GROUND SURVEY SAMPLING PRACTICES TO CONSTRUCT A CONSTRAINED DELAUNAY TRIANGULATED IRREGULAR NETWORK DIGITAL TERRAIN MODEL FOR THE PURPOSE OF LARGE SCALE MAP APPLICATIONS

A Thesis

by

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This thesis meets the standards for scope and quality of
Texas A&M University-Corpus Christi and is hereby approved.

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ABSTRACT

The validation of a digital terrain model's (DTM) accuracy is often defined by de facto standards that do not address data acquisition sampling practices or the reconstruction methods to create the digital terrain. The testing of DTM accuracy for large scale mapping products is rarely performed because completeness in the dataset is the highest value, the raw data is collected with high precision, and the DTM is expected to function during the application process. The standardized root mean square error statistical analysis method that is used to test final DTM accuracy quality and categorically certify final DTM products is not a useful test for the data model provider. Validation metrics need to be developed for use earlier in the DTM process that focus on the data model provider's workflow during the verification phase. These undeveloped quality metrics during the verification phase has led to model contractors defining project directives to the data model provider to include terminology based on derived model products, levels of sampling resolution, and expected raw data accuracies that do not relate to the testing standards of the DTM.

This research examines the current DTM quality validation standard format and the possibility to develop relevant quality standards based on prediction by production to be applied during the data verification phase for large scale mapping products prepared by in situ, heavily biased sampling, and constructed DTMs. Ground survey methods of instrumentation and sampling are presented to identify a best practice method of repeatable survey strategy. The method of reconstruction of the raw data into a digital terrain model is that of a constrained Delaunay triangulated irregular network (CDT). The American Society of Photogrammetry and

Remote Sensing *ASPRS Positional Accuracy Standards for Digital Geospatial Data,* 2014, for testing a DTM are reviewed and presented in a familiar unit and scale factor for ground survey providers. The only accepted verification method for DTM quality by the model contractor is "prediction by production". By analyzing metrics from 61 large scale mapping projects collected using these recommended practices and constructed as a CDT, the criteria for analyzing the verification phase of digital terrain modeling can begin to be identified.

Within the 61 DTMs studied, there is no correlation between eight scale groups using a simple resolution of survey points per DTM planar area and each scale group needs to be analyzed separately. Because the DTM quality benefits from interpolation derived from survey sampling strategy and CDT construction methods, additional factors of sampling efficiency must be developed and applied to the data of the 61 DTMs being analyzed. A DTM that is of high quality functionality can be assumed as statistically confident and metrics of mass point resolution, planimetric interval spacing, number of triangle facets and edges, and the CDT geometries can be used to test for completeness and accuracy in the raw dataset. However, DTMs with very large scales of 1"=5' or 1"=10' require unrealistic resolutions to pass a significant confidence level regardless of efficiency factors applied.

Finally, in the era of digital models deriving computer drafted mapping products, model contractors can stop using antiquated mapping standards of hard published scales to define contour intervals, planimetric accuracies, and mass point resolutions to the data model provider and the data model provider can certify to applicable quality categories.

DEDICATION

"If you are not learning while you are earning, you are cheating yourself out of the better portion of your compensation."

-Napolean Hill

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1.1 Introduction

A valuable service of land surveying personnel is to collect planimetric and topographic data in situ (ground survey) for the purpose of creating large scale map products. A large scale map is used to show a greater level detail in a small area by applying a high level of accuracy over a limited area (Ghilani and Wolf 2012). The area of land represented on the map is a ratio of units on the map over units on the ground, thus a map with the ratio of 1/10 is larger than a ratio of 1/10,000 (Bolstad 2016). Table 1 shows categories of scale with both an imperial scale unit of inches to US survey feet and the metric scale equivalent.

Table 1: Categories of large scale, medium scale, and small scale mapping products (Ghilani and Wolf 2012).

Category	**Imperial Scale Unit**	**Metric Scale Unit**
Large Scale	1 in. = 200 usft or larger	(1:2400) or larger
Medium Scale	1 in. = 200 usft to 1 in. = 1000 usft	(1:2400 to 1:12,000)
Small Scale	1 in. = 1000 usft or smaller	(1:12,000) or smaller

Large scale maps and their derived products are used in applications where positional accuracy and detail are necessary to make decisions. This level of detail is most common in civil, mechanical, and structural engineering and architectural applications where spatial analysis desires a high level of scaled precision. The purpose of the map, the size of the detail area, and the published size of the hardcopy map are all factors that contribute to determining a scale. Using a large scale, a *strip map* is used for projects that are narrow in width and long in length such as pipelines and corridors and an *area map* is used for localized site projects that are more equal in width and depth (Cole and Harbin 2006). Table 2 identifies metric to imperial scale equivalents, the estimated contour interval for average terrain, and the typical use for large scale mapping products at these published scales (Kavanagh and Slattery 2015).

Table 2: Typical Mapping Use per Scale and Contour Interval (Kavanagh and Slattery 2015).

Metric Scale	Inch Scale	Contour Interval for Average Terrain	Typical Use
1:12	1"=1'		Detail
1:60	1"=5'		Detail
1:120	1"=10'		Detail
1:240	1"=20'		Profiles
1:360	1"=30'	1'	Profiles
1:480	1"=40'	1'	Profiles
1:600	1"=50'	1'	Municipal Design Plans
1:720	1"=60'	1'	Municipal Design Plans
1:1200	1"=100'	2'	Site Engineering
1:2400	1"=200'	5'	Engineering Studies

The features shown on a large scale map are both planimetric and topographic. Planimetric features display horizontal positions (Fuechsel). They can be represented by points, polylines, and polygons, complete with symbology and annotations (Lo and Yeung 2007). Although they are shown in a two dimensional horizontal plane, the data points are collected in three dimensions. Two dimensional maps will sometimes display planimetric features in 2.5D by annotating the z value (Turner 1992). In addition, linear planimetric features are computed by 3D polylines between data points and interpolate x,y,z coordinates between the nodes. Planimetric polygons tend to have no z value assigned and are used in planimetric area calculations.

Topographic data is used to represent three dimensional relationships on a surface. The most common are contour lines and grade points. A contour line represents the planimetric location of a level surface at different locations, similar to the edge of water level of a lake. (American Society of Civil Engineers 1994). A grade point is represented by an x,y,z coordinate on the surface and sometimes referred to as a mass point (Jensen and Jensen 2013). Because planimetric features are collected in 3D, they are often used to compute topographic products, and in return, topographic data can be used to compute planimetric data.

The National Map Accuracy Standards of 1947 (NMAS 47) uses the published scale of the mapping product to define planimetric scaling precisions, appropriate contour intervals, and a testing method for data quality accuracy (United States Bureau of Budget 1947). Subsequent de facto standards developed accuracy classifications based on the NMAS 47 published scale and/or contour interval methodology are still in use today to determine data quality classifications to certify mapping products (Texas Society of Professional Surveyors 2006). The published map scale for large scale mapping products has a direct impact on determining appropriate contour intervals, but not always; Contour intervals can be determined by the characteristics of the terrain based on slope and the application of the mapping product.

Today, the large scale mapping product is presented in a digital augmented reality using computer aided design software (CAD). The ground survey data collected is used to construct a digital terrain model (DTM) that represents "real world" conditions. These models are used to derive multiple applications and secondary products that affect cost significant data driven decisions. The methodology to produce the DTM can vary greatly and classifying data accuracy or digital surface functionality based on arbitrary published map scales or derived digital contours is moot. It is obsolete for data model providers to certify classified scaled precision for planimetric features and functional terrain quality based on contour intervals when using CAD to derive large scale mapping products.

The current Positional Accuracy Standards for Digital Geospatial Data, as defined by the American Society for Photogrammetry and Remote Sensing (ASPRS 2014) for quality of the

DTM surface is based on a root mean square error (RMSE) comparison at a 95% confidence level between a sample of interpolated points in the model against a field check measurement of a higher order of precision (American Society for Photogrammetry and Remote Sensing 2014). The Process of Digital Terrain Modeling, as shown in Figure 1, has two phases, verification of raw data and the validation of the DTM surface (Li et al. 2005). The data model provider utilizes the data source through the process of sampling to create raw data. The data model provider also completes the process of reconstructing the raw data into the DTM surface. The quality assessment happens in the validation phase of the Process of Digital Terrain Modeling either by standardized testing methods or by the application process of the DTM surface by the data model contractor to utilize the final DTM product.

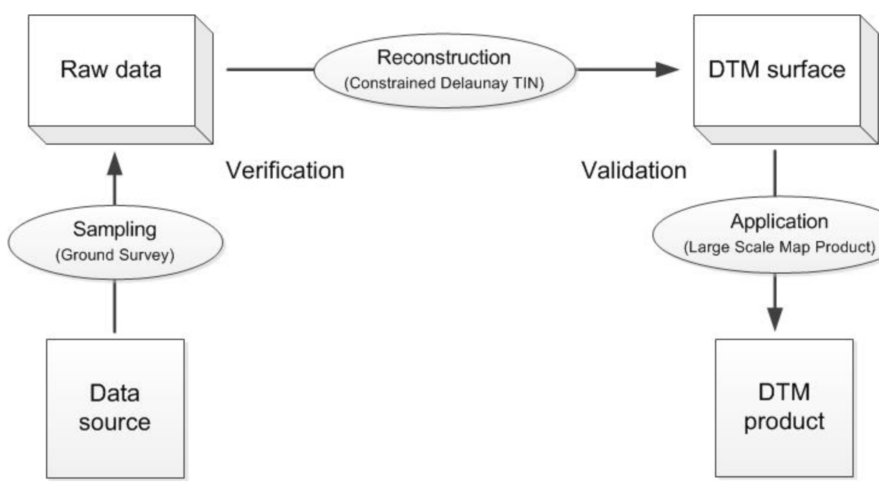

Figure 1: The Process of Digital Terrain Modeling (modified from Li et al. 2005)

Rarely are DTMs used for large scale mapping products tested for accuracy compliance (Chrisman 1991). This can be due to project budget constraints or the expected functioning utility of the DTM used during in the application process. When a region of detail is omitted in the dataset resulting in poor or incorrect reconstructions of the DTM, the map does not function as intended and loses its purpose. Completeness in the dataset becomes the most apparent quality metric, both *spatial completeness* that include the entire area of interests and *thematic completeness* that include all of the descriptors for the intended application (Lo and Yeung 2007). "Completeness of geospatial data refers to the degree to which the data exhaust the universe of all possible items" (Brassel et al. 1995). The National Committee for Digital Cartographic Data Standards Report 3 has sought to address minimum data quality requirements for specific mapping applications, but most of the scholarly progress has been focused on model error evaluations and little has been developed to address minimum data quality standards in the framework of "fitness for use." (Fisher and Tate 2006). Poor completeness data quality will affect the DTM products' accuracy quality after the reconstruction process.

The standards for validating DTMs do little to address quality parameters during the verification phase of the data acquisition process. The most common method to verify data quality prior to a validation test is by "prediction by production" in which errors are assessed during all of the DTM production processes (Li et al. 2005). This method is most common, but does not address standard tests to certify classification accuracies for a delivered DTM product from the data model provider. The data model contractor often request raw data sampling densities from the data model provider that haven't been defined by the mapping industry with levels of data precision and accuracy determined by obsolete contour interval terminology. The best approach to bridge the divide between application and data acquisition would be to: understand the purpose of the large scale map and the importance of a highly accurate DTM, describe the practices and limitations of a ground survey to collect data, consider the methods to reconstruct a DTM, and then compare the current accuracy standards for validation to derive a best practice for sampling and reconstruction.

1.2 Lineage to Develop Standards

Map accuracy data quality standards were first developed by the U.S. Bureau of the Budget in 1947 as the National Map Accuracy Standards (NMAS 47). These standards defined vertical accuracy as a function of horizontal accuracy and classified map products with tolerable error limits on the published hardcopy map scale with a desire of contour intervals. The American Society for Photogrammetry and Remote Sensing produced de facto standards to further define NMAS 47 as the "Accuracy Standards for Large-Scale Maps,1990" (ASPRS 90) (American Society for Photogrammetry and Remote Sensing, 1990). The ASPRS 90 standards endorse classifications based on published scale and contour intervals. Where the NMAS 47 standards are based on map scaling methods, the ASPRS 90 standards included root mean square error (RMSE) as a metric for testing the accuracies of data based on ground distances. The ASPRS 90 standards allow for multiple mapping classes within the same product, limited testing methodology to "well-defined" points, and offset permissible vertical errors with an increased accuracy of the horizontal error.

The Federal Geographic Data Committee (FGDC) updated the de jure data quality standards in 1998 to support the National Spatial Data Infrastructure (NSDI) and published the National Standard for Spatial Data Accuracy (NSSDA). By Executive Order 12906 (Clinton, 1994, Sec. 4. Data Standards Activities, item d), de facto standards and data derivatives must comply with the FGDC; however methodology and threshold accuracy values are not defined by the NSSDA. The NSSDA standard defines RMSE with a 95th percentile confidence level tested with a minimum of 20 "well-defined" check points from a higher order dataset. Horizontal accuracy$_r$ and vertical accuracy$_z$ can be assessed separately and products that do not contain well-defined checkpoints, like contoured derivatives, would be excluded from these testing parameters (Maune 2007).

In 2014, the ASPRS superseded the de facto ASPRS 90 standards to publish the ASPRS Positional Accuracy Standards for Digital Geospatial Data (ASPRS 2014) (American Society for Photogrammetry and Remote Sensing 2014). The ASPRS 2014 standards were developed in response to new technologies and the fact that previous standards based on hardcopy map scale have become an obsolete quantifier for accuracy classes. Digital mediums don't utilize scale to produce various mapping products. The purpose was to conform testing RMSE terminology to the NSSDA and suggest threshold accuracy values. Section 1.2 of the ASPRS 2014 standards list several limitations to these de facto standards that would suggest these standards need to be updated in the future based on improved statistical methods. Section 1.1 states that methodology is not defined for the data provider and the testing recommendations could easily omit critical data that affect the functionality of the digital terrain model in spite of complying with the accuracy classes defined by the ASPRS 2014 standards

These standards are a good foundation to develop more applicable test and provide multiple tables that compare RMSE values to NMAS 47 and ASPRS 90 classification parameters. Additional applicable de facto standards, like the USGS Lidar Base Specifications (Heidemann 2018), reiterate the quality processes and format of the ASPRS 2014 standards and even reference compliance with the ASPRS 2014 standards to comply with the USGS Lidar Base Specifications.

1.3 Practical Background Review

The technology of measurement and drafting is changing exponentially after the advent of electronic distance measurement, GNSS positioning, database structures, and computer aided design software. The theories of sampling field data and the reconstruction of that data into utility mapping products has not. The Yale University text-book, *Plane Surveying*, addresses important questions of accuracy, methods, systemization, and cost based on the purpose for which a survey is made (Tracy 1906). The content of these past and present text-books are focused on familiarity with measurement processes to minimize errors of precision and demonstrate an array of end mapping products for the training of the survey provider. The concepts of systemized data collection and the benefit of survey strategy are vague or omitted.

The survey provider desires to minimize the cost for ground survey points to be sampled in the most efficient method possible to assure that the final DTM is functional in application and that the metadata collected is complete. The mapping contractor relies on the professional service of the provider that the delivered mapping product is accurate.

The most common digital format of a DTM that is prepared for a large scale mapping product from ground survey points is that of a vector-node model with edges of triangle faces connected between sampled points, also called a triangulated irregular network (TIN). The interpolation of points from the digital surface improve resolution as the model is considered a continuous dataset. However, the sampled ground survey points used to create the model are heavily biased in location.

There exist several studies on the feasibility of using technology to produce DTMs for various applications including total stations and GPS for terrain modeling (Nico et al. 2005). It is also apparent that there are efficiency benefits from different field methods (Bangen et al. 2014). The efficiency benefit of interpolation increasing functional resolution of the DTM by biasing the location of ground survey sampled and constructing a TIN is recognized. Varying sampling resolutions have been tested for DTM accuracy (Silveira et al. 2013). Mathematical and computer science research in the construction of TINs has made great progress in accuracy since Delaunay's initial algorithms in 1939. Additional methods of constraining the TIN and embedding multiple resolution TINs has improved DTM accuracy (Zhou and Chen 2011). With so much emphasis on sample bias, studies on crew variability (Bangen et al. 2014), and the effects of repeatability of topographic data collection have been conducted (Wheaton et al. 2009), to conclude that the variation is minimal when consistent survey methods are employed.

Survey text-books are lacking in sampling techniques since the summaries provided in this paper are sourced and combined from multiple text (Lo and Yeung 2007; Ghilani and Wolf 2012; Weibel and Heller 1991). A critical concept in this paper to develop verification metrics for accuracy and completion is to define a best practice for "how-to" collect ground survey points for large scale mapping products. The minimum standard for planimetric features are primarily defined by the mapping contractor, with the most detailed and available being that of an United States Army Corps of Engineer's manual on *Control and Topographic Surveying* (EM 1110-1-1005) (United States Army Corps of Engineers 2007).

The terrain being mapped is not uniform in complexity and the localized increase or decrease in ground points sampled does not diminish the accuracy of the final DTM. To determine quality metrics based on simple resolution is not applicable for mapping products produced by ground survey sampling and constructed as a TIN. Spatial statistics to analyze quality has been dominated by the assumptions of a well-defined mean, and there is a need to develop other metrics (Jiang et al. 2015). There are recent studies to apply statistical significant values from accepted accurate DTMs and determine a level of down-sampling that would simplify the DTM yet still remain a sufficient quality (Wise 2011). It is in this line of logic that this study seeks to develop appropriate resolution metrics to validate raw data. The end goal being that large scale mapping products can be verified as accurate using de jure standard methodology.

Current survey text-books are also absent of complying with standards of accuracy or methods for determining product quality. They often address this shortcoming with a list common sources of error. Current de facto standards specific to the survey industry, like the Texas Society of Professional Surveyor's Manual of Practice for Land Surveying in the State of Texas, focus on minimizing error of precision and use mapping metrics of published scale common to NMAS 47 methodology. These standards are in the process of becoming obsolete and professional societies for surveyors are considering revising these standards. The committees developing these quality standards do not address completeness in the dataset or consider quality metrics that include the benefit of interpolation in the final mapping product.

1.4 Study Purpose and Objectives

The overall purpose of this study is to develop applicable quality standards for the DTM provider during the verification phase of the Digital Terrain Modeling Process by using common in situ ground surveying and sampling practices, within the framework of constructing a CDT, to deliver a functioning large scale mapping product.

This study lays out the following objectives:

- Describe the practices and limitations of a ground survey to collect data and consider the methods to reconstruct the data into a DTM.
- Provide reference tables of current standardized accuracy classes in units of US survey feet to aid data model providers in certifying large scale mapping products.

- Analyze metrics from 61 validated accurate DTMs to develop statistically significant testing methods for data model providers to verify spatial completeness quality in the data set before the validation phase.

CHAPTER 2: BACKGROUND

2.1 Topographic Survey Methods and Techniques

2.1.1 Data Collection

Data that is being used to create large scale topographic maps can be collected either remotely or in situ using a wide source of technologies. The latest and most advanced technologies can include the use of an unmanned aircraft system (UAS) collecting photogrammetric data that can later be processed into classified planimetric features and high density topographic data. Terrestrial Light Detection and Ranging (LiDAR) sensors can collect high density x,y,z data, as well as colorize the data to RGB values for improved resolutions (Wilson 2012). LiDAR and photographic sensors can be terrestrial stationary or attached to moving vehicles or UAVs to create mobile mapping solutions.

Although these technologies are becoming more common to collect data for large scale maps, they still have several limitations that will not supersede conventional in situ survey methods. The biggest hurdle to implement this technology for large scale map data collection is price. The equipment is expensive, the survey technicians who operate the equipment in the field has higher labor cost, the software to process the data is expensive, the drafting technicians who process the data has higher labor cost, and the data itself has its own inherent problems that prevent wide spread use of UAS and LiDAR data collection.

More sampling of topographic data does not necessarily equate to a better product. If the data cannot be used to create a product the engineer or architect can readily use, it would be as if handing the client a bag of sand. High density data that has no descriptions attached is difficult to analyze. The size of digital data has its own problems in computing storage and computer processing capabilities to utilize the data for the purpose of a large scale map although improvements in technology seek to solve these issues. There also exist gaps of coverage in the sampling methods that require conventional in situ field crews to subsidize the dataset and validate positional accuracy by ground survey. The end product that field surveyors deliver is raw data x,y,z coordinates with a descriptor attached to help reconstruct the data into planimetric features and a digital terrain model. Regularly, limited project budgets fail to utilize advanced technology because of the cost for those types of data collection methods and conventional survey methods are most common. There exist several textbook protocols on how to utilize various technologies to improve data quality, but few studies detail which technique to use in specific circumstances (Bangen et al. 2014).

2.1.2 Conventional Survey Methods

Topographic mapping data has been collected in the field by surveyors for over 200 years using optical levels, stadia rods, and hand written measurements. These methods are still common and highly accurate with a maximum elevation precision of 0.01' based on intrinsic manufacturer errors in the equipment and quality of measurement techniques completed in the field. The data collected this way still needs to be converted to a digital format and horizontal accuracy is compromised. "Line of sight" data collection uses electronic digital measurement combined with radial angle measurements in what is called a total station. The methodology of this equipment has been used for large scale mapping for over 100 years and the digital improvements to accuracy and precision since the 1960's. With the deflation cost of technology outpacing the inflation of currency, the use of radial data collection using a total station is the most accurate and precise method for a field survey crew to sample data for collection. Good measurement habits can allow an Instrument man and a Rodman to reach precisions of less than 0.01’ in horizontal as field metrologist. Combining optical leveling techniques can also improve vertical accuracies.

The price of conventional survey equipment is not a barrier for field survey technicians to collect large scale mapping data; however, the labor cost is. There are advances in robotic total stations that eliminate the need for additional field crew personnel. It is now possible for the most experienced field crew member to work alone with the digital data collector in their hands on the prism pole as they select the location for the data point collected.

Another technology advancement for in situ data collection is the use of Real Time Kinetic (RTK) data collection using a Global Navigation Satellite System (GNSS). Although the initial cost of RTK equipment is more expensive than an acceptable total station, the productivity of a field crew collecting data more than compensates in value. With the methods of real time positional corrections, coordinate data can be collected using the geodetic position of a GNSS receiver. There exist constraints with this technology as well that reduce accuracy and productivity like canopy cover, poor satellite constellations, and multipath interference (Van Sickle 2015). However unknown the accuracy of the data collected using GNSS, the data precision gives a false confidence. Using GNSS also forces the survey technicians to become amateur geodesist and understand local and global coordinate reference systems for fear of being branded “button pushers” and delivering compromised data quality.

The most cost efficient of in situ field crews will utilize all of these technologies of optical leveling, radial total stations, and RTK GNSS to collect data. They can also subsidize the dataset with some of the other technologies like range finders, sub-centimeter sonar, and even a tape measure. The coordinate data collected is written, described, and diagramed in field books to add detail and establish forensic evidence of the time collected. Information on critical detail to large scale mapping that does not directly produce a digital terrain model or cannot be collected using conventional measurement technology is recorded in field books, most notably subsurface features like sewer leviations or storm drain topology diagrams. Digital data is collected in small rugged personal computers called field controllers using proprietary software that aides in data validation from the time of collection. This lowest form of digital data is in a tabular format, often comma separated values, which use a unique point label identifier, an x,y,z coordinate, and a descriptor. With the rise of Geographic Information Systems (GIS) infiltrating the survey industry, database schemas are also being used to describe coordinates with even greater detail and utility. Raw digital data delivery formats have grown to include proprietary software files and markup language file types (.xml) in addition to “flat” American Standard Code for Information Interchange (ASCII) file types.

2.1.2 Ground Survey Limitations of Accuracy and Precision

Limitations of conventional survey equipment and field collection practices will constrain the upper limits of accuracy known as acceptable tolerances in error. Differential leveling can produce vertical precisions$_z$ of 0.01’, if proper field practices are followed, but differential leveling does not account for horizontal$_r$ measurements. Optical electronic distance measurement total stations can collect realistic horizontal$_r$ precisions of 0.05’ with compromised precisions in the vertical$_z$. One-Second manufactured total stations combined with redundant angle and distance measurements, and the reduction of measurements can produce 0.005’ precisions (Crawford 2003). However, this is not a common practice for collecting data for large-scale maps because of the time expense involved. It is not common to use differential leveling for vertical$_z$ side shots either. The manufactured limitations of precision achieved with conventional survey equipment limits the data accuracy. However, the accuracy of other ground survey equipment is limited by technology regardless of the precisions reported after the decimal in the dataset. A RTK GNSS in ideal conditions can collect data with a horizontal_r accuracy of <0.09' and a vertical_z accuracy of <0.18' and can be used to quickly gather data for mapping in a large area (Nico et al. 2005). Terrestrial LiDAR can collect x,y,z data with accuracies <0.005' dependent on the reflective surface and post-process data point filters.

Various errors introduced from metrology process can include randomness that affects precision, systematic that affects accuracy, and a combination of the two both systematic and random (Keim et al. 1999). The specific detectability of these errors is based on quality field surveying practices during the validation process. A worse case are the undetectable errors that creep into the final DTM.

2.2 Sampling Methods

2.2.1 Field Survey Sampling Bias versus Systematic Sampling of a DEM

The greatest difference between an in situ field survey crew completing a ground survey and other data collection technologies is the first-person data sampling bias process. Remote sensing deliverables and a Digital Elevation Models (DEM) contain coordinates. The only bias that these methods can create are either predetermined by their sampling method or post-processing methods employed including interpolation to generate a regularized raster DEM. Often, the mechanical methods used by LiDAR or photogrammetry interpolation produces a systematic, uniform grid configuration of x,y,z data. The classification and description of this data is done post-process from the collection and the inclusion of this data becomes very difficult because of the quantity of shots. An in situ field survey crew will purposely bias the data collection sample to collect an appropriate amount of data to define planimetric and topographic features to comply with the level of accuracy standards for the purpose of a large scale map. The advantage to this method is that it relies on the human decision to classify, interpolate, and validate the significance of the data during the time of collection. A downside to this method is that critical data can be omitted. This is a classic example of humans versus computers, a computer can iterate several mundane tasks incapable of humans, but a human can comprehend one anomaly elusive to a computer.

2.2.2 Terrain Data Sampling

It would be impossible to record the location of every point within the scope of a mapping area, so sampling is necessary to create and augmented reality digital terrain model (Lo and Yeung 2007). There are two approaches to sampling: Systematic and Adaptive (Lo and Yeung 2007). Systematic sampling records data at regularly spaced intervals; whereas adaptive sampling is recording data at variable selective intervals. There can also be a combination of the two methods where samples can be collected systematically, but in adaptive areas.

Systematic data collection produces an evenly distributed dataset. This data geometry is most commonly represented in Digital Elevation Models (DEMs). A limitation of systematic sampling of elevation data is that critical points of elevation are most likely not at the intersection of the sampling grid. This can omit critical planimetric features like gradient breaks or maximum elevations. Adaptive sampling collects randomly spaced elevation data that is structured in a digital format, most commonly an arc-node vector model called a triangulated irregular network (TIN) (Ghilani and Wolf 2012). The adaptive method is best for terrains that are complex. The digital representation of a raster format DEM can be converted to the arc-node vector model and vice versa as the TIN model can be interpolated and systematically resampled to produce a raster. The sampling approach to create a DEM or TIN is not a mutually interchangeable process even though a systematic sampling approach can be used to create a TIN.

2.2.3 Systematic Sampling Methods

One of the various methods for a ground survey field crew to sample elevation data systematically is Regular Grid. This is when horizontal distance between sample points is equal regardless of the terrain variation (Cole and Harbin 2006). To augment systematic sampling methods to the regular grid method is called Progressive Sampling. In addition to a regular grid sampling, additional systematic points are sampled at a higher resolution in critical areas. This approach takes concepts of adaptive sampling and utilizes the technique of systematic sampling to improve the DTM quality (Liu et al. 2015).

Another method to sample elevation data systematically is by collecting regularly spaced, parallel intervals, to create a profile of the terrain. This is called Regular Profiles. The interpolation methods to determine slope without that aid of CAD are simplified when the regular spacing is a base 10 horizontal distance. This is also called Cross Sections as they produce a slice of elevation information across the linear plan. To augment this systematic approach, profile locations can be selected to bisect critical features instead of being regularly spaced and parallel. This is called Selective Profiles. When combining progressive sampling with selective profiles, the result is called Composite Sampling and starts to resemble adaptive sampling even though the collection method was purposely systematic (Weibel and Heller, 1991).

2.2.4 Adaptive Sampling Methods

Adaptive sampling methods can either be Direct or Indirect. The process of adaptive sampling using the direct method is when a vertical planimetric feature constrains the sampling locations of the data collected. The most common feature collected by this method is that of a contour line; thus this method of adaptive sampling is also called the Trace-Contour Method. Samples are taken in the field by trial and adjustment by an in situ survey crew. This method is usually employed when the contour elevation has great significance over the horizontal location like along a shoreline of a reservoir or critical "breaking daylight" elevations for hydrographic applications.

The direct method is costly and often an indirect method is used to adaptively sample data, this is called the Controlling-Point Method. The sample bias is determined by "controlling points" that are critical to define the topography (Ghilani and Wolf 2012). These examples are local extremes of elevation like high and low points as well as planimetric features that would critically alter the representation of the digital terrain model. Ridges, valleys, lines of grade breaks at the top of slope or toe of slope, retaining walls, headwalls, wingwalls, back of curb, gutter valleys, edge of pavement, the crown of a centerline, or a top elevation of a drop inlet for storm water collection are all controlling points adaptively sampled, indirectly, to create a digital terrain model.

It may seem that sampling a linear planimetric feature like the edge of a road will be the direct method, but it is considered indirect. The indirect method derives interpolated elevations using a TIN model. The direct method of adaptive sampling eliminates interpolation by validating the horizontal position of a desired elevation where the sample is taken. Whenever digital elevation models are created by systematic sampling approaches, the accuracy of the DEM is often validated by an adaptive direct sampling method to statistically compare the DEM's represented elevation values to the realized elevation values using RMSE comparison.

2.3 Reconstruction Methods of Raw Data into a DTM

2.3.1 Triangulated Irregular Network

A triangulated irregular network is an arc-node vector model that represents a continuous surface made up of a mosaic of triangle facets. In comparison to other digital surface representation formats like raster, the vector model can offer a significant reduction in data size and improve computer processing capabilities (Fowler and Little 1979).

The triangle has three edges represented by vectors which are connected by terminal points called nodes. The face of the triangle is a plane that has slope and directional properties. The edge of the triangle represents grade breaks on the surface of the TIN. Given an array of topographical points becoming the nodes of the triangle, the TIN can be calculated several different ways by creating different connecting vector patterns (Li et al. 2005). This can create a variety of TIN configurations that will directly impact the accuracy of the digital terrain model or any of the subsequent derived products from interpolation like model generated contours (O'Sullivan and Unwin 2010).

The most common method to create an accurate TIN from ground survey raw data uses an algorithm with computer software to complete a Delaunay triangulation solution. Delaunay triangulation creates well shaped triangles that minimize triangular slivers with one small interior angle. The Delaunay triangulation algorithm uses nearest-neighborhood regions, proximal regions, to create a Thiessen polygon (Li et al. 2005). If all of the sampled points share an edge of the derived polygon, then vectors are assigned to connect the nodes and create a triangle. This process of creating a TIN can be tested by creating a circle through the nodes of the triangle and no other nodes will be included within the area of the circle (Petrie and Kennie 1991). Conventional Delaunay triangulation algorithms only consider a 2D distribution to prevent poor triangle geometries, but higher order algorithms that consider height fields can be used to improve the quality of the TIN created purely by data (Wang et al. 2001). Pure data-dependent triangulations are rarely used in practice because of the "slivers" of triangles produced, but as drafting software developers evolve, it is important for the field survey crews sampling mass points to understand how these algorithms construct the data (Rodriguez and Silveira 2017).

The utility of a TIN for analysis in volumetric and surface calculations is more accurate than other methods such as square grid or sectional methods because the benefit of edge and face interpolation (Hao and Pan 2011). The use of a TIN can also provide other surface metrics such as slope and aspect (Bhargava et al. 2014).

2.3.2 Constrained Delaunay TIN

In addition to creating a TIN model using Delaunay triangulation, the solution can be constrained by pre-determining factors that would limit the algorithm's solution. This is called a constrained Delaunay triangulation (CDT). This process is done purposely by defining an edge of the triangle and preventing the solution to calculate another edge crossing the constraint. The CDT method is preferred not only because it modifies the TIN algorithm, but it often produces well shaped triangles (Silveira and Kreveld, 2009).

These constraining lines are called Break Lines. If the location of a valley, ridge line, or grade break is known, the constructing a triangulation solution that accounts for these features is a more accurate solution. Most often break lines are chosen from planimetric features collected by direct and indirect adaptive sampling methods (National Institute of Standards and Technology 2018). Delaunay triangulation solutions can also be constrained by hydrographic features like littoral shorelines or riparian features. The accuracy of the TIN model can be significantly improved when the construction is based solely on systematic mass points and hydrographically constrained (Chen et al. 2012).

2.3.3 Interpolation from DEM to DTM

A DTM can also be produced from high resolution, systematically sampled DEMs. The algorithms used to create the TIN use different interpolation techniques including: inverse distance weighting (IDW), ordinary kriging (OK), universal kriging (UK), multiquadratic radial bias function (MRBF), and regularized spline with tension (RST), each with various results (Chaplot et al. 2006). The use of these interpolation techniques are all improved when the position of topographic structures are used to constrain the solutions (Desmet 1997). These methods of constructing a DTM from DEM data are most closely identified by LiDAR quality standards and easily analyzed because of the spatial uniformity of the data. Because of the universal methodology defined by de jure standards, large scale mapping products derived from interpolating DEM data can easily be analyzed to de facto ASPRS 2014 Standards. Although multiple interpolation techniques exist to construct the DTM, the magnitude of errors found between data sample survey strategies in one specific case study (Heritage et al. 2009) exceeded any of the errors found between the various interpolation techniques. It is important to include this information in the reconstruction methods of raw data into a DTM because field survey crews can subsidize conventional survey methods with other technologies like terrestrial LiDAR, structure from motion (SfM) photogrammetry, or even remote sources.

As interpolation techniques, like kriging, are used in the creation of the DTM; those same interpolation techniques are used to derive secondary products like vectorized contours from the DTM.

2.4 Best Practice for Data Model Providers

With the benefit of a verified control network, comprehensive scope of site conditions, and determined instrument methods, a field survey crew can collect highly accurate and complete datasets for ground surveys. First, the ground survey field crew focuses on planimetric features with the expectation that these objects can be used for the construction of the DTM. Next, breaklines and controlling points used to constrain and construct a Delaunay TIN should be collected as planimetric line features.

Breaklines can be field coded as top of slope, toe of slope, front of step, bottom face of wall, flumes, flowlines, crowning centerlines, edge of water, and any other linear object that will help construct the most accurate DTM (Koch and Heipke 2006). Controlling points are point objects that define a local area's extreme topographic influence like the top of a hill, or the bottom of a depression. Care must be taken to discern which points should be either included or excluded as a node to create the DTM. A planimetric object point collected on the top nut of a fire hydrant will not represent an accurate DTM. Finished floor elevations used to constrain a buildings polygon would also have a negative impact on the DTM. Line objects like fences that are taken specifically to display horizontal properties can mistakenly be used as TIN nodes.

The last series of points to be collected are grade points. It is difficult to locate any published recommendations on grade point density or pattern that has an analytical influence on the DTM. The best practice for collecting topographic data used to construct a constrained Delaunay TIN is an adaptive approach using the controlling point method subsidized by a systematic approach for collecting grade points. It is necessary to collect a high enough density of grade points to prevent inaccurate Delaunay solutions and in a systematic pattern to prevent poor Delaunay solutions (O'Sullivan and Unwin 2010).

2.4 An Appropriate Published Scale for a Large Scale Map

Using a North American ARCH D (24"x36") sized plot and a scale of 1"=100', the maximum area to be displayed is less than 200 acres. Even with increasing the size to ARCH E (36"x48") will create a maximum plotted area of 360 acres. Table 3 lists the border limits size in inches with a ½" margin of International Standards Organization for typical architect drawing sized paper in the United States (Editor, 2007). It is rare for the scale factor of a large scale map to be less than 1"=100' even in linear mapping projects such as sewer line designs or road alignments. The drafted strip map product will create multiple sheets connected at match lines in order to display the level of detail necessary over such a wide area. The practices and analysis presented in this paper will not focus on scales less than 1"=100'. In addition, the level of detail necessary for some applications might mandate a scale closer to 1"=10' regardless of the scope of area to be collected. When the scale becomes larger, it is assumed that a higher density of sampling is necessary to achieve the level of confidence in critical detail.

Table 3: Typical Published Dimensions in Inches with ½" Border Margins (Editor, 2007).

International Standards Organization (ISO)	
Inch Drawing Sizes	
Architect Drawing Size	**Typical Border Size**
A	8.00 x 10.50
B	10.50 x 16.50
C	16.00 x 21.00
D	21.00 x 33.00
E	33.00 x 44.00

2.5 Validating DTM Accuracy to Current Standards

The NMAS 47 Standards establish the precedence of using a minimum sample size of check-points on the map product to be checked against an independent dataset of a higher accuracy order. These points were qualified as well-defined points and omitted map products that had interpolated features. The ASPRS 90 standards still focus on the concept of well-defined points, but allow the x,y coordinate system of the mapping product to qualify a positive field location of check-points.

The data collected by ground surveys is of the highest order of accuracy. However, the accuracy of digital terrain models derived from these ground survey points can quickly degrade based on the modeling methods, interpolation, and sampling bias. "Accuracy should not be specified and tested for the TIN with the expectation that derivatives will meet the same accuracy. Derivatives may exhibit greater error. Specifying accuracy of the final product(s) requires the data producer to ensure that error is kept within necessary limits during all production steps" (National Digital Elevation Program 2004).

The NSSDA does not address the suitability of data for any product or establish error thresholds. The National Digital Elevation Program 2004 Guidelines sought to subsidize the NSSDA standards and warn that deliverables should specify whether they were directly compiled or derived from another data model. These guidelines also suggest that if grade points or contours are specified as the deliverable, check-points can be interpolated at the horizontal location of a derived digital terrain model and tested (Maune 2007).

The ASPRS 2014 standards suggest that vertical check-points "shall be surveyed on flat or uniformly-sloped open terrain and with slopes of 10% or less." This random point sampling does little to validate a digital terrain models functionality used for large scale mapping purposes regardless of the sample size. Data collected by ground surveys are used to construct a constrained Delaunay triangulated (CDT) digital terrain model where the positional accuracy of break lines and TIN facets are the priority.

It is possible for a digital terrain model produced from a high order of accuracy ground survey point set to be within compliance of RMSE thresholds of ASPRS 2014 standards with complete disregard to the functionality of the surface. DTMs are not spatially uniform and have areas of complexity and simplicity combined. The current analysis methods assume spatial uniformity for simplicity, but alternative DTM analysis based on fuzzy inference systems (FIS) can be used to establish better quality classifications (Bangen et al. 2016). The first limitation to the ASPRS 2014 standards listed in the report is a warning that "methodologies for accuracy assessment of linear features (as opposed to well defined points)" may not be relevant. This limitation warning will apply to break lines and TIN vertices. Additional research is necessary to determine proper methods to analyze a TIN vertices using RMSE at a 95% confidence.

Using a sample of data points from the digital terrain model and comparing them to an independent, higher order of accuracy, measurement by ground survey at the same coordinate will provide the qualification values to determine an accuracy class of the DTM by both horizontally and vertically. However, there is no defined ASPRS 2014 accuracy class, only reference to common ASPRS 90 and NMAS 47 classes. Using a few common ASPRS 90 classes, the ASPRS 2014 standards recommend vertical accuracies without contour interval constraints.

The equation for accuracy analysis using RMSE with a coordinate in a specified direction is shown as (American Society for Photogrammetry and Remote Sensing 2014):

$$RMSE_x = \sqrt{\frac{1}{n}\sum_{1=1}^{n}(x_{i(datapoint)} - x_{i(surveypoint)})^2} \quad (1)$$

where

$x_{i(datapoint)}$ is the coordinate in the specified direction of the ith check-point in the data set,

$x_{i(surveyed)}$ is the coordinate in the specified direction of the ith check-point in the independent source of higher accuracy,

n is the number of checkpoints tested,

i is an integer ranging from 1 to n.

The equation for accuracy analysis using RMSE for a horizontal radial distance is shown as (American Society for Photogrammetry and Remote Sensing 2014):

$$RMSE_r = \sqrt{RMSE_x^2 + RMSE_y^2} \quad (2)$$

where

$RMSE_x$ is the root mean square error in the x axis,

$RMSE_y$ is the root mean square error in the y axis.

The equation for vertical accuracy analysis using RMSE is shown as (American Society for Photogrammetry and Remote Sensing 2014):

$$RMSE_z = \sqrt{\frac{1}{n}\sum_{1=1}^{n}(z_{i(datapoint)} - z_{i(surveypoint)})^2} \quad (3)$$

where

$z_{i(datapoint)}$ is the z coordinate value of the ith check-point in the data set,

$z_{i(surveyed)}$ is the z coordinate value of the ith check-point in the independent source of higher accuracy,

n is the number of checkpoints tested,

i is an integer ranging from 1 to n.

2.5.1 ASPRS 2014 Accuracy Classes

Tables 4 and 5 show the absolute horizontal and non-vegetated vertical accuracy classes for geospatial data using the RMSE analysis method (American Society for Photogrammetry and Remote Sensing 2014). The units are in centimeters and the accuracy class is arbitrary based on RMSE results.

Table 4: Horizontal Accuracy Class for Geospatial Data (ASPRS 2014, Table 7.1).

Horizontal Accuracy Class	Absolute Accuracy		
	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_r$ (cm)	Horizontal Accuracy at 95% Confidence Level (cm)
X-cm	≤X	≤1.414*X	≤2.448*X

Table 5: Vertical Accuracy Class for Geospatial Data (ASPRS 2014, Table 7.2).

Vertical Accuracy Class	Absolute Accuracy	
	$RMSE_z$ Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)
X-cm	≤X	≤1.96*X

The metric unit of centimeters is not common to land surveyors in the United States. In addition, large scale maps in the United States commonly use Empirical unit scales of 1” = usft’ instead of the metric scale of 1 unit: scaled unit as reported in the ASPRS 90 standards. For utility and clarity, it is important for data model providers to understand the standardized certifying accuracy classes in units that are applicable to the data model contractor. Tables 6, 7, and 8 are useful tables that the ASPRS 2014 standards provide in their documentation for reference to identify current accuracy classes and legacy equivalents. This study has converted the published data from metric units to US Survey Feet. Table 6 shows horizontal RMSE accuracy classes in reference to ASPRS 90 scaled precision classes. Table 7 shows vertical accuracy classes using the ASPRS 2014 RMSE testing method in US Survey Feet and Table 8 compares those ASPRS 2014 vertical accuracy classes to legacy scaling precision classes based on contour intervals, also in US Survey Feet.

Decimals of a US Survey Foot (usft) can be converted by a scaling factor that is defined by statute in most states, including Texas (V.T.C.A., Natural Resources Code §21.077.(1),(2)). where

"one meter = 39.37 inches exactly",

"one foot = 12.00 inches exactly".

The conversion factor used to compare the ASPRS 2014 standards to the ASPRS 90 standards for horizontal classes is a Map Scale Factor for Class 1 = $RMSE_{x/y}$*40cm and a Class 2 = $RMSE_{x/y}$*20cm. The ASPRS 90 standards identify the contour interval of a Class 1 Large Scale Map as $CI_1 = 3*RMSE_z$ and a Class 2 at half of that value, $CI_2 = 1.5*RMSE_z$. The ASPRS 2014 Standards do not identify a suggested contour interval based on a large-scale map published scale or relate an arbitrary Horizontal Accuracy Class to a Vertical Accuracy Class. The reporting certifications for horizontal and vertical are separate and state that the, "terms are within compliance of RMSE thresholds and other accuracy criteria… in accordance with the FGDC NSSDA Standards" (American Society for Photogrammetry and Remote Sensing 2014).

Table 6: Horizontal Accuracy/Quality Examples for High Accuracy Digital Planimetric Data in US Survey Feet converted from Table B.6 of the ASPRS 2014 Standards

ASPRS 2014			**Equivalent to map scale in**		
Horizontal Accuracy Class $RMSE_x$ and $RMSE_y$ (usft)	**$RMSE_r$ (usft)**	**Horizontal Accuracy at the 95% Confidence Level (usft)**	**ASPRS 1990 Class 1 (Imperial Scale)**	**ASPRS 1990 Class 1**	**ASPRS 1990 Class 2**
0.05	0.06	0.11	1"=5'	1:60	1:30
0.09	0.13	0.22	1"=10'	1:120	1:60
0.18	0.26	0.45	1"=20'	1:240	1:120
0.27	0.39	0.67	1"=30'	1:360	1:180
0.37	0.52	0.90	1"=40'	1:480	1:240
0.46	0.65	1.12	1"=50'	1:600	1:300
0.55	0.78	1.34	1"=60'	1:720	1:360
0.91	1.29	2.24	1"=100'	1:1200	1:600
2.44	3.45	5.97	1"=200'	1:2400	1:1200

Table 7: Vertical Accuracy/Quality Examples for Digital Elevation Data in US Survey Feet converted from Table B.7 of the ASPRS 2014 Standards.

Vertical Accuracy Class (usft)	**Absolute Accuracy**		
	$RMSE_z$ Non-Vegetated (usft)	**NVA at 95% Confidence Level (usft)**	**VVA at 95^{th} Percentile (usft)**
0.03 - usft	0.03	0.06	0.09
0.10 - usft	0.10	0.20	0.30
0.33 - usft	0.33	0.65	1.00
0.66 - usft	0.66	1.31	2.00
1.66 - usft	1.66	3.27	5.00

Table 8: Vertical Accuracy of the ASPRS14 Standard Compared with Legacy Standards in US Survey Feet converted from Table B.8 of the ASPRS 2014 Standards.

Vertical Accuracy Class	**$RMSE_z$ Non-Vegetated (usft)**	**Equivalent Class 1 contour interval per ASPRS 1990 (usft)**	**Equivalent Class 2 contour interval per ASPRS 1990 (usft)**
0.03-usft	0.03	0.09	0.05
0.10-usft	0.10	0.30	0.15
0.33-usft	0.33	1.00	0.50
0.66-usft	0.66	2.00	1.00
1.66-usft	1.66	5.00	2.50

CHAPTER 3: BEST PRACTICE FOR DATA MODEL PROVIDERS

3.1 Preliminary Site Review

When the contractor commissions a firm or a department to complete a ground survey for the purpose of creating a DTM for a large scale map product, it is important to understand the purpose of the map and the map's focus area. There exists a unique environment and related stipulations from the site that will directly affect the procedures of completing a quality ground survey. The in situ field crew collecting the measurements of the planimetric and topographic features needs to have a macro scope of the project before focusing on micro critical features for collection.

It can be difficult in a complex environment to understand the project requirements while focusing on micro detail necessary for a large scale map product. It is best to not "lose sight of the forest in spite of the trees." Though a field crew seeks to be as efficient as possible in data collection, there is usually a necessary budget for return work to collect areas and features that might have been missed or that were omitted in the scope of work before the final raw dataset is verified. Similar to driving a vehicle at night, you can only see as far as the headlights; eventually the driver will reach their destination. These are good maxims for field crews contemplating an approach for completion.

Field crews have the use of several measuring technologies at their disposal. During the preliminary site review period, it is best to determine which method will return the most efficient expense of energy in relation to the accuracy, precision, and completeness necessary to compile the raw data. RTK GNSS will be difficult to use in canopy and impossible near buildings. A total station might not be as efficient as RTK GNSS mounted on a vehicle at collecting ground points. A field book might require post-processing measurements into a digital format, but may be the only method available to increase completeness in the dataset. Often, a single project site will require a variety of collection methods.

Dependent on the post-processing software or coordinating personnel, a specific syntax used for field coding data points is necessary. In addition, there will be specific coordinate system parameters that will need to be accounted for before any data is collected to help facilitate multiple contributions in the ground survey process. The expected level of accuracy and completeness will also need to be considered prior to beginning data collection because accuracy is an inverse function of effort.

3.2 Establishing Local Control Points

After becoming familiar with the site area, a primary control network needs to be identified away from the site area. This can be done by locating published geodetic control monuments or site specific control monument and then using those validated points to establish a secondary control network. Secondary control monuments are usually established near or within the site area. These are stable monuments like brass capped concrete monuments or 5/8" diameter capped iron rods that serve as site specific control points. The projects coordinate system is realized using these secondary control points, so it is important to establish the position of these points in protected and accessible locations. The secondary control network can actually become the primary control network whenever the field survey crew publishes coordinate positions on these secondary monuments either by independent system observations or by defining the sites local coordinate system to these realized monuments. There is no hard and fast rule for the number of secondary and primary control points, but these located and protected positions will permeate the life cycle of the mapping project and will establish the sites coordinate system. It is always good practice to have at least 5 stable control points within a 3 mile radius in case a local GNSS system is used to broadcast corrections via radio based on a site calibration (McNamee 2014). Some popular field controller software like Trimble Access requires 4 known x,y,z points, and the 5^{th} coordinate can be used as an independent check. Some additional precaution for establishing secondary control points is that they be constructed in inter-visible "sister" pairs so that conventional optical equipment can occupy one monument and backsight the other (California Department of Transportation 2016).

3.3 Referencing Control Points to Construct a Control Network

The secondary control points are observed either by redundant RTK GNSS sideshots at sessions greater than 180 epochs, static GNSS observations greater than 30 minutes, open or close ended optical traverses, differential leveling to adjust the vertical, all with the intent to establish additional precise control points. In practice, all of these methods can be used and observations can be mathematically reduced to create the most relative accuracy and highest precision available to the limitations of measurement error. Often, horizontal precision is only reported to the 0.001 decimal and vertical precision to the 0.01. The relative error of closure between two measured points is reported as a ratio of error per inversed distance. With today's quality of equipment, there is no reason for a control network to have an error greater than 1:15,000 (Texas Society of Professional Surveyors, Category 6, Condition I).

In addition to establishing control points horizontally, it is good practice to complete differential leveling throughout the entire secondary control points and adjust elevations to a "father" point (Cole and Harbin 2006). Vertical accuracy obtained by GNSS or optical equipment will not guarantee a 0.01 precision. Another reason to adjust vertical by leveling is to reduce the liability of the field crew whenever errors are discovered in the large scale map applications.

Using the secondary control points, tertiary control points can be established throughout the project, either by a comprehensive initial effort or by ad hoc during the data collection process. It is good practice to establish a quality tertiary control network prior to collecting sideshots though. These points can be translated, rotated, and error distributed throughout the entire control network, as well as adjusted for elevation based on differential leveling.

Regardless of how the control points are established or what order of stability, when the raw data is verified, all of these points become validated and truncated as primary control and will be used in the application of large scale map product. One method to assess the quality of the topographic survey is to analyze the order of accuracy and precision of the control points used as the framework to collect subsequent sample points (Bruin et al. 2001). The process of establishing control helps the field crew improve their position from the initial Preliminary Site Review. It also prevents systematic error during the sampling process and allows for efficient data collection.

3.4 Field Codes and Line Work

The most finalized system for field coding stems from a relational database that develops a field code library .fxl. Feature classes can be selected from a list, attributions are formatted, and optional domains are available. The export from the field controller can be directly inputted into verification software and inputted into a Geodatabase. Although point, polyline, and polygon are supported by this method, some .fxl only utilize the point type. Polylines can be determined in the field during the collection process by using “Start” and “End” descriptors, but these methods are custom to the verification software.

Other proprietary field coding systems are developed by either the data acquisition provider, the model constructor, or the DTM contractor. These systems vary in simplicity from not coding descriptions at all, to coding descriptive attributes as integer values, to combining alphanumeric descriptors, or complying with a published style. Custom import modules, parsing programs, or even manual entry will help digitize planimetric features and topographic data points. Point number ranges can also be managed to prevent overwrite errors or identify field crews responsible for the data collection.

Regardless of the coding system, quality hand written diagrams and journal entries recorded at the time of data collection are valuable sources of information to be used during the verification phase of processing raw data. How well the field crew codes the data points will directly affect the quality of the dataset and the accuracy of the DTM.

3.5 Planimetric and Topographic Data Collection In Situ

After a control network is established in the project area, what practices and sampling methods will be best for an in situ field survey crew completing a ground survey? The application of large scale mapping products demand completeness in the dataset of all planimetric features. Point objects like tree trunks, utility poles, water meters, or a sign post can cause significant consideration based on the object's location and often what the object represents. A power pole for example will probably have overhead electric connected, a sewer manhole is terminus point for a gravity sewer line, and a tree trunk location will have a geofence buffer of a root ball to protect.

Planimetric line objects like back of curb, edge of pavement, and barbed wire fences need to be sampled at all significant points. It takes two points to create a line, and three points to define an arc. Where point objects can be collected to define a line object, line objects can also be used to define topographic features. If this is the case, significant points that define a planimetric line object would include vertical changes in addition to horizontal changes. With the inclusion of redundant shots, the line objects will create polygon objects. Line coding three sides of a concrete slab is not enough to close the fourth side without the aid of detailed field notes.

One recommendation for nominal data density shot intervals for various planimetric features is specified in the United States Army Corps of Engineer's manual on *Control and Topographic Surveying* (EM 1110-1-1005) (United States Army Corps of Engineers 2007). The shot interval density is based on published map scale similar to the NMAS 47 Standards and does not quantify recommendations at scales less than 1"=100'. The best practice is to bias every sample based on significant points with the expectation that planimetric line objects can be used for constraining a Delaunay TIN.

3.6 Scope of Area Drape

The large scale mapping product depends on planimetric and topographic clarity of features that enter and exit into the targeted project focus area. This is called area drape and include significant point objects within a few feet of the project focus area that need to be annotated, polygon objects that might dominate a viewport, and line objects that need to project outside of the viewport. There is no defined rule for the buffer distance other than the data collector imagining they are the one also drafting the final map product.

There is a more important aspect to area drape beyond planimetric feature details and that is the topographic data points used to create the DTM. The DTM application contractor often wants to know what the terrain represents outside of the focus site area. Most civil engineers request an additional 20'-50' topographic data collection buffer of grade points or significant breaklines during the ground survey for large scale mapping projects. When this data lacks, the DTM constructor will often calculate additional raw data points to help define the DTM.

3.7 Ground Point Sampling Methods

Systematic sampling, even with the use of progressive sampling and composite sampling methods, is a poor approach for large scale mapping projects. Large scale maps are purposely designed to show great detail of critical features. The systematic sampling methods are inherently flawed to omit critical features being the case that controlling points will most likely not be located at the intersection of a regular interval. This does not mean that systematic sampling methods should be rejected for the purpose of sourcing data for large scale maps though. Adaptive sampling techniques identify critical data points both in vertical and horizontal that increase the accuracy of the digital terrain model, but the topological geometry of these points used alone tend to produce a poor triangulated irregular network.

Adaptive sampling methods has the potential to create a weak Delaunay triangulation solution by forcing “sliver” triangles along linear features. Systematic sampling methods will easily create “well-shaped” triangles. The difference isn’t the sampling method, but rather the geometric organization of the sampled points. Systematic sampled data needs adaptive sampled methods to improve the accuracy of the digital terrain model by identifying controlling points and determining constraints to the Delaunay triangulation solution, but adaptive sampling methods need systematic sampled data to create a stronger Delaunay triangulation solution that would benefit from regular interval nodes. During the reconstruction process, the accuracy of the DTM can be improved by combining TINs that are made from both a CDT adaptive sampling method and DEMs that are created from systematic sampling methods (Yang et al. 2005). The combination of field sampling techniques can be prescribed by the DTM contractor based on the accuracy requirements of the model compared to the cost of data collection process (Januchowski et al. 2010).

3.8 Survey Strategy Exceptions

Not all breaklines need to be collected to create a high accuracy DTM. In complex topographic areas, a high density of grade points can be taken with the hope that the Delaunay algorithm will configure the TIN correctly. This can be done around random small stockpiles or voids that are anomalies to the surface.

There are situations when a high density of collected ground points will not improve the accuracy of the DTM. When the reconstruction method is that of a constrained Delaunay TIN, an identified breakline is necessary. Systematic removal of mass points and purposefully defining breaklines can improve a DTMs functionality and accuracy (Vallé and Pasternack 2006). The stockpile scenario where volume of the material needs to be calculated would require the field crew to locate the finite edge of the material, the same for volumes of voids. The reason is because of the difficulty in constructing the TIN from just nodes. Another issue with high density ground points to create a DTM is that the number of points exceed the processing capabilities of some computers to calculate the TIN. Although a modern machine with point cloud specific software can handle 100s of millions of points, a standard drafter’s workstation would fail to function. Sometimes the systematic data collection of mass points using auto logging features of time or distance with RTK GNSS or depth sounders will collect poor accuracy points or awkward spatial distribution. When a TIN is constructed from these points, the facets are incorrect and the DTM does not resemble reality. The drafting technician may need to down sample, “point-subtractive” method, to minimize errors during the reconstruction process (Schröder and Roßbach 1994). Constructed DTMs can have very different outcomes based solely on the resolution of the sampled points in the dataset (Cook and Merwade 2009). It is difficult for the drafting technician to verify quality and time consuming to omit mass points in order to construct a better TIN model.

3.9 Reconstruction of Raw Data

The verification of field survey data to reconstruct the data as a constrained Delaunay TIN involves compiling all sources of field data into a complete and validated dataset. The data can be collected for the project from different field crews using different field controllers, different point label ranges, various hard copy notes that would need to be digitized, and can contain attribute errors. Once the dataset has been compiled and verified, it is best to omit all points from being included in the surface to prevent inaccuracy of the DTM. Next, select only the feature classes that needs to be included in defining the surface. This would include planimetric features that have quality ground point elevations (not the top nut of a fire hydrant, the outlier wooden fence corner, or a prismless shot on the face of a building or overhead electric). Select natural ground and spot elevation grade points to be included in the surface, (not finished floor elevations or flowline elevations). These are the points to include in the software's surface algorithm. Finally, analyze the TIN that was initially created and begin to manually constrain the solution by selecting and defining breaklines. With the breaklines identified, iterate the surface algorithm again.

Using a "point-additive" method, the TIN framework can be improved by the drafting technician in both areas that the TIN algorithm software is not correct or in areas that the field crew did not collect enough surface area drape (Zhou and Chen 2011). If the final deliverable is a TIN derived product at a higher resolution, like vectorized contours or a DEM dataset, then using the "point-additive" method can preserve the constructed TIN in other formats (Zheng et al. 2017). In areas that a more complex TIN needs to be nested within a simple TIN solution, the field crew should delineate specific breaklines and increase the resolution in that area. However, a drafting technician can use the “feature-point” method to better constrain the TIN (De Floriani et al. 1984). This would include the use of structural lines like retaining walls and building slabs as breaklines to either mask parts of the DTM or improve the DTM quality (Little and Shi 2001).

Now that the DTM surface is prepared and ready for delivery, this is the phase of the DTM process that standardized error testing and validation of the DTM should be performed using a ground check method and root mean square error analysis. However, this is rarely done in large scale mapping applications using data collected by ground survey because of cost. The most common method for DTM validation is simply a check by visualization; does the model appear to be correct (Lo and Yeung 2007)? The best assessment of DTM accuracy prior to the DTM delivery is “prediction by production” and a strong professional liability insurance should the model fail its utilization. There exists no current accuracy or completeness assessment standards for field surveyors sampling the data other than minimizing errors during the acquisition process and reconstructing the raw data as a constrained Delaunay TIN.

CHAPTER 4: STUDY AREAS AND DATA SETS

A practicing data model provider has collected in situ ground survey data using the best practice methods described in Chapter 2 on hundreds of large scale mapping projects over the last decade. This study focuses on sixty-one (61) of those DTMs that classified categorically as an area map as opposed to a strip map in the parameter that the plotted area of the DTM would fit on an ARCH D sized sheet and the scale would not exceed 1"=100'. All of these models qualify as ASPRS90 Class 1 equivalents and are validated as functioning models. These sites are primarily located in northeast Texas, west Texas, and northeast Louisiana. The utility of the large scale mapping projects ranges from civil engineering site design for commercial or industrial development, to volumetric surveys of aggregate stock piles, to volumetric surveys of frac ponds, to volumetric design for site balancing excavation requirements.

The field data was collected by an adaptive sampling approach using the Controlling-Point Method and the accuracy of the ground survey data is < 0.03 usft horizontal and < 0.05 usft vertical. There are no known quality of completeness issues found in the dataset after delivery to the data model contractor. Using Traverse PC survey software, field codes and line work are classified as topographic and planimetric features to be included in the surface creation as mass points and breaklines to construct a CDT.

4.1 DTM Metrics Used for Analysis

Each surface is identified by a Job Number and placed in an appropriate mapping scale group of either 1"=5', 1"=10', 1"=20', 1"=30', 1"=40', 1"=50', 1"=60', and 1"=100'. A surface report feature in Traverse PC provides metrics of the DTM including: the number of topographic points used to create the surface, number of triangles, number of edges, and the number of breaklines. Another set of metrics returned by Traverse PC is the surface's minimum and maximum Z value. This metric is not used for analysis because a range in elevation will not contribute to the complexity index or a recommended contour interval for publication.

The planar area of the TIN perimeter and the summation of the surface area of the triangles is populated in units of acres. Acres is an acceptable area unit per ASPRS14 standards, but by multiplying these values by 43,560; acres can be converted to square feet and the two attributes of planar area and surface area can be readily analyzed in a different unit.

Using the published scale, the planar areas, the surface area, number of topo points, number of edges, and number of breaklines per Job Number, all other metrics in this study are derived from these values.

CHAPTER 5: METHODOLOGY

5.1 Prediction by Production

The ASPRS 2014 Standards are designed to validate the accuracy of a DTM and provide the terminology parameters for those contracting large scale mapping products. Prior to the validation phase, this terminology for accuracy doesn't apply. One approach for analyzing the accuracy of DTM is "prediction by production", in which each process used to finalize the DTM is analyzed for error (Ley 1986).

The two processes prior to the validation phase are sampling and reconstruction. The method for sampling in this paper is ground survey procedures. By evaluating measurement limitations of precision and accuracy and considering multiple sampling methods, it is possible to define a best practice for data acquisition to achieve completeness in the raw dataset.

The reconstruction method used to create the DTM surface from the raw data is a constrained Delaunay triangulated irregular network (CDT). It is important to understand how the raw data is reconstructed to provide the most accurate model representation of the real world prior to the validation phase. Evaluation of the DTM product will not only require suitable procedures of sampling and reconstruction, but also suitable measurement and statistical procedures to determine quality (Fisher and Tate 2006). In addition, there still exists a lack of methodologies to assess the accuracy of a CDT within the ASPRS 2014 standards. The goal of this analysis is to identify possible metrics that will assist the data model provider to validate DTM quality during the verification phase.

5.2 Compiling Metrics from 61 DTMs for Analysis

This study uses a compiled dataset of metrics in table format using Microsoft Excel software. The surface of each DTM is identified by a Job Number and stored within Traverse PC as an individual .TRV file. Each Job Number is plotted on ARCH D sized paper, either in landscape or portrait orientation, at an appropriate scale to best fit the surface area on the page. This scale is used to classify the 61 DTMs into 8 scale groups. Using a surface report feature in Traverse PC: planar area (acres), surface area (acres), topo points, edges, and breaklines are output in a notepad document. This data is manually entered into columns in the table to correspond with the Job Number row. Additional data metric columns are derived from these four metrics output from Traverse PC using Excel cell formulas. The final master worksheet is created by cutting and pasting values only to prevent unseen data contamination and is shown in Appendix 1.

The test for simple resolution is completed by creating another worksheet in Excel using the values from scale, planar area, and topo points. For the ANOVA test, a column header of the scale category has the simple resolution values input into rows beneath and the Data Analysis Tool within Excel allows to select the columns, rows, and alpha value for output. For the Kruskal-Wallis test, the values in the simple resolution worksheet need to be ranked from 1 to 61 with the lowest simple resolution value being 1 (Rogerson 2015). This is done in a new worksheet. In another new worksheet, the Nonparametric Median Test requires the simple resolution value to be ranked in order and a number of values *(k)* per scale category above and below the median is counted. This *k* value per category is compared to an expected number of samples (Rogerson 2015). Excel does not have a Data Analysis Tool for the Kruskal-Wallis statistical test or the Nonparametric Median Test, so cell formulas are created.

The pursuit to identify additional efficiency factors creates several other metrics including: needed point spacing interval, surface area per planar area, number of mass points needed per planar area, recommended edges per TIN, sample bias edge benefit factor, field mass points equivalent ratio, and interpolated field collected mass points. All of these values are created using cell formulas in Excel.

5.3 Simple Resolution

First, is there a statistically significant correlation within the eight scale groups of all 61 DTMs using a simple resolution for each site?

Simple Resolution (ρ) is given as the following equation:

$$\rho = \frac{A}{B} \qquad (4)$$

where

Number of Topo Points (A) is the total number of nodes collected in the field survey used to construct the CDT,

Planar Area (B) is the area of the TIN surface on a plane.

Using analysis of variance (ANOVA) with the assumptions that: observations between and within samples are random and independent, observations in each category are normally distributed, and the population variances are assumed equal for each category.

The null hypothesis is as follows:

$$H_o: \mu_5 = \mu_{10} = \mu_{20} = \mu_{30} = \mu_{40} = \mu_{50} = \mu_{60} = \mu_{100}$$

H_A: that any one of the groups mean is not equal to another group

If the Simple Resolution value shows correlation between the scale groups, then this can be a valuable metric to determine if the data set is complete. This test will also show that NMAS 47 scaling precision tests can be applied uniformly between the scaled groups.

Multiple variations of this ANOVA test are attempted. First, by decreasing the level of confidence, then omitting different groups like the 1”=100’ that only had three samples, and finally by using different attributes: feet between points, planar area of surface with and without scaling factors, all to try and normalize the data.

In case the results of ANOVA did not fail to reject the null hypothesis, two additional statistical tests are attempted. The Kruskal-Wallis test is used to verify that either the ANOVA assumptions are incorrect or that the data is ordinal (Rogerson 2015). The Nonparametric Median Test is also tried in case the resolutions in each scale group is not normally distributed (Rogerson 2015).

If all three of these tests, with their multiple variations and confidence levels, reject the null hypothesis that Simple Resolution (Equation 5) are equal across the eight scale groups, then these results suggest that there are other normalizing factors that account for resolution metrics of these DTMs prepared by ground survey methods other than a Simple Resolution.

5.4 Identifying Efficiency Factors for Comparisons

Second, if Simple Resolution is not a valid metric to determine completeness in the dataset, what metrics can be derived to assess quality in the dataset other than precision of measurement and account for the efficiency of sample bias? Under the assumption that an accurate DTM constructed as a CDT using sample biased mass points is comparable to a statistically significant DTM constructed from a uniformly spaced DEM, parameters for a statistical significant dataset during the verification phase can start to be identified and used to verify quality in the data set.

To compare these 61 DTMs prepared by adaptive sampling methods to a statistically significant resolution of systematic sampling, the number of n^{th} samples of systematic mass points per planar surface area needs to be determined and applied to the planar area of the TIN model. Based on the published scale of the TIN model, as platted on an ARCH D sized print: The minimum Number of Mass Points Needed per Scale (*n*) is given as (Rogerson 2015):

$$n = \frac{\mathrm{t}^2}{4W^2} \quad (5)$$

where

a two tailed test with ∞ degrees of freedom at a 95% level of confidence gives a $t_{critical}$ value = 1.96 using a t-distribution table,

width of confidence level is derived from the published scale (Rogerson 2015):

$$W = \frac{\sqrt{\mathrm{S}^2+\mathrm{S}^2}}{2} \quad (6)$$

where

Scale (S) is the ground unit factor of the published scale for the TIN on ARCH D sized paper in US survey feet.

The Number of Mass Points Needed per Scale (*n*) value can then derive a nominal point spacing distance for systematic sampling per scale category. The Needed Point Spacing Interval (α) can be determined by:

$$\alpha = \sqrt{\frac{\mathrm{B}}{(\frac{\mathrm{B}}{\mathrm{S}^2})(n)}} \quad (7)$$

where

Planar Area (B) is the area of the TIN surface on a plane,

Scale (S) is the ground unit factor of the published scale for the TIN on ARCH D sized paper in US survey feet,

Number of Mass Points Needed per Scale *n* as defined by Equation 5.

The resolution value of Number of Mass Points Needed per Planar Area (β) can be determined by the following equation:

$$\beta = \frac{\mathrm{B}}{\alpha^2} \quad (8)$$

where

Planar Area (B) is the area of the TIN surface on a plane,

Needed Point Spacing Interval (α) as defined by Equation 7 is a nominal point spacing distance for systematic sampling per scale category.

The reconstruction process of the raw data into a CDT improves the final DTMs quality by interpolation. The task of a ground survey crew is to collect data as cost efficiently as possible with the understanding that sample bias and CDT reconstruction will produce the most accurate DTM. It is well accepted that an increase in cross section densities will produce a higher accuracy DTM, but lower profile spacing can produce an acceptable error DTM with less effort and minimized cost solely by the benefit of interpolation (Silveira et al. 2013).

It is necessary to account for the benefit of these efficiency factors to compare a DTM prepared in this method to a statistically significant systematic resolution. If the minimum Number of Mass Points Needed per Scale (*n*) is determined and applied to the TIN planar area, then additional unknown efficiency benefit factors of adaptive sampling bias can be determined for each TIN model per scaling category. A better indicator of accuracy for variable complexity surfaces would be the density of edges used to construct the CDT.

One of the TIN metrics reported is number of edges. Using the data from the 61 DTM projects, the average of the number of edges divided by the topo points provides a constant of 2.892 as the result. This value should be close to 3, but it also accounts for the topo points along the perimeter of the TIN model that creates the TIN boundary.

The Recommended Edges per TIN (δ) is the number of statistically significant edges per planar area as defined:

$$\delta = \beta * 2.892 \qquad (9)$$

where

Number of Mass Points Needed per Planar Area (β) as defined in Equation 8,

the constant of 2.892 is derived from the 61 DTMs in this study's data set.

A Sample Bias Edge Benefit Factor (η) can be determined as:

$$\eta = \frac{\delta}{\mathrm{E}} \qquad (10)$$

where

Recommended Edges per TIN (δ) is the number of statistically significant edges per planar area as defined in Equation 9,

Number of Edges (E) is the total number of edges of the constructed the CDT.

Using the Sample Biased Edge Benefit Factor (η), another factor can be determined: Field Mass Points Equivalent Ratio (ξ) to normalize the functioning resolution of the TIN Model that is prepared from sample bias in order to compare the systematically distributed and statistically significant Number of Mass Points Needed per Planar Area (β).

$$\xi = \frac{\beta}{\mathrm{A}+(\eta * \mathrm{A})} \qquad (11)$$

where

Number of Mass Points Needed per Planar Area (β) as defined in Equation 8,

Number of Topo Points (A) is the total number of nodes collected in the field survey used to construct the CDT,

Sample Bias Edge Benefit Factor (η) as defined in Equation 10.

In order to compare a ground survey sample biased DTM, constructed as a CDT, to a statistically significant systematic resolution DTM, a derived resolution of Interpolated Field Collected Mass Points (Υ) needs to be determined using the number of Topo Points collected, the number of Mass Points Needed Planar Area (β), and the Field Mass Points Equivalent Ratio (ξ). This value of Interpolated Field Collected Mass Points (Υ) is the number of points that the ground survey field crew would have sampled systematically had they not used an adaptive sample bias method of controlling-point method.

The Interpolated Field Collected Mass Points (Υ) can be calculated as:

$$\Upsilon = A + (\beta * \xi) \qquad (12)$$

where

Number of Topo Points (A) is the total number of nodes collected in the field survey used to construct the CDT,

Number of Mass Points Needed per Planar Area (β) as defined in Equation 8,

Field Mass Points Equivalent Ratio (ξ) as defined in Equation 11.

When these efficiency factors are applied to the TIN report metrics of accuracy validated DTMs, then a model provider can compare the Interpolated Field Collected Mass Points (Υ) value to the statistically significant Number of Mass Points Needed per Planar Area (β) to determine spatial completeness in the data set. The Interpolated Field Collected Mass Points (Υ) can be a quality metric that a data model provider can use to compare a resolution parameter required from the data model contractor. This study also presents a method to identify efficiency factors that are evident when creating DTMs by ground survey practices described in this paper.

A test to determine if the data set of a DTM prepared from biased ground survey samples and constructed as a CDT is statistically significant is given as:

$$\text{Ground Survey Resolution Test} = \Upsilon - \beta \qquad (13)$$

where

Interpolated Field Collected Mass Points (Υ) as defined in Equation 12,

Number of Mass Points Needed per Planar Area (β) as defined in Equation 8.

If the number is positive, then the bias adaptive sampling method of the ground survey field crew and the interpolation expectation of the DTM is more than statistically significant. If the number is negative, then the DTM model is not statistically significant.

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Results

6.1.1 ANOVA Test for Simple Resolution

Using the Simple Resolution (Equation 5) of topo points per acre in between the eight groups of scale for all 61 DTMs, the first test is to determine if the variance of resolution mean is equal between the groups. The null hypothesis (H_o) and alternate hypothesis (H_A) are as follows:

H_o: $\mu_5 = \mu_{10} = \mu_{20} = \mu_{30} = \mu_{40} = \mu_{50} = \mu_{60} = \mu_{100}$
H_A: that any one of the groups mean is not equal to another group

There are 8 scaling groups and 61 samples.

$$F_{Critical} = \frac{k-1}{n-k}, \quad (14)$$

where

k is the number of scaling groups

n is the number of samples

Using a F-distribution table with 7 as the numerator and 53 as the denominator, $F_{Critical} = 2.188$.

Figure 2 shows the results of the ANOVA test run using Microsoft Excel software to have a $F_{test} = 8.604$ in which the H_o is rejected because $F_{test} > F_{Critical}$.

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
5	11	7787.754588	707.9776899	324152.1924		
10	12	1335.083175	111.2569312	4573.998927		
20	9	722.8969155	80.3218795	2400.037785		
30	5	314.5400672	62.90801345	571.0742024		
40	8	365.1201348	45.64001685	564.4020873		
50	6	175.9091076	29.3181846	275.6595705		
60	7	288.3709501	41.19585001	775.7069038		
100	3	49.42849401	16.47616467	24.10699811		
	61					
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3776726.291	7	539532.3273	8.604328601	5.23039E-07	2.18806055
Within Groups	3323352.079	53	62704.75621			
Total	7100078.37	60				

Figure 2: Excel Results from ANOVA Test on Simple Resolution

There is no correlation using the ANOVA test within multiple iterations of changing test parameters like decreasing the level of confidence, omitting different groups, and using different metric attributes. There is no correlation using the Kruskal-Wallis test or the Nonparametric Median Test with multiple iterations either. These results show that additional metrics need to be developed to account for the benefit of sampling bias and DTM construction processes other than a Simple Resolution.

6.1.2 Results from Applying Efficiency Factors

The next set of results show that classifying the TIN models by published scale radically affects the data analysis and TIN models prepared at the 1”=5’ scale has little to do with models prepared at the next smaller scale. The results of Number of Mass Points Needed per Scale (Equation 5) are shown in Table 9. When the Number of Mass Points Needed per Scale values are applied to the TIN planar area by Equation 8 to produce the Number of Mass Points Needed per Planar Area, two of the DTMs at the 1”=5’ scale (Job Numbers: 1500138 and 1700085) are extreme outliers showing that they needed over 45,000 points to be considered statistically significant at a 95% level of confidence!

Table 9: Number of Mass Points Needed per Scale

		Number of Mass Points Needed per Scale	
		P value at 0.05 LOC	P value at 0.10 LOC
Scale	Weight	*1.96*	*1.645*
1"=5'	0.03536	27.16	19.13
1"=10'	0.07071	13.58	9.57
1"=20'	0.14142	6.79	4.78
1"=30'	0.21213	4.53	3.19
1"=40'	0.28284	3.40	2.39
1"=50'	0.35355	2.72	1.91
1"=60'	0.42426	2.26	1.59
1"=100'	0.70711	1.36	0.96

These two sites are plotted at the 1”=5’ scale and are about one acre in size. It would be best to change these two sites to a 1”=10’ size and move them to that scale group because most of the sites at the 1”=5’ scale size are less than 0.5 acres. Even with these group changes, the scales of 1”=5’ and 1”=10’ on sites less than 3 acres in size has very unrealistic point densities. The other extreme is a surface plotted at a 1”=100’ scale that recommends a spacing of 85.81’ between points. The greatest systematic spacing of mass point grids collected by ground survey methods is 50.00’ so that 9 points will be used to define a 100’x100’ cell. This analysis helps refine the classification of certain TIN models into appropriate scale groups for analysis.

When the largest scale groups of 1”=5’ and 1”=10’ and the smaller scale of 1”=100’ are omitted from the dataset, the Number of Mass Points Needed per Planar Area (Equation 8) is graphed in Figure 3 in relationship to the Planar Area of the TIN Model. The regression pattern shown at each scale group is very linear, but the regression line of all the datasets is a power log and it does not fit the data very well other than showing that large planar areas of the TIN need less density of mass points and smaller planar areas need a higher density of mass points.

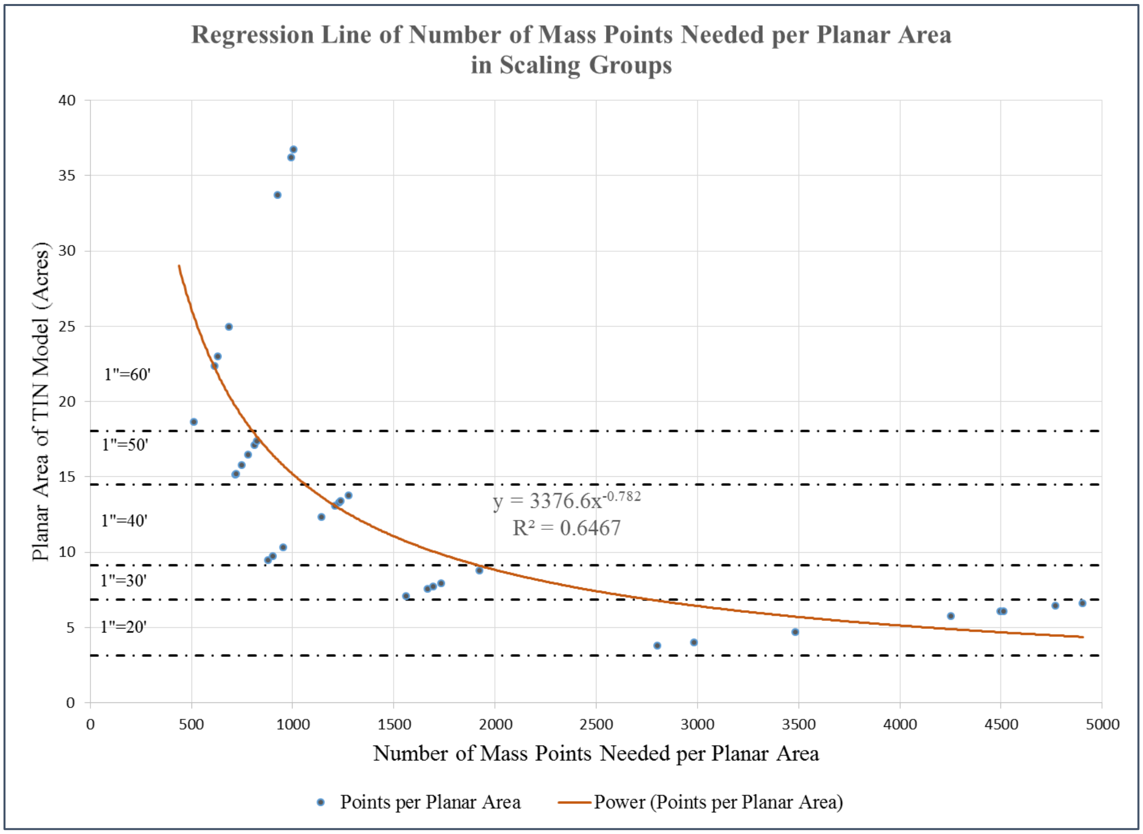

Figure 3: Number of Recommended Mass Points per Planar Area at Scale

This information shows that each scale group needs to be analyzed separately and that there is no correlation between the scale groups even with a linear, statistically recommended sample of Number of Mass Points Needed per Planar Area without applying a power coefficient. Figure 4 classifies the scale groups by maximum planar areas of the TIN model using the data from the 61 DTM projects. Since the Number of Mass Points Needed per Scale (Equation 5) is based on scale and additional analysis is based on planar area, it is important to identify the relationship between published scale and the planar TIN area.

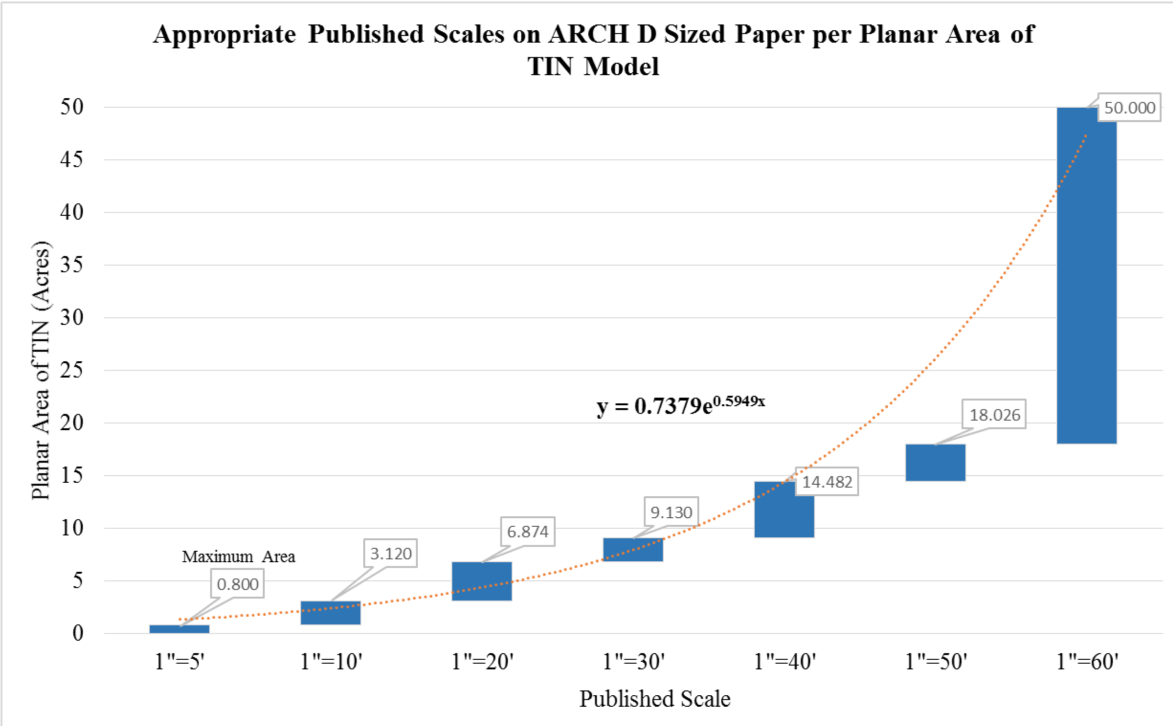

Figure 4: Appropriate Published Scales on ARCH D Paper per Planar Area of TIN Model

Although TIN models that are less than 1.10 acres in size can be platted at 1”=5’ scales, the analysis produces extreme outliers. Also, scales of 1”=50’ and 1”=60’ can easily be interchanged. A scale smaller than 1”=60’ will need to be used on TIN models greater than 50 acres in size and TIN Models that are displayed at 1”=100’ can range in size from 50 acres to 200 acres, greatly skewing any significant analysis.

Two DTM projects out of the 61 DTMs studied are easily identified as outliers during the study. Job Number: 1206011 is a volume survey of an aggregate stockpile that was 0.067 acres in planar area with 148 topo points at a scale of 1”=5’. There are no breaklines used in the construction of the TIN and this surface is the most complex with a surface per plan ratio of 1.179. The most simplistic surface is Job Number: AN2016 being surveyed in a flat pasture for a future gas well pad that is 5.749 acres in planar area with 125 topo points at a scale of 1”=20’. No breaklines are used and the surface per plan ratio is 1.000. Where Job Number: 1206011 has an average point spacing of 4.44 feet, Job Number: AN2016: has an average point spacing of 44.76 feet.

6.1.3 Ground Survey Resolution Test

The metrics from the 61 DTMs are plotted in Figure 5 using the Ground Survey Resolution Test (Equation 13). DTMs of the greatest scales, 1”=5’ and 1”=10’ fail the test where DTMs of smaller scales are shown to be statistically significant. The y-axis is a ratio to show a surface’s complexity:

$$(TIN\ Surface\ Area)/(TIN\ Planar\ Area) \qquad (15)$$

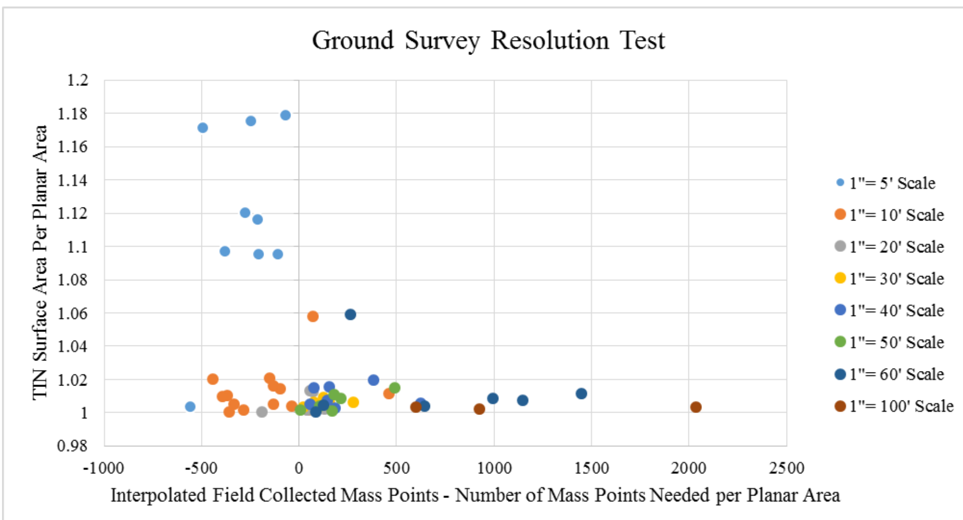

Figure 5: Ground Survey Resolution Test of scale category with surface complexity

6.2 Discussion

The statistical analysis of the 61 DTMs hinges on the infallibility of the final DTM as being validated for accuracy and that the sampling bias of the ground survey field crew is completed correctly. Had the data not been collected using the best practice methods as described in this paper and constructed the TINs from actual large scale mapping projects over the course of 10 years, it would have been difficult to develop these efficiency factors. However, data sets that are collected using consistent surveying methods by various field crews are sufficient to support derivation of topographic metrics (Bangen et al. 2014).

The current standard for assessing the accuracy of a DTM is commonly practiced in small scale mapping applications, but the industry sentiment for large scale mapping products is that if the model fails to function based on poor interpolation accuracy post-delivery, then the model provider will be held financially liable. If too many errors or omissions are discovered in the dataset, the ground survey provider will lose clients based on reputation. There is a need in the survey industry to develop metrics to analyze DTMs with consideration of adaptive sampling methods.

These metrics of number of topo points, number of TIN edges, number of breaklines do not equate for comparison to a simple systematically spaced resolution. It is the purpose of this analysis to determine efficiency factors that the ground survey field crew can benefit from during the collection process. The utility of an accurate constructed TIN model should be comparable to a statistically significant DTM that is prepared from systematic sampling methods. Field surveys are nonrandom by design, but derived products from the DTM by interpolation techniques can be used for statistical analysis to ASPRS 2014 standards (Barton et al. 1999).

A common technique for ground survey crews collecting data on extremes of both complex and simplistic surfaces is to not collect breaklines at all. The most complex surfaces being evaluated are at scales of 1”=5’ and has the highest resolution of points per acre with no breaklines. The increase in resolution on complex surfaces is a ground survey crew’s dependency on the TIN algorithm to correctly identify the triangle edges while saving time in the field collecting data. This is also done on very simplistic models where the surface “sheet drains” and the interpolation of points along the facet of the triangle is very accurate. For the surfaces in the other scale groups that use a high number of breaklines, this breakline value is not being accounted for in resolution analysis.

The Number of Mass Points Needed per Planar Area (Equation 8) at scales of 1”=5’ exceed realistic ground survey sampling numbers to be statistically significant. In practice, surfaces prepared at the 1”=10’ also fail to meet these minimum resolutions even with the applied Sample Bias Edge Benefit Factor (Equation 10) using the Ground Survey Resolution Test (Equation 13). When the published scale is greater than 1”=10’, it is good practice for field crews to increase the number of mass points.

Classifying the planar surface area into scale groups as commonly published on ARCH D sized plots helps a ground survey data provider to estimate planar surface size. Often, a site is bid for data collection based on the area of topo. By knowing that a planar surface area between 3 and 7 acres will be plotted on a 1”=20’ scale, the Needed Point Spacing Interval (Equation 7) to be statistically significant based on scale can help determine mass point resolution in cases where the surface is very simplistic and breaklines are not collected. The nominal point spacing of traditional airborne LiDAR data ranges from 1.14’ to 4.62’ (Heidemann 2018), only comparative to scales greater than 1”=10’.

By showing that there is no correlation between the statistically significant Number of Mass Points Needed per Planar Area (Equation 8) between the scale groups, it should make a ground survey field crew aware that what might have been an acceptable number of mass points and sampling bias on one site might not be acceptable on another site. Once again, planar area of surface has more of a statistical impact on functioning resolution than did any index for surface complexity.

The surfaces studied in this analysis are square in shape (area maps) instead of being linear like route surveys (strip maps). It is possible to have linear segments of a surface model that need practical resolutions of 1”=10’ although the length of the surface model can be thousands of feet. Derived contours for the design of gravity flowing sewers is very important. It is also difficult to analyze the functionality of the model based on resolution at scales smaller than 1”=60’ because a significant feature can dominate the models functionality, yet based on this statistically significant comparison fail. A good example of this is a complex eroded gully that has simple surfaces expanding out from the rims. There are multiple studies on combining necessary high resolution mass points in specific areas with areas of low resolution mass points, yet the surface model is validated as accurate. This analysis only focuses on the aggregated data.

More study is necessary to validate constrained TIN models during the verification phase from the ground survey data acquisition process. This analysis focuses on point types, but other analysis can focus on the linear attributes of the TIN edges. Creating DTMs for the purpose of large scale mapping products by ground survey adaptive sampling methods is widely practiced in spite of advancing technologies like terrestrial LiDAR and aerial structure from motion. It is important to understand comparative techniques between mapping products created by heavily biased adaptive sampling methods and products created by high density systematic sampling methods. This will help DTM contractors make better decisions on cost of delivery and accuracy of the product being delivered.

6.2.1 Application of Ground Survey Sampling Procedures

Expectations of the DTM contractor for large scale mapping products is that the dataset is complete and the DTM has a perfect level of functionality. When the DTM is 100% functional, all points interpolated from the model are accepted as accurate with a high level of precision. In

DTM applications used to study surface morphology, varying data sources or sampling and reconstruction methods of the DTM over time on the same location can cause misinterpretation (Wheaton et al. 2009). There is an economic incentive for the ground survey field crew to collect the minimum number of significant points to fulfil these expectations. In order to do this, the ground survey field crew needs to understand the construction of the constrained TIN model and the benefits of model interpolation during the field collection process.

The application of preliminary site review will add to the completeness of the dataset and improve efficiency in biasing data points. The importance of a realized control network on and off site adds value to the large scale mapping products. An on-site control network improves accuracy of the data collected by reducing the possibility of measurement errors. An off-site control network will allow third parties the ability to utilize the project's coordinate system for additional applications like construction or subsidized spatial products like GIS or additional phases of design. Personnel in ground survey field crews have multiple instruments and techniques at their disposal. It is important that they understand both the advantages and limitations of these methods to provide the best data product in the most cost efficient timeframe. Ground survey field crews can also vary mass point resolutions and the use of breaklines in both surfaces that are either complex or simple.

The office technician is at the mercy of whatever robust algorithm their commercial software initially calculates the TIN. By omitting features with false elevations from the algorithm and constraining the TIN solution with the use of coded breakline features, the drafter is the final quality check before delivery.

There is no substitute for experience in the field or office, but the best application of these procedures is for all members of the DTM provider to be knowledgeable of these processes. This includes the customer service representative that estimates bid proposals. When projects go over budget, the final DTM product suffers. Often bid estimates are decided on the application of the mapping product, size of area, intensity of field labor, and risk factors. The cost of realizing control networks can be unaccounted for in the bid estimate, but the loss of those benefits can be costly.

There is a serious disconnect in communication between the provider and the contractor when accuracy standards are based on derived DTM products. The DTM provider will try and base accuracy verification on published scales and contour intervals using outdated de facto standards while the DTM contractor is expressly concerned with delivered digital TIN model. The validation of DTMs to current de facto standards and accuracy methods is rare for large scale mapping products. It is important to adapt some of the arbitrary certification classes of validating DTMs to more applicable methods of verifying that the DTM is significant before delivery.

CHAPTER 7: CONCLUSION

By understanding that DTM quality assessment standards only apply to the validation phase of the DTM, the preparation of the DTM must be verified as accurate by production. Best practices of adaptive sampling and instrumentation methods by the ground survey field crews are necessary for data completeness and significance. It is important for all personnel of the DTM provider to be aware of the construction methods of the TIN model and the benefits of interpolation that model provides in order to efficiently bias their data samples. Applicable current standards provide reference tables for the data model provider to certify accuracy classes in metric units. These reference tables are converted to US survey feet units to aid data model providers who work in those units.

The analysis of 61 DTMs of large scale mapping projects adds insight to the relationship of TIN planar areas to published scales. A Simple Resolution of adaptively sampled points per planar area fails to be a useful quality metric. It is difficult to identify the efficiency benefit factors of adaptive sampling, but by comparing accurate DTMs to statistically significant DTMs prepared by systematic sampling, these metrics can be derived. More study is needed in this area to help the DTM provider verify accuracy when standardized validation methods are rarely completed (Meneses et al. 2005).

With de facto standards focusing on smaller scaled mapping products and the validation of those models post-delivery, it is important to focus on data verification of the DTM provider earlier in the DTM process. It is unlikely that any DTM provider has ever reviewed a published copy of relevant de facto standards or that they are aware of the de jure standards for DTM accuracy validation. The application of the large scale mapping product must function well before any statistical analysis to validate quality is considered. Completeness in the dataset is the greatest quality indicator and the most common metric for completeness is that of resolution for mass points to assure that terrain complexity and planimetric features are accounted for. It is difficult to communicate the completeness expectations between the heavily biased, adaptively sampled, ground survey field data and the continuously interpolated model. Data model providers and contractors continue to use obsolete quality metrics based on published map scales and contour interval terminology common to NMAS47 standards when the final delivered DTM is in a scale-less, continuously interpolated, digital format.

In order for standards to be relevant to data model providers, the professional societies that publish de facto standards need to focus on the production methods of large scale mapping products. It is apparent that statistical significance is the quality method to be used to validate, but additional metrics need to be developed to account for the benefits of ground survey sampling strategy. Precision of measurements takes a secondary importance while the benefits of interpolation increase DTM accuracy

Most data model providers are practicing surveyors by trade and regulated by state licensures to certify legal boundary location. However, there is no statue certifications for mapping activities other than a few states prohibiting any occupation activities that resemble map making, generally reserved for the surveying profession. This is a “grey” area as global professional cartographic societies are more relevant in certifying the quality of large scale mapping standards than professional surveyor societies. Current de facto standards published by professional surveying societies focus on relative precision of measurement and reiterate outdated NMAS 47 accuracy standards based on published scale and contour intervals. The use of standards to certify DTM functionality is dangerous. A DTM can be certified as statistically significant by aggregation of data, and critical omissions in the completeness of the dataset can be costly! As professional societies update de facto standards, it is important to update quick reference tables to include practical units, common published scales, and the conversion formulas used to validate mapping products.

Often the most significant work in academics is on the frontier of two disciplines. By focusing on a best practice for ground survey sampling and the reconstruction of that data into the most accurate DTM, statistical methods can be developed to identify data completeness metrics. Quality can be determined and validated by the data provider based on the DTM contractor's model application and vice versa as the contractor communicates expectations in light of budget.

7.1 Suggestions for Future Work

This study focuses on a common method of DTM providers who use data sampled by ground surveys and construct a CDT for delivery to the DTM contractor for large scale mapping applications. It is expected that this method will continue to permeate the survey industry and technical training of personnel on best practices is necessary to assure quality in the data set and derived models. Alternative methods of instrumentation and sampling strategy may change with the adoption of technology, as well as improvements in the software used to process that data. Best practices for digital terrain modeling using other work flows need to be identified in order to establish a comparable baseline that the model is functional and complete.

The basis for this analysis is to compare the interpolated surface of a functioning model to a minimum statistical significance. It seeks to account for the efficiency of sample bias during survey strategy and the benefit of constraining a TIN model. The equations and methodology presented in this study to normalize metrics of DTMs could be improved by additional studies in the field of geometry. If the simple resolution of nodes used to construct the TIN framework is not a valuable metric, then an analysis of a higher geometric order could be the solution. This is why this study focuses on edges of the triangular face to determine a valuable metric. This study also does not account for a surface complexity index that could be used as a better classification of the surfaces instead of grouping by published scale.

Should a viable solution to analyzing CDT quality be developed, the testing algorithms could be employed by the same software manufacturers who facilitate in the TIN construction as a quality assurance report. These new metrics could be endorsed by de facto standard organizations and the responsibility of the data model provider to validate DTM quality could happen during the verification phase. The development of statistical quality tests during the verification phase would help to make de facto standard organizations relevant to the data model provider and allow the data model contractor to determine project objectives.

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LIST OF APPENDICES

Appendix 1: Data from 61 Large Scale Mapping Projects

Job Number	Scale	Needed Point Spacing Interval	Planar Area (Acres)	Surface Area per Planar Area	Topo Points	Edges	Breaklines	Simple Resolution	Number of Mass Points Needed per Planar Area	Recommended Edges per TIN	Sample Bias Edge Benefit Factor	Field Mass Points Equivalent Ratio	Interpolated Field Collected Mass Points	IFCMP - NMPNpPA
1206011	1"=5'	0.96	0.067	1.179104	148	416	0	2209	3171	9171	22.046	0.92975	3096	-75
1208005	1"=5'	0.96	0.164	1.097561	133	365	0	811	7762	22448	61.503	0.93377	7381	-381
1206009	1"=5'	0.96	0.167	1.095808	173	486	0	1036	7904	22859	47.035	0.95116	7691	-213
1400037	1"=5'	0.96	0.240	1.004167	75	206	25	313	11359	32851	159.473	0.94383	10796	-563
1206010	1"=5'	0.96	0.261	1.095785	163	467	0	625	12353	35726	76.501	0.97789	12243	-110
1208006	1"=5'	0.96	0.265	1.120755	211	596	0	796	12543	36273	60.862	0.96092	12264	-279
1208009	1"=5'	0.96	0.290	1.175862	185	525	0	638	13726	39696	75.610	0.96846	13478	-248
1208008	1"=5'	0.96	0.408	1.171569	244	687	0	598	19311	55847	81.292	0.96174	18816	-495
1208007	1"=5'	0.96	0.438	1.116438	202	578	0	461	20731	59954	103.726	0.97997	20518	-213
1500138	1"=10'	1.92	0.961	1.010406	132	369	75	137	11371	32886	89.121	0.95589	11002	-370
1700085	1"=10'	1.92	0.987	1.016211	162	463	80	164	11679	33775	72.949	0.97489	11548	-131
1700104	1"=10'	2.71	1.012	1.020751	134	377	8	132	5987	17315	45.930	0.95210	5835	-153
1800036	1"=10'	2.71	1.228	1.057818	322	939	198	262	7265	21011	22.376	0.96521	7335	69
1700063	1"=10'	2.71	1.660	1.004217	198	570	102	119	9821	28403	49.830	0.97585	9782	-39
1302003	1"=10'	2.71	1.915	1.014621	157	450	100	82	11330	32766	72.813	0.97767	11234	-96
1700179	1"=10'	2.71	2.049	1.009761	137	383	62	67	12123	35059	91.537	0.95623	11729	-394
1800031	1"=10'	2.71	2.069	1.001450	196	569	49	95	12241	35401	62.216	0.98795	12289	48
1400095	1"=10'	2.71	2.531	1.005136	378	1067	149	149	14974	43306	40.586	0.95258	14642	-332
1700160	1"=10'	2.71	2.550	1.000784	129	364	55	51	15087	43631	119.865	0.96762	14727	-359
1211010	1"=10'	2.71	2.872	1.020195	146	411	40	51	16992	49140	119.563	0.96532	16549	-443
1500194	1"=10'	2.71	2.990	1.001672	192	546	32	64	17690	51159	93.698	0.97293	17403	-287
1600003	1"=10'	2.71	3.022	1.011582	632	1876	352	209	17879	51707	27.562	0.99047	18341	462
1800030	1"=10'	2.71	3.029	1.004952	162	465	81	53	17921	51827	111.455	0.98369	17790	-130
1600035	1"=20'	7.67	3.211	1.013391	342	997	187	107	2375	6868	6.888	0.88024	2432	58
1700013	1"=20'	7.67	3.790	1.002111	580	1705	248	153	2803	8106	4.754	0.83983	2934	131
1400173	1"=20'	7.67	4.033	1.001488	598	1682	89	148	2983	8626	5.128	0.81388	3025	43
1600079	1"=20'	7.67	4.712	1.002971	331	968	129	70	3485	10078	10.411	0.92261	3546	61
AN2016	1"=20'	7.67	5.749	1.000348	125	344	0	22	4252	12296	35.744	0.92569	4061	-191
1307001	1"=20'	7.67	6.080	1.002632	572	1666	269	94	4496	13004	7.805	0.89274	4586	90
1206007	1"=20'	7.67	6.102	1.002458	130	377	37	21	4513	13051	34.617	0.97461	4528	15
1210009	1"=20'	7.67	6.446	1.012876	355	1038	237	55	4767	13786	13.282	0.94025	4837	70
1304012	1"=20'	7.67	6.631	1.001659	349	1021	178	53	4904	14182	13.890	0.94365	4977	73
1700107	1"=30'	14.10	7.118	1.003231	233	668	130	33	1560	4511	6.753	0.86347	1580	20
1400092	1"=30'	14.10	7.597	1.009214	500	1459	92	66	1665	4814	3.300	0.77433	1789	124
1212001	1"=30'	14.10	7.723	1.006215	564	1655	211	73	1692	4894	2.957	0.75825	1847	155
1305014	1"=30'	14.10	7.919	1.006566	379	1102	186	48	1735	5018	4.554	0.82438	1810	74
1400046	1"=30'	14.10	8.780	1.006264	835	2478	382	95	1924	5564	2.245	0.70997	2201	277
1106016	1"=40'	21.71	9.480	1.015084	275	808	168	29	876	2534	3.137	0.77037	950	74
1104007	1"=40'	21.71	9.740	1.003080	502	1467	74	52	900	2604	1.775	0.64635	1084	184
1500010	1"=40'	21.71	10.315	1.002811	330	964	152	32	954	2758	2.861	0.74846	1044	90
1010004	1"=40'	21.71	12.356	1.004937	258	752	59	21	1142	3303	4.393	0.82097	1196	54
1301004	1"=40'	21.71	13.064	1.005588	1223	3619	466	94	1208	3493	0.965	0.50251	1830	622
1700093	1"=40'	21.71	13.302	1.015336	502	1472	213	38	1230	3556	2.416	0.71710	1384	154
1600109	1"=40'	21.71	13.380	1.007250	474	1395	134	35	1237	3577	2.564	0.73213	1380	143
1700094	1"=40'	21.71	13.802	1.019635	896	2649	236	65	1276	3690	1.393	0.59508	1655	379
1700092	1"=50'	30.34	15.163	1.014839	882	2611	196	58	718	2076	0.795	0.45333	1207	490
1201018	1"=50'	30.34	15.201	1.008552	506	1488	74	33	719	2081	1.398	0.59287	933	213
1800055	1"=50'	30.34	15.818	1.001201	440	1297	117	28	749	2165	1.669	0.63743	917	169
AN2043	1"=50'	30.34	16.467	1.001822	131	371	21	8	779	2254	6.076	0.84087	786	7
1400110	1"=50'	30.34	17.127	1.004146	360	1028	81	21	811	2344	2.281	0.68641	916	106
1700090	1"=50'	30.34	17.388	1.011157	481	1406	215	28	823	2380	1.693	0.63540	1004	181
1207001	1"=60'	39.88	18.664	1.003804	977	2894	0	52	511	1478	0.511	0.34633	1154	643
1303004	1"=60'	39.88	22.385	1.011660	1913	5688	1112	85	613	1773	0.312	0.24434	2063	1450
1500049	1"=60'	39.88	22.990	1.004437	342	1003	15	15	630	1821	1.816	0.65393	754	124
1700091	1"=60'	39.88	24.942	1.008500	1456	4324	139	58	683	1976	0.457	0.32206	1676	993
1400114	1"=60'	39.88	33.734	1.058932	635	1862	219	19	924	2672	1.435	0.59755	1187	263
1400151	1"=60'	39.88	36.197	1.007211	1781	5292	674	49	991	2867	0.542	0.36106	2139	1148
1500174	1"=60'	39.88	36.718	1.000790	341	988	0	9	1006	2909	2.944	0.74783	1093	87
1304009	1"=100'	85.81	73.848	1.003494	893	2652	223	12	437	1264	0.476	0.33138	1038	601
1600006	1"=100'	85.81	82.034	1.001999	1276	3795	455	16	485	1404	0.370	0.27767	1411	925
1400149	1"=100'	85.81	118.862	1.003458	2589	7720	0	22	703	2034	0.263	0.21499	2740	2037