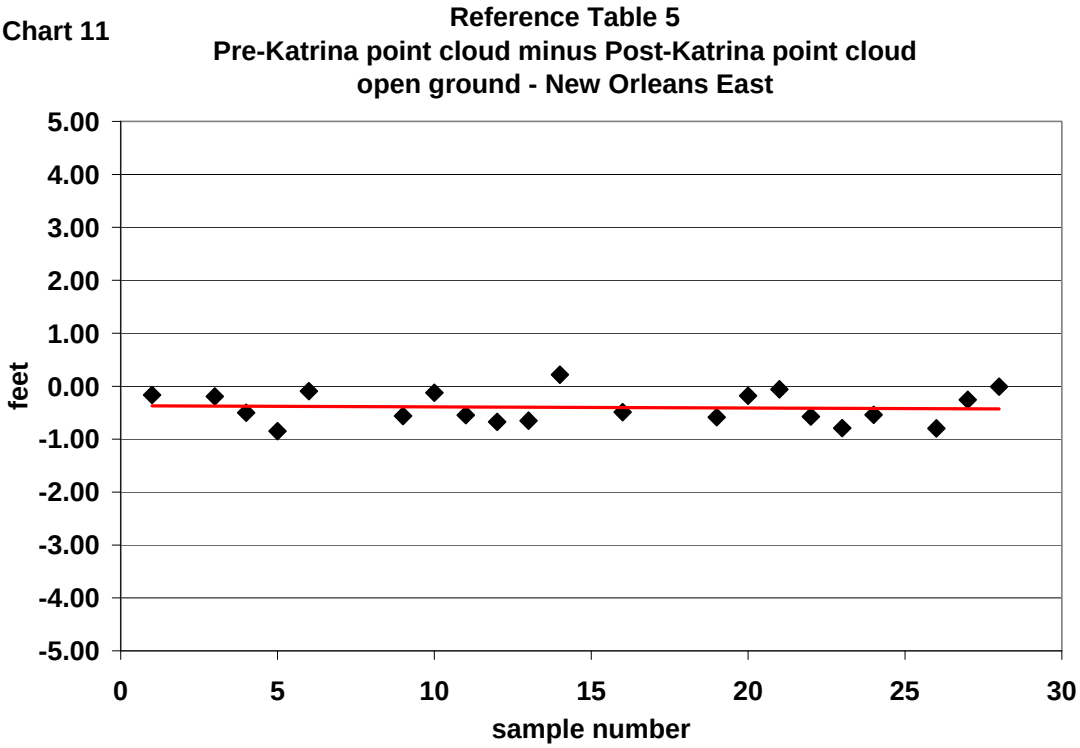


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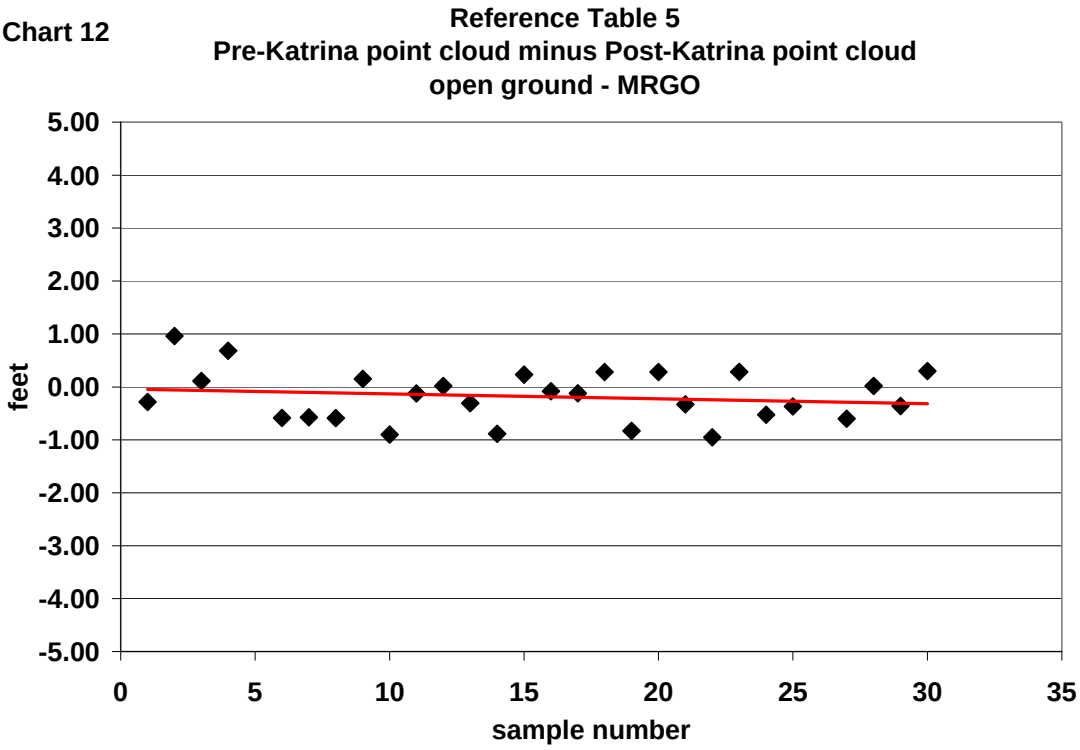


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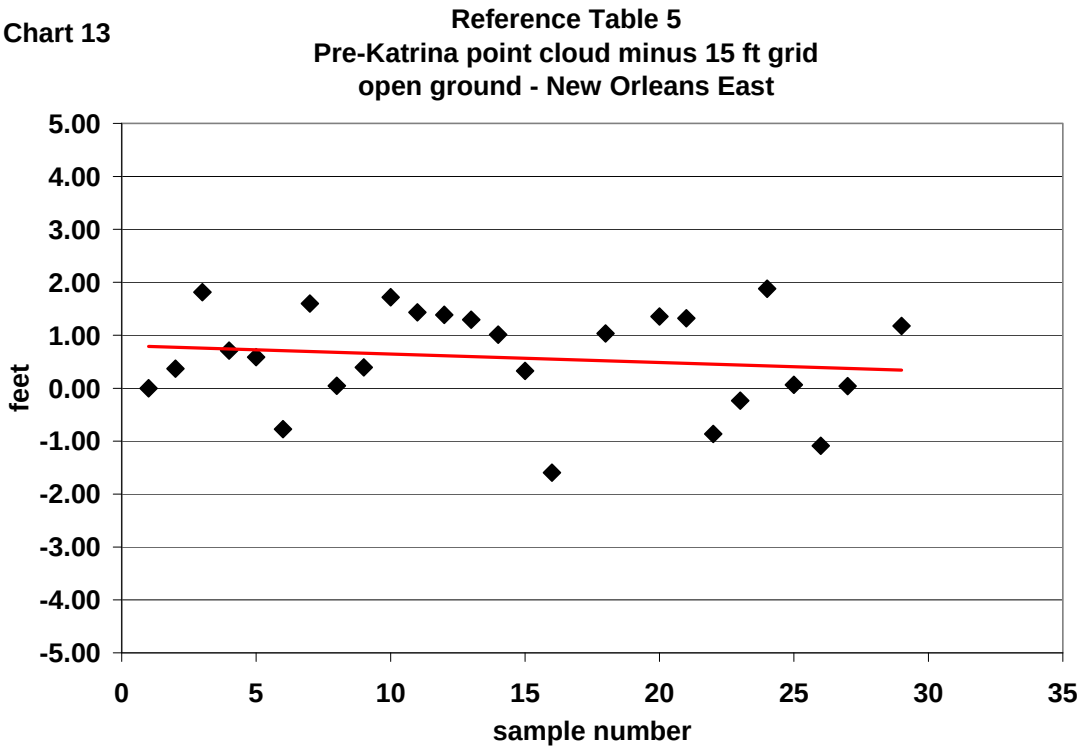
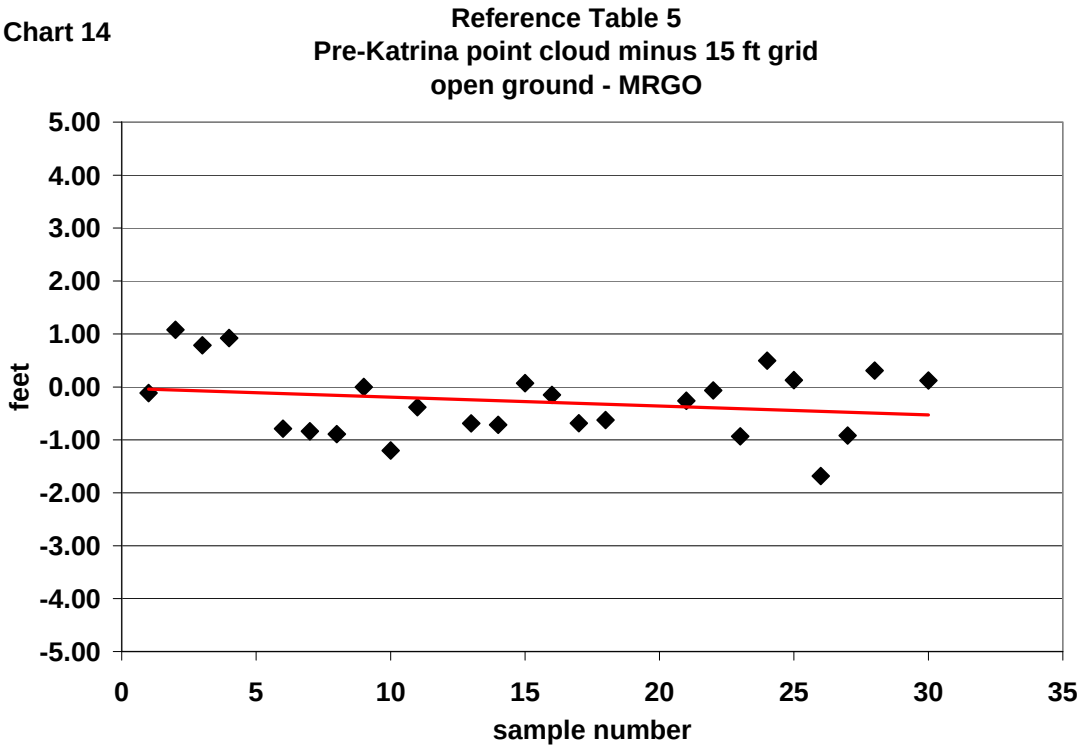


Chart 14



APPENDIX: Height difference MRGO reaches vs. New Orleans East

Chart 15

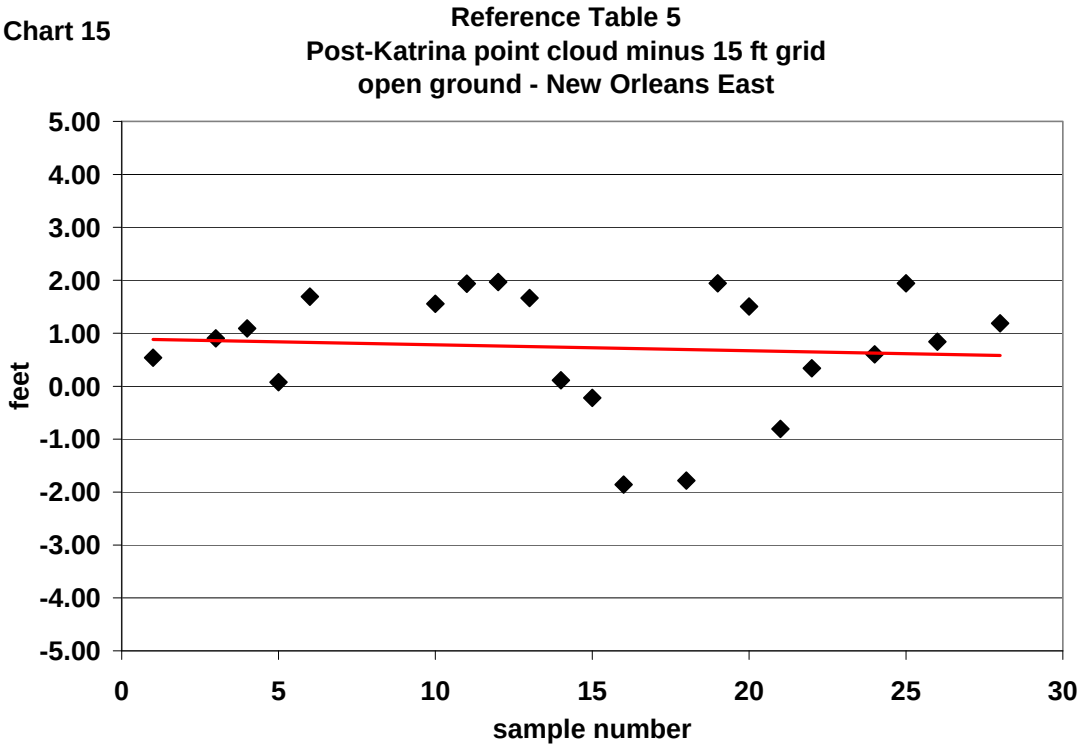


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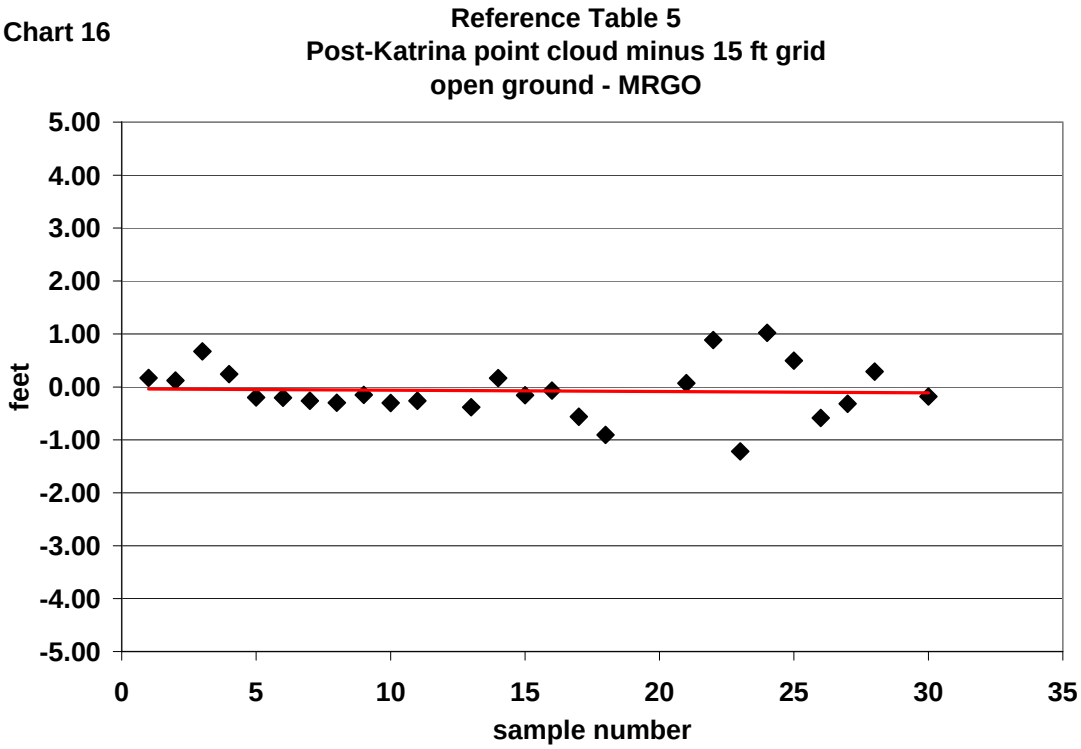


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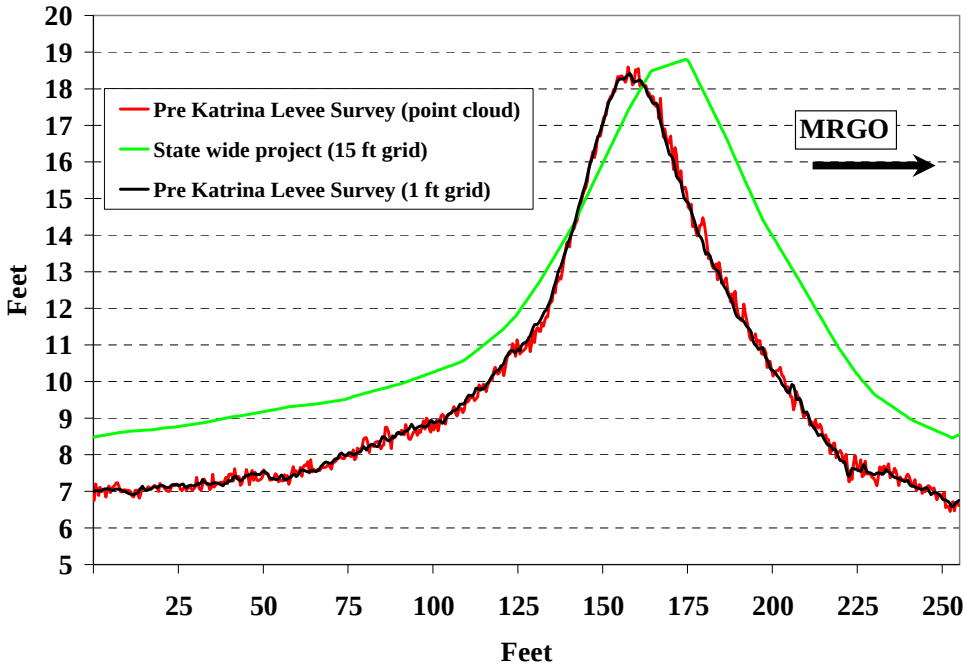
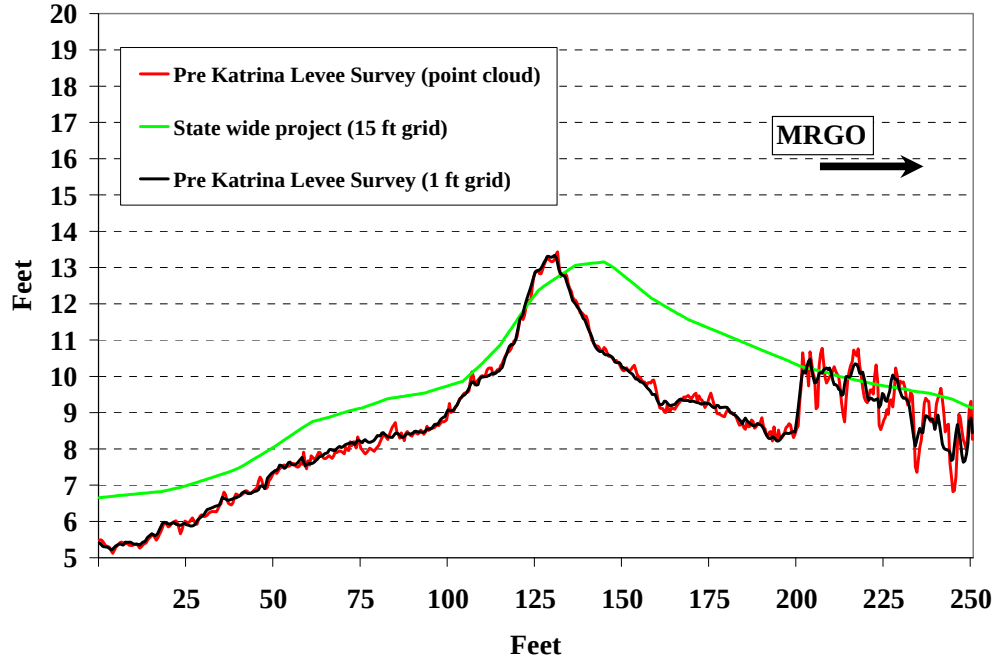


Chart 18



RESUME for:



Stephen R. DeLoach, P.E., L.S.
Myersville, MD

Experience:

Current	Smithsonian Institution, Washington, D.C. Associate Director, Office of Engineering, Design and Construction
1996 to 2003	EarthData International, Frederick, Maryland President, EarthData Technologies and EarthData Aviation
1985 to 1996	U.S. Army Topographic Engineering Center, Ft. Belvoir, Virginia Branch Chief and Civil Engineer, Surveying Division
1980 to 1985	U.S. Army Corps of Engineers, Norfolk District, Norfolk, Virginia Civil Engineer, Survey Branch
1978 to 1980	Tennessee Valley Authority, Bellefonte Nuclear Power Plant, Hollywood, Alabama Field Engineer

Education:

Virginia Polytechnic Institute and State University, Blacksburg, Virginia
Civil Engineering, Bachelors Degree
University of New Brunswick, Fredericton, New Brunswick, Canada
Geodesy and Geomatics Engineering, Masters of Engineering Degree

License:

Professional Engineer	Virginia # 13812
Land Surveyor	Virginia # 1476

Associations:

- Fellow, American Society of Civil Engineers
  - Geomatics Division, Past Chair
  - Journal of Surveying Engineering, Reviewer
  - *Glossary of the Mapping Sciences* Joint Committee, Past Chair
- Fellow, National Society of Professional Surveyors
- International Federation of Surveyors (FIG), United States delegate (1992–1998)
- Construction Industry Institute, Breakthrough Strategy Committee, Co-Chair
- National Acadamies, Federal Facilities Council, Emerging Technologies Committee, Co-Chair

Community Service:

2006 to 2008	Member, Myersville Town Council
Current	Board of Directors, The ARC of Frederick County

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