THE UNIVERSITY OF THE WEST INDIES
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Faculty of Engineering
Department of Surveying and Land Information

SURV3007-Research Project

ASSESSMENT OF ELEVATION MEASURING TECHNIQUES FOR NATIONAL MAPPING

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Abstract

This study assessed the vertical accuracy of measurement using different types of survey techniques namely LiDAR, Aerial Photogrammetry and Topographic Maps against the Ground Truth collected by RTK GPS. The study used the same geographical area for each of the land surveying techniques and was compared to elevations readings taken by RTK GPS. Measurements were taken over different types of land cover including open terrain, tall weeds and crops, brush lands and low trees, forested areas fully covered by trees, residential areas as well as land surfaces of different gradients

Applying the regulations stipulated by the National Mapping Standards of United States of America and Australia, LiDAR was found to be more accurate than Aerial Photogrammetry for remapping the national maps of Trinidad and Tobago. This is because in Trinidad and Tobago, the national maps have contour lines generated at 25ft intervals and LiDAR has met the accuracy within the study area for generating contour lines at intervals up to 10ft in accordance to the American Society for Photogrammetry and Remote Sensing (ASPRS).

Apart from meeting the accuracy standards required by international bodies, LiDAR would be recommended because of the very dense point cloud captured of the earth's terrain. The datasets can be easily automated requiring a low level of manual labour. This is in contrast to Aerial Photogrammetry which requires spot heights to be manually extracted and tend to be very time consuming depend on training of the photogrammetrist.

Acknowledgement

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Last, but not least, I thank my family: my grandmother, Rookmin Seepersad, thank you for your comfort and warmth as well as always being there for me when I needed you the most. My parents, Govind Seepersad and Asha Seepersad for giving me life, unconditional support and encouragement to pursue my interests. My sister, Dawn Seepersad for listening to my complaints and frustrations. My baby brother, Noah Seepersad, for believing in me. In closing, I would like to dedicate this research project to my grandmother.

Garrett G. Seepersad
09/04/09

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Chapter 1

Background

1.1 Introduction

Globally, a variety of surveying techniques have been evolving. Each one has been introducing new attributes as well as different levels of accuracy and costs and also requires various levels of human effort. As a necessity, Trinidad and Tobago will need to keep up-to-date with these technological developments as it relates to the efficiency, economics and accuracy in order to remain competitive in the global marketplace.

As these new techniques emerge, they are required to be tested to ensure the accuracy is met before they can be used to update the National Maps of Trinidad and Tobago. These maps are a vital part of the administrative bodies in charge of monitoring land formation and changes, storm water and floodplain management in flat terrain, management of wetlands and other ecological sensitive areas, for infrastructure management in the dense urban areas and for special engineering applications where elevation data of the highest accuracy are required (ICSM, 2008).

This study originated out of this necessity. The study seeks to assess the accuracy of new Airborne LiDAR (Light Detection and Ranging) system as compared to the conventional Aerial Photogrammetry and Topographical Maps. Airborne LIDAR permits elevation accuracy of 15 cm and up to 30 m on contours (Flood, 2004). High-resolution elevation surveys utilizing LiDAR are now becoming available to the Geomatics' society of the Caribbean to generate very high resolution digital elevation models (DEM).

In order to carry out the assessment of the varying surveying techniques, the study used an area of land in south Trinidad bounded by Bhagwantie Trace and Torrib Tabaquite Road on the north and the Naparima Mayaro Road on the west and an area known as the La Gloria Estate of the former Caroni (1975) Ltd.

1.2 Aim and Objectives

1.2.1 General Objectives

The general objective or aim of this study is to assess the vertical accuracy of measurements using different types of survey techniques namely LiDAR, Photogrammetry and Topographic Maps. The study used the same geographical area for each of the land surveying techniques and used Ground Truth or Global Positioning System (GPS) as the benchmark. It took into consideration measurements over different types of land cover including open terrain, tall weeds and crops, brush lands and low trees, forested areas fully covered by trees, residential areas as well as land surfaces of different gradient.

1.2.2 Specific Objectives

More specifically, the study set out to determine the following:

1. Establish survey elevation data points using GPS in La Gloria estate, an area of land in south Trinidad bounded by on the north by the Bhagwantie Trace and Torrib Tabaquite Road on the west by the Naparima Mayaro Road. These are considered of a higher vertical accuracy than LiDAR, Photogrammetry, and thus were used as the benchmarks for comparison.

2. Measure elevation at points in the same study area using LiDAR, Photogrammetry and Topographic Maps for comparison.
3. Establish the vertical accuracy of each survey technique and to establish the most accurate technique as it related to the National Mapping Specification of Trinidad and Tobago, United States of America and Australia.

1.3 Methodology

In order to undertake the study, the following procedure was followed:

1. Review existing literature relating to vertical accuracy on different land cover types, accuracy validation and national mapping standards. The main focus would be with respect to how previous case studies assessed the vertical accuracy of surveying equipment. Research would also be done on existing mapping standards of Trinidad and Tobago as well as mapping standards set by other countries such as the United States of America and Australia.
2. Choose a geographic location for the study. The study area required that there be an overlap of both the LiDAR flight path and the flight line taken to capture the aerial photographs.
3. Obtain the Aerial photographs for the study area from the Government of Trinidad and Tobago Land and Surveys Division for the Photogrammetric evaluation.
4. Obtain the Topographic Maps from the Department of Surveying and Land Information, UWI for the Topography evaluation.
5. Obtain the LiDAR datasets from the Department of Surveying and Land Information, UWI.
6. Establish control points within the chosen geographic location to geo-reference the aerial photographs using Static GPS.

7. Process the Static GPS data to derive the control point's co-ordinates.
8. Use the control points as the extremities of the study area to extract the LiDAR datasets.
9. Pick up elevation survey data using RTK GPS which would be used as the benchmark.
10. Extract elevations from Aerial Photographs using DVP at the same RTK GPS locations.
11. Extract elevations from Topographic Maps at the same RTK GPS locations.
12. Carry out statistic evaluation of the elevations extracted.
13. Group points in different land cover categories.
14. Analyze RMSE and 95th percentile of the results and determine if they meet the National Mapping Standards of Trinidad and Tobago, Australia and America.

1.4 Structure of the Report

This study contains 6 chapters. The first chapter contains the introduction of the research, research background and research objectives. Chapter 2 contains the literature which discusses different techniques of measuring elevation. Chapter 3 the covers the literature which provides review of the National Mapping Standards of Trinidad and Tobago, United States of America and Australia as well as the factors that influence vertical accuracy. Chapter 4 describes the methodology of the research in greater detail. Chapter 5 consists of the results and analysis of the study. Chapter 6 contains the discussion of the results to determine which surveying techniques met National Mapping Standards of Trinidad and Tobago, United States of America and Australia. Chapter 7 contains conclusion and recommendations.

Chapter 2

Techniques for Measuring Elevation

This Chapter presents a review of previous studies done and other literature relevant to the study. The type of equipment / technology and their attributes are described in some detail to assist the reader to obtain a better understand.

2.1 Geomatics Technology

The influential factors in the production of any Digital Terrain Map (DTM) are the cost, accuracy and resolution. Conventional methods for generating DTM would increase significantly for higher resolution accuracy and number of elevation readings taken. The cost associated with the range of methods used to generate DTMs is dependent on the amount of labour and time required for the processes. The Figure 1 below shows a comparison of the cost (in U.S. dollars) of producing 1km^2 against the accuracy of the different techniques presented in this chapter (El-Sheimy *et al.* 2005).

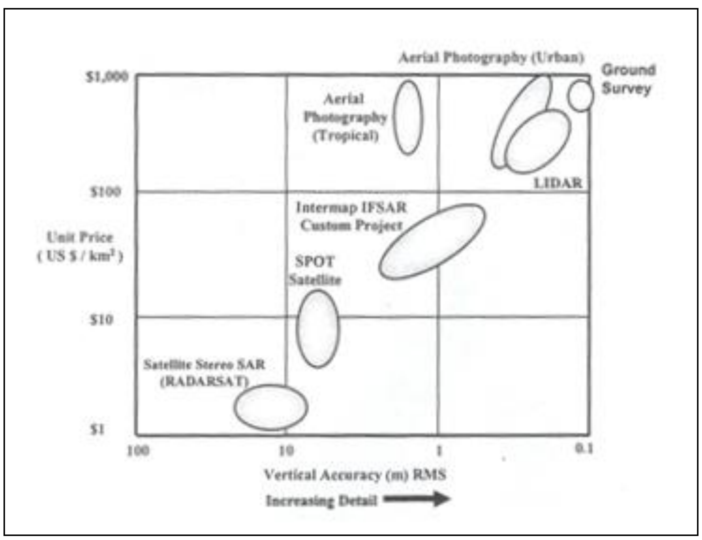


Figure 1: Unit cost comparison of DTMs as a function of typical vertical accuracies addressed by various technologies Source: El-Sheimy *et al.* (2005).

2.1.1 Global Positioning Systems (GPS)

Global Positioning Systems (GPS) is a NAVSTAR Satellite system that was launched into orbit by the United States Department of Defence. It is a system of 24 earth orbiting satellites that is used for navigation, time purposes and to provide positioning. GPS can be used to accurately determine both horizontal and vertical control (French, 1996).

The GPS consists of three parts, the space segment, ground control segment and user segment. The GPS satellite constellation which consists of 24 satellites and 3 spares is referred to as the Space segment. Orbiting approximately 20,000km above the Earth's surface, the satellites are continuously broadcasting measurement singles and navigation messages to GPS users (Li *et al.* 2004).

2.1.1.1 Static GPS

Static GPS survey techniques consist of two GPS receivers that are used to measure a GPS baseline distance. The baseline is the line between a pair of GPS receivers from which simultaneous GPS data have been collected and processed. The differences in station co-ordinates are calculated in terms of a three dimensional, earthcentred co-ordinate system that utilizes X, Y, Z- values based on the WGS84 geocentric ellipsoid model. The derived co-ordinate differences are shifted to fit the local project co-ordinate system (SDDOT, 2007).

GPS receiver pairs are set up over stations of either know or unknown location. One of the receivers is positioned over a point whose co-ordinates may be known and the data is logged for a longer period of time. The second is positioned over desired locations whose co-ordinates are unknown. GPS receivers must receive signals from same four (or more) satellites for a period of time. Data may be logged for a few minutes to several hours, depending on the conditions of observations and precision required (SDDOT, 2007).

2.1.1.2 Kinematic GPS

Kinematic surveying provides the user a quick and accurate method to establish relative survey control. In kinematic surveying, one or more reference receivers (for e.g. CORS Stations) remain fixed during the observation period and one or more remote receivers are rovers that occupy points of interest for several seconds at each point. During the survey, the receivers must continuously track a minimum of the four satellites (Fosburgh, 1998).

2.1.2 Airborne LiDAR

Airborne laser scanning is an active remote sensing technology and consists of a Light Detecting and Ranging (LiDAR) instrument, inertial navigation system (INS), a highly accurate motion sensor and GPS. The basic principle of airborne laser scanning is the measurement of distance between the laser instrument and a point on the ground. The distance is calculated by multiplying the speed of light by the time taken for the lasers first or last returns' pulse to be reflected back to the sensor which is stored directly onto a computer as an (x, y, z) co-ordinate (Shrestha , 2001).

LiDAR is classified as an active digital sensor which implies they are not dependent on sunlight and has the capability of operating 24 hours a day (El-Sheimy *et al.* 2005). Together with the LiDAR data and digital aerial photographs can be collected at the same time providing an additional layer of data (Veneziano, n.d.). Figure 2: LiDAR data collection process, illustrates the method laser scanners are used in the data collection process.

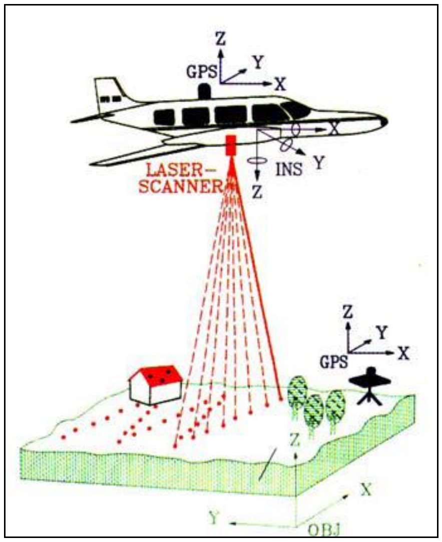


Figure 2: LiDAR data collection process
Source: http://www.sbgmaps.com/lidar_technologies.htm

LiDAR is highly cost efficient based on two factors. The data obtained by LiDAR is cost effective because the processing sequence of the data can be largely automated from the acquisition in flight, through the evaluation, all the way to the end product of the elevation model, as described by El-Sheimy *et al.* (2005). Also, stated by Berg *et al.* (2002) "…the larger the project area, the more cost-effective."

Errors in the location and orientation of the aircraft, the beam director angle, atmospheric refraction model and several other sources degrade the co-ordinates of the surface point to 5 to 10 centimetres Shrestha *et al.* (1998). An accuracy validation study by Murakami *et al.* (1999) showed that LiDAR has the vertical accuracy of 0.10 - 0.20 metres and the horizontal accuracy of approximately 1 metre.

In another research, Butler, (2005) stated the following which was obtained from an Optech Promotional Pamphlet. "RMSE values greater than 0.150 m suggest there are problems within the LiDAR data that have to be identified and rectified before it can be released to the customer.

Optech specifies a vertical accuracy specification of 0.150 m RMSE at an operating altitude of 1200 m for the ALTM 2033 instrument.”

2.1.3 Aerial Photogrammetry

Photogrammetry is the process involved in obtaining information of an entity indirectly by measuring photographs taken of that entity. Aerial Photogrammetry consists of an aircraft that has a high-precision camera mounted with the aircraft that takes photographs in an organized manner over the earth’s surface (Anderson & Mikhail, 1998).

A vertical photograph is taken of the earth’s surface and this is ensured by keeping the camera axis vertical. Aircraft motion may cause it to tilt a few degrees from the vertical (usually a maximum of 5°, although the average often is 1° or less) (Paine & Kiser, 2003).

The aerial photograph is a square with dimensions typically 9 × 9 in., representing the ground-area coverage of a single photograph is square (Anderson & Mikhail, 1998). As the airplane proceeds along its flight line, photographs are taken to ensure two adjacent photographs cover a common area that is more than half the single photo coverage. This common area, called forward overlap, usually is 60 percent and each three successive photographs by about 20 percent (Anderson & Mikhail, 1998) as can be seen in Figure 13 below showing the flight line and the 60% overlap. This type of coverage is necessary to ensure that each area on the ground could be recreated to form a three dimensional geometry.

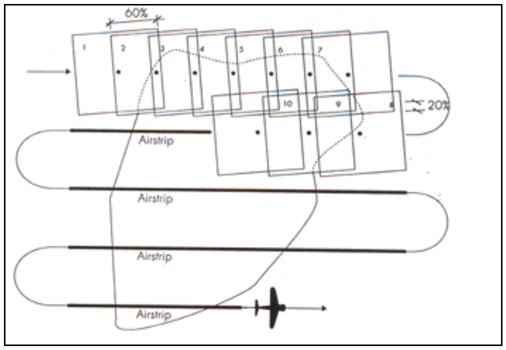


Figure 3: Flight path for aerial photography

Source: The University of Melbourne, (2005)

The third dimension (usually the elevation) is lost in a given photograph because the object is projected on the plane of the photograph. However, with two different such projections and knowing the proper relationships between photographs, the object can be accurately recovered in all three dimensions (Anderson & Mikhail, 1998).

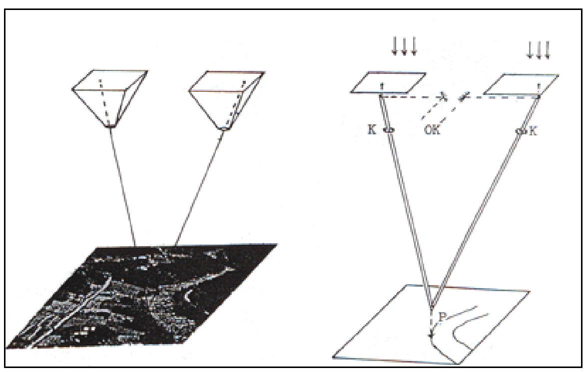


Figure 4: Concept behind the use of a pair of stereo images for stereo-plotting or image interpretation

Source: The University of Melbourne, (2005)

2.1.4 Topographic Maps

Every country has topographic maps that are used as a main data source for generating Digital Terrain Models (DTM). The accuracy of these maps is dependent on the data sources. Contour accuracy depends upon whether the isolines have been generated from primary or derived data (The University of Melbourne, 2005).

If aerial photographs were used as the primary data source to generate the contours, a high level of accuracy would be present. If the contours have been generated from point data, the location of the contours must be interpolated between known values. A major disadvantage of contours is the only represent the elevation along the isolines. Surface anomalies between contour intervals cannot be represented. Once the surface has been represented as contours, interpolation can be used to derive an elevation for locations between contours (El-Sheimy *et al.* 2005).

The largest scale of topographic maps that cover the whole country with contour lines is usually referred to as the basic map scale. This varies from country to country due to its physical size. For example, the basic map scales for China, United Kingdom and United States are 1:50 000, 1:10 000 and 1:24 000 respectively. This indicates the best quality of DTM that can be obtained from existing contour maps. There are usually some other topographic maps at scales smaller than the basic map scale. Of course, such smaller-scale topographic maps have a higher degree of generalization and thus lower accuracy (Li *et al.* 2004).

In Trinidad and Tobago, engineering maps are available with scales generally between 1:1 250 and 1:2 500 and topographic maps are typically available from 1:10 000 to 1:25 000.

2.2 Other Assessment Studies

2.2.1 Synthetic Aperture Radar (SAR)

Synthetic aperture radar (SAR) is a side looking systems also referred to as, side-looking airborne radar (SLAR) where the microwave pulse beam is radiated at an angle orthogonal to the flight direction (El-Sheimy *et al.*2005). SAR refers to a technique used to synthesize a very long antenna by incoming signals (echoes) received by the radar as it moves along its flight track (Pike, 2000).

There are two ways to estimate terrain height with SAR, the first is radargrammetry which is based on SAR images from two passes having different viewing geometries and the second is to compare the phases of returns from two antennas observing the scene from approximately the same flight path. This second technique is called interferometry (IFSAR). Interferometry depends on estimation of the phase difference between the returns from two antennas. In principle, interferometry can be more precise, given a certain resolution, than radargrammetry (El-Sheimy *et al.*2005).

An airborne interferometric SAR (IFSAR) system combines SAR equipment with an interferometer, two antennae and direct georeferencing system (GPS and INS). IFSAR emits microwave signals through its two antennae and receives signals from the two antennae to form interference patterns called an interferogram (El-Sheimy *et al.*2005).

The basic concept of IFSAR is in having two image scenes of the same area being collected by two antennas separated in the across track (range dimension) by a small distance. The phase difference between the returns is measured. The elevations of terrain points are calculated by using the difference of phase from the same terrain object and the position of the antenna determined by onboard navigation sensors (GPS and INS) (El-Sheimy *et al.*2005).

Radar provides at least two significant benefits from the fact it's not dependent on natural light, the ability to image through clouds and the ability to image at night. The wavelength of the microwaves used in radar are longer than those of visible light and are less responsive to the boundaries between air and the water droplets within the clouds. As well, IFSAR data can be collected at any time of day or night, and because of its wide wavelength, it can penetrate haze, clouds, water, snow and even sand. Therefore, SAR data make a good supplement to passive image data in modern photogrammetry. The result for SAR is that the clouds appear homogeneous with only slight distortions occurring when the waves enter and leave the clouds (El-Sheimy *et al.*2005).

The images they generate are useful for monitoring shoreline erosions, investigation of ancient rivers beneath desert sands, studying glaciers and mapping snow-covered rock formations. SAR's long wavelength is more sensitive to physical properties, shape and size of a sensed object that it is to colour and chemical composition (Wang & Dahman, 2002).

2.2.2 Satellite Probatoire pour l'Observation de la Terre (SPOT)

Satellite Probatoire pour l'Observation de la Terre (SPOT) is a joint project between French, Swedish and Belgian organization, which is ran by a French-based company in Toulouse called SPOT Image (Christian, 1999).

The first satellite, SPOT 1, was launched on February 1986 by the French Government Agency, Centre National d'Etudes Spatials (CNES). This was followed by SPOT 2, 3 and 4. In May 2002 the fifth SPOT satellite was launched. SPOT 5 has the same orbit as the rest of the SPOT satellites but with new capabilities such as, a high resolution stereoscopic instrument producing 5m and 2.5 m pixel sizes in panchromatic mode, and higher resolution in multi-spectral mode (Pritchard, 2007).

In a study carried out Gao *et al.* (2006) to analyze the DEM accuracy generated from SPOT 5 imagery they concluded that with no ground control points the errors were too large but this could have been due to the initial attitude angle was low. With sparse ground control points (2 to 6 points) there is a significant reduction in the RMSE for the x-axis from 165.58m to 11.34m. This reduction is significant enough to satisfy the mapping accuracy of 1:50000 in Beijing China (Gao *et al.* 2006).

2.3 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) is a numeric representation of the terrain surface represented by a very dense network of points known as X, Y, and Z coordinates (Anderson & Mikhail, 1998). The DEM will be generated by the data obtained from LiDAR, Aerial Photographs, GPS and Topographic Maps.

A Digital Surface Model (DSM) is generated by data obtained from LiDAR maps the first returned laser pulse, thus resulting in elevations at the tops of manmade and natural features. A Digital Terrain Model (DTM) represents the elevation of the bare terrain without surface objects such as trees and houses. The quality of a DTM is reliant on many factors such as the method used to derive the DSM, and the methods used to identify and remove surface features from the DSM.

2.5 Summary

This chapter provided a brief review of the most popular surveying techniques and their various attributes. The next chapter presents the accuracy standards for measuring elevations.

Chapter 3

Accuracy Standards for Measuring Elevation

A national mapping standard provides insurance that maps will conform to an established accuracy specification, thereby providing reliability and assurance to the user. Maps are a vital part of the administrative bodies in charge of monitoring land formation and changes, storm water and floodplain management in flat terrain, management of wetlands and other ecological sensitive areas, for infrastructure management in the dense urban areas and for special engineering applications where elevation data of the highest accuracy are required (ICSM, 2008).

This chapter presents a brief review of the local and international accuracy standards.

3.1 National Mapping Standards

Maps must correctly represent real world entities both geometrically and geographically to some measurable degree in order for them to be useful. Local officials producing maps as public documents have a responsibility to adhere to good standards of map production (Taupier 1999).

3.1.1 National Elevation Specification of Trinidad and Tobago

To test the vertical accuracy of a model, the Land and Survey Division requires a random sample of points be chosen and tested. The elevation of the spot heights will be measured using a "first order analytical stereo-instrument" and assessed with those previously recorded. The only points that would be observed are those that are visible at the ground surface level (Land and Surveys Division, Ministry of Housing and Settlement, 1999). In Table 1 below, the allowable vertical accuracy is shown.

Table 1: Acceptable Quality Level

Maximum error for any one height	4m
Maximum RMSE for all measured heights in test	±2m

Source: Land and Surveys Division, Ministry of Housing and Settlement, 1999

3.1.2 National Digital Elevation Guidelines of Australia

The vertical accuracy is the principal criteria in determining the quality of elevation data which is dependent on the vertical accuracy requirements of the intended user applications (ICSM, 2008). Table 2 belows shows the National Mapping Standards set for mapping elevations set be ICSM for different categories and their uses.

Table 2: Uses, Specifications and Accuracy of the Categories of DEM

Category	**Special**	**1**	**2**	**3**
Typical Use	Surveys required for engineering and infrastructure design	Modelling of inundation from floods or storm surges in areas of high value assets	Modelling of inundation from floods or storm surges in areas with minimal infrastructure.	Modelling of large areas for preliminary route assessment.
Vertical Accuracy (RMSE, 1 sigma or 68%)	<0.1m	+/-0.15m	+/-0.3m	+/-0.5m
Recommended contour interval	<0.3m	0.5m	1m	2m
Minimum grid cell size (DEM)	<1m	1m	2m (5m ALB)	5m (10m ALB)
Maximum tile size	1km x 1km	2km x 2km	2km x 2km	4km x 4km

Source: ICSM (2008)

Before calculating the data accuracy, ICSM recommends the following steps be taken:

- Separate checkpoint datasets produced according to important variations in expected error
- Edited collected checkpoints to minimize errors

- Interpolate elevation surface for each checkpoint location
- Identify and eliminate systematic errors and blunders

Upon completion of these steps, the fundamental vertical accuracy must be derived. Additional land cover categories may be tested.

For all Airborne Laser Scan (ALS) surveys, the contractor is required to carry out an independent accuracy test to verify that fundamental accuracy specifications have been met. Also, they are required to provide information on the supplementary accuracy and therefore reliability of the elevation data in various land cover categories (ICSM, 2008). Table 3 contains the land cover categories and check point numbers should be used as guide.

Table 3: Land Cover Categories

Category	Description	Total Number of Test Points
1	Clear ground	40
2	Grass or low lying bushes	40
3	Scrubland, woodland and open forest	40
4	Dense vegetation	40

Source: ICSM 2008

3.1.3 National Mapping Standards of United States of America

In the United States there are three different map standards that can be used to derive the vertical accuracy. Those are: The National Maps Accuracy Standard (NMAS), The National Standard for Spatial Data Accuracy (NSSDA) and The American Society for Photogrammetry and Remote Sensing (ASPRS) standard (Abdullah, 2007).

3.1.3.1 National Map Accuracy Standard (NMAS)

The National Map Accuracy Standard (NMAS) specifies vertical accuracy in terms of the contour interval at the 90% confidence level as follows: “Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10% of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement with the permissible horizontal error for a map of that scale (National Digital Elevation Program, 2004).” NMAS refers to the one-half contour interval as the Vertical Map Accuracy Standard (VMAS).

The NMAS became outdated for digital mapping products because computers can easily edit the scale and contour interval of a map.

3.1.3.2 National Standard for Spatial Data Accuracy (NSSDA)

The National Standard for Spatial Data Accuracy (NSSDA) was published in 1998 by the Federal Geographic Data Committee (FDGC). The NSSDA replaced the outdated NMAS for digital mapping products. Vertical Root Mean Square Error ($RMSE_{z)}$ calculations were introduced, and vertical accuracy ($Accuracy_z$) at the 95% percent confidence level was established. This assumes that all systematic errors have been eliminated and the errors are normally distributed. $Accuracy_z$ is defined as “the linear uncertainty value, such that the true or theoretical location of the point falls within ± of that linear uncertainty value 95% of the time” (National Digital Elevation Program, 2004).

The NSSDA/NMAS conversion factors are as follows, assuming all vertical errors have a normal distribution (National Digital Elevation Program, 2004):

$$Accuracy_z = VMAS \times 1.1916 \quad \text{...Eq 1}$$

Table 4: Comparison of NMAS/NSSDA Vertical Accuracy, on page 22 shows the vertical accuracy requirements for various contour intervals.

3.1.3.3 The American Society for Photogrammetry and Remote Sensing (ASPRS)

The ASPRS guidelines have adopted the sections on vertical accuracy testing and reporting from the Guidelines for Digital Elevation Data (Version 1.0) released by the National Digital Elevation Program (NDEP) (Flood, 2004).

ASPRS recommends the following guidelines to be followed:

1. The fundamental vertical accuracy of a dataset must be determined with checkpoints located only in open terrain. The fundamental accuracy is the value, by which vertical accuracy can be assessed and compared among different data sets. Fundamental accuracy is calculated at the 95-percent confidence level as a junction of RMSE. There should be no fewer than 20 checkpoints (preferable 30) for vertical accuracy to be statistically measured at a fundamental vertical accuracy control site (Flood, 2004).
2. Supplemental Vertical Accuracy tests are carried out in areas other than open terrain either to meet the same specification as the fundamental vertical accuracy or a less

sensitive specification. The vertical accuracy would be tested using the 9^{5th} percentile method and reported for each land cover class of interest.

3. Vertical accuracy testing in very irregular or steep slope sloping terrain is not recommended due to the high probability that the error in the testing process is a significant contributor to the final error statistic and thus biases the results. ASPRS recommends that vertical accuracy testing always be done in areas where the terrain is as level and consistent as possible. A small but acceptable horizontal shift in the data may reflect in an unacceptable vertical error measurement.

ASPRS recommends the following NSSDA guidance be followed when choosing checkpoint locations (Flood, 2004):

"Checkpoints may be distributed more densely in the vicinity of important features and more sparsely in areas that are of little or no interest. When the distribution of error is likely to be non-random, it may be desirable to locate checkpoints to correspond to the error distribution. For a dataset covering a rectangular area that is believed to have uniform positional accuracy, checkpoints may be distributed so that points are spaced at intervals of at least 10% of the diagonal distance across the dataset and at least 20% of the points are located in each quadrant of the dataset."

Flood (2004) suggested that the magnitude and distribution of errors with LiDAR vary primarily occur amongst different land cover types. ASPRS Guidelines for reporting vertical accuracy of LiDAR data expresses the following guide lines to stratify the landscape into different land cover classes.

1. Open Terrain

2. Tall weeds and crops
3. Brush lands and low trees
4. Forested areas fully covered by trees
5. Urban areas with dense human-made structures

ASPRS have adopted from NSSDA, the vertical accuracy requirements for different contour intervals as shown in

Table 4: Comparison of NMAS/NSSDA Vertical Accuracy.

Table 4: Comparison of NMAS/NSSDA Vertical Accuracy

NMAS Equivalent Contour Interval	**NMAS** VMAS 90% confidence level. Maximum Error Tolerance	**NSSDA** $RMSE_z$	**NSSDA** $Accuracy_z$ 95% confidence level
1ft	0.5ft	0.30ft or 9.24cm	0.60ft or 18.2cm
2ft	1ft	0.61ft or 18.5cm	1.19ft or 36.3cm
4ft	2ft	1.22ft or 37.0cm	2.38ft or 72.6cm
5ft	2.5ft	1.52ft or 46.3cm	2.98ft or 90.8cm
10ft	5ft	3.04ft or 92.6cm	5.96ft or 1.816m
20ft	10ft	6.08ft or 1.853m	11.92ft or 3.632m
40ft	20ft	12.16ft or 3.706m	23.83ft or 7.264m
80ft	40ft	24.32ft or 7.412m	47.66ft or 14.528m

Source: Flood (2004)

Abdullah (2007) in the article Mapping Matters, recommended, the user should adopt a RMSE value given by the American Society for Photogrammetry and Remote Sensing (ASPRS) standard and used together with National Standard for Spatial Data Accuracy (NSSDA). With this approach both group of map standard users are satisfied, the ASPRS and NSSDA (Abdullah, 2007).

Abdullah (2007) states, *"ASPRS is widely used among large scale clients and NSSDA, is strongly recommended by the Federal Geographic Data Committee (FGDC)"*.

3.1.4 Calculating Fundamental, Supplemental and Consolidated Vertical Accuracies

Australia and United States of America have both subdivided the analysis of vertical accuracies in three categories: Fundamental, Supplemental and Consolidated Accuracy.

3.1.4.1 Fundamental Accuracy

A fundamental vertical accuracy dataset is determined with checkpoints located only in open flat terrain. In open terrain there is a very high probability that the sensor will detect the earth's surface. The fundamental vertical accuracy would be compared to the other datasets. Fundamental accuracy is calculated by finding the 95% confidence level of the vertical RMSE using the equation 3 below (ICSM, 2008) and (Flood, 2004).

$$Accuracy_z = 1.9600 \times RMSE_z \qquad \text{Eq 2}$$

The ICSM and ASPRS both require the accuracy to be reported as "Tested ___ (meters) fundamental vertical accuracy at 95 percent confidence level in open terrain using $RMSE_Z$ * 1.9600."

3.1.4.2 Supplemental and Consolidated Vertical Accuracies

Supplemental or consolidated accuracy values may be calculated for other ground cover categories or for combinations of ground cover categories. Intergovernmental Committee on Surveying and Mapping (ICSM) states that elevation errors often varies with height and density of ground cover therefore a normal distribution of errors cannot be assumed. The RMSE is not recommended to calculate the 95 % accuracy value. The nonparametric testing method (95^{th} Percentile) is recommended for supplemental and consolidated accuracy tests (ICSM, 2008) and (Flood, 2004).

ICSM (2008) and Flood (2004) recommends that the 95^{th} percentile method be used if the errors follow or don't follow a normal distribution and whether or not errors qualify as outliers. The 95^{th} percentile indicates that 95% of the errors in the dataset will have absolute values of equal or lesser value and 5% of the errors will be of larger value. Accuracy is directly related to the 95^{th} percentile, where 95% of the errors have absolute values that are equal to or smaller than the specified amount (ICSM, 2008).

The ICSM and ASPRS both require the accuracy to be reported as:

"Tested ______ (meters, feet) supplemental vertical accuracy at 95th percentile in (specify land cover category or categories).

Tested ______ (meters, feet) consolidated vertical accuracy at 95th percentile in: open terrain, (specify all other categories tested)."

3.2 Root Mean Square Error (RMSE)

The RMSE reflects the differences between the interpolated values from the true values (Kroll, 2006). This is a dispersion measure because it is the average deviation between the two datasets (Wood, 1996). This is an uncertainty measurement is based on the assumption that the distribution of the errors are normal with zero mean (Kroll, 2006).

$$RMSE = \frac{\sqrt{\sum_{n=1}^{n=m}(\mathrm{GPS_n} - \mathrm{LiDAR_n})^2}}{n-1} \quad \text{.. Eq 3}$$

m = number of test points for comparison

$LiDAR_n$ - LiDAR surface elevation value

GPS n = ground survey elevation value

3.3 Percentile

For data that is not grouped, the K^{th} percentile is defined by Frank & Althoen, (1994) as "the unique value below which falls no more than K percent of the scores and above which fall no more than (100-K) percent of the scores."

To determine a unique value the following procedure adopted from Frank & Althoen, (1994) is followed:

- Arrange the N scores in order from smallest to largest.
- Number the positions occupied by the scores 1… N.
- Calculate K percent of N. Call this value N_k.
- If N_k is an integer, then the K^{th} percentile is the average of scores in positions N_k and N_k + 1.

- If N_k is not an integer, then the K^{th} percentile is the smallest score with position number greater than N_k.

3.4 Factors affecting DEM accuracy

LiDAR data suffers from systematic and random errors of different kinds (Huising & Pereira, 1999). Systematic Errors are biases in the measurement and can be calculated by dividing the sum of all elevation differences between known and unknown points, with one less than the number (n) of points being compared (n-1). This statistic can be used to show whether the LiDAR surface is higher or lower than it should be (Adams, 1999).

Causes of systematic errors include (Adams, 1999):

- Laser detector bias and gain
- GPS and INI U drift
- Atmosphere
- Data integration
- Slope of the target
- Vegetation

Random errors are caused by inherently unpredictable fluctuations of errors away from the overall systematic error and are sometimes referred to as noise or scatter (Adams, 1999).

Causes of random errors include (Adams, 1999):

- Signal-to-noise ratio of the received signal

- Width of laser beam
- Response of the receiver
- Timing accuracy of the electronics
- Position and orientation of the platform
- Viewing direction of the system
- Atmosphere
- Type of terrain

3.5 Topographic Variation

Slope affects planimetric and vertical accuracy, which is why fundamental vertical accuracy assessment is only carried out on flat ground so that effects inherent in sampling on gradients are removed. Flood (2004) recommends that elevation of terrain slope should not be steeper than approximately 11° because horizontal errors will influence the vertical RMSE calculations.

Sloped terrain will induce a vertical error due to a ranging (distance between sensor and object) error caused by an increased return time (Baltsavias, 1999). There is a reduction in the number of laser points interacting with the surface of steep terrains resulting in gaps to appear more often and is larger causing a reduction in interpolation accuracy (Butler, 2005). Kraus & Pfeifer (1998) found vertical accuracy was dependant strong slope of woodland DTM with slopes up to 30°.

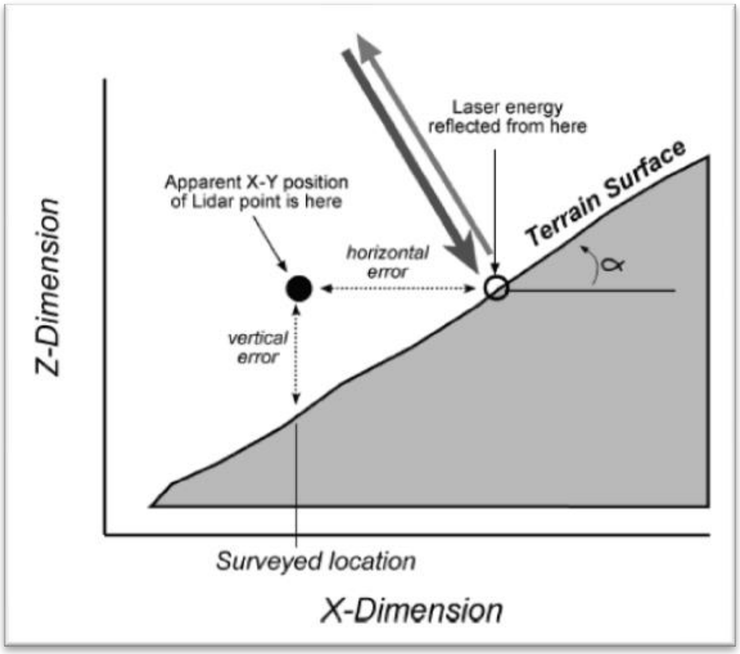


Figure 5: Illustration of the effects of terrain slope on observable elevation error.
Source: Michael E. Hodgson, (2004)

3.6 Land-Cover affecting DEM Accuracy

A land-covered surface will affect the vertical accuracy based on different characteristics such as: surface roughness, surface reflectivity and density (Schuckman & Graham, 2008). In a study carried out by Hoggson *et al.* (2003) reports elevation error with the LiDAR data ranged from 33 cm (low grass) to 153 cm (scrub/shrub). The RMSE in low and high grass were much smaller than those compared to heavily vegetated canopies, except for the pine forests. Elevation errors were only associated with increasing slope for the scrub/shrub land cover. Little relationship with the slope was assumed because mean absolute error in slope ranged from only 1.7° to 4.8° by land-cover category (Hoggson *et al.* 2003).

In a study on LiDAR point-labelling research, 17-cm (RMSE) accuracy was observed in a grass and cereal crop land cover Coby *et al.* (2001). Elevation accuracy from the LiDAR data was found to decrease in a densely wooded environment. Coby *et al.* (2001) found that dense canopy cover can have a profound effect on the percentage of LiDAR “shots” reaching the ground.

For these reasons, ASPRS requires open terrain to be tested separately from other ground cover types. Open terrain is referred to as “Fundamental vertical accuracy” and measured samples taken from non-open terrain are called “Supplemental accuracy”. “Consolidated vertical accuracy” is a combination of samples taken from both open terrain and other ground cover classes (Flood, 2004).

3.7 Summary

This chapter provided a review of the National Mapping Specfications of Trinidad and Tobago, Australia and United States of America as well as review literature on factors that affect the vertical accuracy of different surveying techniques.

The next chapter details the data acquisition process. It also presents visuals of the study area.

Chapter 4

Data Acquisition Process for the Study Area

This study focuses on assessing the vertical accuracy of measurement using different types of survey techniques namely, LiDAR, Photogrammetry and Topographic Maps. The study will use the same geographical area for each of the land surveying techniques. It will take into consideration measurements over different types of land and land surfaces of different gradient. The flowchart illustrated in Figure 6 below details the logical steps followed in the study.

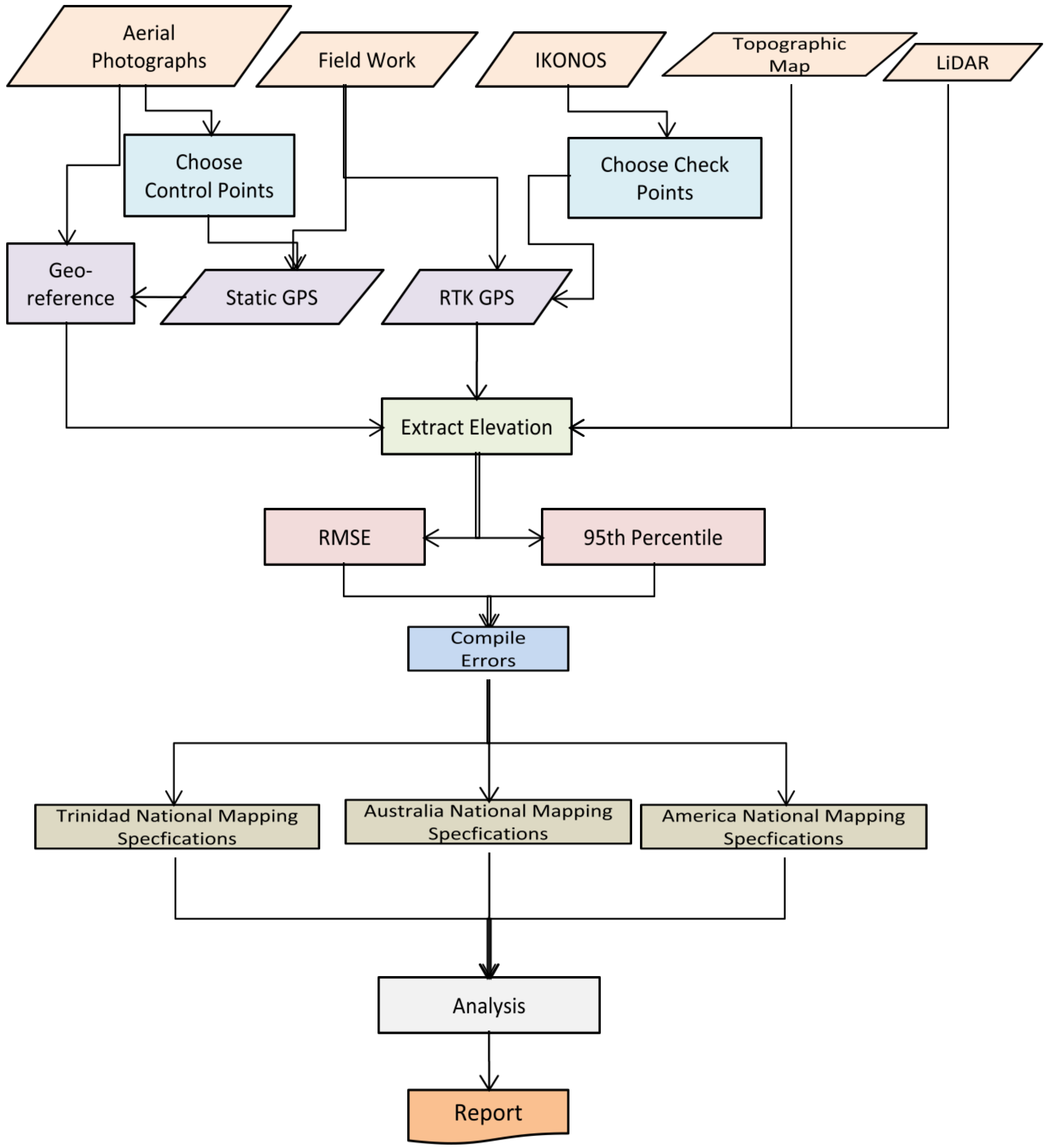
4.1 Data Acquisition

4.1.1 Data requirement

To determine the vertical accuracy of Aerial Photogrammetry, LiDAR and Topographic Maps the elevations have to be extracted at the same RTK GPS x, y co-ordinates. The elevations would be compared to the GPS elevation because it is currently the most accurate system of determining x,y,z co-ordinates. The points would be grouped into different land cover categories and statistical tests would be performed to determine the relationship between:

- Land Cover and Vertical Accuracy
- Slope and Vertical Accuracy

Figure 6: Schematic diagram of research work flow



The statistical tests would include:

- The Root Mean Square error (RMSE) at a 95% and 68% Confidence Interval
- 95th Percentile

Upon deriving the RMSE and 95th Percentile for each of the categories, the results would be analyzed to determine if they National Mapping Standards of Trinidad and Tobago, Australia and America.

4.1.2 Secondary Data

During the fieldwork and post fieldwork the data necessary for this research have been collected from various sources, there are three sources of data, from government offices, from private organization and from laboratory work. The type data have been collected can be seen in the table below:

Table 5: Type of research data

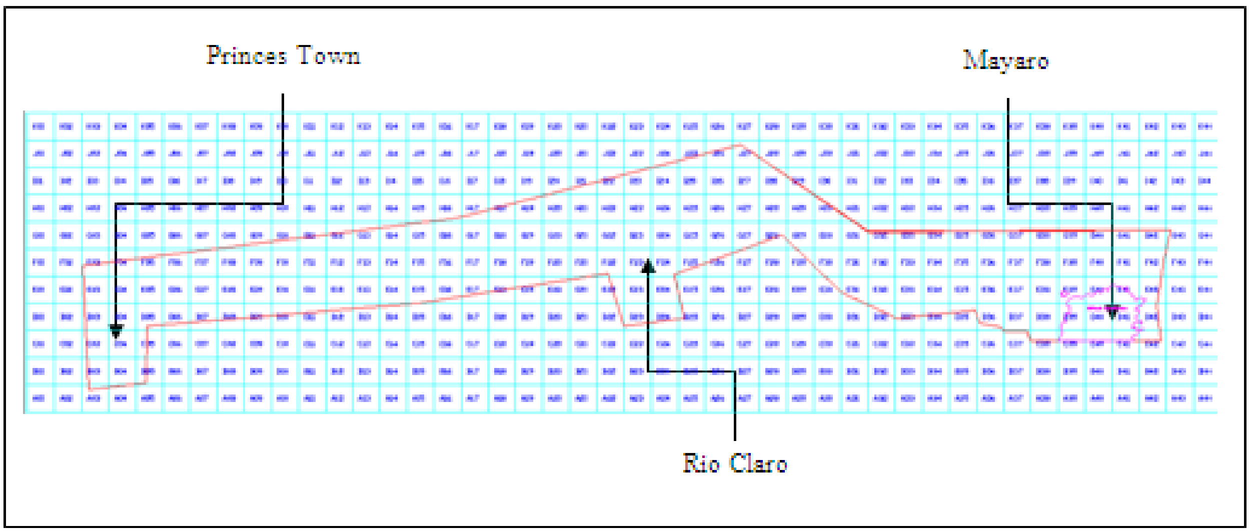
Type of Data and Map	Specification	Sources	Purpose
Map of Photo coverage-Trinidad. 1: 10 000	Scanned	Department of Surveying and Land Information, UWI	Assist in choosing aerial photographs.
LiDAR Index Map	Digital	Department of Surveying and Land Information, UWI	Assist in obtaining desired LiDAR datasets.
Aerial Photographs	Scanned	Government of Trinidad and Tobago Land and Surveys Division	To extract surface elevation to determine Aerial Photogrammetry vertical accuracy.
Topographic Map. 1: 25 000	Scanned	Department of Surveying and Land Information, UWI	To extract elevations to determine Topographic Map vertical accuracy.
IKONOS 2007	Digital	Department of Surveying and Land Information, UWI	Assist in choosing location for control points and checkpoints.
Static GPS Data	Digital	Equipment: Department of Surveying and Land Information, UWI	Static GPS data to georeference Aerial Photographs
RTK GPS Data	Digital	Equipment: Department of Surveying and Land Information, UWI	RTK GPS data used as a bench mark for comparison to LiDAR, Aerial Photogrammetry and Topographic Maps

4.2 Research phase

To elaborate the main objectives of this study has been divided into 5 phases, which are as follows:

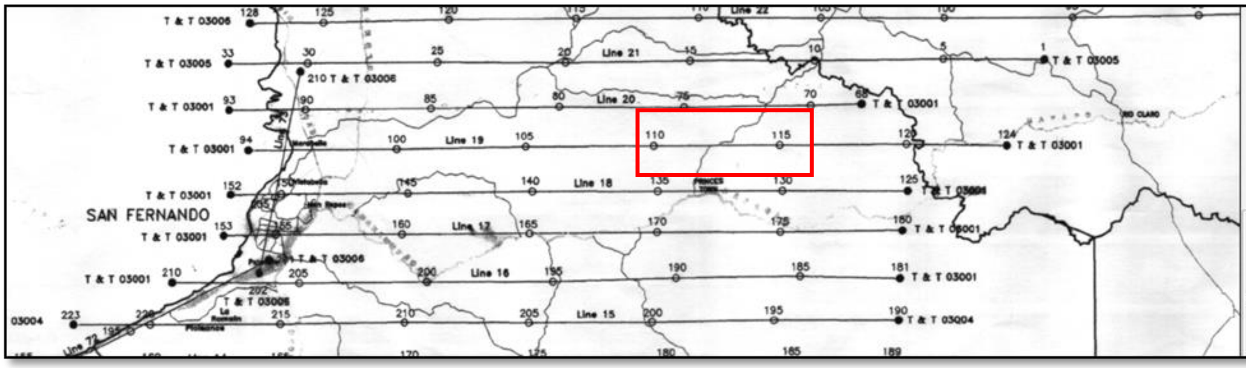
4.2.1 Defining the Study Area

The criteria for choosing a geographic location for the study area required there to be an overlap of both the LiDAR flight path and the flight path taken to capture the aerial photographs and there must exist a variety of land cover categories and varying topographical features. Map 1 show the LiDAR index of the datasets which was captured during the flight. The mapping corridor is located between Princes Town and Mayaro. The dimensions of the corridor are approximately 5km by 45km (DESSAU SOPRIN INTERNATIONAL 2006).



Map 1: LiDAR Index

Map 2 below shows an index of the aerial photographs taken for part of Trinidad and Tobago. The red box indicates the intersected region where all the desired conditions were met.



Map 2: Map of Photo Coverage

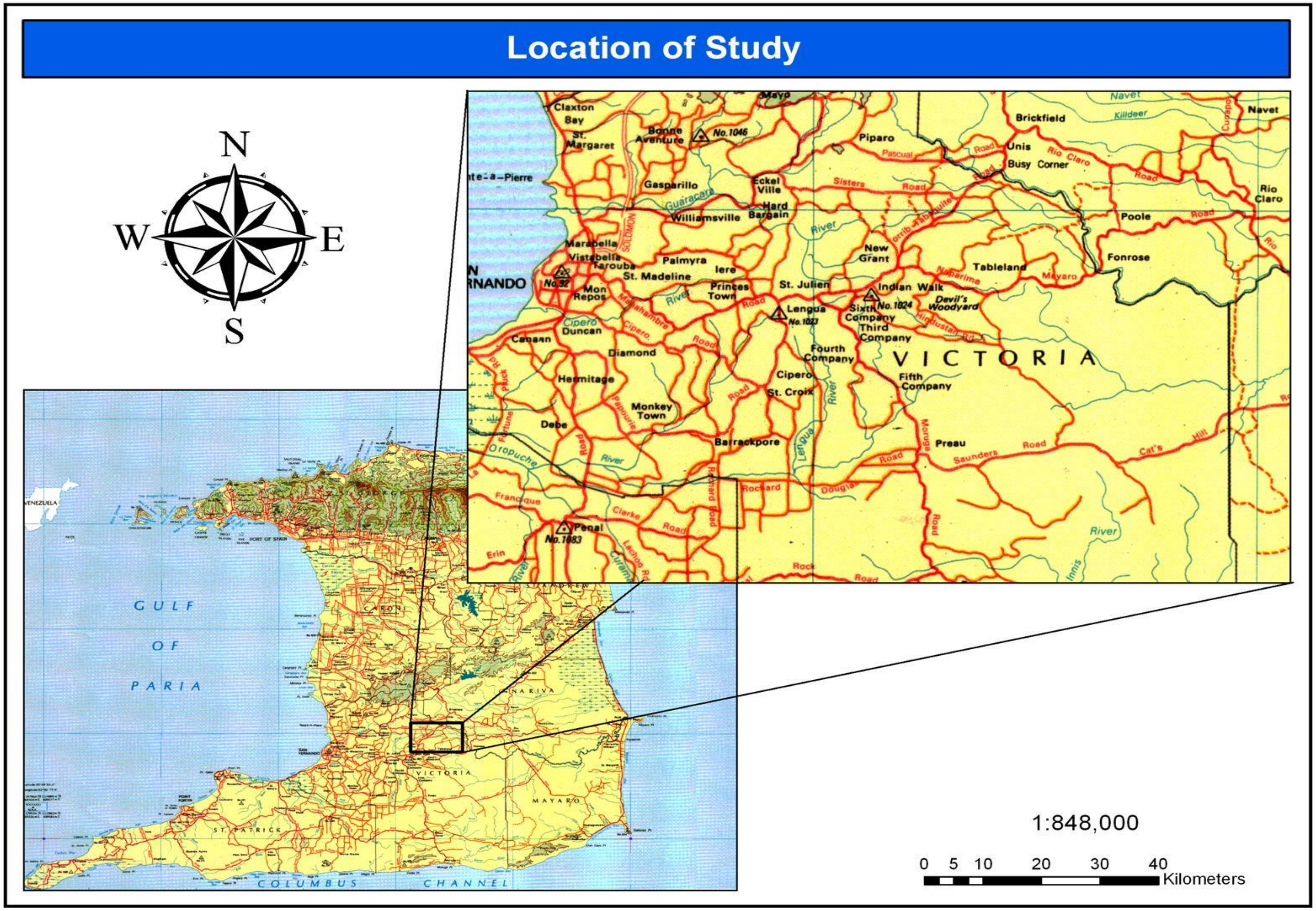
4.2.1.1 Study Area

The chosen study area is located in south Trinidad, bounded by Bhagwantie Trace and the Torrib Tabaquite Road in the North and the Naparima Mayaro Road on the west and an area known as the La Gloria Estate of the former Caroni (1975) Ltd. This study area is located within a settlement of New Grant (Map 3) which would be used as the benchmark.

The study area was chosen as it was the only path that the LiDAR data overlapped the available flight lines that covered several different land-cover types with varying elevations, range of slopes and the Aerial Photograph.

4.2.1.1 Study Site

The study area was split into different study sites (Map 5) and was arranged into 5 categories based on their land-cover types. The land-cover categories were chosen as they represent typically different land-cover types found in Trinidad and Tobago.



Map 3: Overview of study area

4.2.1.2 Site Description

The fundamental vertical accuracy site was located in a flat, open terrain with no surface objects. The site was a savannah grass cricket field.

There were five different types of site readings taken. This consisted of Asphalt, Concrete, Mud, Savannah Grass and Cultivated Citrus. The asphalt sites are subdivided into two further groups, flat and steep slopes (10°-30°) as shown in Panel 1 to 3. The concrete site had an underlying elevation was generally flat with slope varying little (0° - 5°) as shown in Panel 4. The mud site was an access road to an abandoned citrus estate and had a shallow slope (0° - 5°) as can be seen in Panel 5. The savannah grass site consisted of two areas, a flat, open cricket field (Panel 6) and a lawn with savannah grass yard with a medium slope (5° - 10°) as shown in Panel 7. The savannah grass was approximately 0.03m tall. The cultivated citrus site (Panel 8) was made up of orchard trees approximately 1.5m tall on a steep slope (10° - 30°).

Panel 1

Asphalt Road consisting of varying conditions such as changing gradient and varying environment (forest and settlements)

Panel 2

Flat Asphalt Road

Panel 3

Steep Asphalt Road

Panel 4

Concrete Surface with a shallow gradient located at the base

Panel 5

Flat Mud Road located at La Gloria estate

Panel 6

Playground with Savannah Grass. This site was used to test the fundamental vertical accuracy.

Panel 7

Lawn Grass located at the base with a shallow gradient

Panel 8

Cultivated Citrus field located at the La Gloria estate with a steep gradient

4.2.2 Data Collected

The Aerial Photographs for the study area were purchased from the Government of Trinidad and Tobago Land and Surveys Division for the Photogrammetric evaluation. The aerial photographs were taken of the study area within the months of February and March 2003. The flight line was 03001 and photos numbers were 111 to 115 as can be seen in Table 6 below.

Table 6: Aerial Photograph Specifications

Date	February and March 2003
Camera	Zeiss Top 15 (FMC)
Principal Distance	152.910
Scale of Photogrammetry	1:10 000
Forward Overlap	60%
Scanning Resolution	800dpi

Source: Land and Surveys Division, Ministry of Housing and Settlement, (1999)

The Topographic Map was obtained from the Department of Surveying and Land Information, UWI for the Topographic evaluation. The Topographic Map was Sheet 54 at a scale of 1:25 000, of the study area was obtained from Surveying and Land Information mapping department. The map specifications are listed in Table 7 below.

Table 7: Topographic Map Specifications

Grid	U.T.M. Zone 20
Projection	Transverse Mercator
Spheroid	International
Unit of Measurement	Meter
Meridian of Origin	63° West of Greenwich
Latitude of Origin	Equator
Datum	Naparima 1955

Source: Topographic Map Sheet 54

The LiDAR datasets were obtained from the Department of Surveying and Land Information, UWI for evaluation. The department provided the LiDAR DTM and DSM datasets covering from Princes Town to Mayaro. An Optech ALTM 2050 sensor was used to capture the data. Flight parameters and instrument settings are shown in Table 8.

Table 8: LiDAR flight and scanner settings

Date	October 13^{th} and 20^{th} , 2005
Flight Altitude	750m
Aircraft Speed	$70ms^{-1}$
Scan Rate	35Hz
Scanning Angle	+/-15°
Scan Width at ground level	402m
Navigation System	DGPS with +/- 5m accuracy

Source: DESSAU SOPRIN INTERNATIONAL (2006)

4.2.3 Collecting Ground Control Points and Check Points

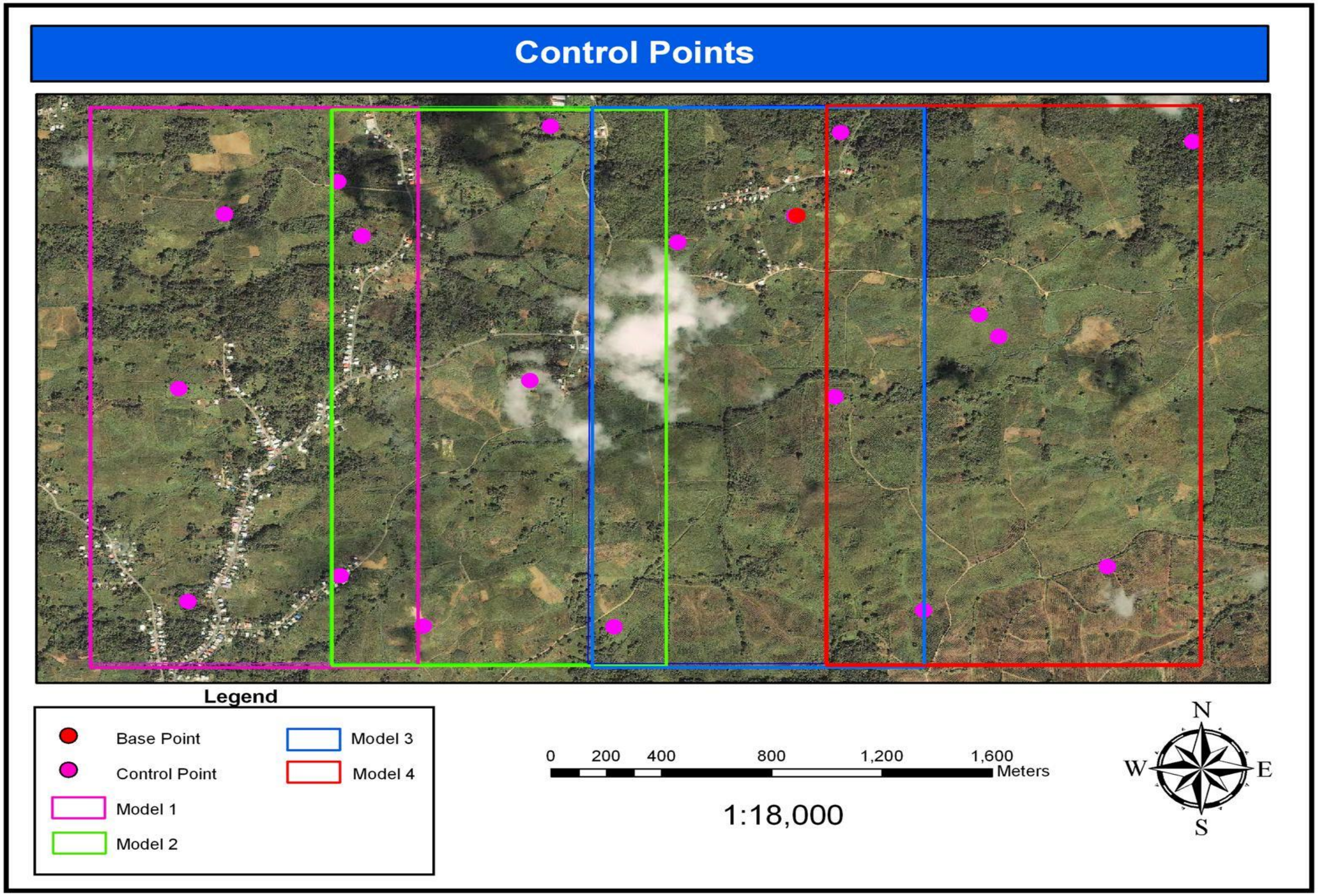
- Determine location of control points and check points using IKONOS 2007 imagery to have a better understanding of the terrain as it may have changed over the years due to development. Map 4 shows the desired locations for the control points.
- Establish control points within the chosen geographic location to geo-reference the aerial photographs using Static GPS as can be seen in Panel 9. These control points were used to setup four stereo-models.
- Pick up elevation survey data using RTK GPS which would be used as the benchmark. The location of the check points are shown in Map 5.

Panel 9: Establishing Control Point

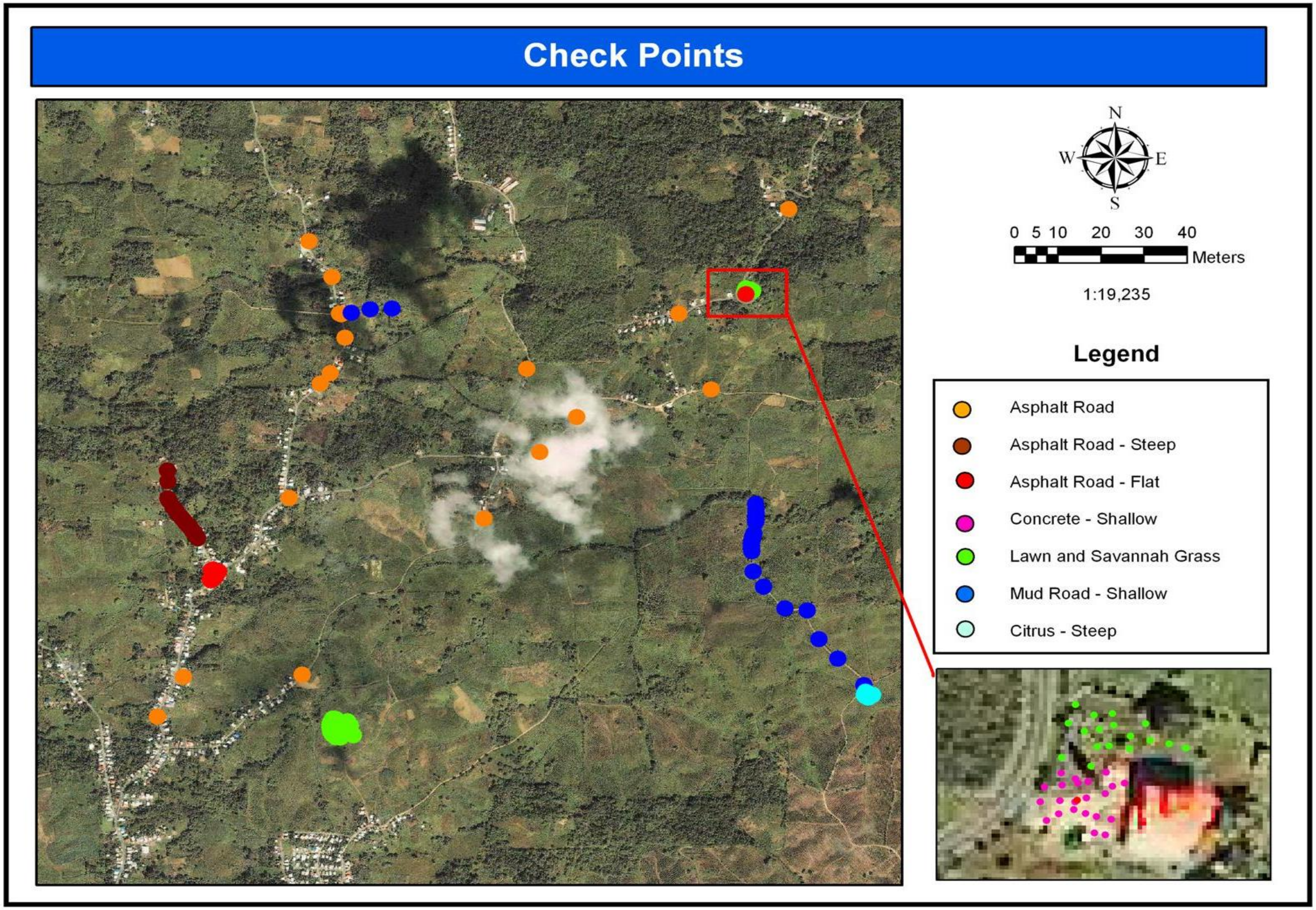
4.2.4 Post Fieldwork Analysis

- A base point was established using Static GPS. This was done on each of the days using a Trimble 5500 Receiver and a Zephryl Geodetic Antenna. The data was logged for approximately 8 hours per day on November 8th, 9th and December 15th. This location was chosen because it was the most secure (from possible criminal activities) and central location to ensure a strong geodetic network as shown in Panel 10.
- While the base was constantly logging data, the rover was set up at different locations and logged for 15 to 30 minutes. To determine the logging period, control points within 1 km was logged for 15 minutes and every additional kilometre 5 minutes more of data was logged. The location of the control points are show in Map 4.
- Using the same type of equipment base, use a Trimble 5500 Receiver and a Zephryl Geodetic Antenna to establish the control points. A total of twenty-one control points was established over a period of three days.

Panel 10: Base Station



Map 4: Control Points and Model



Map 5: Location of Check Points

4.2.5 Data Processing

4.2.5.1 Trimble Geomatics Office

Use Trimble Geomatics Office (TGO) to carry out the post-processing of the Static GPS data. These points would be used as the control points for the Aerial Photographs.

Coordinate System Group: UTM

Zone: 20 North

Datum Transformation: Naparima 1995 (Molodensky)

Geoidal Model: CARIB97 (Caribbean)

Transformation: Naparima 1955

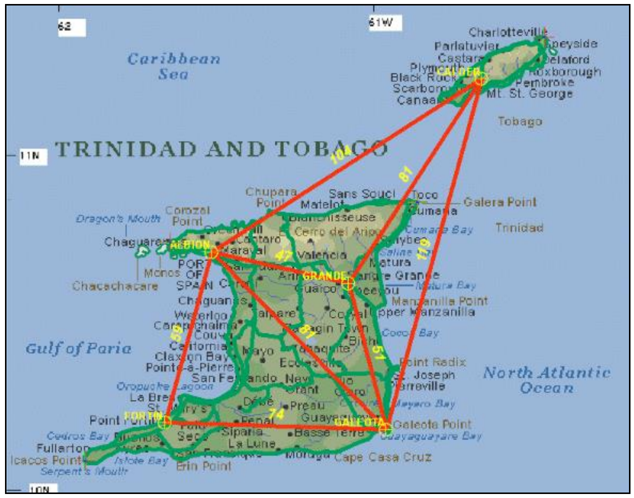
Dx :-0.216

Dy : 372.252

Dy :172.231

- The precise ephemerides were obtained for the day of the observation from the International GNSS Service website, http://igscb.jpl.nasa.gov. This IGS web site was used because the ephemerides given here are the result of an average of the Ephemerides provided by IGS and other organizations such as National Geodetic Survey (NGS). Hence, the ephemerides posted on the IGS website are of the best accuracy available (Miller, 2007).
- Using the TGO software, a new project was started using the following information
- The RINEX files for the local CORS site (ALBION, GRANDE, GALEOTA, and FORTIN) were obtained from the Trinidad and Tobago Active Geodetic Network,

http://www.gpstt.com for the respective days. The locations of the CORS sites are shown in Map 6 below.



Map 6: Location of local CORS Sites
Source: http://www.gpstt.com

- The precise ephemerides files (igs15045.sp3 igs15046.sp3 igs15100.sp3) were downloaded from http://igscb.jpl.nasa.gov/ and imported into TGO.
- Timelines were viewed and the data was cleaned by disabling the glitches seen in the timelines. As can be seen in Figure 7 below.

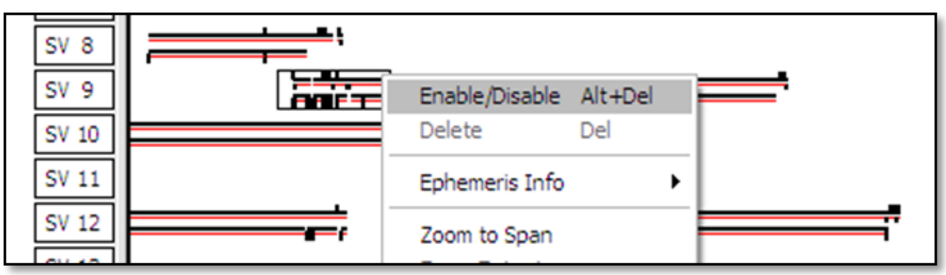
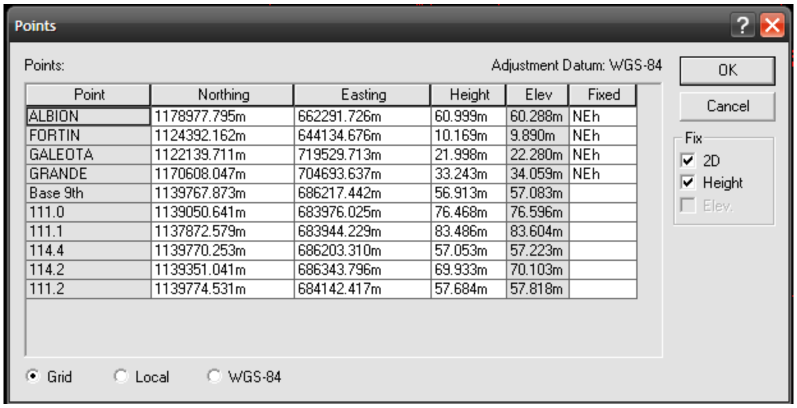


Figure 7: Cleaning the data

- The RINEX files for the local CORS site and were imported together with the DAT files containing the GPS data for the areas that data was logged throughout the study area.
- The Local CORS Station points were held fixed as can be seen in Figure 8.



Point	Northing	Easting	Height	Elev	Fixed
ALBION	1178977.795m	662291.726m	60.999m	60.288m	NEh
FORTIN	1124392.162m	644134.676m	10.169m	9.890m	NEh
GALEOTA	1122139.711m	719529.713m	21.998m	22.280m	NEh
GRANDE	1170608.047m	704693.637m	33.243m	34.059m	NEh
Base 9th	1139767.873m	686217.442m	56.913m	57.083m	
111.0	1139050.641m	683976.025m	76.468m	76.596m	
111.1	1137872.579m	683944.229m	83.486m	83.604m	
114.4	1139770.253m	686203.310m	57.053m	57.223m	
114.2	1139351.041m	686343.796m	69.933m	70.103m	
111.2	1139774.531m	684142.417m	57.684m	57.818m	

Figure 8: Fixed Co-ordinates

- The network was adjusted with a 95% confidence interval and outliers were removed.
- The baselines were readjusted and the weighting was selected as “User-defined” and the baselines were adjusted for the last time.

4.2.5.2 Pre-processing of Aerial Photographs

The Digital Video Plotter (DVP) was used to orthorectify and georeference the aerial photographs as well as extract the elevation of the earth’s surface at the same x, y co-ordinates RTK GPS co-ordinates were collected.

The process of triangulation in DVP (Digital Video Plotter) follows traditional steps specific for analytical photogrammetry. A “**New Workspace**” was opened under the option “**File**” and saved, “**Save Workspace**”. For each stereo-model, a new model is created by selecting “**Model | Create New Model”**.

Inner orientation required the measurement of the image coordinates of fiducial marks. The residuals was important for ensuring the accuracy of the stereo models, they were required to be less than 0.6mm. To orient the first left photograph, **“Orientation | Interior | Left”** was selected as can be seen in Figure 9.

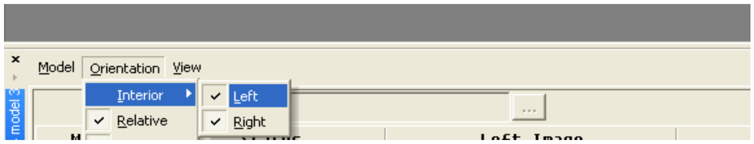


Figure 9: Orientation

A camera file was created by selecting **"View | Camera Window"** and the following information was entered and save by selecting **"File | Save As"**. Figure 10 below shows the camera file when created.

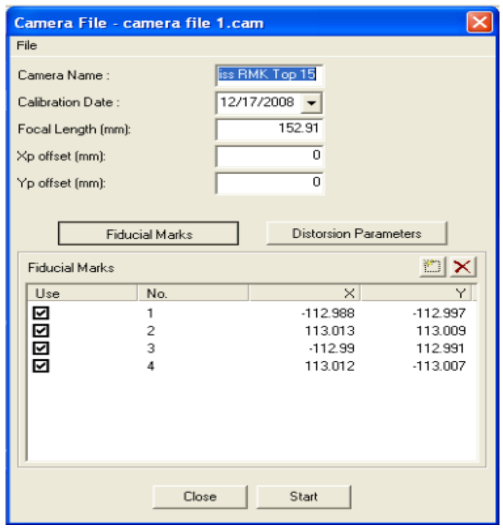


Figure 10: Camera File

The same steps were repeated for the right photograph by selecting **"Interior | Right"**

Relative Orientation is based on image matching. This process requires the accurate measurement of corresponding points in stereo images. Estimation of the errors in relative orientation can be by the residuals in vertical parallax. The Py residuals are also required to be less than 0.015mm. To initiate relative orientation **"Orientation | Relative"** is selected as shown in Figure 11.

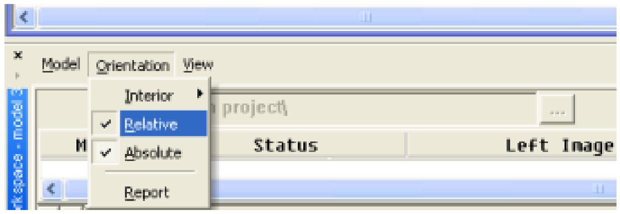


Figure 11: Relative Orientation

The following options are selected to **"Position | Create | Von Gruber Points"** as shown in Figure 12 and 13.

Figure 12: Von Grubber Points

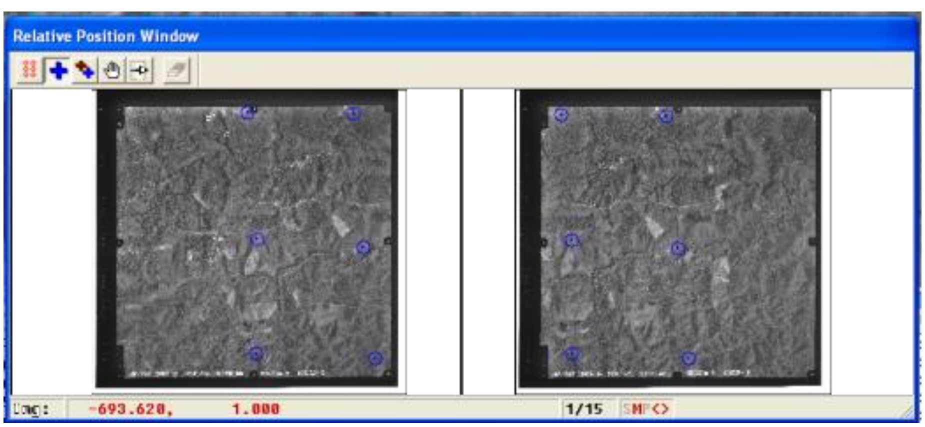


Figure 13: Creating Von Grubber Points

The final phase in completing the photogrammetric model is called **Absolute Orientation.** This phase requires a minimum of four control points. The quality of stereo viewing was dependent on the accuracy of the control points, which affected the stereo measurement. The accuracy of measurements could have been controlled by recalculation of adjustment after each change of image co-ordinates. To begin the absolute orientation **"Orientation | Absolute"** was selected as shown in Figure 14.

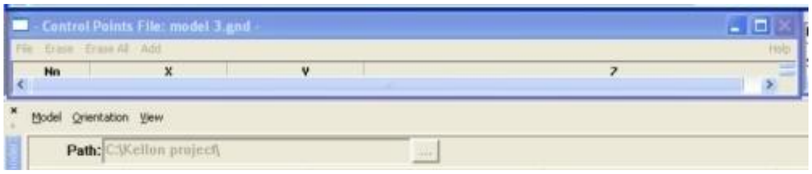


Figure 14: Control Points

In the Control Points Window all the control points were individually added and labeled. In the Absolute Orientation Results window, the Dx, Dy and Dz values should be less than 0.5m as shown in Figure 15.

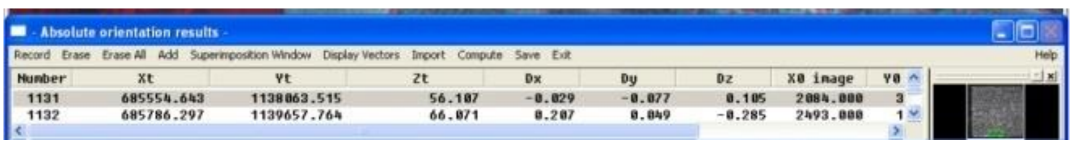


Figure 15: Absolute Orientation Results

4.2.5.3 Surface modeling

Surfer is a surface mapping system that was used in the analysis of the elevations of the LiDAR datasets.

The LiDAR dataset used was at Full Intensity. The DTM data set was stored with an extension ".grd". Surfer 8 required the data to be stored as Comma Separated Variables (csv). The data set was opened with Surfer as a worksheet and the delimiter used was "space". The files were saved as ".csv".

When all the datasets were stored as CSV, Surfer is now able to generate the surfaces by creating Grid Files. This feature can be selected under the tab **"Grid | Data"** and the CSV file is selected. The Gridding Method used was Kriging. A grid file would be created and the surface could be viewed under the tab "Map".

To extract the heights from the LiDAR surface at the same GPS (x,y) co-ordinate a method called "Residuals" was used.

The **"Grid | Residuals"** menu command calculated the difference between the LiDAR elevation and GPS elevation at same XY location. Surfer used a **bilinear interpolation** method to calculate Z values at points that do not coincide.

A list of GPS XY data points was created and the "C" column was filled with 0's. The changes are saved, worksheet window is closed, and the plot window is opened. The **"Grid | Residuals"** menu command is selected. The GRD file (LiDAR data) was selected first, then the GPS XY which was saved as a ".csv" and the column containing the residual values. In Figure 16, "OK" was selected and the worksheet displayed the data file with the residuals column.

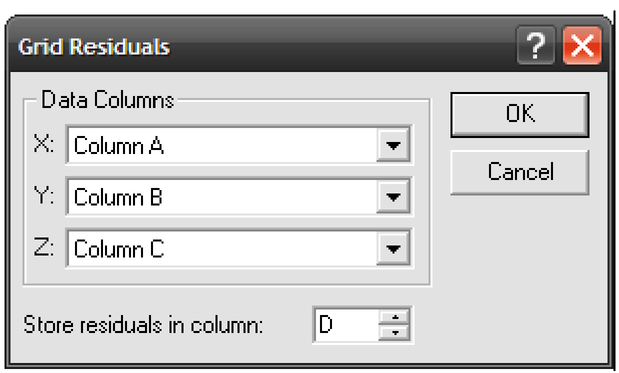


Figure 16: Specify XYZ and residual columns

The **Residuals** command calculated the residuals by subtracting the grid value from the data value, the negative of the grid value is returned when the values in the data column are 0.

4.3 Summary

This chapter provides a review of the steps taken to collect, extract and process the elevations from GPS, LiDAR, Photogrammetry and Topographic Maps. The next chapter presents the results and an analysis of the results.

Chapter 5

Results and Analysis to the Study

The data collection process was carried out under the various land cover categories and varying topographic conditions. Presented in this chapter are the results of the study and analysis of the results.

5.1 Check Point Assessment

Single base RTK GPS is the most accurate and mobile form of GPS technology currently available at Department of Surveying and Land Information, UWI. The RTK GPS was positioned on the base point and an average difference of -0.089m was noted which implied it was within the desired accuracy range to collect the check point data. A total of 185 RTK GPS points were taken at various locations throughout the estate to statistically analyze the vertical accuracy of each of the systems. Of the 185 points collected, 10 of the points were discarded because they had fallen outside the flight path of the LiDAR and 12 were used as checks to ensure the accuracy of the single base RTK by comparing them to the elevation of the base. Table 9 below shows the number of check points collected for each system of measuring elevation and further sub-divided into different land cover categories.

ASPRS stated that there should be no less than 20 checkpoints, preferably 30, for vertical accuracy to be statistically analyzed to determine the vertical accuracy. While NSSDA suggested that checkpoints may be distributed more densely in the vicinity of important features and more sparsely in areas that are of little or no interest. The ICSM in Australia requires a minimum of 40 points per land cover category. In Trinidad and Tobago there isn't any mapping standards established for analyzing the vertical accuracy of LiDAR.

Table 9: Number of Check Points by Land Class

Land Class	**Number of Check Points**		
	LiDAR	**Aerial Photogrammetry**	**Topographic Maps**
All	163	157	163
Asphalt Road	21	21	21
Asphalt Road - Steep	24	24	24
Asphalt Road - Flat	11	11	11
Concrete - Shallow	20	15	20
Lawn Grass - Shallow	20	20	20
Mud Road - Shallow	24	24	24
Playground/Savannah Grass - Flat	22	22	22
Cultivated Citrus - Steep	21	20	21

The land cover category "Asphalt Road- Flat" did not meet any of the standards because only 11 points were taken as can be seen in Figure 17. The decision was made in the field that this was a flat area with no distinguishing features allowing points to be sparsely collected in accordance with NSSDA. Aerial Photogrammetry for the category Concrete – Shallow, 5 of the checkpoints elevations were unable to be extracted because they were taken adjacent to a large shed for the GPS co-ordinates the height of the shed was being derived, a horizontal shift in the co-ordinates had occurred. The assumption was made that this was due to the flight path of airplane.

The remaining 23 categories met ASPRS's minimum requirements which stipulated that no check points per land cover category should be less than 20 check points to be statistically valid.

None of the points met the preferable amount for ASPRS or ICSM's minimum requirement of 40 points except when all the points were tallied to give the consolidated vertical accuracy.

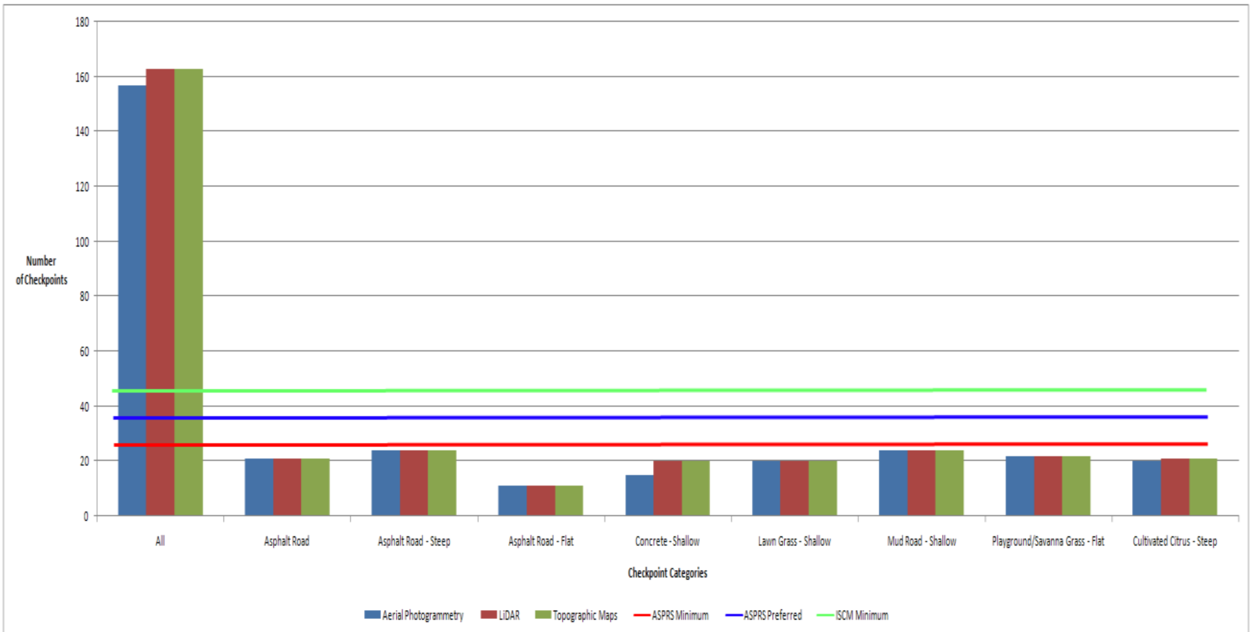


Figure 17: Frequency of Check Points

5.2 Vertical Accuracy Assessment

This assessment considered all the readings collected for each system of measuring elevations and the overall RMSE was calculated. Aerial Photogrammetry had the highest vertical accuracy with an RMSE of 0.369m with a total of 157 checkpoints. With 163 check points for both LiDAR and Topographic Maps, LiDAR had a vertical accuracy of 0.427m and the Topographic Map was the most inaccurate with a vertical accuracy of 2.802m as shown in Figure 18.

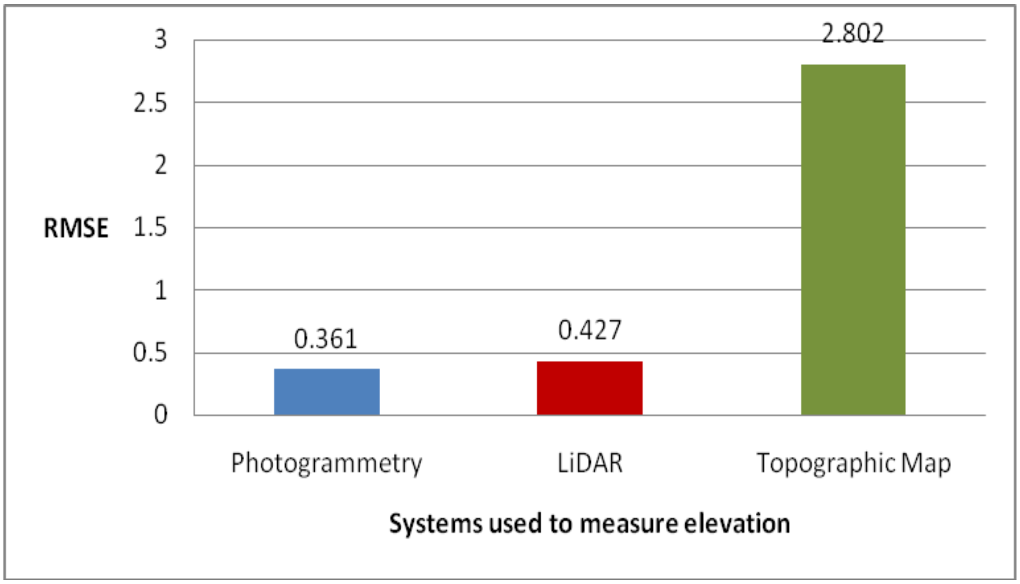


Figure 18: Comparison of the Vertical Accuracy using various methods of measurements techniques

Table 10: RMSE by Land Class

Land Class	**RMSE**		
	LiDAR	**Aerial Photogrammetry**	**Topographic Map**
All	0.427	0.369	2.802
Asphalt Road	0.335	0.321	2.732
Asphalt Road - Steep	0.444	0.459	2.723
Asphalt Road - Flat	0.383	0.407	1.908
Concrete - Shallow	0.253	0.338	3.636
Lawn Grass - Shallow	0.336	0.237	2.392
Mud Road - Shallow	0.425	0.219	1.356
Playground/Savannah Grass - Flat	0.334	0.221	1.616
Cultivated Citrus - Steep	0.480	0.383	3.255

5.3 Topographic Variation

Varying types of topography (such as rolling and flat terrain) within the study area have shown to affect the accuracy at which the elevation surface is modelled. Within each land cover category, there was not enough data to test the points within the groupings flat, shallow, medium and steep. Sufficient data was collected in two land cover categories Asphalt surfaces and Grass surfaces. The Asphalt category was split into two, flat (0°) and steep (10°-30°) slopes. The Grass surfaces were divided into two categories; the playground which was located on top of a hill was generally a flat surface and the lawn grass field with a shallow slope (0°-5°). Points were taken for cultivated citrus along a steep slope but there weren’t any accessible areas where citrus fields were located on a flat surface.

In Figure 19, the relationship between asphalt surfaces with two different gradients for the three systems of measuring elevation is shown. As can be seen in Figure 19, there is little difference in RMSE between LiDAR and Aerial Photogrammetry in contracts to Topographic Maps. The Topographic Maps were most affected by slope. For Topographic Maps, there was a difference in RMSE between steep and flat of 0.815m. LiDAR had the second largest difference of 0.061m and Aerial Photogrammetry 0.052m. LiDAR was the most accurate of the three systems under these conditions with an RMSE of 0.444m in the steep areas and 0.383m in the flat area. Panel 11 below show a 3D Surface Model generated by Surfer 8 with the individual check points overlaid. The panel shows the change in gradient of the earth’s surface.

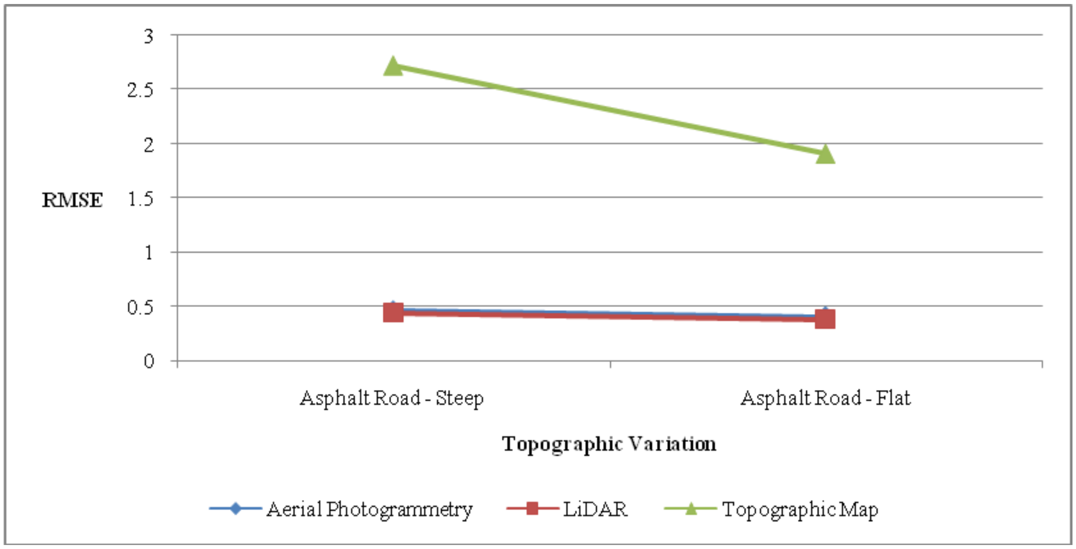
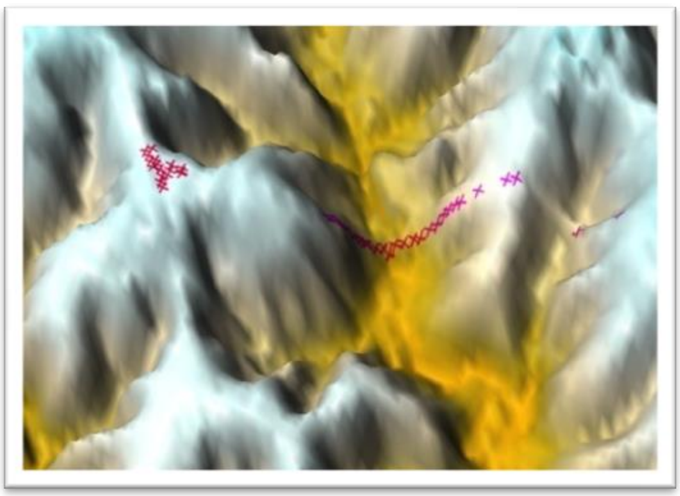


Figure 19: Slope variation between flat and steep Asphalt surfaces



Panel 11: Asphalt surfaces- Flat and Steep

Figure 20: Slope variation between shallow and flat Grass surfaces, shows the relationship between the three systems of measuring elevation of points located on a grass surface with a small difference in slope. As can be seen in Figure 20, there is little difference between LiDAR and Aerial Photogrammetry in contrast to the Topographic Maps. Aerial Photogrammetry was the most accurate with an RMSE of 0.237m with the shallow lawn grass and 0.221 in the

playground. LiDAR had the smallest difference between the RMSE of the shallow and flat grass surfaces with a value of 0.002m. The Topographic Map was found to be the least accurate with a RMSE of 2.932m in the shallow lawn grass and 1.616m on the flat playground.

These findings were similar to that of Baltsavias (1999) and Kraus and Pfeifer (1998) with respect to the gradient of the topography affected the vertical accuracy. ASPRS does not recommend vertical accuracy testing in very irregular or steep slope sloping terrain because there is a high probability that the error in the testing process is a significant contributor to the final error statistic and thus biases the results. ASPRS recommends that vertical accuracy testing always be done in areas where the terrain is as level and consistent as possible. A small but acceptable horizontal shift in the data may reflect an unacceptable vertical error measurement.

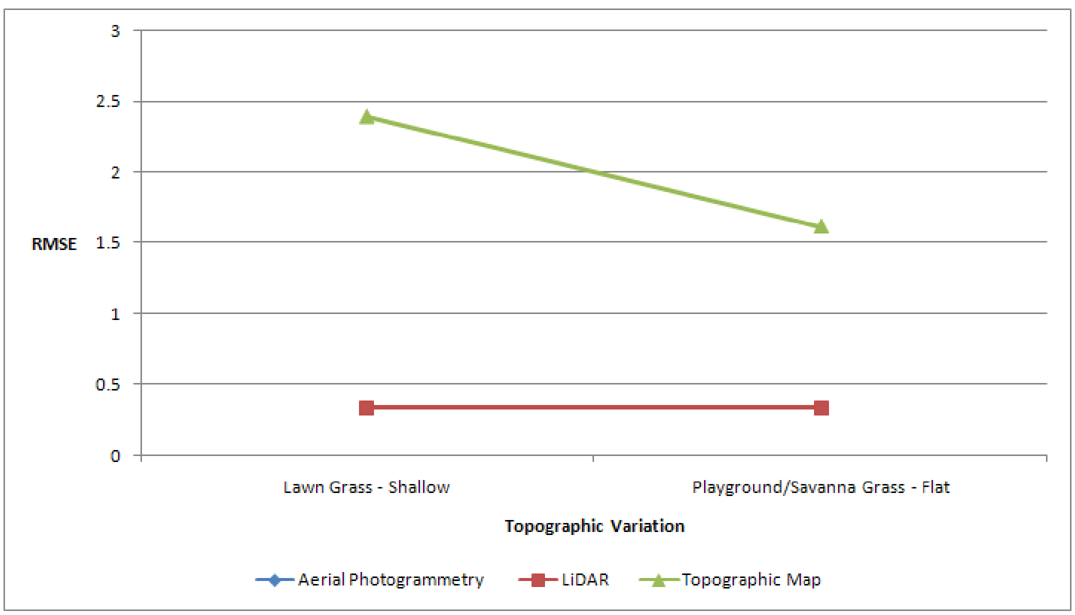
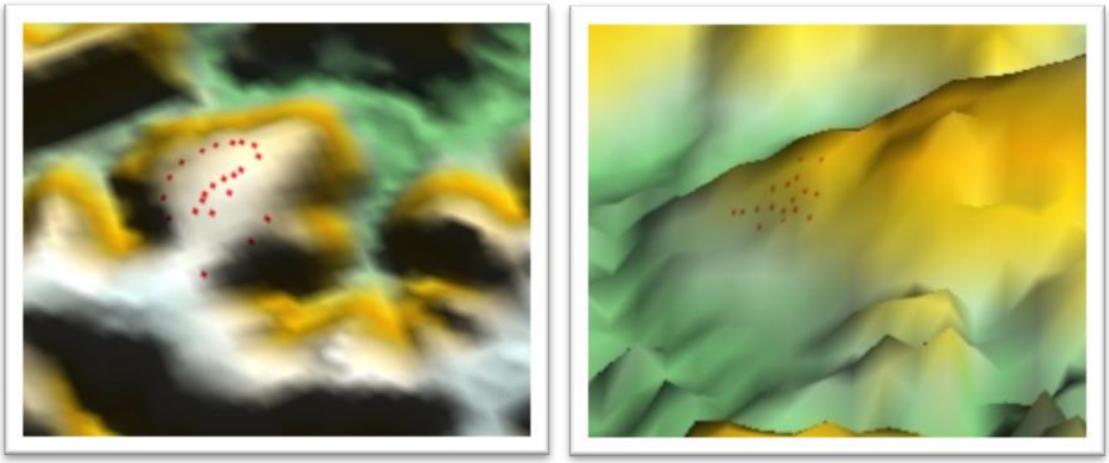


Figure 20: Slope variation between shallow and flat Grass surfaces



A **B**

Panel 12: Grass Surfaces on LiDAR Surface Map

A: Playground (Flat)

B: Lawn (Shallow)

5.4 Land Cover Assessment

Studies carried out by, Baltsavias (1999), Butler (2005), Kraus & Pfeifer (1998), Hoggson *et al.* (2003), Schuckman & Graham (2008) and Coby *et al.* (2001) have shown LiDAR errors are affected by various ground cover types. As well as errors measured in areas of different ground cover also tend to be distributed differently from errors in unobstructed terrain. These trends are not only restricted to that of LiDAR as can be seen in Figure 21. There were two major groups:

1. Paved Surfaces which consisted of asphalt, concrete and mud.
2. Vegetation which consisted of grass and cultivated citrus.

Asphalt and Grass surfaces were further divided to illustrate if the gradient of the surfaces would have an effect on the vertical accuracy.

Of the three paved surfaces Aerial Photogrammetry was most accurate on the mud road surface with an RMSE of 0.219m and the least accurate was the concrete surface with an RMSE of 0.338m. LiDAR was the most accurate on the concrete surface with an RMSE of 0.253m and least accurate on the mud road with an RMSE of 0.425m. The Topographic Map was the most inaccurate system of measuring elevation on the paved surfaces but had a similar trend to that of Aerial Photogrammetry being most accurate on the Mud Road with an RMSE of 1.356m and least accurate on the concrete surface.

Aerial Photogrammetry was the most accurate system of the three within the vegetated areas. The most accurate surface was at the playground with an RMSE of 0.221m. The most inaccurate area was within the cultivated citrus with an RMSE of 0.383. This could have been due to the vegetation being grown on a steep surface and it was difficult to estimate the earth’s surface through the vegetation. There was little difference in the vertical accuracy between either of the grass surfaces but the cultivated citrus had an RMSE of 0.48m. This could have been due to the method of interpolation used, the spacing of the points and the gradient of the land.

LiDAR and Topographic Maps had similar trends to that of Aerial Photogrammetry. The most accurate surface was at the playground with an RMSE of 0.334m for LiDAR and 1.616m for Topographic Maps. The most inaccurate area was within the cultivated citrus with an RMSE of 0.480m for LiDAR and 3.255m for the Topographic Map. The larger error within the cultivated citrus field for LiDAR may have been due to a poor filter being used to remove the vegetation from the dataset resulting in the heights of vegetation to be included in the elevation of the earth’s surface.

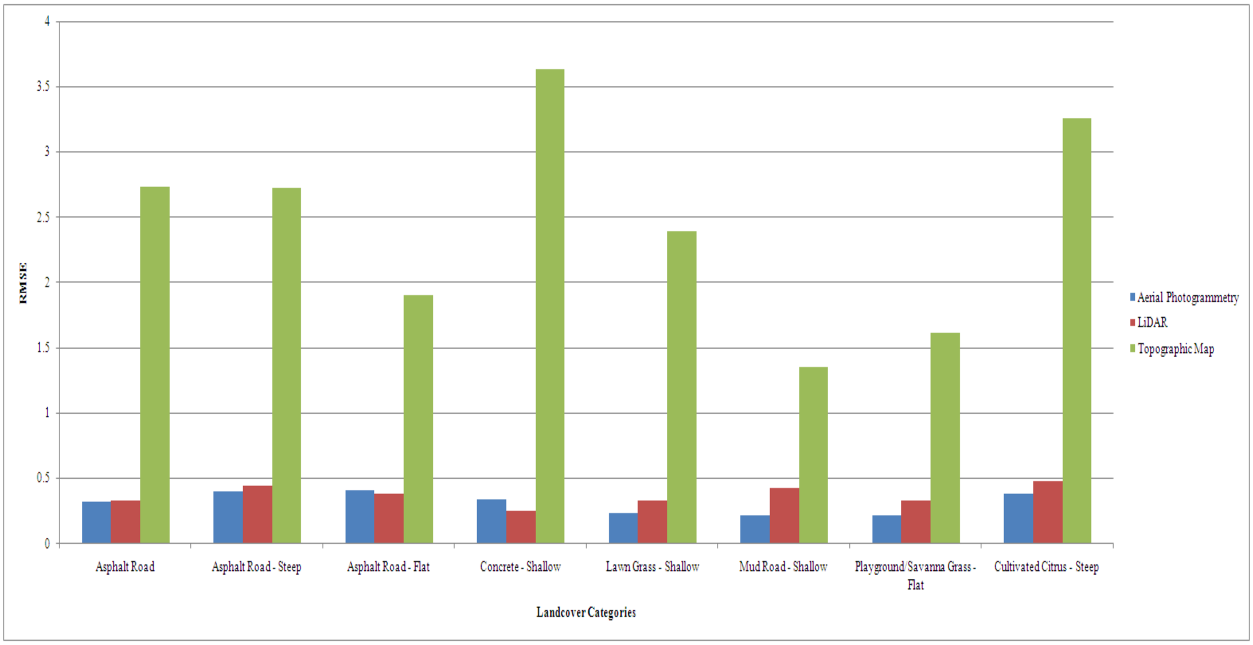


Figure 21: RMSE for each land cover category

5.5 95th Percentile

Table 11: 95th Percentile

Land Class	95% Percentile (m)		
	LiDAR	**Aerial Photogrammetry**	**Topographic Map**
All	0.810	0.589	4.668
Asphalt Road	0.566	0.547	3.760
Asphalt Road - Steep	0.625	0.655	4.183
Asphalt Road - Flat	0.513	0.567	1.980
Concrete - Shallow	0.504	0.509	4.252
Lawn Grass - Shallow	0.565	0.529	3.884
Mud Road - Shallow	0.885	0.299	3.314
Playground/Savannah Grass - Flat	0.554	0.340	2.570
Cultivated Citrus - Steep	0.888	0.664	7.851

Aerial Photogrammetry had the lowest vertical error when the 95th Percentile was calculated with an error value of 0.589m with 157 check points. With 163 check points for both LiDAR and Topographic Maps, LiDAR had a 95th Percentile error of 0.810m and the Topographic Map was the most inaccurate system with an error of 4.668m as depicted in Figure 22.

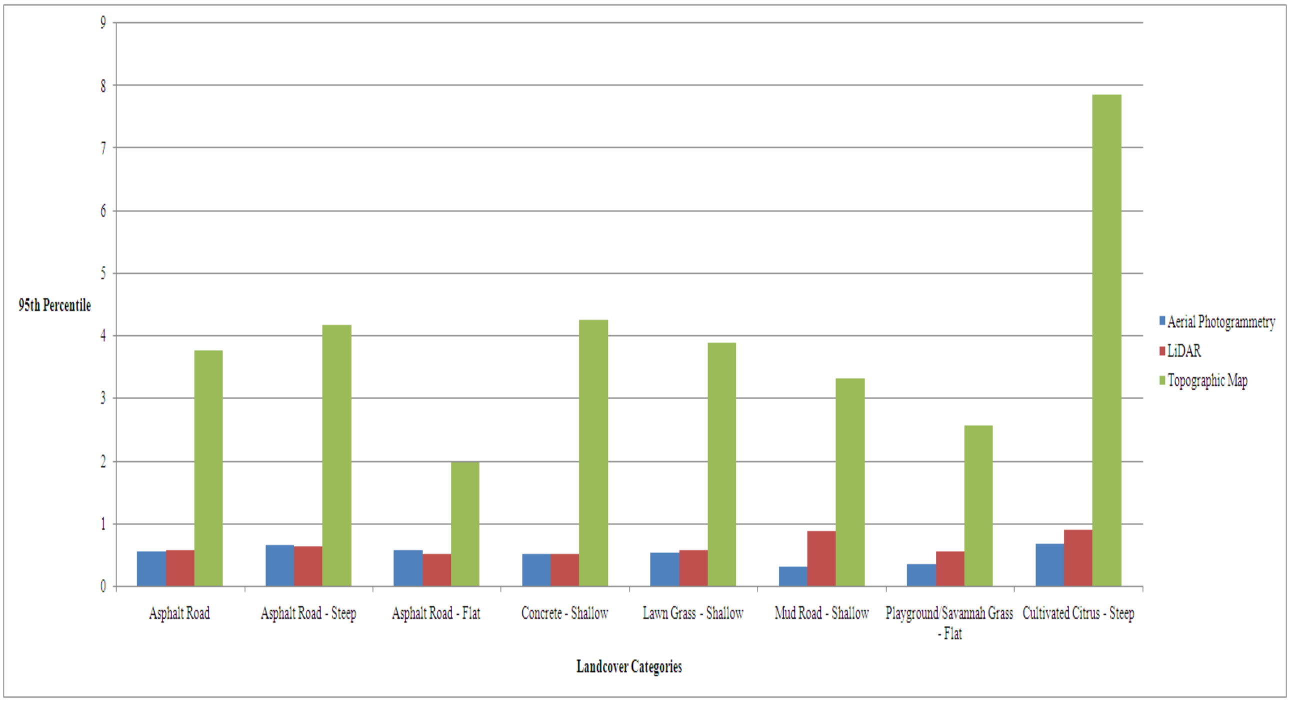


Figure 22: 95th Percentile of each Land cover Category

Chapter 6

Discussion

In this study the vertical accuracy of LiDAR, Aerial Photogrammetry and Topographic Maps were assessed to determine if they met the mapping specifications of Trinidad and Tobago, United States of America and Australia. The study was carried out by taking the elevations in an irregular pattern throughout the Caroni Limited La Gloria Estate located New Grant, Princes Town using single base RTK GPS. The points were grouped in different land cover categories to examine if land-covered surfaces will affect the vertical accuracy based on different categories such as: surface roughness, surface reflectivity and density.

6.1 National Mapping Specification

6.1.1 Analysis of National Elevation Specification of Trinidad and Tobago

The Land and Survey Division of Trinidad and Tobago required a random sample of points to be chosen and tested. The only points observed are those visible at the ground surface level. The maximum RMSE for all measured heights in the test should be ±2m and the maximum error for any one height is 4m.

The RMSE for both LiDAR and Aerial Photogrammetry at ground surface level was 0.333m and 0.221m respectively. Topographic Maps also met this accuracy requirement with an RMSE of 1.616m. For the other land cover categories, LiDAR and Aerial Photogrammetry fell within the stipulated accuracy with the most inaccurate being on Steep Asphalt Hill but was still less than a quarter of the maximum allowable RMSE. Apart from the open Playground Surface, only the

Mud Road and Flat Asphalt Surface met the maximum RMSE requirements for elevations taken from Topographic Maps.

6.1.2 Analysis of National Digital Elevation Guidelines of Australia

The guidelines stipulated by ICSM were followed and all the conditions were met apart from the minimum number of control points required per land cover category. A minimum of 40 check points were recommended and an average of 20 check points per land cover category was collected.

6.1.2.1 Fundamental Vertical Accuracy

The fundamental vertical accuracy was derived for each of the three systems of elevation measurement and judged against Table 2: Uses, Specifications and Accuracy of the Categories of DEM. Aerial Photogrammetry met the vertical accuracy requirements of Categories 2 and 3 with a fundamental vertical accuracy of 0.221m. LiDAR had a fundamental vertical accuracy of 0.334m which met the vertical accuracy requirement of Category 3only. The RMSE derived from the Topographic Map did not meet the standards for any of the categories with a fundamental vertical accuracy of 1.616m.

ICSM recommended for categories that isn’t located on open terrain, the 95th percentile be found to determine the Supplemental and Consolidated Vertical Accuracy. The RMSE of the other land cover categories were still judged against Table 2 to determine what standards they could have met. For Aerial Photogrammetry, apart from the Playground, the only other land cover categories that met the accuracy for Category 2 were the Lawn Grass and Mud Road surfaces with an

RMSE of 0.237m and 0.219 respectively. All the other land cover categories had fallen within the accuracy required for Category 3.

LiDAR had a sufficient accuracy on the concrete surface with an RMSE of 0.253m for Category 2. All the other land cover categories only had sufficient accuracy for Category 3 apart from Mud Road and Cultivated Citrus with an RMSE of 0.581m and 0.722m respectively were outside of the permitted accuracy.

6.1.3 Analysis of National Digital Elevation Guidelines of United States of America

ASPRS's guidelines for obtaining and processing checkpoints were successfully carried out. ASPRS required a minimum of 20 check points per land cover category. All land cover categories were met apart from on the Flat Asphalt surface where 11 check points were collected.

6.1.3.1 Fundamental Vertical Accuracy

The fundamental vertical accuracy was derived for each of the three systems of elevation measurement and judged against

Table 4: Comparison of NMAS/NSSDA Vertical Accuracy. Aerial Photogrammetry met the vertical accuracy requirements required for contour intervals between 4ft to 80ft with a fundamental vertical accuracy of 0.221m. LiDAR had a fundamental vertical accuracy of 0.334m which met the vertical accuracy requirement for contour intervals between 4ft and 80ft as well. The RMSE derived from the Topographic Map met the vertical accuracy for contour intervals from 20ft to 80ft with a fundamental vertical accuracy of 1.616m.

ASPRS recommended for categories that isn't located on open terrain, the 95th percentile be found to determine the Supplemental and Consolidated Vertical Accuracy. The RMSE of the other land cover categories were still judged against Table 2 to determine what standards they could have met.

Asphalt, Concrete, Lawn Grass and Mud Road land cover categories for Aerial Photogrammetry and LiDAR had fallen within the vertical accuracy for contour intervals from 4ft and 80ft. On the Steep and Flat Asphalt Surfaces and Cultivated Citrus land cover categories contour intervals from 5ft to 80ft was permitted for Aerial Photogrammetry and LiDAR.

The Mud Road elevations taken from Topographic Maps were the only land cover category that had the accuracy required to generate 20ft contour intervals. All the remaining land cover categories could have been used to generate contour intervals from 40ft to 80ft.

6.5.4 Supplemental and Consolidated Vertical Accuracies in accordance with ICSM and ASPRS

In accordance to ICSM and ASPRS requirements for Supplemental and Consolidated vertical accuracies, the 95th percentile was calculated. Aerial Photogrammetry had the overall lowest consolidated vertical accuracy of 0.589m, LiDAR was 0.810m and the Topographic Map was 4.668m

None of the consolidated vertical accuracies met the allowed vertical accuracy for any of the four categories of DEM vertical accuracy stipulated by the ICSM. The consolidated vertical accuracy of Aerial Photogrammetry and LiDAR met ASPRS's accuracy requirements for generating contour lines between 10 and 80ft. Topographic maps met ASPRS's accuracy requirements for generating 80ft contour intervals only.

None of the supplemental vertical accuracy of LiDAR and Topographic Maps met the accuracy requirements for any of ICSM's categories. The only land cover category to meet any of the requirements stipulated by ICSM were the elevations taken by Aerial Photogrammetry along the Mud Road had the lowest accuracy of 0.299m which barely passed the accuracy limit for Category 2 (0.300m) stipulated by ICSM.

The land cover category with the highest supplemental vertical accuracy for LiDAR was on the concrete surface with an accuracy of 0.504m and the most inaccurate were the elevations taken in the cultivated citrus with an accuracy of 0.888m. This implied all the land cover categories for LiDAR met ASPRS's accuracy requirements for generating contour lines between 10 and 80ft. The highest supplemental vertical accuracy for Topographic Maps was on the flat asphalt road with a value of 1.98m and most inaccurate was in the cultivated citrus field with a value of 7.581m which permitted Topographic Maps to generate contour lines at intervals between 40 and 80ft.

Chapter 7

Conclusion and Recommendation

The general objective or aim of this study was to assess the vertical accuracy of measurement using different types of survey techniques namely LiDAR, Photogrammetry and Topographic Maps. The study used the same geographical area for each of the land surveying techniques and Ground Truth or Global Positioning System (GPS) was used as the benchmark. It took into consideration measurements over different types of land cover including open terrain, tall weeds and crops, brush lands and low trees, forested areas fully covered by trees, residential areas as well as land surfaces of different gradient.

The RMSE and 95th percentile was used to measure the variations between each of the techniques. The study found that Aerial Photogrammetry had the highest fundamental vertical accuracy with an RMSE of 0.221m. LiDAR and Topographic Maps had a fundamental vertical accuracy of 0.334m and 1.616m respectively.

Varying types of topography (such as rolling and flat terrain) within the study area have shown to impact on the accuracy of the elevations. Despite Aerial Photogrammetry showing the best overall accuracy, LiDAR was the most accurate of the three systems on the asphalt surfaces with an RMSE of 0.444m in the steep areas and 0.383m in the flat area. Sloped terrain induced a vertical error due to a ranging (distance between sensor and object) error caused by an increased return time as expected (consistent with Baltsavias, 1999). Also, there was a reduction in the number of laser points interacting with the surface of steep terrains and resulted in gaps which appear more often and was larger and caused a reduction in interpolation accuracy (consistent with Butler, 2005).

Studies carried out by, Baltsavias (1999), Butler (2005), Kraus & Pfeifer (1998), Hoggson *et al.* (2003), Schuckman & Graham (2008) and Coby *et al.* (2001) have shown LiDAR errors are affected by various ground cover types. As well as errors measured in areas of different ground cover also tend to be distributed differently from errors in unobstructed terrain. This study has shown, apart from LiDAR, these trends also exist within Aerial Photogrammetry. Of the three paved surfaces (mud, asphalt and concrete) Aerial Photogrammetry was most accurate on the mud road and least accurate on the concreted surface. LiDAR was the most accurate on the concreted surface and least accurate on the mud road. Amongst the vegetation, LiDAR and Aerial Photogrammetry were most accurate on the playground and least accurate in the cultivated citrus field.

For Aerial Photogrammetry, it was difficult to estimate the earth's surface through the vegetation located at the cultivated citrus field. When the LiDAR data was filtered to remove the vegetation, it may not have been cleaned efficiently, allowing the heights of the citrus trees to remain in the DEM dataset. During interpolation, it may have taken into consideration the heights of the citrus plants as the elevation height of the earth's surface. Also, the gradient of the earth's surface was steep within the cultivated citrus field.

This study assessed the National Mapping Standards of Trinidad and Tobago with respect to the vertical accuracy standards to determine how efficient the current standards are in comparison to that of the United States of America and Australia. The National Mapping Standards of Trinidad and Tobago need to be updated to become more rigorous. All the categories for Aerial Photogrammetry and LiDAR passed and the RMSE of these systems were less than half of the maximum allowable error.

The mapping standards set by ASPRS (United States of America) and ICSM (Australia) both adopted their standards from the National Standard for Spatial Data Accuracy (NSSDA). The NSSDA replaced the outdated NMAS for digital mapping products. There were little difference between ASPRS and ICSM. The main differences are, the minimum checkpoints required per land cover category, 20 points for ASPRS and 40 checkpoints for ICSM and the RMSE requirements for the different contour intervals. The procedures for determining fundamental, consolidated and supplemental vertical accuracy were the same for NSSDA, ASPRS and ICSM.

In accordance to ICSM and ASPRS requirements for Supplemental and Consolidated vertical accuracies, the 95th percentile was calculated. Aerial Photogrammetry had the overall lowest consolidated vertical accuracy of 0.589m, LiDAR was 0.810m and the Topographic Map was 4.668m

None of the consolidated and supplemental vertical accuracies met the allowed vertical accuracy for any of the four categories of contour interval's vertical accuracy stipulated by the ICSM. The consolidated and fundamental vertical accuracy of Aerial Photogrammetry and LiDAR met ASPRS's accuracy requirements for generating contour lines between 10 and 80ft.

Applying the regulations stipulated by ASPRS's National Mapping Standards, LiDAR is suitable for remapping the national maps of Trinidad and Tobago. In Trinidad and Tobago, the national maps have contour lines generated at 25ft intervals and LiDAR has met the accuracy of generating contour lines at intervals up to 10ft.

Apart from meeting the accuracy standards required by international bodies, LiDAR would be recommended because of the very dense point cloud captured of the earth's terrain. The datasets can be easily automated requiring a low level of manual labour. In contrast to Aerial

Photogrammetry which requires spot heights to be manually extracted and tend to be very time consuming depend on training of the photogrammetrist.

The following are recommended:

1. Further analysis in other parts of the country to more rigorously assess the accuracy of LiDAR in contrast to Aerial Photogrammetry.

2. Further studies to be carried out on different times of the year to determine to what extent the growth of vegetation and change in climatic conditions would affect the accuracy of LiDAR.

3. Further studies to find out why the degree of accuracy was outside that stated by the manufacturers. Optech Inc. claimed an absolute vertical accuracy of 0.15m and this was not obtained in this study.

4. Further studies to determine why LiDAR did not meet the accuracy stipulated by ICSM for the supplemental vertical accuracy.

5. Examine the possibility of Trinidad and Tobago revising the current National Mapping Standards of Trinidad and Tobago and adopting the vertical accuracy standards from ASPRS.

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