DEVELOPMENT OF A SEMI-AUTOMATED SYSTEM FOR STRUCTURAL DEFORMATION MONITORING USING A REFLECTORLESS TOTAL STATION

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DEVELOPMENT OF A SEMI-AUTOMATED SYSTEM FOR STRUCTURAL DEFORMATION MONITORING USING A REFLECTORLESS TOTAL STATION

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PREFACE

This technical report is a reproduction of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Geodesy and Geomatics Engineering, January 2008. The research was co-supervised by Dr. Adam Chrzanowski and Dr. James Secord, and support was provided by the Natural Sciences and Engineering Research Council of Canada.

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ABSTRACT

The failure of a large structure could have severe consequences. For this reason, early detection of possible structural damage is critical. This stimulates the need for a reliable methodology for routine structural deformation monitoring. Large, above-ground oil storage tanks are examples of structures that must be routinely surveyed to monitor their stability and overall integrity. Presented here is the research and development of a methodology and software system to perform the semi-automated deformation monitoring of such tanks. The new system, "SCAN", greatly improves upon a current, drastically outdated monitoring scheme with the implementation of a robotic total station with reflectorless laser technology. SCAN has been interfaced with an existing deformation monitoring software system, ALERT, developed by the Canadian Centre for Geodetic Engineering at the University of New Brunswick.

The full functionality and reliability of this system were tested by simulating an oil tank with a large water tank of comparable dimensions. The results from this field test indicate that the ALERT SCAN system greatly increases surveying efficiency by reducing the time required to collect entire tank data from two weeks (with three persons) to one half-day (with one person). The system is also tested to be a reliable method to perform semi-automated data collection and processing. Based on this system, research has continued into a more sophisticated, adaptable version of SCAN that would have the potential to perform the automated deformation monitoring of almost any structure.

TABLE OF CONTENTS

ABSTRACT II
TABLE OF CONTENTS III
LIST OF FIGURES AND TABLES V
ACKNOWLEDGEMENTS VII

1 INTRODUCTION 1

2 STRUCTURAL DEFORMATION MONITORING USING A REFLECTORLESS ROBOTIC TOTAL STATION 4
  2.1 Deformation Monitoring Schemes 5
  2.2 Automated Monitoring Using a RTS 7
  2.3 RL RTS Field Test 10
  2.4 Semi-Automated Deformation Monitoring using a RL RTS 18

3 DEVELOPMENT OF SOFTWARE TO SCAN A PLANAR SURFACE 21
  3.1 Internal Methods and Algorithms 23
  3.2 Functionality 27
    3.2.1 Plane Scanning Procedure 29

4 SPECIFICATIONS FOR MONITORING VENEZUELAN OIL TANKS 34
  4.1 Venezuelan Oil Tank Survey Design 36

5 "ALERT SCAN" MONITORING APPROACH 41
  5.1 Development of ALERT SCAN for Venezuelan Oil Tanks 42
    5.1.1 Data Collection 43
    5.1.2 Linking SCAN with ALERT 51
  5.2 Functionality of ALERT SCAN 52
    5.2.1 The ALERT SCAN Process 53
    5.2.2 SCAN Setup 56
    5.2.3 Data Collection 66
    5.2.4 Data Processing 82
    5.2.5 Coordinate Plotting 85
    5.2.6 Viewing SCAN Points 87

6 FIELD VERIFICATION: WATER TANK 89
  6.1 Procedure 90
  6.2 Results 93

7 RECOMMENDED METHODOLOGY TO PERFORM VENEZUELAN OIL TANK MONITORING 102
  7.1 Computing the Minimum Number of RTS Setups 103
  7.2 Example Using Typical Tank Values 109

8 CONCLUSIONS 111

REFERENCES 112

APPENDIX I – LIST OF ACRONYMS 116

Vita

LIST OF FIGURES AND TABLES

Figure 2.1 Typical large storage tank (approximately 15 m high) 5
Figure 2.2 Control reference network surrounding a structure.. 7
Figure 2.3 Typical ALERT setup in a large open-pit mine 9
Figure 2.4 Leica TRCA1101 technical specifications -1.. 11
Figure 2.5 Leica TRCA1101 technical specifications -2.. 11
Figure 2.6 Leica TRCA1101 technical specifications -3.. 12
Figure 2.7 Leica TRCA1101 technical specifications -4.. 12
Figure 2.8 RL RTS feasibility test results at zero degrees... 14
Figure 2.9 RL RTS feasibility test results at 30 degrees.. 15
Figure 2.10 RL RTS feasibility test results at 45 degrees.. 15
Table 2.1 Average SDs (mm) for all targets varying incidence angles 16
Figure 2.11 Plot of average SDs for all targets at varying incidence angles 17
Figure 2.12 RL RTS method to scan a structure... 19
Figure 2.13 Deformation monitoring scheme using a RL RTS 20

Figure 3.1 Grid to Scan a Plane 22
Figure 3.2 Vertical grid boundaries 24
Figure 3.3 Horizontal grid "lines"... 25
Figure 3.4 Horizontal point calculations.. 26
Figure 3.5 RL3DScanning “RTS Controls” tab.. 28
Figure 3.6 RL3DScanning RTS communication settings... 29
Figure 3.7 RL3DScanning “Train Corners” 30
Figure 3.8 RL3DScanning point to TL corner.. 30
Figure 3.9 RL3DScanning four corners defined... 31
Figure 3.10 RL3DScanning start plane scan... 32
Figure 3.11 RL3DScanning during scan... 33
Figure 3.12 Sample RL_test.txt data file 33

Figure 4.1 Typical Venezuelan oil tank farm 35
Figure 4.2 Typical oil tank in Venezuela.. 36
Figure 4.3 Tank panels.. 38
Figure 4.4 Etched cross for vertical line “13”... 39
Figure 4.5 Surface tank measurements by intersection of angles (simulated).................. 40

Figure 5.1 RTS-SCAN setup 47
Figure 5.2 Seek Value Computations 49
Figure 5.3 ALERT Project Manager.. 57
Figure 5.4 ALERT SCAN main window.. 59
Figure 5.5 Edit tank parameters.. 61
Figure 5.6 Edit tank panels 62
Figure 5.7 Edit Tank vertical lines.. 63
Figure 5.8 Edit scanning divisions.. 64
Figure 5.9 Edit log file stored destination... 65

Figure 5.10 ALERT Portable Task Setup trained targets 67
Figure 5.11 Select vertical lines to be scanned 69
Figure 5.12 Training a vertical line 70
Figure 5.13 SCAN settings 72
Figure 5.14 Edit advanced SCAN settings 73
Figure 5.15 Confirm ALERT cycle 77
Figure 5.16 Confirm overwrite of previous SCAN data 77
Figure 5.17 Tank Graphic during SCAN 79
Figure 5.18 Successful measurements 80
Figure 5.19 Unsuccessful measurements 81
Figure 5.20 Manually scanned point 82
Figure 5.21 ALERT Data Browser process SCAN data 85
Figure 5.22 Tank coordinate XY plot 86
Figure 5.23 Tank coordinate XZ plot 87
Figure 5.24 All Scan Points 88

Figure 6.1 Water Tank in Fredericton, NB 89
Figure 6.2 ALERT SCAN and the RL RTS collecting data of the water tank 92
Figure 6.3 Line verticality calculations 94
Figure 6.4 Trend Lines for Vertical Line “VL_13” 97
Figure 6.5 Trend Lines for Vertical Line “VL_14” 98
Figure 6.6 Trend Lines for Vertical Line “VL_15” 99

Figure 7.1 Minimum number of RTS Setups 103
Figure 7.2 Oil tank XY plane 104
Figure 7.3 Oil tank-RTS 3D view 106

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1 INTRODUCTION

There are many severe consequences that could result from the failure of a large structure. In addition to jeopardizing public health and safety, environmental contamination and significant economic loss are also of major concern. It is for these reasons that any large deforming structure must be monitored to enable early detection of possible structural damage. Even a slight change of the object shape or changes to the surrounding area due to external factors (e.g., changes in ground water level or tectonic phenomena), no matter how insignificant they may appear, could compromise the integrity of a large structure and could lead to disaster. Examples of recent events (failures of bridges in the U.S.A [CNN, 2007]; collapse of a highway overpass in Quebec, Canada [CBC News, 2007]; rock failures in coal mines in China [Olesen, 2007]; and roof collapses of large civil structures in Europe [Associated Press, 2006]) increase the awareness and consequent demand for monitoring structural behavior.

The topic of this thesis was stimulated by the need of a Venezuelan oil company to develop a reliable and cost effective methodology and software system for monitoring their many large oil storage tanks. The containment of hazardous liquids stored within a tank is critical, as any structural failure could result in a leak having a devastating economic and environmental effect on local communities. An example of such a structural failure was the leakage of oil from a large storage tank in Japan in December 1974 caused by local ground subsidence underneath the base foundation of the tank [Japan Science and Technology Agency, 2007]. The result was a leak of 43,000 kilolitres of hot oil which flowed into the Setonaikai Sea causing much environmental pollution.

Had there been some type of on-site tank deformation monitoring scheme in place, the tank failure may have been prevented.

The main objective of the research described in this thesis has been to develop a methodology for monitoring large structures, focusing on large cylindrical above-ground storage tanks, using a reflectorless (RL) robotic total station (RTS) with automatic target recognition (ATR). In addition to the methodology, a software program to perform semi-automated deformation monitoring has been designed and developed for use on large oil storage tanks located throughout the Venezuela landscape. The software developed within this research provides a reliable and efficient tool to perform deformation monitoring surveys and does not address the analysis of the data to determine and study the structural integrity of the monitored object. The system is an immediate solution to the problem in Venezuela, adapted to meet current rudimentary survey specifications, and designed for use by technicians without extensive geodetic surveying expertise. Continued research into the development of more sophisticated methods utilizing cutting-edge technology (e.g., on-line real-time monitoring or image-based total-stations [Topcon, 2007]) is ongoing.

This thesis outlines the research, development, and testing of the software system utilizing a RL RTS. Chapter 2 describes the theory, methodology, and implementation of a RL RTS to perform the semi-automated deformation monitoring of large structures. The results from a feasibility test of a RL RTS are summarized and compared to the precision specifications provided by the manufacturer. Chapter 3 outlines the development of a software program to scan a planar surface using a RL RTS. The code, methods, algorithms, and procedure designed to create an artificial scanning grid on the surface are described. Chapter 4 discusses the deficiencies of the current oil tank monitoring scheme used in Venezuela which leads into Chapter 5, the main objective of this research, the development of a new, more efficient system to perform semi-automated oil tank deformation monitoring. The limitations of an existing automated deformation monitoring system and the required enhancements of it, to meet the demands for the specified problem in Venezuela, are discussed. The algorithms, structure, and functionality of the developed system are described. Chapter 6 discusses the use, results, and reliability of the new system during a field test simulating a real-life situation. Chapter 7 proposes an alternative approach to the Venezuelan oil tank monitoring scheme to further improve data collection efficiency and conclusions are given in chapter 8.

2 STRUCTURAL DEFORMATION MONITORING USING A REFLECTORLESS ROBOTIC TOTAL STATION

The basic purpose of any structural deformation monitoring scheme is to detect any significant movements of the structure. An effective approach is to model the structure by using well-chosen discrete points located on the surface of the structure which, when situated correctly, accurately depict the characteristics of the structure. It can then be said that any movements of those points represent deformations of the object [Reiterer et al., 2007]. Any movements of the point locations (and thus deformations of the structure) can be detected by maintaining the same point locations over time and by performing measurements to them at specified time intervals enabling direct point displacement comparisons. A common approach for this method is to place physical targets on each chosen discrete point to which measurements can be made. However, there are certain situations in which monitoring the deformations of a large structure using direct displacement measurements of targeted points is uneconomical, unsafe, inefficient, or simply impossible. Reasons for this limitation vary, but it may be as simple as placement of permanent target prisms on the structure is too difficult or costly. This chapter discusses the implementation of a RL RTS to perform structural deformation monitoring in such cases. The sample structure used throughout this chapter is a large cylindrical storage tank (Figure 2.1), however the basic theory and methodology is applicable to most large structures that have similar characteristics.

Figure 2.1 Typical large storage tank (approximately 15 m high)

2.1 Deformation Monitoring Schemes

Historically, many different methods have been used to monitor the deformations of large structures. New monitoring techniques and methodologies emerge as new technology is developed and enhanced, for example, the combination of a total station with image based measurement systems or laser scanners [Reiterer et al., 2007]. Each monitoring scheme has unique advantages, disadvantages, and limitations whether it is based on traditional geodetic surveying techniques, geotechnical measurements, the global positioning system (GPS), or remote sensing principles [Chrzanowski et al., 2007]. The cost, effectiveness, and reliability of a monitoring scheme are important factors in the decision to implement a certain monitoring system over another. Among geodetic techniques, the RTS provides a reliable tool for automated and continuous (if required) monitoring of large structures at a relatively low cost.

Most deformation monitoring schemes consist of measurements made to the monitored object that are referred to several reference points (assumed to be stable) [Chen et al., 1990]. To obtain correct object point displacements (and thus deformations), the stability of the reference points must be ensured [Chen et al., 1990]. The main conclusion from the many papers written on this topic states that every measurement made to a monitored object must be connected to stable control points. This is accomplished by creating a reference network of control points surrounding a particular structure (Figure 2.2).

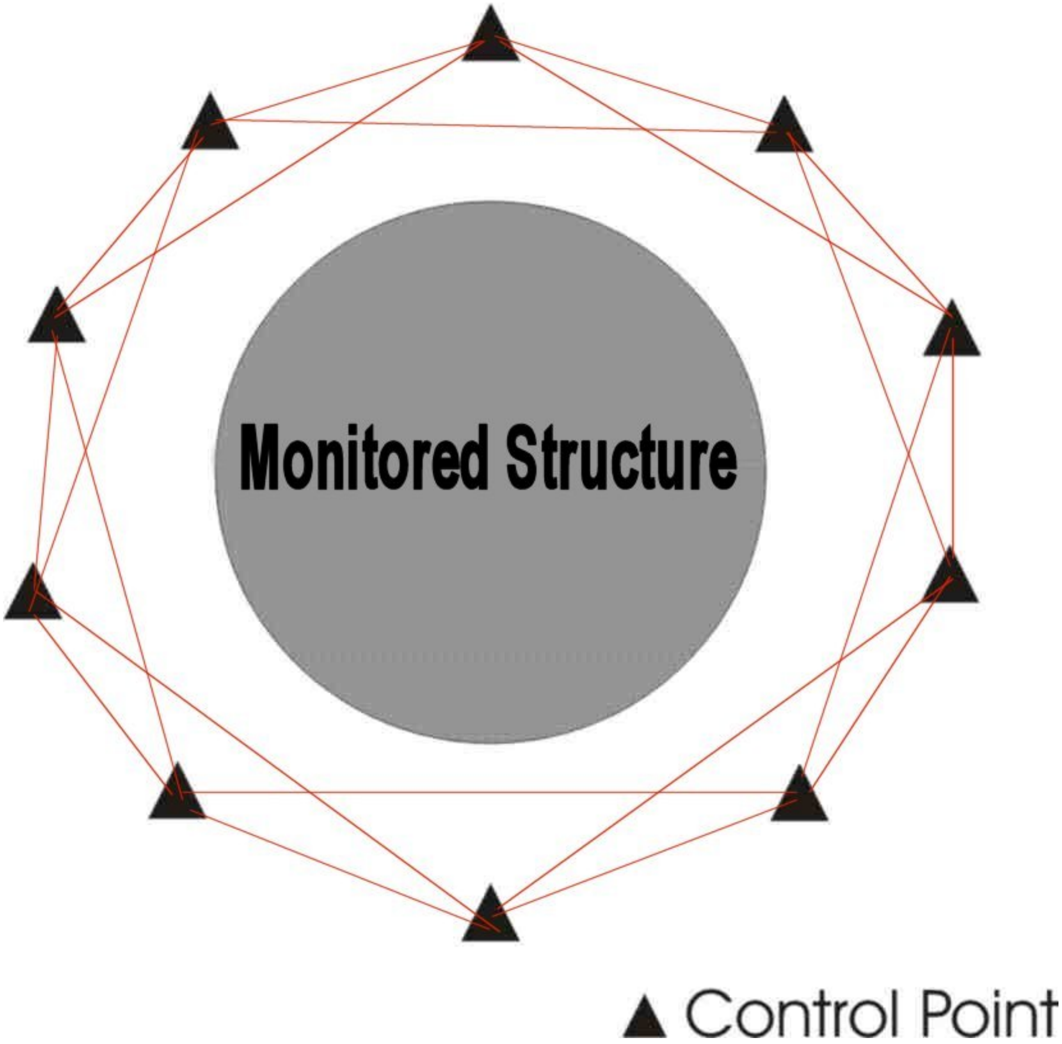


Figure 2.2 Control reference network surrounding a structure

2.2 Automated Monitoring Using a RTS

A relatively new methodology for monitoring structural deformations utilizes a combination of traditional methods (geodetic surveying with angular and distance measurements), improved surveying instruments (RL RTSs), and advanced computer power and programming capabilities. The Canadian Centre for Geodetic Engineering

(CCGE) has already developed a software package to perform fully automated deformation monitoring utilizing a RTS with ATR [Lutes et al., 2001]. The CCGE is a research and development group at the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB) [CCGE, 2007b]. The CCGE provides expertise in geodetic, engineering, and mining surveys of high precision, specializing in the automation of integrated deformation surveys and in the numerical modelling and physical interpretation of structural and ground deformations [CCGE, 2007b].

Over the years, RTSs have been continually improved by providing users with more functions and greater accuracy [Duffy et al., 2001]. The system developed by the CCGE, known as ALERT, uses a RTS interfaced to a computer to perform electronic distance and angle measurements to selected (targeted) points on the monitored object to provide the continuous, automated, stand-alone monitoring of structures [Wilkins et al., 2003]. Data is corrected for atmospheric conditions, target and instrument offsets and then processed through a rigorous least-squares station adjustment, followed by data reduction algorithms to remove blunders [Wilkins et al., 2003]. ALERT can support single RTS observations or multiple RTS networks and can also be used as a tool to perform semi-automated “portable” surveys of control networks (i.e., surveys where neither the targets nor the RTS(s) are permanently installed) [CCGE, 2007b]. A typical ALERT application and setup, in an open-pit mine environment, is shown in Figure 2.3.

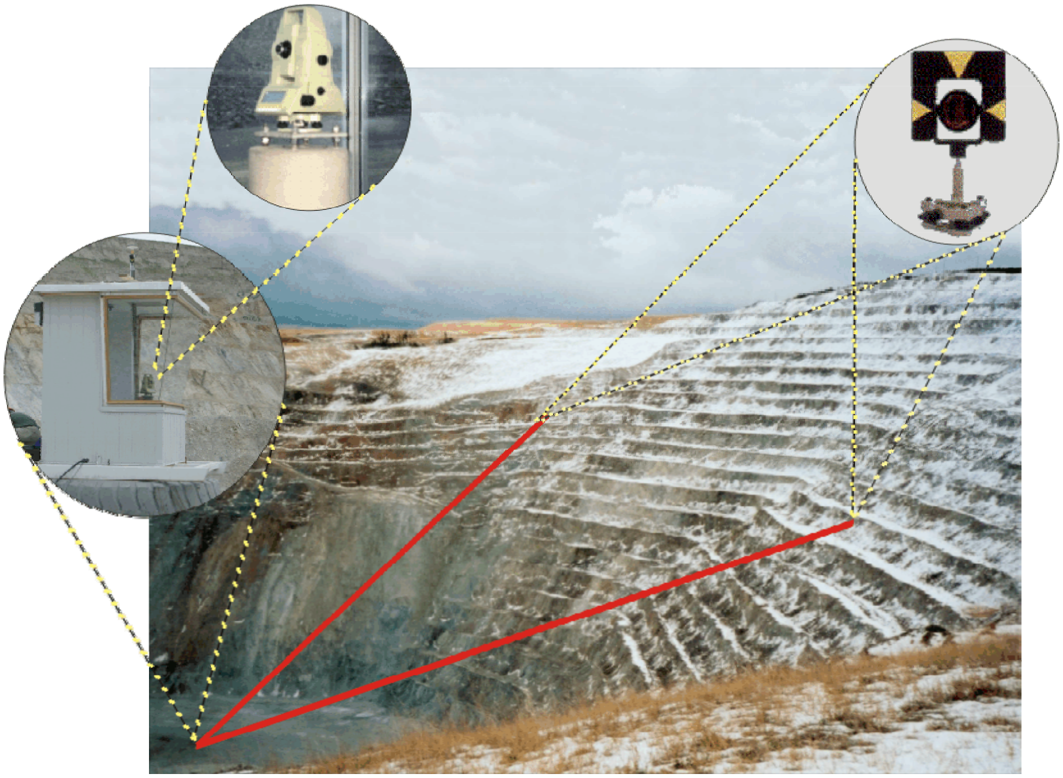


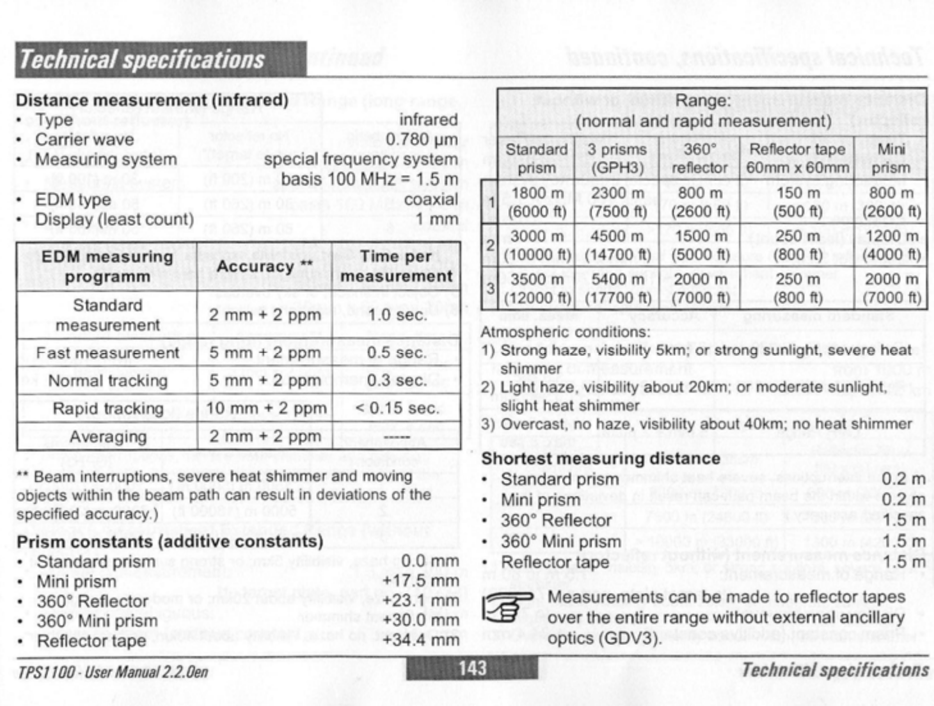
Figure 2.3 Typical ALERT setup in a large open-pit mine [CCGE, 2007b]

Despite the robust effectiveness and power of the ALERT system it is not without its limitations. The ALERT system, in its current configuration, requires placing reflecting prisms (targets) at every monitored point location [Chrzanowski et al., 2003]. This requirement prohibits the use of ALERT in situations where placing of the prisms is either difficult or makes the system uneconomical. Typical examples are large storage tanks for oil or other hazardous liquids, water towers, bridges, buildings, or any other structure with limited wall access. In order to provide a more adaptable system, it is desired for ALERT to have the capability to perform in such cases (i.e., using a RL RTS).

2.3 RL RTS Field Test

Prior to the development of a system utilizing a RL RTS, the functionality, performance, and reliability of the instrument required testing. A RL RTS can perform successful distance measurements to almost any surface without the need for a reflecting prism located at the target. The RL electronic distance measurement (EDM) is accomplished with the use of a visible red laser beam emitted by the RTS and reflected back from the surface of the structure [Leica Geosystems Inc., 2003]. Examples of RL RTSs are the Trimble 5600, Topcon GPT-9000Ai, and Leica TPS1200+.

The particular RL RTS used throughout this research was the Leica TCRA1101. The technical specifications for this instrument are shown in Figure 2.4, Figure 2.5, Figure 2.6, and Figure 2.7 (borrowed from Leica Geosystems Inc. [2003]). The quoted accuracy value for a RL EDM measurement is ± 3 mm + 2 ppm (Figure 2.6) at a 95% confidence level, as stipulated by the International Organization for Standardization (ISO) #17123-3 (as seen in Figure 2.7) [Zeiske, 2007]. However, this value was computed from tests in a lab environment (i.e., ideal conditions), without the influence of systematic biases (e.g., refraction), which occur in real-life situations. Therefore, this quoted “accuracy” value is very optimistic and can be treated as the precision of the instrument. This feasibility study was performed by the author to test and evaluate the instrument to perform repeated RL EDMs over varying distances and incidence angles to various surface types and compare the results with the quoted precision value.



Technical specifications

Distance measurement (infrared)

• Type	infrared
• Carrier wave	0.780 µm
• Measuring system	special frequency system basis 100 MHz = 1.5 m
• EDM type	coaxial
• Display (least count)	1 mm

EDM measuring programm	Accuracy **	Time per measurement
Standard measurement	2 mm + 2 ppm	1.0 sec.
Fast measurement	5 mm + 2 ppm	0.5 sec.
Normal tracking	5 mm + 2 ppm	0.3 sec.
Rapid tracking	10 mm + 2 ppm	< 0.15 sec.
Averaging	2 mm + 2 ppm	-----

** Beam interruptions, severe heat shimmer and moving objects within the beam path can result in deviations of the specified accuracy.)

Prism constants (additive constants)

• Standard prism	0.0 mm
• Mini prism	+17.5 mm
• 360° Reflector	+23.1 mm
• 360° Mini prism	+30.0 mm
• Reflector tape	+34.4 mm

	Range: (normal and rapid measurement)				
	Standard prism	3 prisms (GPH3)	360° reflector	Reflector tape 60mm x 60mm	Mini prism
1	1800 m (6000 ft)	2300 m (7500 ft)	800 m (2600 ft)	150 m (500 ft)	800 m (2600 ft)
2	3000 m (10000 ft)	4500 m (14700 ft)	1500 m (5000 ft)	250 m (800 ft)	1200 m (4000 ft)
3	3500 m (12000 ft)	5400 m (17700 ft)	2000 m (7000 ft)	250 m (800 ft)	2000 m (7000 ft)

Atmospheric conditions:

1) Strong haze, visibility 5km; or strong sunlight, severe heat shimmer
2) Light haze, visibility about 20km; or moderate sunlight, slight heat shimmer
3) Overcast, no haze, visibility about 40km; no heat shimmer

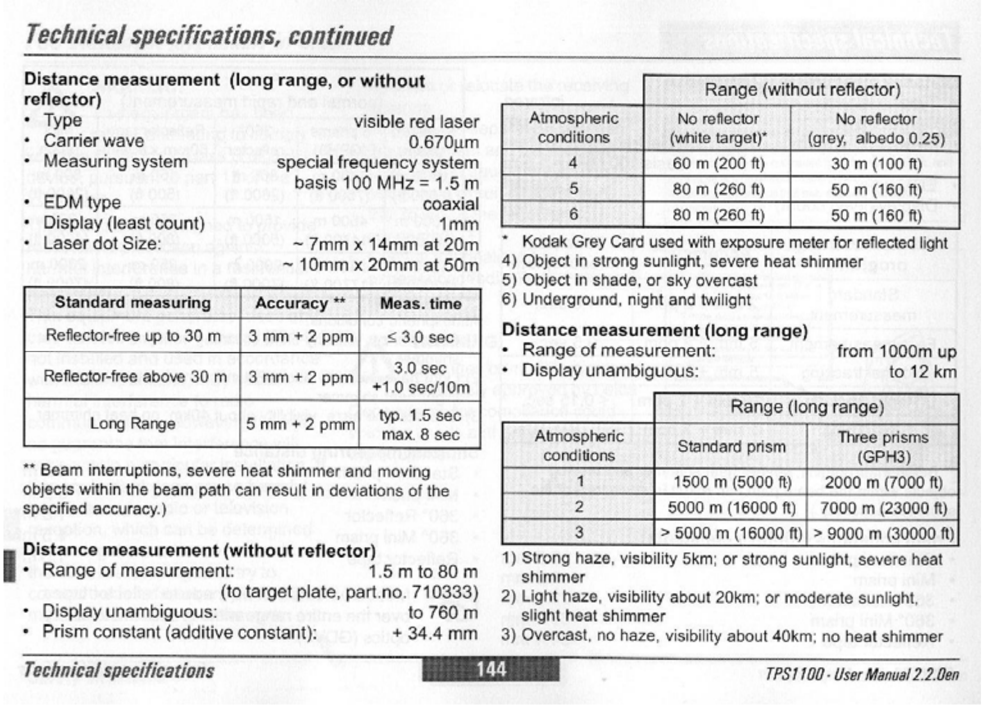
Shortest measuring distance

• Standard prism	0.2 m
• Mini prism	0.2 m
• 360° Reflector	1.5 m
• 360° Mini prism	1.5 m
• Reflector tape	1.5 m

☞ Measurements can be made to reflector tapes over the entire range without external ancillary optics (GDV3).

TPS1100 - User Manual 2.2.0en 143 *Technical specifications*

Figure 2.4 Leica TRCA1101 technical specifications -1



Technical specifications, continued

Distance measurement (long range, or without reflector)

• Type	visible red laser
• Carrier wave	0.670µm
• Measuring system	special frequency system basis 100 MHz = 1.5 m
• EDM type	coaxial
• Display (least count)	1mm
• Laser dot Size:	~ 7mm x 14mm at 20m ~ 10mm x 20mm at 50m

Standard measuring	Accuracy **	Meas. time
Reflector-free up to 30 m	3 mm + 2 ppm	≤ 3.0 sec
Reflector-free above 30 m	3 mm + 2 ppm	3.0 sec +1.0 sec/10m
Long Range	5 mm + 2 pmm	typ. 1.5 sec max. 8 sec

** Beam interruptions, severe heat shimmer and moving objects within the beam path can result in deviations of the specified accuracy.)

Distance measurement (without reflector)

• Range of measurement:	1.5 m to 80 m (to target plate, part.no. 710333)
• Display unambiguous:	to 760 m
• Prism constant (additive constant):	+ 34.4 mm

	Range (without reflector)	
Atmospheric conditions	No reflector (white target)*	No reflector (grey, albedo 0.25)
4	60 m (200 ft)	30 m (100 ft)
5	80 m (260 ft)	50 m (160 ft)
6	80 m (260 ft)	50 m (160 ft)

* Kodak Grey Card used with exposure meter for reflected light

4) Object in strong sunlight, severe heat shimmer
5) Object in shade, or sky overcast
6) Underground, night and twilight

Distance measurement (long range)

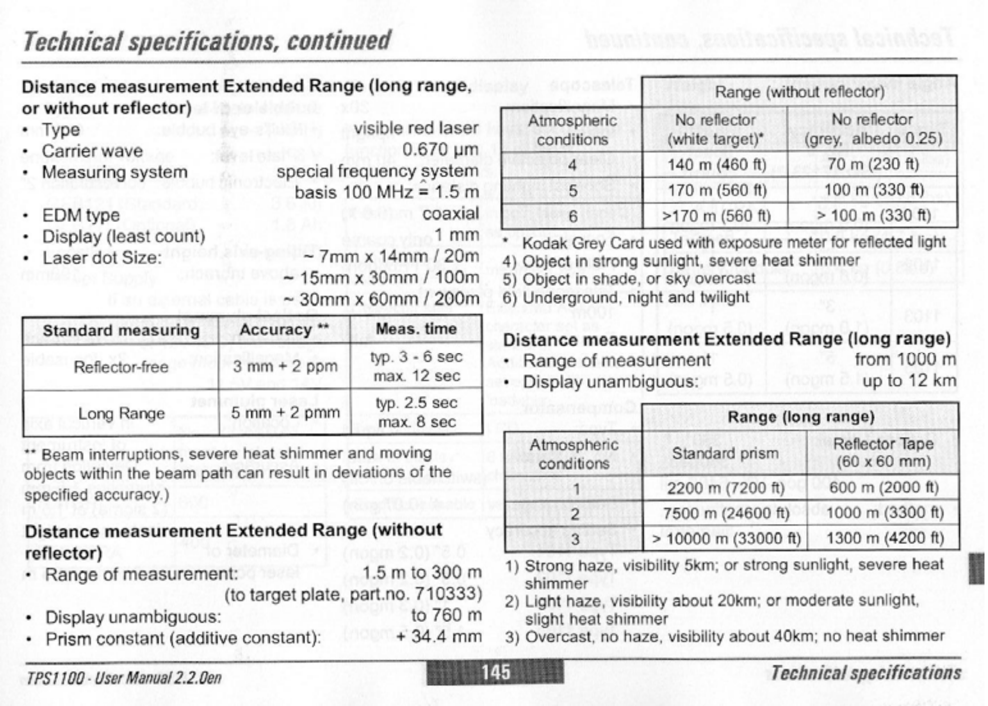
• Range of measurement:	from 1000m up
• Display unambiguous:	to 12 km

	Range (long range)	
Atmospheric conditions	Standard prism	Three prisms (GPH3)
1	1500 m (5000 ft)	2000 m (7000 ft)
2	5000 m (16000 ft)	7000 m (23000 ft)
3	> 5000 m (16000 ft)	> 9000 m (30000 ft)

1) Strong haze, visibility 5km; or strong sunlight, severe heat shimmer
2) Light haze, visibility about 20km; or moderate sunlight, slight heat shimmer
3) Overcast, no haze, visibility about 40km; no heat shimmer

Technical specifications 144 *TPS1100 - User Manual 2.2.0en*

Figure 2.5 Leica TRCA1101 technical specifications -2



Technical specifications, continued

Distance measurement Extended Range (long range, or without reflector)

- Type: visible red laser
- Carrier wave: 0.670 µm
- Measuring system: special frequency system basis 100 MHz ≙ 1.5 m
- EDM type: coaxial
- Display (least count): 1 mm
- Laser dot Size: ~ 7mm x 14mm / 20m
  ~ 15mm x 30mm / 100m
  ~ 30mm x 60mm / 200m

Standard measuring	Accuracy **	Meas. time
Reflector-free	3 mm + 2 ppm	typ. 3 - 6 sec max. 12 sec
Long Range	5 mm + 2 pmm	typ. 2.5 sec max. 8 sec

** Beam interruptions, severe heat shimmer and moving objects within the beam path can result in deviations of the specified accuracy.)

Distance measurement Extended Range (without reflector)

- Range of measurement: 1.5 m to 300 m (to target plate, part.no. 710333)
- Display unambiguous: to 760 m
- Prism constant (additive constant): + 34.4 mm

	Range (without reflector)	
Atmospheric conditions	No reflector (white target)*	No reflector (grey, albedo 0.25)
4	140 m (460 ft)	70 m (230 ft)
5	170 m (560 ft)	100 m (330 ft)
6	>170 m (560 ft)	> 100 m (330 ft)

* Kodak Grey Card used with exposure meter for reflected light
4) Object in strong sunlight, severe heat shimmer
5) Object in shade, or sky overcast
6) Underground, night and twilight

Distance measurement Extended Range (long range)

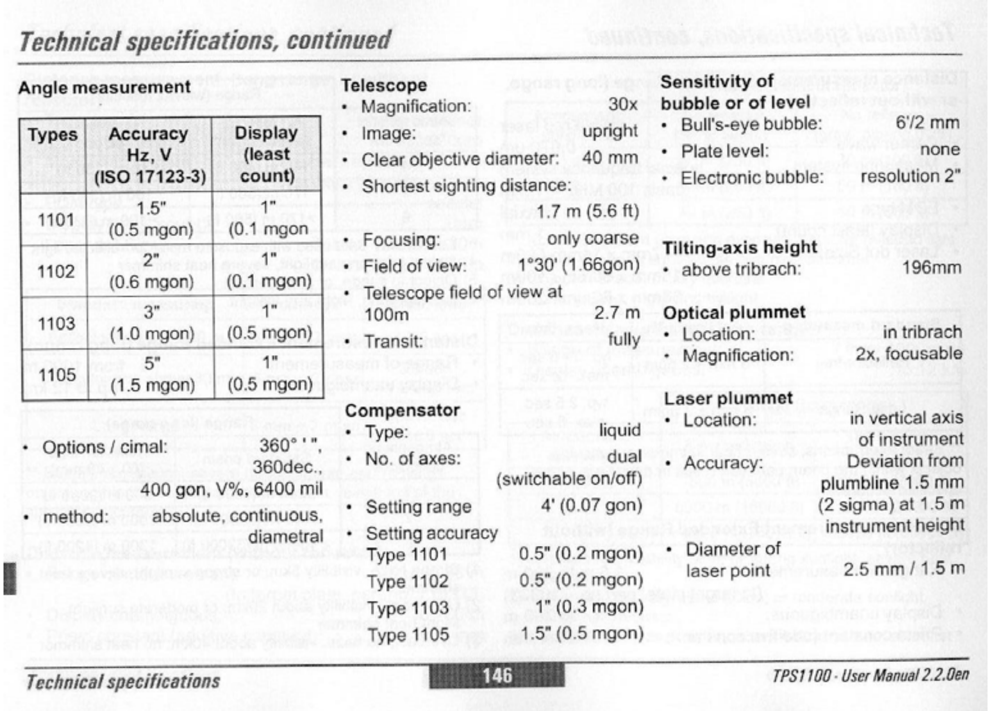
- Range of measurement: from 1000 m
- Display unambiguous: up to 12 km

	Range (long range)	
Atmospheric conditions	Standard prism	Reflector Tape (60 x 60 mm)
1	2200 m (7200 ft)	600 m (2000 ft)
2	7500 m (24600 ft)	1000 m (3300 ft)
3	> 10000 m (33000 ft)	1300 m (4200 ft)

1) Strong haze, visibility 5km; or strong sunlight, severe heat shimmer
2) Light haze, visibility about 20km; or moderate sunlight, slight heat shimmer
3) Overcast, no haze, visibility about 40km; no heat shimmer

TPS1100 · User Manual 2.2.0en 145 *Technical specifications*

Figure 2.6 Leica TRCA1101 technical specifications -3



Technical specifications, continued

Angle measurement

Types	Accuracy Hz, V (ISO 17123-3)	Display (least count)
1101	1.5" (0.5 mgon)	1" (0.1 mgon
1102	2" (0.6 mgon)	1" (0.1 mgon)
1103	3" (1.0 mgon)	1" (0.5 mgon)
1105	5" (1.5 mgon)	1" (0.5 mgon)

- Options / cimal: 360° ' ", 360dec., 400 gon, V%, 6400 mil
- method: absolute, continuous, diametral

Telescope

- Magnification: 30x
- Image: upright
- Clear objective diameter: 40 mm
- Shortest sighting distance: 1.7 m (5.6 ft)
- Focusing: only coarse
- Field of view: 1°30' (1.66gon)
- Telescope field of view at 100m: 2.7 m
- Transit: fully

Compensator

- Type: liquid
- No. of axes: dual (switchable on/off)
- Setting range: 4' (0.07 gon)
- Setting accuracy
  Type 1101: 0.5" (0.2 mgon)
  Type 1102: 0.5" (0.2 mgon)
  Type 1103: 1" (0.3 mgon)
  Type 1105: 1.5" (0.5 mgon)

Sensitivity of bubble or of level

- Bull's-eye bubble: 6'/2 mm
- Plate level: none
- Electronic bubble: resolution 2"

Tilting-axis height

- above tribrach: 196mm

Optical plummet

- Location: in tribrach
- Magnification: 2x, focusable

Laser plummet

- Location: in vertical axis of instrument
- Accuracy: Deviation from plumbline 1.5 mm (2 sigma) at 1.5 m instrument height
- Diameter of laser point: 2.5 mm / 1.5 m

Technical specifications 146 *TPS1100 · User Manual 2.2.0en*

Figure 2.7 Leica TRCA1101 technical specifications -4

Equipment used in this field test included a Leica TCRA1101 RL RTS and five different rectangular targets (chosen to simulate a variety of structure surface colors and textures), including grey, white, gold, glossy white, and sandpaper. A single target plate (# 710333), provided in the Leica TCRA1101 RTS package, was used as the grey and white surfaces (using both sides of the plate) [Leica Geosystems Inc., 2003]. This target had an approximate size of 150 mm by 100 mm (and could not be altered), therefore, in order to maintain a constant target size for all surfaces within the test, the other targets were designed to similar dimensions.

The procedure used to gather the field test data consisted of placing the instrument and target at an approximate distance of 20 m apart. The incidence angle was set to zero degrees (i.e., perpendicular) and the instrument was then manually sighted to the centre of the target. Five distance measurements were then performed in succession, without further adjustment to the telescope orientation (i.e., the HCR and VCR values were not changed between any of the five distance measurements). The target was then rotated to an incidence angle of 30 degrees, manually re-sighted from the instrument, and five more distance measurements were performed (again, with the same HCR and VCR values). This was repeated at incidence angles of 45, 60, and 75 degrees for a total of 25 measurements. These 25 measurements were then repeated for the remaining four targets at this distance. The instruments were then moved to a distance of 40 m apart and the entire process was repeated.

To gather results from this data, the sample standard deviation (SD) of the five repeated measurements for each individual target, distance, and incidence angle were computed. Combining the measurements for all the targets into a single sample size at each distance was impossible because the thickness of the targets were not equal. Figure 2.8, Figure 2.9, and Figure 2.10, show the sample SD (indicated by "$\hat{\sigma}$") of five repeated measurements made to five different surfaces at incidence angles of 0, 30, and 45 degrees at varying distances. (Note that the symbols on the figures do not represent a value, they simply provide a way to decipher the difference between target types).

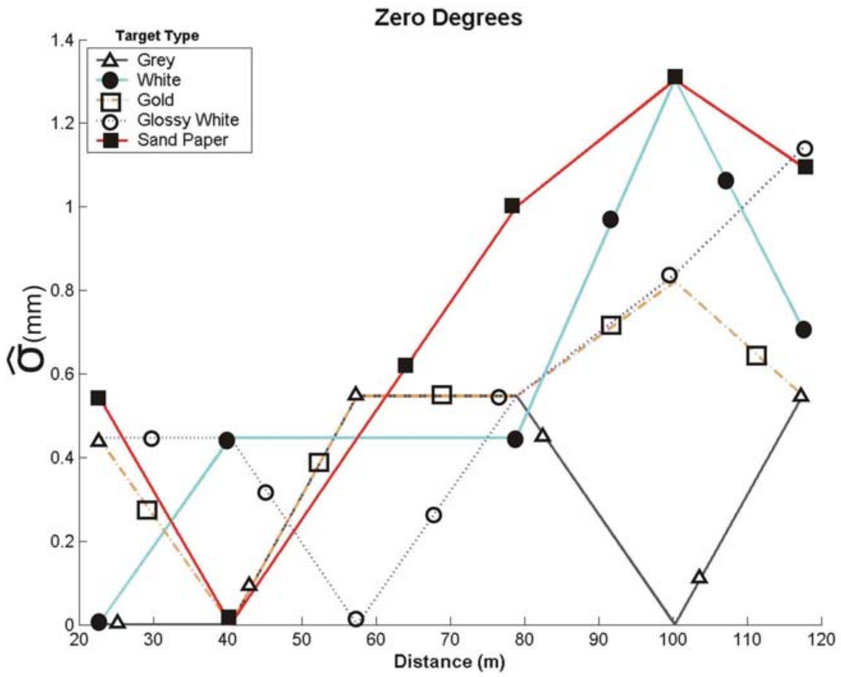


Figure 2.8 RL RTS feasibility test results at zero degrees

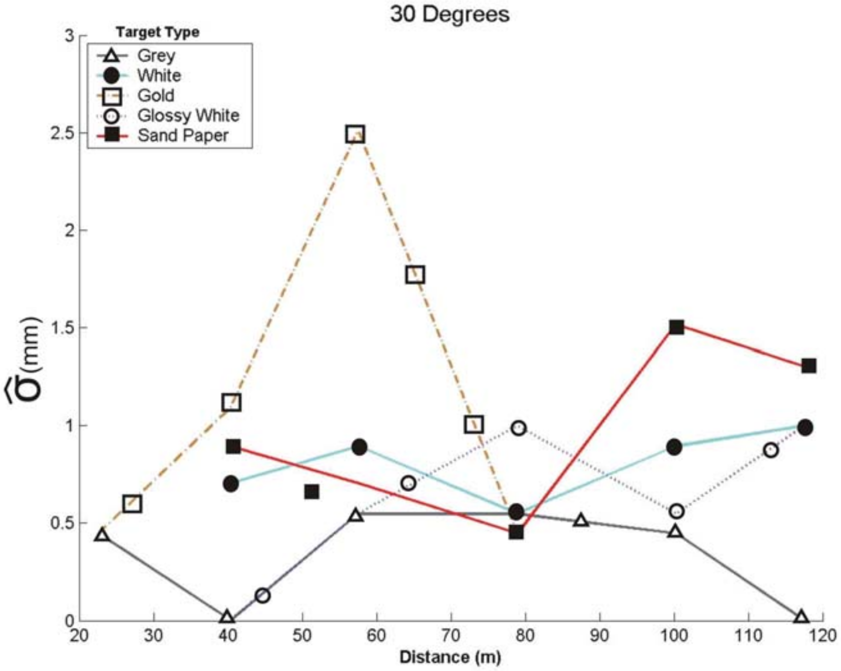


Figure 2.9 RL RTS feasibility test results at 30 degrees

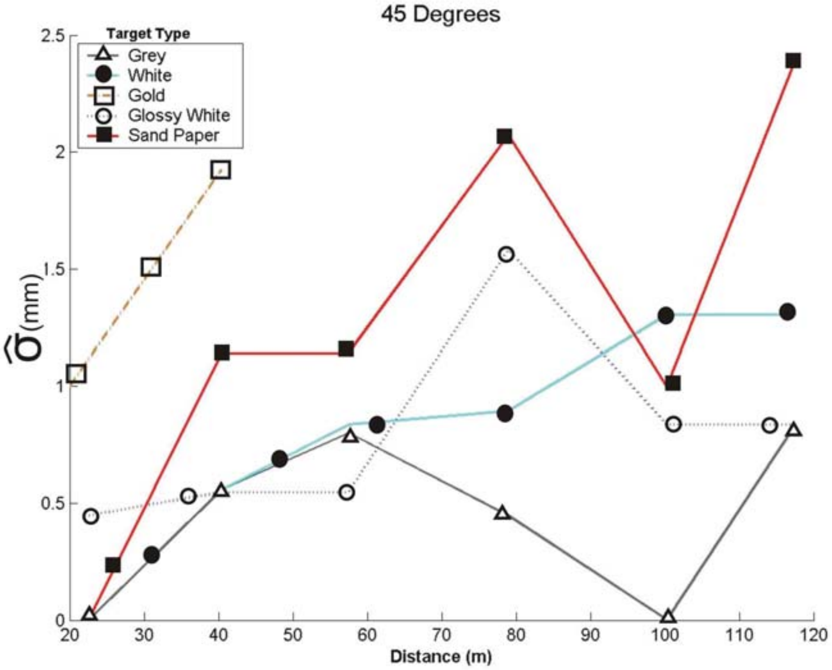


Figure 2.10 RL RTS feasibility test results at 45 degrees

In general, the RL RTS had the most success measuring a distance value with the grey Leica target number 710333 [Leica, 2003]. The RL RTS was able to perform a successful measurement to the grey target at a distance of 120 m with an angle of 60 degrees and all targets (except gold) were successful at 100 m and an incidence angle of 60 degrees. At an incidence angle of 45 degrees, the RL RTS was successful to all surfaces up to a distance of 120 m.

To further quantify the precision of the RL RTS from the gathered data, the averages of the sample SDs for all targets at each distance and incidence angle were computed. These SD values (mm) can be seen in Table 2.1 and plotted versus distance in Figure 2.11. The average of the sample SDs (in Table 2.1) is 0.82 mm

Table 2.1 Average SDs (mm) for all targets varying incidence angles

		Incidence Angle (deg)				
		0	**30**	**45**	**60**	**75**
Distance (m)	**20**	0.3	0.4	0.4	0.5	1.0
	40	0.2	0.5	0.9	0.9	1.1
	60	0.4	1.0	0.8	1.2	1.3
	80	0.6	0.6	1.2	0.9	1.3
	100	0.9	0.9	0.8	1.7	----

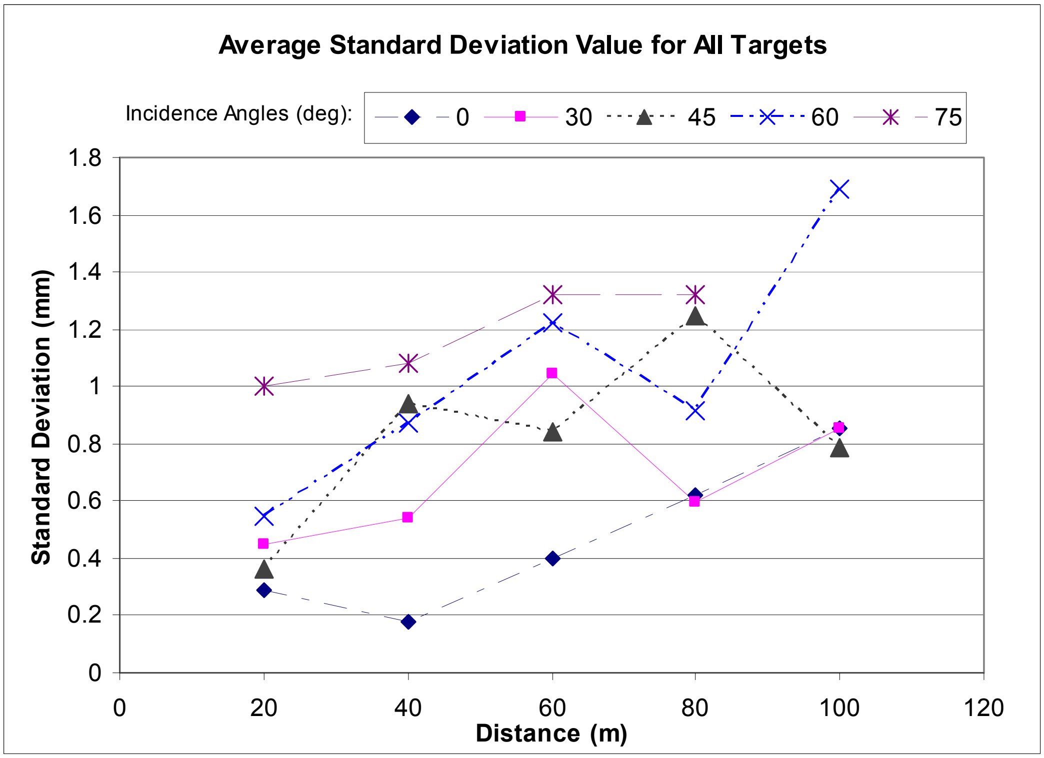


Figure 2.11 Plot of average SDs for all targets at varying incidence angles

The main objective of this experiment was to test the capability of the Leica TCRA1101 to perform RL EDM measurements to the given precision quoted in the technical specifications manual (figure 2.6) of ± 3 mm + 2 ppm at 95% confidence level [Leica Geosystems Inc., 2003]. Multiplying the tested sample SD value of 0.82 mm by 1.96 will give the value at a 95% confidence level [Secord, 2003b]. This value is 1.6 mm, which is less than the quoted value. Therefore, the test showed that the instrument can perform RL distance measurements to various surfaces, distances, and incidence angles to a precision no worse than the quoted value.

2.4 Semi-Automated Deformation Monitoring using a RL RTS

In situations where repeated measurements to identical physical surface points cannot be performed, deformations can be detected by comparison of the approximated overall surface shape at each survey epoch. Using a well-defined and complete point cloud (one with full surface coverage), the structure can be represented by the data points. The basic principle is uniform placement of points around the surface of the structure to get complete coverage and thus produce an accurate depiction. Resulting analysis of the surface measurements can be used to detect any possible deformations and any possible trends within the structural integrity of the structure by comparing the values obtained from repeated surveys.

A RTS with RL EDM capability can be an effective tool in creating a data point cloud by “scanning” the surface of the structure to a specified grid. A simple rectangular grid used to scan the side of a surface with a RL RTS is shown in Figure 2.12.

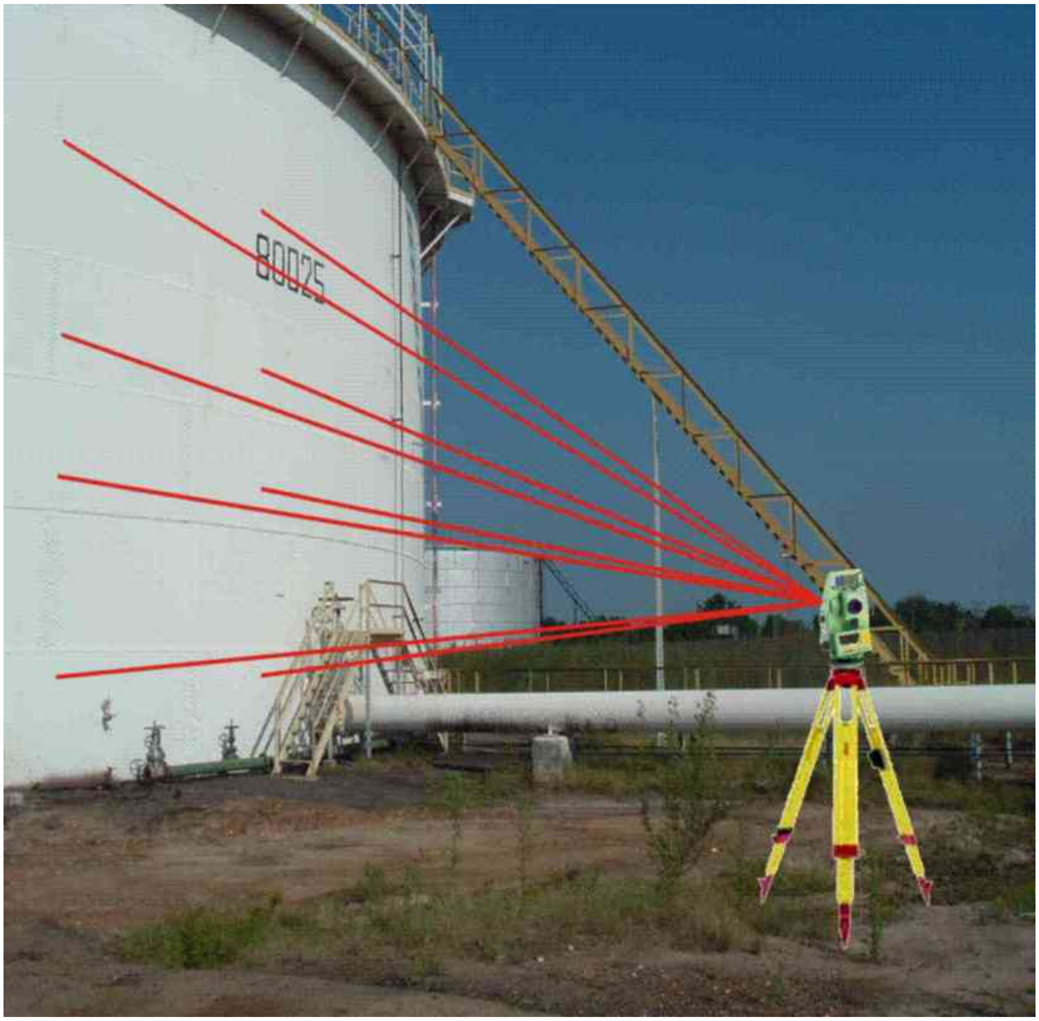


Figure 2.12 RL RTS method to scan a structure

The deformation monitoring scheme is similar to that shown in Figure 2.2. A reference network of control points is situated around or adjacent to the monitored object to which measurements made to the surface of the structure using the RL RTS are referenced. For the specific case of using a RL RTS to perform these surveys, the measurements made to the reference control points are best done using target prisms located at the points. The RL RTS performs reference point measurements while in "reflector" EDM mode (using a prism) and surface point measurements are done using

"RL" EDM mode. This scheme is seen in Figure 2.13 using an oil tank as the monitored structure.

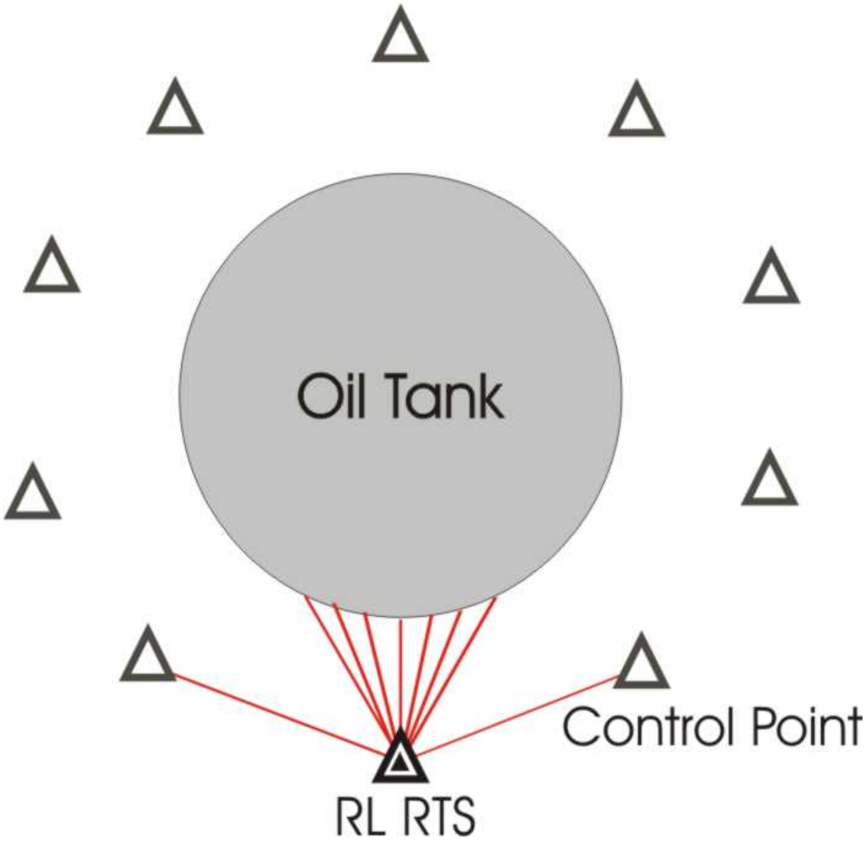


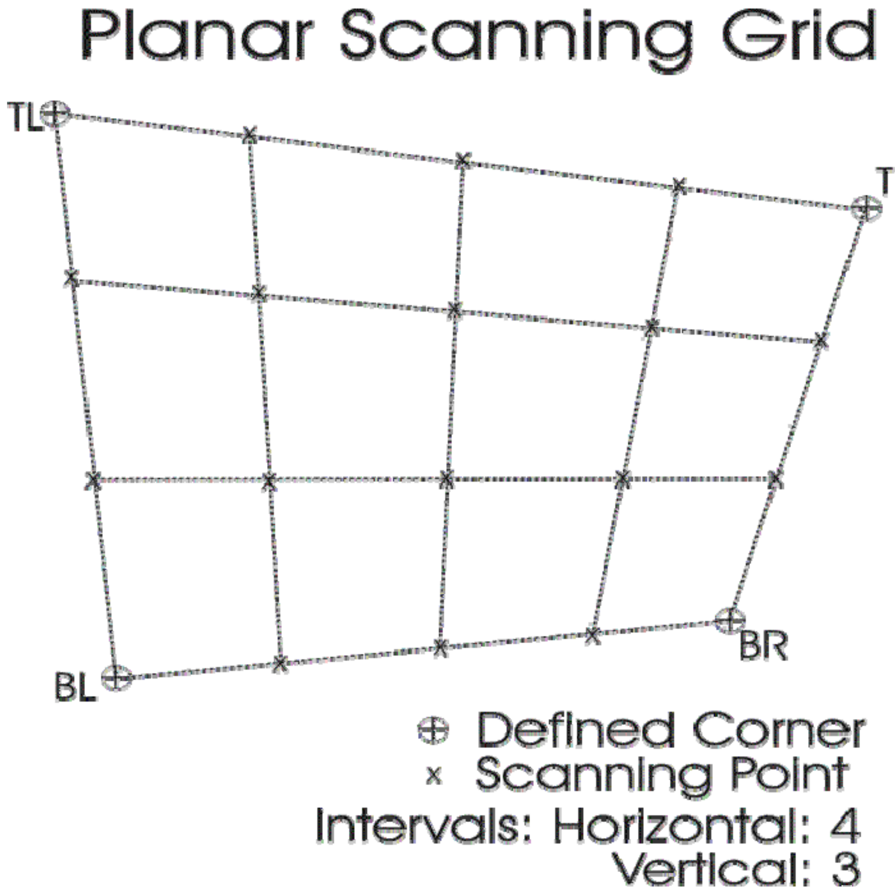
Figure 2.13 Deformation monitoring scheme using a RL RTS

3 DEVELOPMENT OF SOFTWARE TO SCAN A PLANAR SURFACE

Prior to the development of a software system for scanning the surface of a cylindrical object, a software program was developed to scan a planar surface. The purpose for this development was to create the theory, methods, and commands required to perform reflectorless data collection by communicating to the instrument via a connection to a computer. This version of the program was designed for testing the feasibility of the internal methods and commands and, in its current configuration, can be used for research purposes only. A planar surface represents the most basic object shape and most of the developed code from the resulting program can be transformed into software to scan more complex structures. This chapter outlines the development, theory, and testing of a software program to semi-automatically scan a surface of a plane to a user-defined grid using a Leica TCRA1101 RL RTS.

The software communicates with the RL RTS to perform automated data collection of angular and distance measurements and performs a scan of a quadrilateral positioned (artificially or physically) on a planar surface (e.g., a wall) to a user-specified grid density. Although the functions and code located within the software are used as a "platform" for future, more advanced programs, the robustness of the algorithms in this program allow for the wall surface to be situated at any angle or distance with respect to the RTS. The software program is called "RL3DScanning", written in Visual Basic (VB) .Net [Holzner, 2002] using a combination of existing code (classes), written in VB 6 [Schneider, 1999].

The basic method used to perform a surface scan is done by setting up a “grid” of the quadrilateral, using the user-defined four corners and number of horizontal and vertical intervals which determine the density of the grid (Figure 3.1). Using all four corners to define the grid, as opposed to simply using two diagonally opposite corners, enables the program to create a grid in situations where the opposite sides of the quadrilateral are not equal, as seen in Figure 3.1. The four corners are labeled “TL” (i.e., top left), “TR”, “BL”, and “BR” indicating the location of each corner point. The density of the grid and how many total scanning points is defined by the number of horizontal and vertical intervals chosen by the user.



3.1 Grid to Scan a Plane

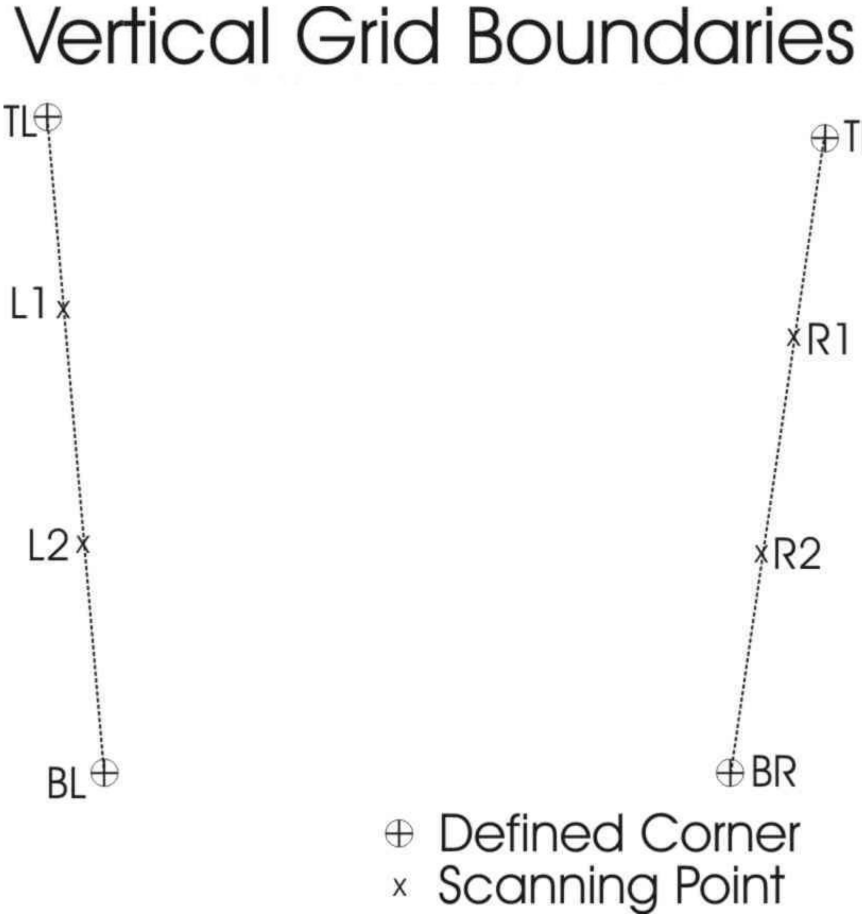
The scanning procedure of the software begins at the TL corner and scans across the top line, performing measurements of HCR, VCR, and distance values at each grid (or "scan") point, to the corner point TR. The software then scans across to the next line below the previous one, again beginning at the left-most point of that line. This continues until the final line has been scanned (i.e., from the BL corner to the BR).

3.1 Internal Methods and Algorithms

This section describes the internal algorithms within the RL3DScanning program and how they work as the user configures the program to perform a grid scan. Using an initial definition (HCR, VCR, and distance) of the four corners of the quadrilateral and the number of intervals required, the seek values (HCR and VCR) for each individual grid point can be computed.

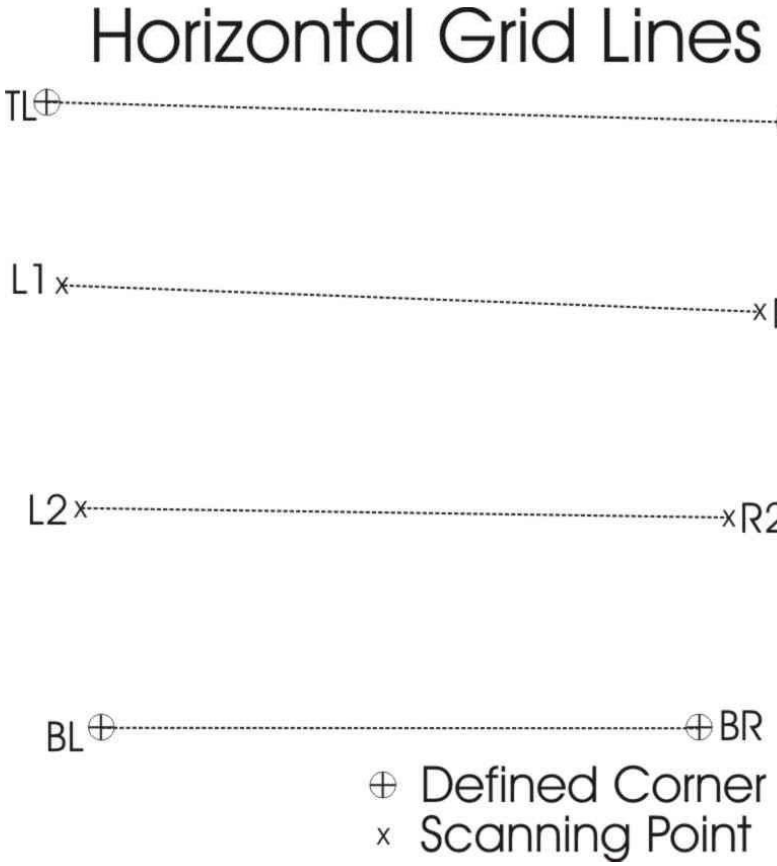
The way in which every seek value is calculated is done by creating an artificial vector between the two outer points of a particular line (e.g., TL and TR). Each vector in space is divided into equal sections based on the number of user-defined intervals. Using the distances measured from the RTS, the length of this line can be calculated and thus how long each interval should be. For instance, a 10 metre long vector would be divided into four 2.5 metre sections (four user-defined intervals), meaning there would be three grid points situated along this line to split the vector. Once the vector is divided, the seek values are computed for each grid point using basic trigonometry.

Computing the seek values for the entire grid of points is done in two main steps. The first step is to create two vertical boundaries on either side of the quadrilateral using the four defined corners (Figure 3.2). For the two vertical boundaries, a vector between corners TL and BL is derived for the left-most boundary and similarly, between TR and BR for the right boundary. These vertical boundaries are divided into intervals by intermediate grid points ("L1", "L2", "R1", and "R2" in Figure 3.2).



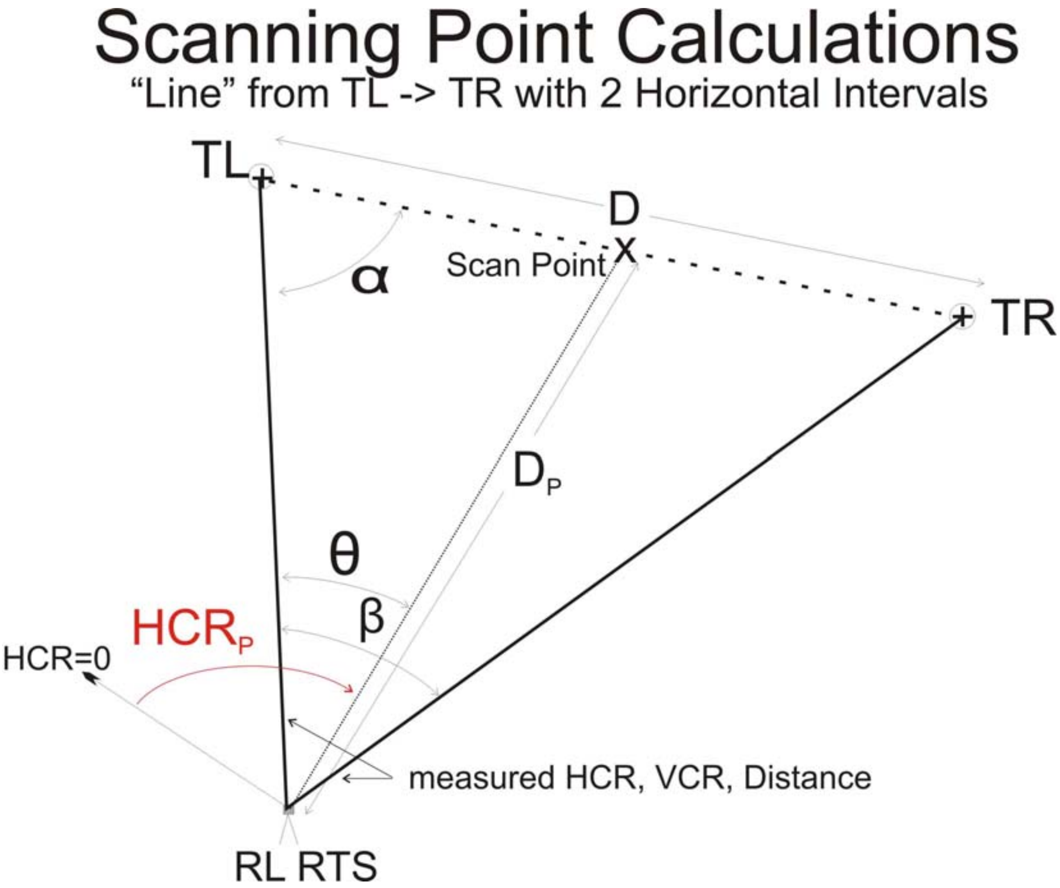
3.2 Vertical grid boundaries

The second step is to define the "horizontal lines", by connecting pairs of associated boundary points and creating a vector between them. As seen in Figure 3.3, the top line from TL to TR is defined, as is the line from L1 to R1 as so on. These vectors are also divided into intervals of equal parts determined by the number of horizontal intervals chosen by the user. When all the seek values for every intermediate point along the horizontal lines, the entire “grid” has been defined (similar to Figure 3.1).



3.3 Horizontal grid "lines"

Once the vectors has been constructed, the seek values for each scan point can be computed. This is done using the measured HCR, VCR, and distance values for the two outer-most points of the vector (e.g., “TL” and “TR”). The HCR (“HCR_P”) and VCR (“VCR_P”) seek values are computed individually. The horizontal case for a single vector (“TL” to “TR”) is shown in Figure 3.4



3.4 Horizontal circle point calculations

The following equations (3.1) are used to compute HCR_P for the Scan Point:

$$\beta = \left|\mathrm{HCR}_{\mathrm{TL}} - \mathrm{HCR}_{\mathrm{BL}}\right|$$

$$\mathrm{D} = \sqrt{\left(\mathrm{D}_{\mathrm{TL}}{}^{2} + \mathrm{D}_{\mathrm{BL}}{}^{2} - 2 \cdot \mathrm{D}_{\mathrm{TL}} \cdot \mathrm{D}_{\mathrm{BL}} \cdot \cos(\beta)\right)}$$

$$\alpha = \sin^{-1}\left(\frac{\sin(\beta)}{\mathrm{D}} \cdot \mathrm{D}_{\mathrm{BL}}\right)$$

$$\mathrm{D}_{\mathrm{P}} = \sqrt{\left(\frac{\mathrm{D}}{\mathrm{n}_{\mathrm{H}}} \cdot i\right)^{2} + \mathrm{D}_{\mathrm{TL}}{}^{2} - 2 \cdot \left(\frac{\mathrm{D}}{\mathrm{n}_{\mathrm{H}}} \cdot i\right) \cdot \mathrm{D}_{\mathrm{TL}} \cdot \cos(\alpha)}$$

$$\theta = \sin^{-1}\left(\frac{\sin(\alpha)}{\mathrm{D}_{\mathrm{P}}} \cdot \left(\frac{\mathrm{D}}{\mathrm{n}_{\mathrm{H}}} \cdot i\right)\right)$$

$$\mathrm{HCR}_{\mathrm{P}} = \mathrm{HCR}_{\mathrm{TL}} + \theta$$

(3.1)

Where:

n_H: number of horizontal intervals; and

i: interval number.

The methods to compute VCR_P are identical to the horizontal case, except VCR values are used in place of HCR values and “n_V” (number of vertical intervals) is used in place of “n_H” (in Figure 3.4 and equations 3.1).

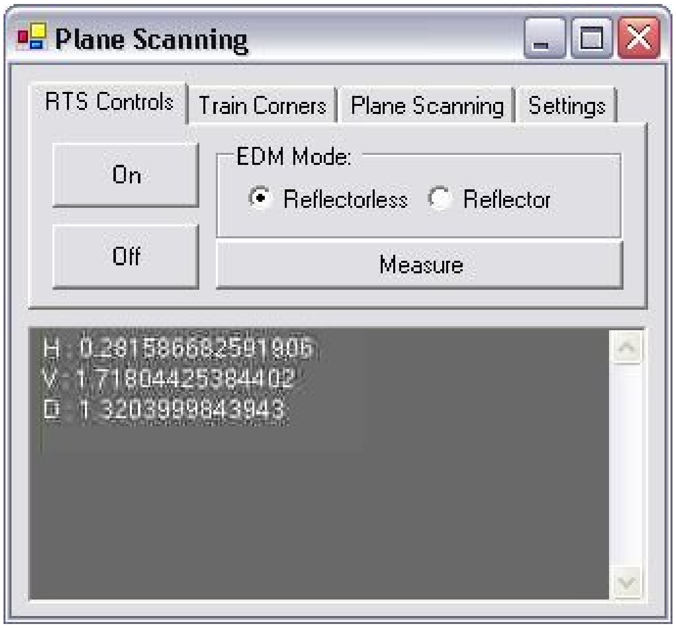
3.2 Functionality

This section outlines the functionality of the RL3DScanning program. At this point of the software development there is no data verification or data processing. The collected observation data is stored in a text file that is available to the user for further study.

The first time the program is initiated on a computer, a directory called “RL Test” is created on the C:\ drive on the local computer and also a text file called “RL_test.txt” is created and placed within that directory. This text file contains all the observed data from this session which can be easily extracted for processing. In subsequent scans, this file is never overwritten and newly collected data is time-stamped and added to the end of the file.

When RL3DScanning is run, by default, the “RTS Controls” tab is displayed (Figure 3.5). From here, the user can verify that the RTS and the program are communicated by attempting to turn the instrument on and off and perform reflectorless measurements or those with a reflector, using the appropriate buttons. (Note that the

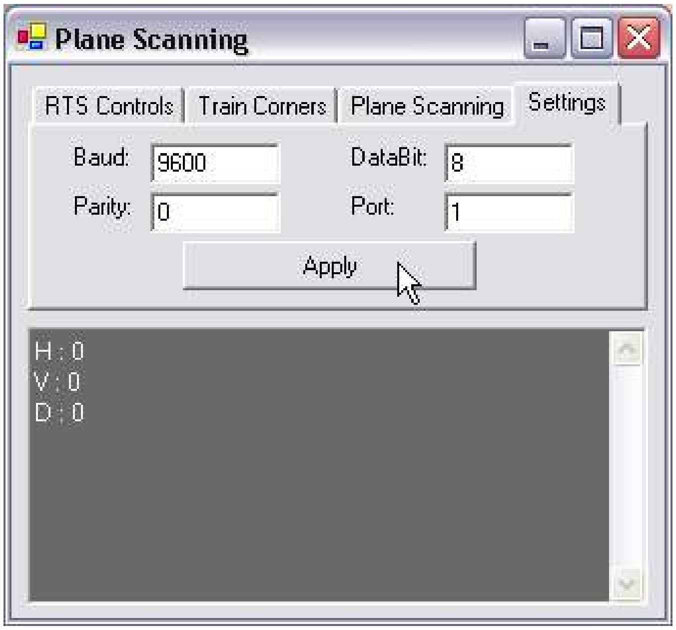
"EDM Mode" chosen here only pertains to this measurements made from this "tab", and for all other RL3DScanning functions, the RL EDM mode is always used). If the observation was performed successfully, the values are shown in the "status" text box (as shown in Figure 3.5). "H" and "V" represent the horizontal and vertical angular measurements (in radians) and "D" represents the distance measurement (in metres).



```
H : 0.281586682591906
V : 1.71804425384402
D : 1.3203999843943
```

Figure 3.5 RL3DScanning "RTS Controls" tab

If the observation was not performed, then values of "0" are shown and the user must navigate to the "Settings" tab (Figure 3.6) and adjust the RTS communications settings as required.



Baud: 9600
DataBit: 8
Parity: 0
Port: 1

```
H : 0
V : 0
D : 0
```

Figure 3.6 RL3DScanning RTS communication settings

3.2.1 Plane Scanning Procedure

This section outlines the methodology for scanning a planar surface using RL3DScanning. The user must run the program, edit the RTS communication settings, and ensure they are correct, by performing a test measurement using the buttons in the “RTS Controls” tab (Figure 3.5). The program is now ready to set up a wall scanning quadrilateral. The following steps are used to define a quadrilateral and then scan the surface to a user-specified grid density:

1. This first step is to define the grid area to be scanned. The user must navigate to the “Train Corners” tab (Figure 3.7). If this is the first time that this particular quadrilateral is to be setup, then each corner of this shape must be

defined. This is done by selecting one of the four corners to define first, in this case, the top left corner. By clicking on the “Top Left” button under the “Set Boundaries” title, the program prompts the user to point the instrument at the top left corner of the wall quadrilateral (Figure 3.8). Once this is completed, the user clicks the “OK” button. Upon doing so, the program initiates a measurement and stores the seek values for this corner.

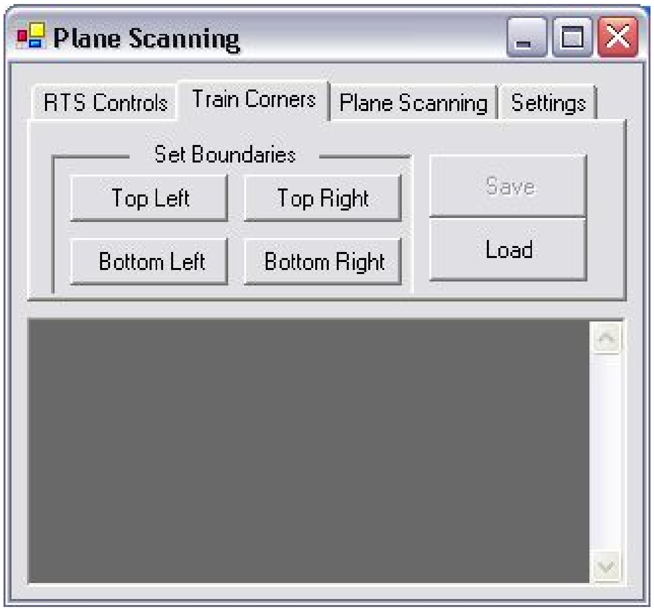
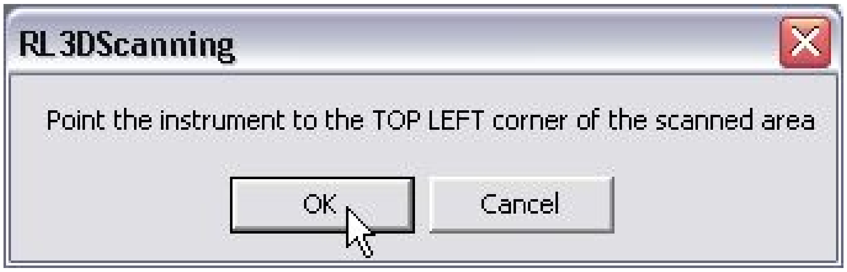


Figure 3.7 RL3DScanning “Train Corners”

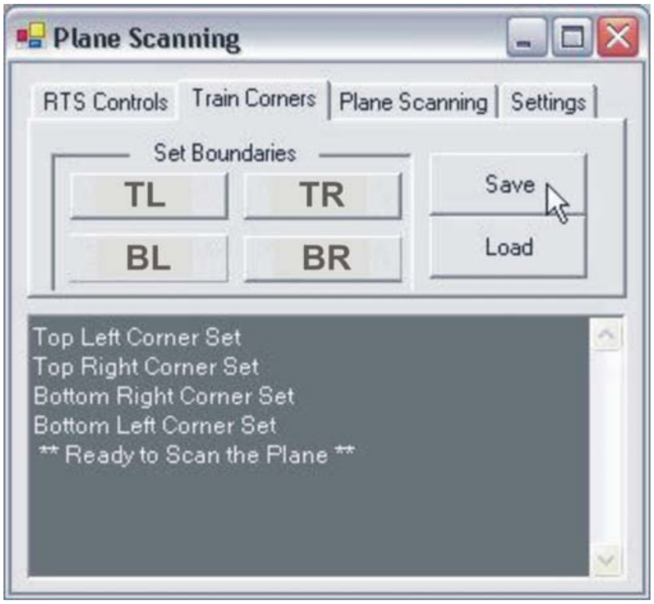


Point the instrument to the TOP LEFT corner of the scanned area

Figure 3.8 RL3DScanning point to TL corner

2. The user must repeat step 1 for the remaining three corners. The user can see in the status text box the progress of the corner definitions (Figure 3.9). In

addition, the text on the associated corner button becomes bold face and changes when the corner is defined.

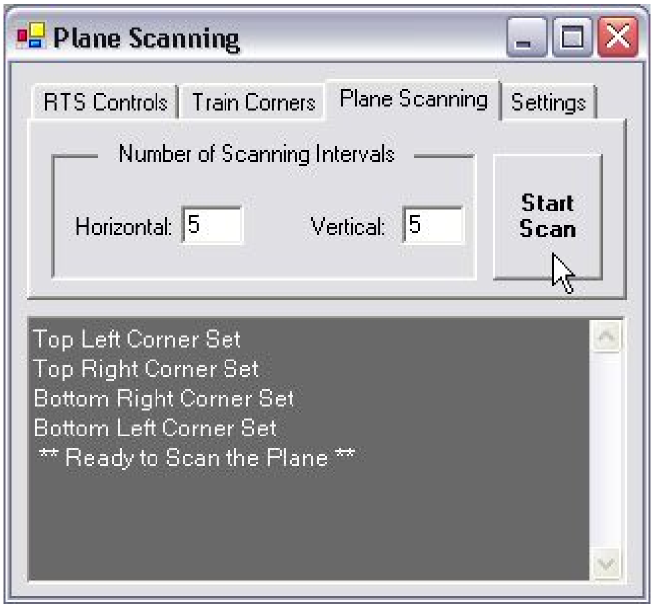


Top Left Corner Set
Top Right Corner Set
Bottom Right Corner Set
Bottom Left Corner Set
** Ready to Scan the Plane **

Figure 3.9 RL3DScanning four corners defined

The user has the option to save these corner definitions for future scans, by selecting “Save”. This action records the seek values for the four corners and the data is written to a text file called “CornerFile3D.txt” located in the “RL Test” directory. These corners can then be loaded into the program the next time it is started, and provided that the same grid area is to be scanned and the RTS orientation and location have not changed, steps 1 and 2 can be skipped.

3. The user now selects the grid density by choosing how many shots (one less than the number of intervals) are to be taken along these “lines”. The user navigates to the “Plane Scanning” tab and enters the number of “Horizontal” and “Vertical” intervals to be used (Figure 3.10). The program is now configured to perform a scan of the quadrilateral.



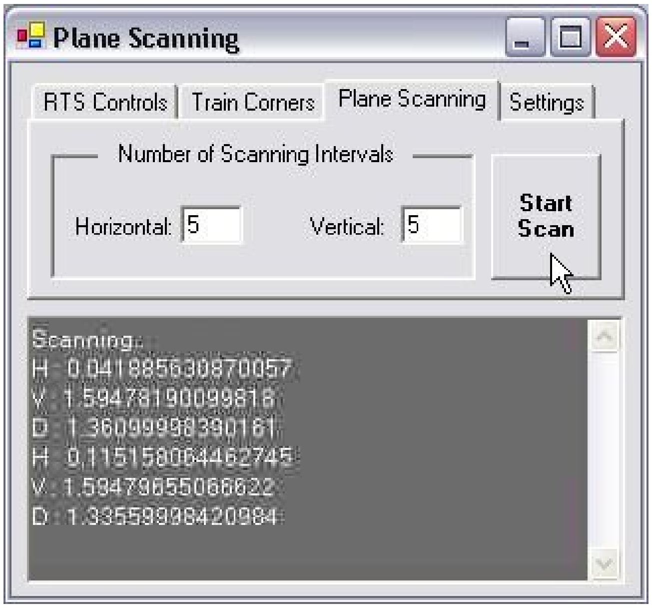
Horizontal: 5

Vertical: 5

```
Top Left Corner Set
Top Right Corner Set
Bottom Right Corner Set
Bottom Left Corner Set
 ** Ready to Scan the Plane **
```

Figure 3.10 RL3DScanning start plane scan

4. Once the grid and scan density have been defined, the user clicks on the “Start Scan” button and the program initiates a command sequence with the RTS to perform measurements of the specified surface area. First, starting on the top left corner and proceeding across to the top right corner, dividing that horizontal distance equally by the number of intervals specified. The user can see where the instrument is pointing to by following the red dot on the surface of the wall. Data is displayed in the text box (Figure 3.11) and also written to the text file “RL_test.txt” (Figure 3.12), where angular values are shown in radians and distances in metres.

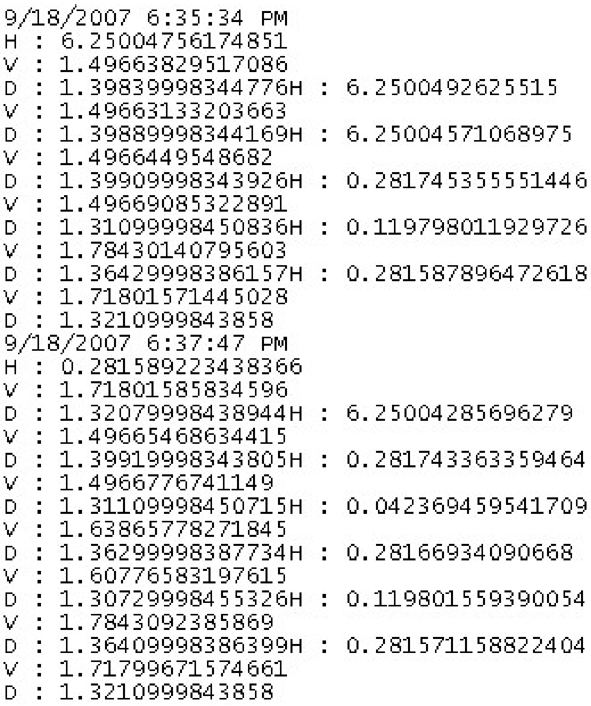


Horizontal: 5

Vertical: 5

```
Scanning:
H : 0.041885630870057
V : 1.59478190099818
D : 1.36099998390161
H : 0.115158064462745
V : 1.59479655066622
D : 1.33559998420984
```

Figure 3.11 RL3DScanning during scan



```
9/18/2007 6:35:34 PM
H : 6.25004756174851
V : 1.49663829517086
D : 1.39839998344776H : 6.2500492625515
V : 1.49663133203663
D : 1.39889998344169H : 6.25004571068975
V : 1.4966449548682
D : 1.39909998343926H : 0.281745355551446
V : 1.49669085322891
D : 1.31099998450836H : 0.119798011929726
V : 1.78430140795603
D : 1.36429998386157H : 0.281587896472618
V : 1.71801571445028
D : 1.3210999843858
9/18/2007 6:37:47 PM
H : 0.281589223438366
V : 1.71801585834596
D : 1.32079998438944H : 6.25004285696279
V : 1.49665468634415
D : 1.39919998343805H : 0.281743363359464
V : 1.4966776741149
D : 1.31109998450715H : 0.042369459541709
V : 1.63865778271845
D : 1.36299998387734H : 0.28166934090668
V : 1.60776583197615
D : 1.30729998455326H : 0.119801559390054
V : 1.7843092385869
D : 1.36409998386399H : 0.281571158822404
V : 1.71799671574661
D : 1.3210999843858
```

Figure 3.12 Sample RL_test.txt data file

4 SPECIFICATIONS FOR MONITORING VENEZUELAN OIL TANKS

Venezuela is a world-leading oil-producing country with hundreds of large oil storage tanks located throughout the country. These tanks are cylindrical in shape and usually situated in "tank farms" comprised of a number of tanks enclosed within a secure area (Figure 4.1). The tanks are designed and built to withstand the effects of wind pressures, temperature variations, seismic activities, or any other external force [Sosa, 2005]. But, as with any human-made structure, there is a potential for failure. For this reason, oil companies must perform routine deformation surveys to ensure safe working conditions and guard against any possible environmental and economic disaster (e.g., collapse). This chapter describes the size, shape, and construction of large oil storage tanks in Venezuela and the specifications of the method currently used to monitor them. Information gathered regarding the tanks is from an on-site personal inspection by the author or from documents provided to the CCGE from the oil company [PDVSA, 2003].

Figure 4.1 Typical Venezuelan oil tank farm [Google Earth, 2007]

A typical tank is 35-40 metres in diameter and 12-15 metres in height (Figure 4.2) and most are constructed of welded thin sheets of steel anchored to the foundation [PDVSA, 2003]. The typical ratio between the radius of the tank and the thickness of the shell walls is typically 1500:1 to 2000:1 [Sosa, 2005]. The walls of the tank are clamped to the foundation at the base and constructed by a series of welded steel plates.

Figure 4.2 Typical oil tank in Venezuela

4.1 Venezuelan Oil Tank Survey Design

The Venezuelan oil tanks are routinely filled with hot oil and a survey must be performed on the surface of the tank on each occasion. This section outlines the technical specifications which the oil tank deformation surveys must meet as required by the Venezuelan company.

Each oil tank is surrounded by eight to twelve permanent physical survey points. A reference network is constructed between these survey points and measurements are made to the surface of the tank from these monuments. The coordinates of these control points must be determined to a relative precision of 1:100000 [PDVSA, 2003]. This value is computed by comparing the misclosure of the network to the total length of the network. In other words, fixing the coordinates of one point within the network and traversing “around” the network results in computed coordinate values for that “fixed” point. The difference between these computed coordinates and the initial given (fixed) coordinate values is the misclosure of the network which is compared to the total length of the traverse [Elfick et al., 1994].

The basic idea behind the specific survey style is to create a set of measurements made to a specified grid of points on the surface of the tank. These points are distributed around the tank to ensure complete coverage and the locations of these points must be measured to an accuracy of one centimetre. The specifications decree that points are to be located on the same “level” with respect to the base of the tank. In other words, to design the point positions to create a series of concentric “rings” [PDVSA, 2003].

The surface of a tank is constructed of a series of steel sheets (or panels), which are essentially concentric circles of varying heights. Panels (shown in Figure 4.3) are visible on the surface on each tank and are used to determine the relative locations of the points to be measured [PDVSA, 2003].

Figure 4.3 Tank panels

Each point to be measured on the surface of the tank is located with respect to a particular panel. In general, the tank is to be covered with points near the borders of each panel. This is in the form of a percentage value of the particular panel. Most often the points are to be placed at twenty and eighty percent of the height of that sheet [PDVSA, 2003]. For example, if a sheet has a height of 1.2 metres, then measurement points are placed at 0.24 metres and 0.96 metres "up" from the bottom of this particular panel.

Artificial vertical lines (VL) distributed around the circumference of the tank are used to group these points within individual panels. The distribution of the VLs around the surface of the tank is initially made by measuring the perimeter of the tank and dividing every three metres [PDVSA, 2003]. These locations are distinguished by a physical marking on the tank which is usually a cross etched into the surface of the tank. Figure 4.4 displays the cross (approximately size of 5 cm by 5 cm) for the VL "13".

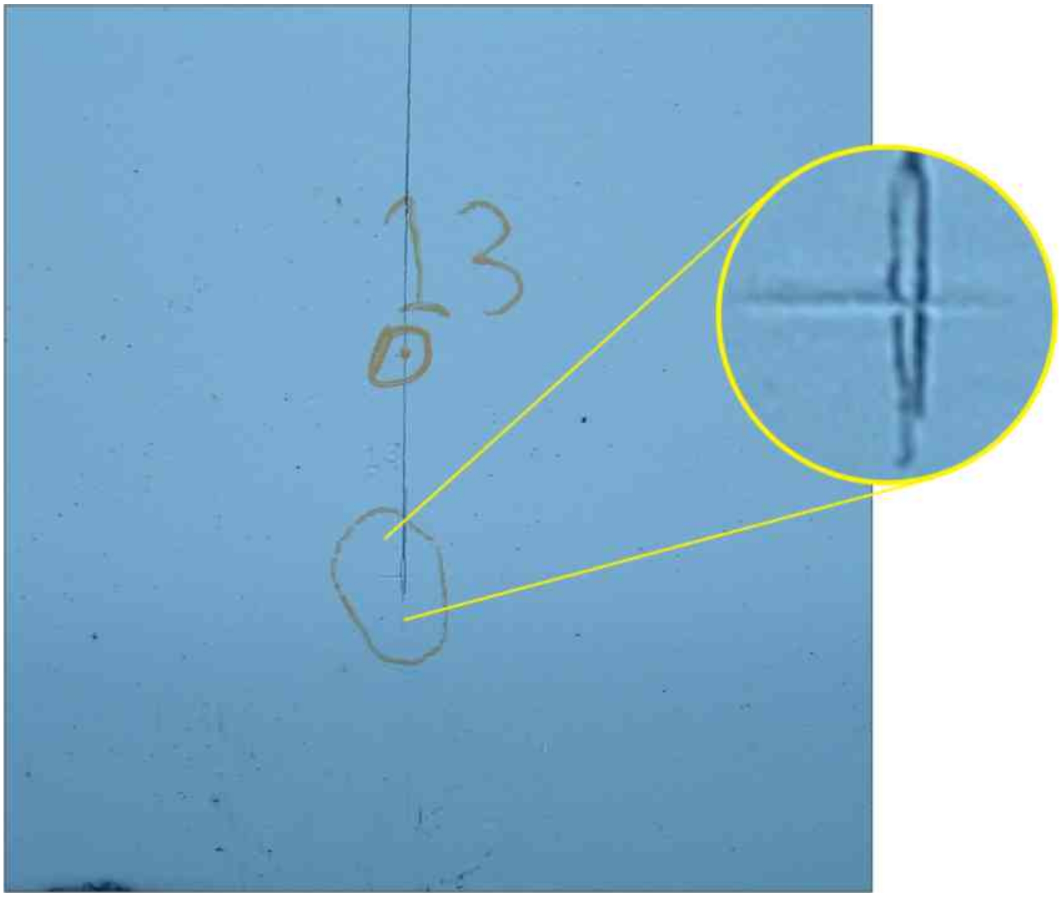


Figure 4.4 Etched cross for vertical line "13"

The current surveying method used by the oil company involves simultaneous angular intersection with two theodolites to a laser spot projected onto the surface of the tank (simulated in Figure 4.5) [PDVSA, 2003]. This method is tedious, time consuming, and expensive as it can take up to two weeks to collect the data for a single tank while requiring two or three persons working simultaneously. It also must be performed during low-light instances (dusk, dawn, or night) to allow the laser spot to be visible on the surface of the tank.

Figure 4.5 Surface tank measurements by intersection of angles (simulated)

5 “ALERT SCAN” MONITORING APPROACH

As discussed in the chapter 4, there are many aspects that render the current survey method used in Venezuela very inefficient and in need of improvement. It was shown in section 2.3 that a RL RTS can perform repeated distance measurements to meet the monitoring specifications set forth by the oil company in chapter 4. Utilizing this technology could provide great improvements upon the existing survey method. The surveying efficiency would be greatly increased saving time and money, in addition to providing a more thorough overall monitoring scheme as each tank can be monitored more frequently.

Prior to development of the full SCAN system, a preliminary version of the SCAN software was developed and tested on actual tanks in Venezuela, during an on-site investigation by the author. This was used as another feasibility test to ensure the instrument and software were capable of performing successful measurements to the tank surface, from the control points, in typical Venezuelan weather conditions. The results from this test indicated that the SCAN method using a RL RTS was capable of meeting the overall monitoring requirements set forth by the company and development into the full SCAN system began.

Although the CCGE already has a powerful automated deformation monitoring package, ALERT, as discussed in section 2.2, it was not capable of performing oil tank surveys in its current configuration. This chapter outlines the need for the enhancement of the ALERT system to allow for the capability to meet the Venezuelan specifications for monitoring oil tanks. The way in which the new system, entitled “ALERT SCAN” (or simply “SCAN”), functions and how it will meet these requirements is outlined. All references and information about the ALERT system are gathered from personal use by the author or taken from the ALERT manual [CCGE, 2006]. This method implements the use of a RL RTS which does not need reflecting prisms to perform a successful distance measurement. This version of the system has been customized to meet the exact specifications provided by the company and to decrease the total time required for a complete tank survey.

The SCAN software, developed by the author, has been interfaced with the existing ALERT system and both systems are used in the ALERT SCAN method. A module of the current ALERT system is used to perform the measurements to the control points (which are targeted) surrounding a tank and the SCAN module is used to perform measurements to the tank surface (no target prisms). Data collected from both sources are combined and processed through existing ALERT processing to provide adjustment of the network and coordinates for all observed points. These can then be examined and analyzed to derive information about the structural integrity of the tank.

5.1 Development of ALERT SCAN for Venezuelan Oil Tanks

This section outlines the theory, research, methodology, and mathematical algorithms behind the development of the SCAN portion of the system. SCAN software has been written in VB .Net [Holzner, 2002], and is designed to work in conjunction with the ALERT system.

The underlying structure of ALERT is a large, specifically designed Microsoft Access database (DB) [Microsoft, 2007] stemming from a software package DIMONS [Lutes et al., 2001] developed earlier. Each ALERT project has its own DB which holds all the project information including collected data, processed data, cycles, survey settings, and much more [Lutes, 2002]. Therefore, the structure and integrity of the DB is critical as most of the ALERT modules access data from many different tables at one time. Any error or inconsistency in a single table or line of data in the ALERT DB may render undesired results from any of the ALERT modules. It is for this reason that any editions or additions of data to the ALERT DB from ALERT SCAN had to be done very carefully with full testing to ensure the integrity and quality of the data.

An important aspect to note when designing software is that a good graphical user interface (GUI) design is critical to the success of a software program [Sommerville, 2001]. In order to accommodate all users, a GUI must be designed to provide the user with easily understood but concise access to information and program functions. A GUI can consist of interactive menus, windows, icons, buttons, graphics, and text that must be easily accessed by the users [Sommerville, 2001]. Each GUI developed for SCAN has been designed with these criteria in mind.

5.1.1 Data Collection

This section outlines the methodology and algorithms designed and implemented into SCAN. The algorithms are utilized to perform semi-automated scans of the oil tank surface with minimal effort by the user. Equations and figures are provided for a better understanding of the designed method.

5.1.1.1 **Algorithms to Compute SCAN Point Seek Values**

The most important function of the SCAN software is the ability to automatically compute the locations of every point on the surface of the tank to be scanned. The algorithm used to compute the locations of each individual Scan point is designed to calculate the horizontal and vertical circle readings (HCR and VCR) and the expected distance value for each point. These computations are based on user-defined settings, tank attributes, RTS setup information, and initial field observations. The calculations must be robust enough to account for all different possible setup configurations and user-defined settings. This section outlines the algorithms used within SCAN to perform these computations which have been built into the SCAN system.

The computed HCR, VCR, and distance values for each Scan point are communicated to the RTS by ALERT SCAN during the data collection phase of the survey. The sequence in which the Scan points are observed is based on the vertical lines that are "seen" from that particular RTS setup. More specifically, a left-to-right VL measurement order is used. In other words, if an individual is standing on the control point on which the RTS is mounted looking at the tank, the VLs (positioned on the tank) to the individual's most left would be scanned first, then the move to the next VL to the right, and so on. The order of scanning individual points within each VL starts at the bottom-most point (largest VCR value) and proceeds “upward” to all the Scan points in that VL.

The HCR, VCR, and distance seek values for each point are calculated based upon a combination of measurements and input values for each VL. They include the HCR, VCR and distance values measured from the RTS setup to the cross point (physically etched into the surface of the tank) for each the VL; the height (from the base of the tank) of each cross point for each VL; the height of each tank sheet/panel and; the percent value (e.g., 20% or 80%) of the panel to position the point.

Using these values, SCAN automatically computes the HCR, VCR, and estimated distance values for each Scan point. There are two main steps in the algorithm. The first of which comprises a set of equations used to derive a series of common “setup” values based on the specific configuration of the RTS with respect to tank and VL cross points. The second step uses the “setup” values to compute the Scan values for each point based on each individual VL configuration.

5.1.1.2 **Definition of Setup Values**

The first step in the process to compute the seek values for each SCAN point is to define a number of “setup” values. These values are defined with respect to the RTS and a VL and are defined separately for each VL. Once defined, these values are used to compute the seek values for all the SCAN points within that VL. Some of the “setup” values are measured directly while the others are computed from measured values and are best understood by a cross-sectional view of the RTS-Tank setup. The definition of the "setup" values are as follows:

Z_C: zenith angle measured to the cross on the surface of the tank from the RTS (observed);

D_C: distance measured from the RTS to the cross on the surface of the tank (observed);

$H_{C:}$ height of the cross point with respect to the base of tank (value entered from user);

Z_B: zenith angle to the base of the tank from the RTS (computed);

D_B: distance from the RTS to the base of the tank (computed);

D_H: horizontal distance between the zenith (vertical) axis from the RTS and the surface of the tank (computed);

H_M: vertical distance between the base of the tank and the horizontal line (X-axis) from the RTS (computed);

α: angle between the horizontal line (X-axis) from the RTS and the zenith direction angle to the cross point (Z_C) (computed) and;

β: angle between the horizontal line (X-axis) from the RTS and the zenith direction angle to the base of the tank (Z_B) (computed).

In order to define these "setup" values, the position of the RTS with respect to the tank must be considered. There are many different ways in which the RST can be positioned with respect to the tank and each situation would pose a unique configuration of the RTS, tank, and cross point. However, the computations used to derive the "setup" values are only concerned with values in two dimensions (X-Z axes). Therefore, there are fewer possible configurations (all of which are accounted for within SCAN), but for this discussion, only the most common configuration in Venezuela is used. Figure 5.1 depicts the situation where the RTS is "above" the cross point. In other words, the zenith value from the RTS to the cross point is greater than 90 degrees.

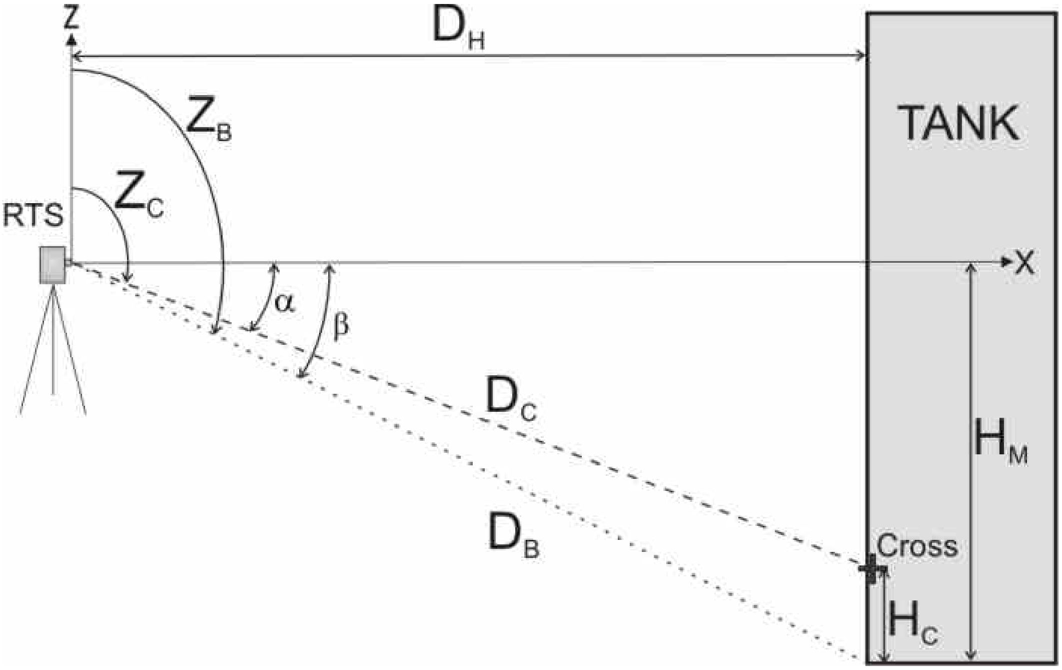


Figure 5.1 RTS-SCAN setup

The following equations (5.1) are used to compute the "setup" values:

$$\alpha = Z_C - \frac{\pi}{2}$$
$$H_M = H_C + \sin(\alpha) \bullet D_C$$
$$D_H = \cos(\alpha) \bullet D_C$$
$$Z_B = \frac{\pi}{2} + \tan^{-1}\left(\frac{H_M}{D_H}\right)$$
$$D_B = \sqrt{{D_H}^2 + {H_M}^2}$$

(5.1)

5.1.1.3 **Compute Seek Values for SCAN Points**

The second step in the process to compute the seek values for the Scan points involves using the calculated "setup" values, user-defined tank parameters, and configuration-specific equations. For this step, the important values to be computed are the zenith angle and distance from the RTS to the Scan point. The HCR value is simply the same value for the initial observation to the cross point for that VL. The values to be computed are "Z" and "D" (in bold italics in Figure 5.2). In addition to the values computed in step 1, extra variables are used here:

H: height from the base of the tank to the SCAN point (computed from user input values);

H_V: vertical distance from the SCAN point to the X-axis (computed);

H_B: vertical distance from the base of the tank to the bottom of the particular panel in which the Scan point is located (computed from user input values, not shown on Figure 5.2);

Pt: percentage value of the panel (e.g., 20% or 80%) for this SCAN point (value enter by user) and;

H_P: height for the panel (value enter by user).

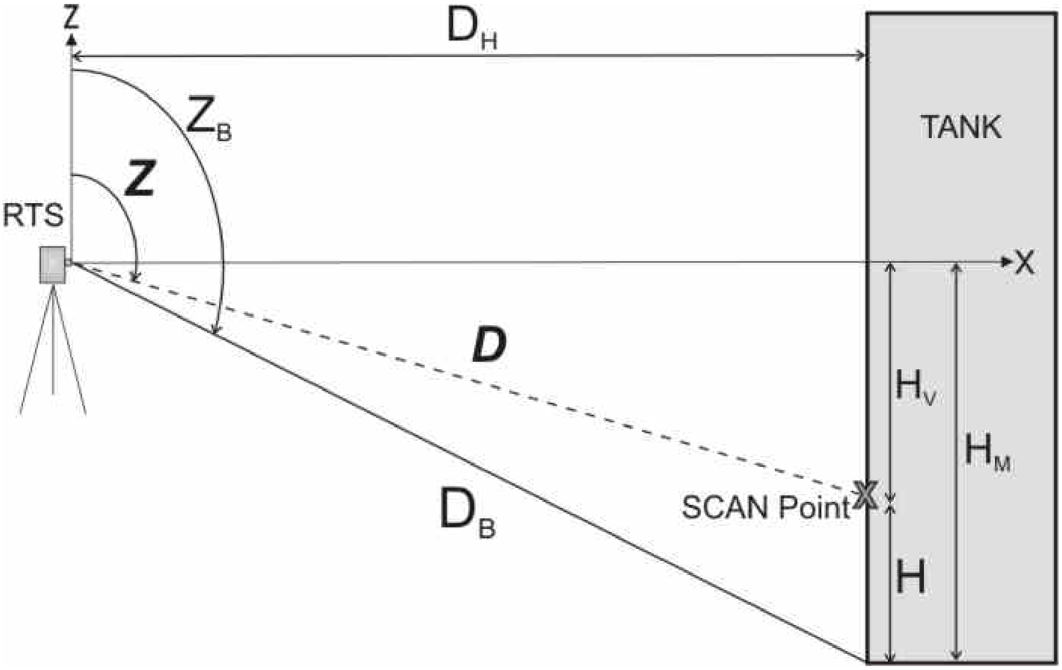


Figure 5.2 Seek Value Computations

The algorithm used to derive the height for each individual Scan point utilizes a combination of the user-defined tank parameters and RTS-Cross point measurements shown in equation (5.2). Each calculation is referenced to the panel in which the particular Scan point is located.

$$H = H_B + \left(\frac{Pt}{100} \bullet H_P \right) \tag{5.2}$$

A final algorithm is used to compute the Scan values for a particular point. This algorithm determines where this Scan point is located with respect to the RTS. In situations where the SCAN point is located "below" the X-axis (H is less than H_M), the following equations (5.3) are used:

$$
\begin{aligned}
&H_V = H_M - H \\
&Z = \left(\frac{\pi}{2}\right) + \tan^{-1}\left(\frac{H_V}{D_H}\right) \\
&D = \sqrt{{H_V}^2 + {D_H}^2}
\end{aligned}
\tag{5.3}
$$

Otherwise, when the SCAN point is located "above" the X-axis (H is greater than H_M), the following equations (5.4) are used:

$$
\begin{aligned}
&H_V = H - H_M \\
&Z = \left(\frac{\pi}{2}\right) - \tan^{-1}\left(\frac{H_V}{D_H}\right) \\
&D = \sqrt{{H_V}^2 + {D_H}^2}
\end{aligned}
\tag{5.4}
$$

5.1.1.4 **SCAN "Tolerances"**

Oil tank monitoring surveys are also concerned with efficiency. The new SCAN software is meant to be semi-automated, easy to use, efficient, and reliable. For this reason, ALERT SCAN should be capable of automatically verifying the quality of the observation data.

The main purpose for this data verification is to account for the physical shape of the tank and objects attached to its surface. For instance, there are many obstacles (e.g., ladders) connected to the outer surface of an oil tank that may lie in the "line-of-sight" to a Scan point. Measurements made to a ladder are obviously not to be included when attempting to monitor the structural integrity of the tank shell. Thus, automatic observation quality verification is embedded into SCAN and is used to identify such a situation, adjust for it, and continue seamlessly with the data collection.

This verification is based on the estimated distance measurement (section 5.1.1.3) to each Scan point and the user-defined tolerance value. If the measured distance to a Scan point is not within the tolerance value, with respect to the estimated distance value, then a routine is triggered to attempt to locate an acceptable observation (see section 5.2.3.3). The expected distance values are computed using the algorithms in the previous section and assuming that the tank surface is vertical. Even if the tank is not perfectly vertical (most likely), it does not affect this verification because the typical objects protruding from the tank are quite large (metres). In other words, the tolerance value would be set a value in the metre-level range and thus a slight tilt of the tank surface would not result in a distance measurement exceeding the tolerance.

5.1.2 Linking SCAN with ALERT

As mentioned previously, the ALERT system is predominately built and controlled by a large Microsoft Access DB [Lutes, 2002]. Information from the ALERT DB is required for project setup, data collection, and data processing portions of the survey. This includes settings to communicate with the RTS, RTS setup information (e.g., instrument height), and data used for the processing and plotting of observations.

The format of the data within the ALERT DB is very specialized because ALERT had been "pieced" together at different times to adapt the system to various projects.

New modules were created and existing ones were continually modified to satisfy requirements of new clients. Each time the system was modified the formats of the data stored in the DB also changed. Over time and a number of modifications the ALERT DB became a convoluted mass of redundant tables, fields, and records.

The functionality of the ALERT DB is primarily based on “time-stamped” records. In other words, data is organized and accessed by ALERT based on the time in which that particular piece of data was inserted or modified in the DB. The idea behind structuring the data in this way may have been appropriate in the early versions of ALERT and DIMONS [Lutes et al., 2001], but as projects became more complex and the system was adapted, this way of managing the data became incredibly confusing and complicated.

In order for SCAN to work directly with ALERT, SCAN had to be configured to access and add to the data within the ALERT DB. The inserting of data into the ALERT DB is done during the data collection segment. As data are being collected, via ALERT SCAN, the data are stored within the existing ALERT DB. Routines were written to automatically perform these tasks correctly and quickly. SCAN observation data had to be configured and formatted, within SCAN, to “mesh” seamlessly (in the ALERT DB) with data collected via existing ALERT modules.

5.2 Functionality of ALERT SCAN

This section outlines and summarizes the functionality of the ALERT SCAN software system. Instructions and a sample project are used to provide all the needed information. ALERT SCAN has been designed to be used simultaneously with the ALERT system and thus screen shots of both software programs are shown and briefly described. More detailed descriptions or further information about ALERT or ALERT SCAN can be found in the associated manuals [CCGE, 2006] and [CCGE, 2007a].

There are six steps required to perform a full survey of an oil tank. All but steps 3 and 4 are meant to be done "in-office" but can be done in the field if required. They entail the project design, setup, and post-processing parts of the survey. The steps include the:

1. creation and configuration of an ALERT project;
2. configuration of the SCAN settings;
3. data collection of control point measurements using ALERT;
4. data collection of tank surface measurements using ALERT SCAN;
5. processing of all observation data; and
6. preliminary plotting of final coordinates.

5.2.1 The ALERT SCAN Process

This section describes the basic process used in the ALERT SCAN method for semi-automated data collection. As stated in the previous section, a module of ALERT called "ALERT Portable Task Setup" (PTS), used to perform "portable" surveys, is used to perform the measurements made to the network control points surrounding each oil tank. ALERT SCAN is used to collect measurement data to the surface of the oil tank.

The entire oil tank survey process begins with the setup of the project. Since ALERT is used for a portion of the data collection, an ALERT project must be setup and configured for each particular oil tank to be monitored. The project settings include the names of the control points, the RTS type and communication settings, the prism type and constants, the method by which to measure the control network (e.g., number of sets, tolerances, etc.), and more (this is described in further detail in section 5.2.2.1). The SCAN settings include the number and height of the tank sheets, the number of VLs, and the position of every point to measure. Both the ALERT and SCAN settings can be configured in the office.

Once the project setup is complete, field measurements can be performed. Tripods are centered over the control points to be observed using ALERT. The instrument is setup on one point and reflector prisms are placed on the tripods on the adjacent control points. The heights of instrument and the prisms are measured and entered into ALERT.

Collection of control point measurements must be performed before tank measurements. The ALERT PTS utility is used here and is launched once the RTS and prisms are positioned correctly. Upon completion of the control point measurements (from the current RTS point), the PTS automatically launches into ALERT SCAN and tank observations can be performed. Note that both series of measurements are made from the same RTS setup.

Upon completion of the semi-automated data collection, the raw observation data, from both network point and tank observations, can be processed. The data from both sources is combined into a single group of data called a “cycle” within ALERT. This is done automatically within the software to configure the raw data for ALERT Processing.

The first step in processing the raw observations is to derive approximate coordinates for all the network control points surrounding the tank. This must be done manually (“by hand”) using the raw observation data and requires knowledge of basic surveying traverse computations. Once these values are calculated, they can be used in the ALERT “Processing Manager” and the ALERT “Data Browser” to compute adjusted coordinates for all control and tank points. Using the ALERT “Data Plotter” the final coordinates can be plotted to give a two-dimensional plan view including uncertainty values via error ellipses. The ALERT Manual provides complete documentation regarding Data Collection, Processing, and Analysis [CCGE, 2006].

The final coordinates can also be exported into any data form desired and can be interpreted and analyzed in any way. In the specific case of Venezuelan oil tank monitoring, the coordinates of individual VLs are required to construct vertical cross-sections of the tank walls. In this manner, the verticality of the walls can be computed and analyzed. Any bulging of deforming sections of the tank walls can easily be noted and the structural integrity of the entire tank can be investigated.

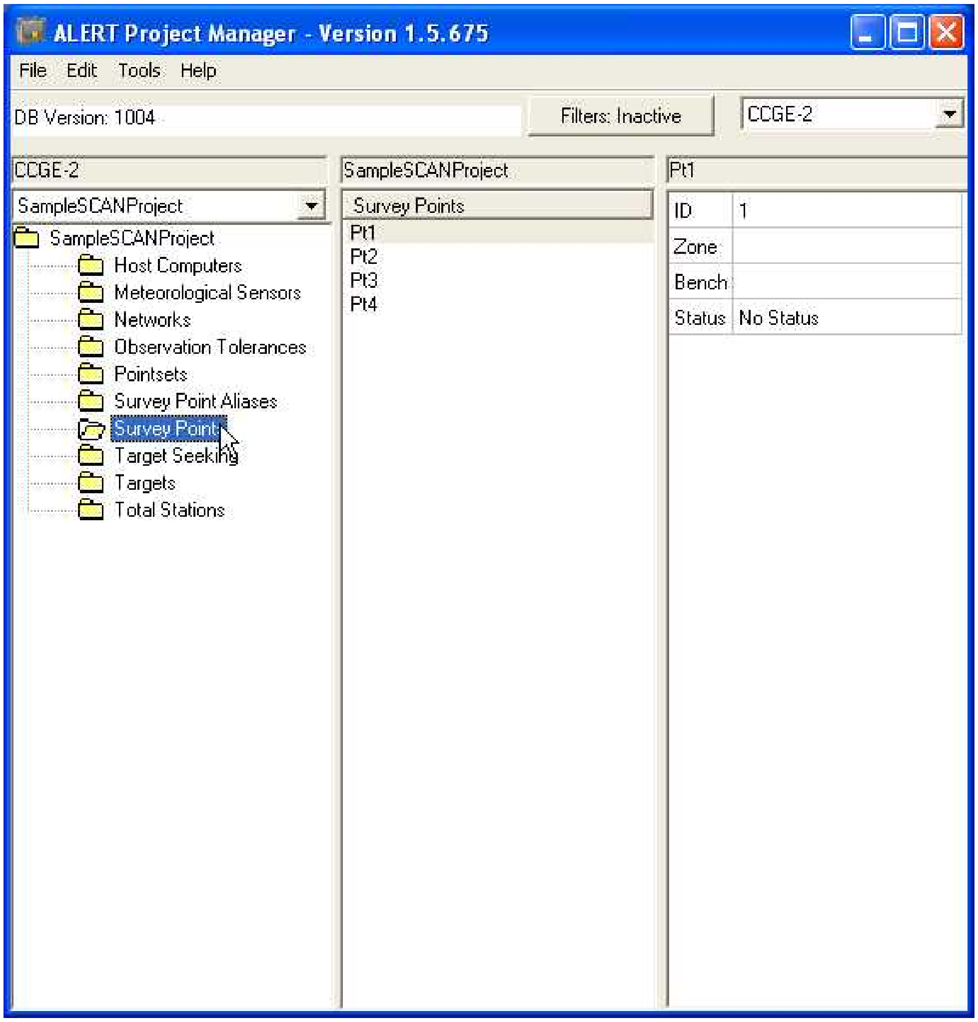
Throughout the chapter, the process of obtaining distance measurements made to each tank are referred to as “scanning” and the positions of these measurements on the surface of the tank are referred to as “Scan” points. The Panel percentage values associated with each Scan point are referred to as “Scanning Divisions” or “Scanning Percentages”.

5.2.2 SCAN Setup

The first step in the tank survey process is to setup the project. Once both ALERT and ALERT SCAN have been loaded and installed on the computer work station, an ALERT project is created.

5.2.2.1 Configuring an ALERT Project

Before any ALERT SCAN attributes (i.e., Panels, VLs, and Scanning Divisions) can be configured for a particular tank, an ALERT Project must be setup in the ALERT Project Manager (Figure 5.3). The minimum required attributes are a Total Station(s), Target(s), Survey Points, Observation Tolerance(s), Pointset(s), and a Network(s). The ALERT User Manual contains complete examples and descriptions [CCGE, 2006].



DB Version: 1004

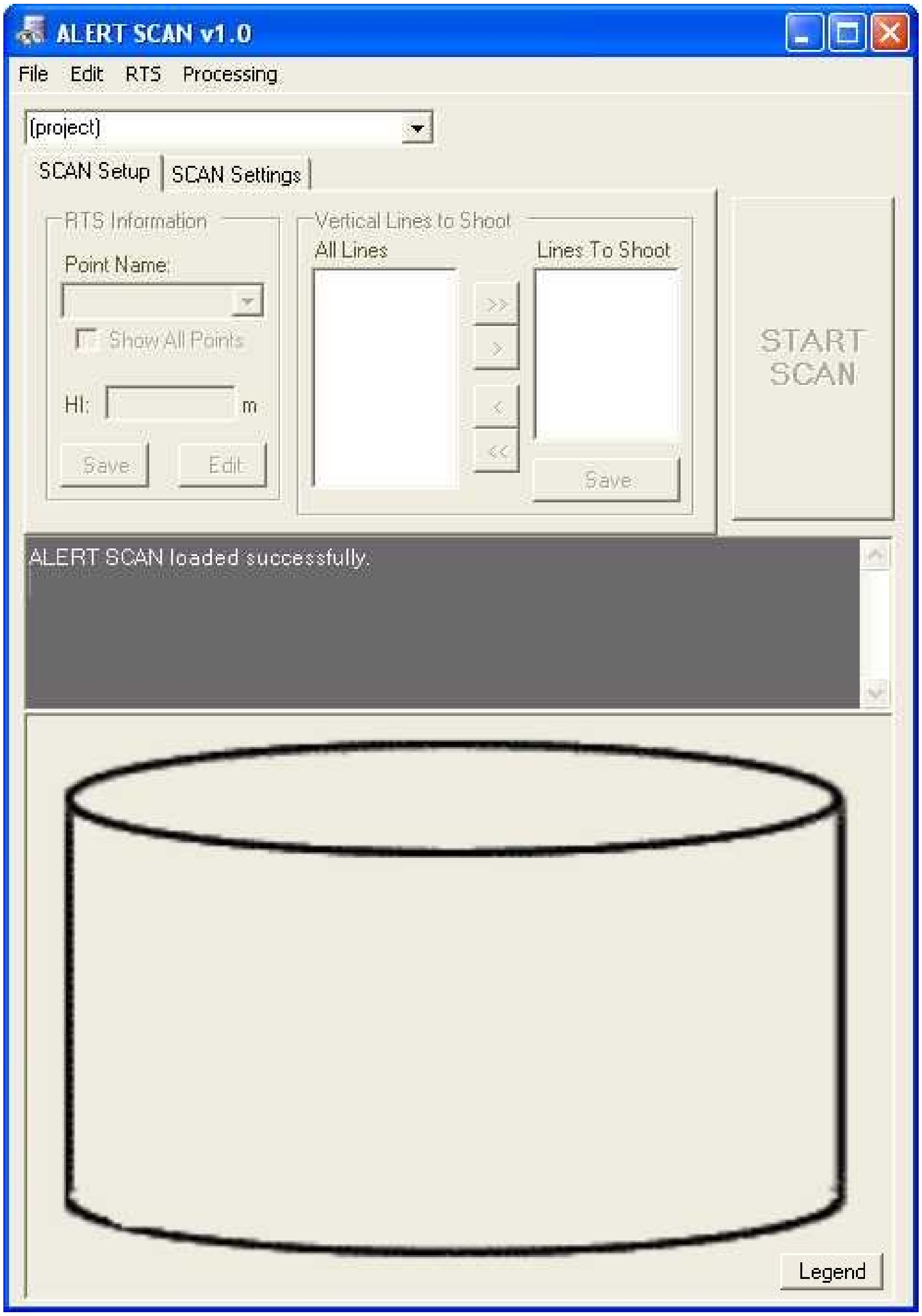
ID	1
Zone	
Bench	
Status	No Status

Figure 5.3 ALERT Project Manager

For the purposes of this example a sample ALERT project titled “SampleSCANProject” is used. This project consists of four network control points (Pt1, Pt2, Pt3, Pt4) situated around an artificial test tank.

5.2.2.2 **ALERT SCAN Main Window**

Once the ALERT project is created and configured, ALERT SCAN is launched. The first automated check is a message box which appears prompting the user to connect to a RTS. During the “setup” phase of the project the user need not connect to the RTS. However, if that is desired, a separate window appears where the user can configure the settings to communicate directly with the RTS. After this initial check, the main window for ALERT SCAN is displayed (Figure 5.4).



ALERT SCAN loaded successfully.

Figure 5.4 ALERT SCAN main window

There are five main elements to the ALERT SCAN main window that are used to navigate through the setup and performance of an ALERT SCAN project:

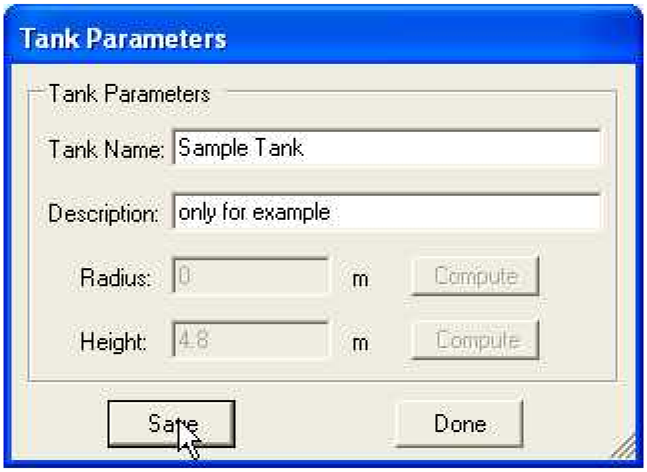
1. Menu Items: “File”, “Edit”, “RTS”, “Processing”. These menu items are used primarily in setting up an ALERT SCAN project, communicating with a RTS, and viewing processed SCAN data;
2. ALERT Project List: A complete list of every ALERT project that has been used on the current work station;
3. Tabs: Labeled “SCAN Setup” and “SCAN Settings”. The options associated in each tab in critical in setup a tank SCAN to the desired user specifications;
4. Status Bar: The scrollable text box located below the Tabs will inform the user as to the progress of a running SCAN and of any updates in the SCAN project.
5. Tank Graphic: The most important and easily understandable item located on the main window. This graphic displays all the Scan points that are to be scanned from that particular control point that the RTS is “setup” on.

5.2.2.3 **Defining Tank Attributes**

As stated earlier, a “tank” used in a SCAN project is comprised of tank parameters (e.g., tank name, height, etc.), a series of horizontal panels, any number of vertical scanning lines, and specific Scan points defined by a percentage value of the particular panel height. The user must define each of these attributes as described below.

Tank Parameters

Under the "Edit" menu the user selects "Tank Parameters". This displays the window where the tank parameters can be edited (Figure 5.5). The only required attribute is the name of the tank, the remaining are optional. The user fills in the values and clicks the "Save" button.



Tank Name: Sample Tank

Description: only for example

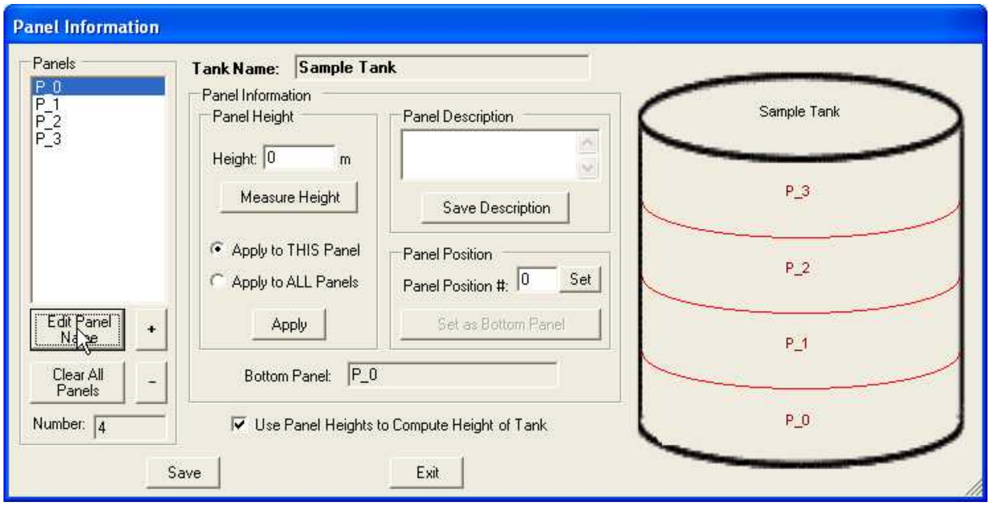
Radius: 0 m

Height: 4.8 m

Figure 5.5 Edit tank parameters

Panels

Under the "Edit" Menu, the user selects "Panels", then "Edit". This displays the window where the tank Panels are edited (Figure 5.6). The Panels that have been added to this tank are seen in the list box on the left of the window and are shown on the smaller tank graphic on the right. This tank graphic is the best way for the user to determine the order to which the Panels will be "positioned" on the tank. Height values for each Panel are required before they can be saved to the ALERT DB. The "position" of a Panel can be edited and charges are reflected in the tank graphic. The Panel which has been set as the “bottom” Panel is displayed in the “Bottom Panel” text box.



Panels: P_0, P_1, P_2, P_3

Tank Name: Sample Tank

Height: 0 m

● Apply to THIS Panel

○ Apply to ALL Panels

Panel Position #: 0

Bottom Panel: P_0

Number: 4

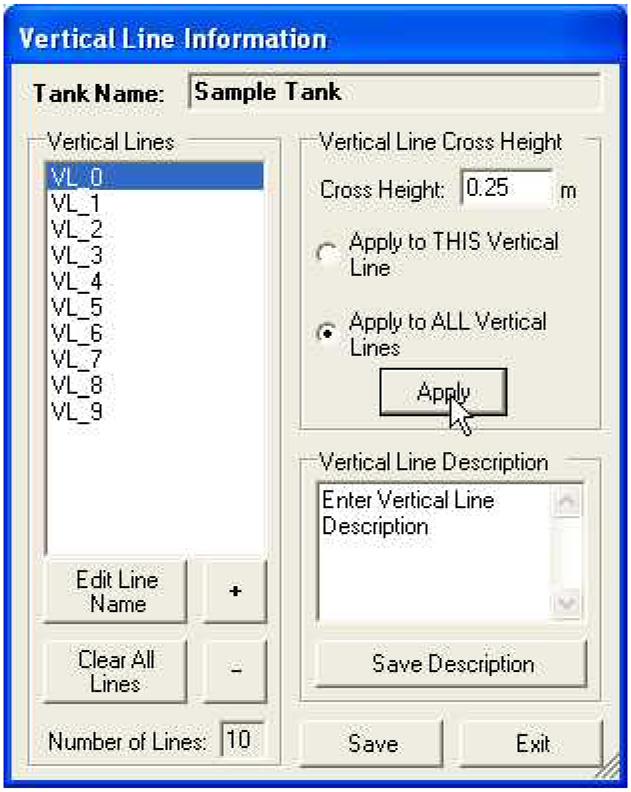
☑ Use Panel Heights to Compute Height of Tank

Figure 5.6 Edit tank panels

As previously mentioned, the user must check box “Use Panel Heights to Compute Height of Tank”. This enables the height of the tank to be calculated based on the entered Panel heights. This value is used during data processing, surface fitting, and tank analysis.

Vertical Lines

Under the “Edit” menu the user selects “Vertical Lines” then “Edit”. This displays the window where the tank VLs are edited (Figure 5.7). The user must enter a Vertical Lines Cross (“+”) Height for every VL before they can be saved to the ALERT DB. This “Cross” height is the distance measurement between the base of the tank and the physical cross (“+”) etched into the surface of the tank associated with every VL. This Cross point height is a critical value as the seek values for every SCAN point are referenced to it. If this value is not entered correctly, every Scanning point in that particular VL will not be positioned in the correct location on the tank during the scan.


Vertical Line Information

Tank Name: Sample Tank

Vertical Lines:
VL_0
VL_1
VL_2
VL_3
VL_4
VL_5
VL_6
VL_7
VL_8
VL_9

Cross Height: 0.25 m

○ Apply to THIS Vertical Line

● Apply to ALL Vertical Lines

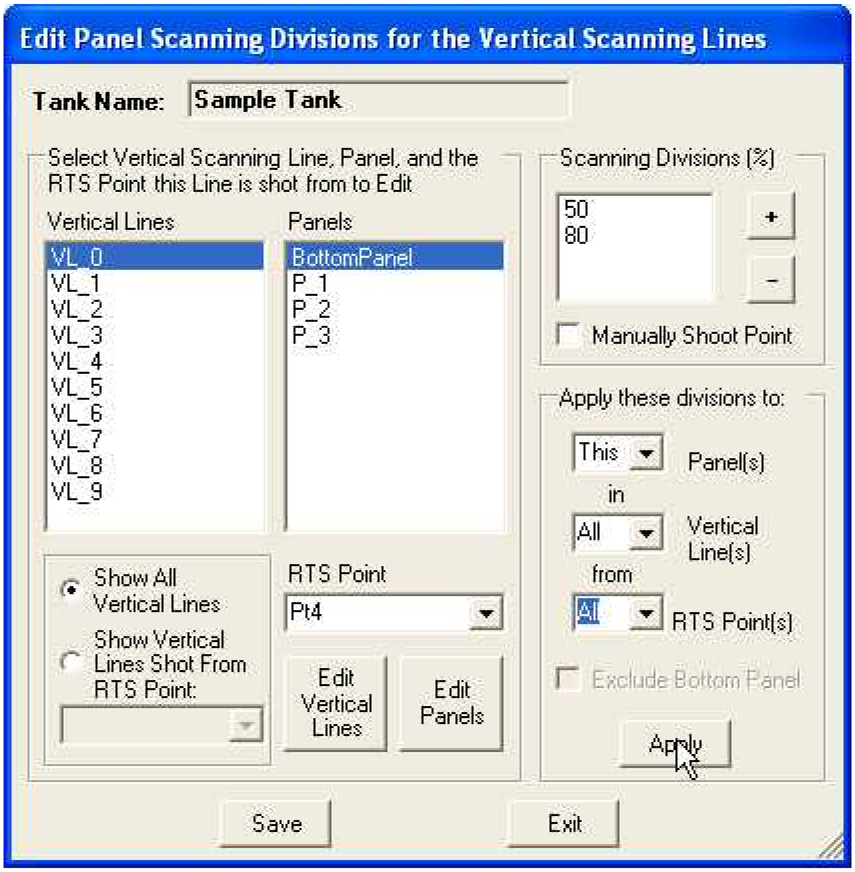
Enter Vertical Line Description

Number of Lines: 10

Figure 5.7 Edit tank vertical lines

Scanning Divisions/Percents

Under the “Edit” Menu the user selects “Scanning Divisions (%)” then “Edit”. This will display the window where the Scanning Points are configured (Figure 5.8). This application is the single, most useful and powerful tool built into the ALERT SCAN module. It enables the user to apply a vast number of SCAN parameters in a single, simple step.


Edit Panel Scanning Divisions for the Vertical Scanning Lines

Tank Name: Sample Tank

Select Vertical Scanning Line, Panel, and the RTS Point this Line is shot from to Edit

Vertical Lines: VL_0, VL_1, VL_2, VL_3, VL_4, VL_5, VL_6, VL_7, VL_8, VL_9

Panels: BottomPanel, P_1, P_2, P_3

● Show All Vertical Lines

○ Show Vertical Lines Shot From RTS Point:

RTS Point: Pt4

Scanning Divisions (%): 50, 80

☐ Manually Shoot Point

Apply these divisions to: This Panel(s) in All Vertical Line(s) from All RTS Point(s)

☐ Exclude Bottom Panel

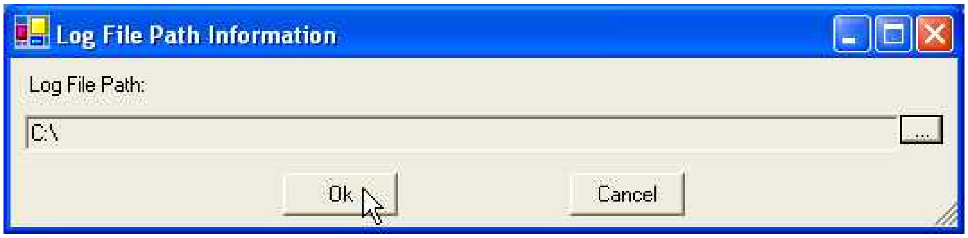
Figure 5.8 Edit scanning divisions

This window is designed to allow the user to configure a “set” (i.e., 20% and 80%) of percentage Scanning values for one Panel in one Vertical Line observed from one RTS point. This set of Divisions (percents) can then be applied to any, all, or none of the other panels in any, all, or none of the VLs shot from any, all, or none of the RTS points. In the Venezuelan oil tank surveys, most Panels observed are measured at 20% and 80% of the Panel. This window allows the user to configure these values for one Panel and easily apply these percent values to all other Panels.

If a point is to be observed “manually” (i.e., a user points the RTS to a specific point on the tank), the user must select the Division (from the list on the right) and check the box “Manually Shoot Point”. For example, this option would be used if a known obstruction (e.g., a ladder) is in the line-of-sight to a particular Scanning Point. When ALERT SCAN proceeds to measure to this point during the data collection portion of the survey it will temporarily stall the automated scanning process. SCAN will then automatically prompt the user to aim the RTS to the appropriate location for this Scanning point. This option may seem as if it may add time to the survey, but it actually saves time. The reason being that by setting the point to "manual", ALERT SCAN will not automatically initiate the "search" protocol that occurs when an observation does not meet the distance tolerance value (section 5.1.1.4).

Log Files

ALERT SCAN automatically creates and continuously updates a log file for each project with information concerning RTS functions and commands. This log is used primarily for debugging purposes, but can also be useful to a user if required. The name is this log file is "SCAN_Log_" followed by the project name (e.g., "SCAN_Log_SampleSCANProject.txt"). The user can change the stored location of the log file by selecting "Log Files" under the "Edit" menu (Figure 5.9).



Log File Path: C:\

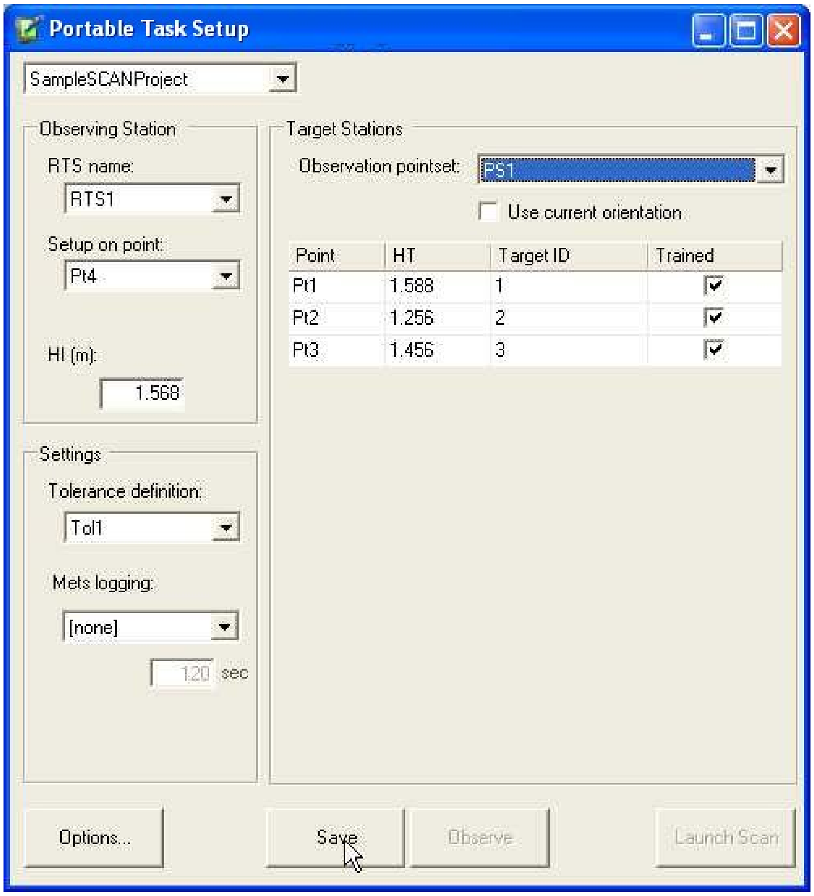
Figure 5.9 Edit log file stored destination

5.2.3 Data Collection

As previously mentioned collecting observation data for a tank structure and the surrounding control network points is performed using a combination of existing ALERT modules and the newly created ALERT SCAN module. Specifically, the ALERT PTS utility is used to perform measurements to the control network points [CCGE, 2006].

5.2.3.1 Network Points Observations

The ALERT PTS is used to configure and perform manual network observations (Figure 5.10). The user must select the ALERT Project, RTS, RTS Point, enter the height of the RTS ("HI"), select the Tolerance settings, and the "Observation Pointset". The targets (network points) to be measured are automatically listed. Only targets that have been "trained" are to be observed (denoted by a check mark in the check box). A "trained" target is one that has had the seek values measured from the particular RTS setup station. At each individual RTS station, each point that is to be measured from that station must first be trained. The user must use the ALERT Trainer utility to train any targets which are not already trained [CCGE, 2006].



SampleSCANProject

RTS name: RTS1

Setup on point: Pt4

HI (m): 1.568

Tolerance definition: Tol1

Mets logging: [none]

120 sec

Observation pointset: PS1

☐ Use current orientation

Point	HT	Target ID	Trained
Pt1	1.588	1	☑
Pt2	1.256	2	☑
Pt3	1.456	3	☑

Figure 5.10 ALERT Portable Task Setup trained targets

The user clicks the "Observe" button to begin measurements to the network target points which automatically launches the ALERT Data Collection Monitor (DCM) to perform the measurements [CCGE, 2006]. Upon completion of the data collection, the DCM is closed and the user is returned to the Portable Task Setup window where the "Launch Scan" button is now available. This enables ALERT SCAN to be launched from this same RTS Setup.

An important point should be made here: Network observations must be completed before tank observations can be initiated. Also, no subsequent network observations can be completed until the tank observations from that particular RTS Point are complete. The reason for this sequence of data collection is based upon the ALERT DB and maintaining the integrity of the data within the DB (discussed in section 5.1.2). Here is a sample order of events:

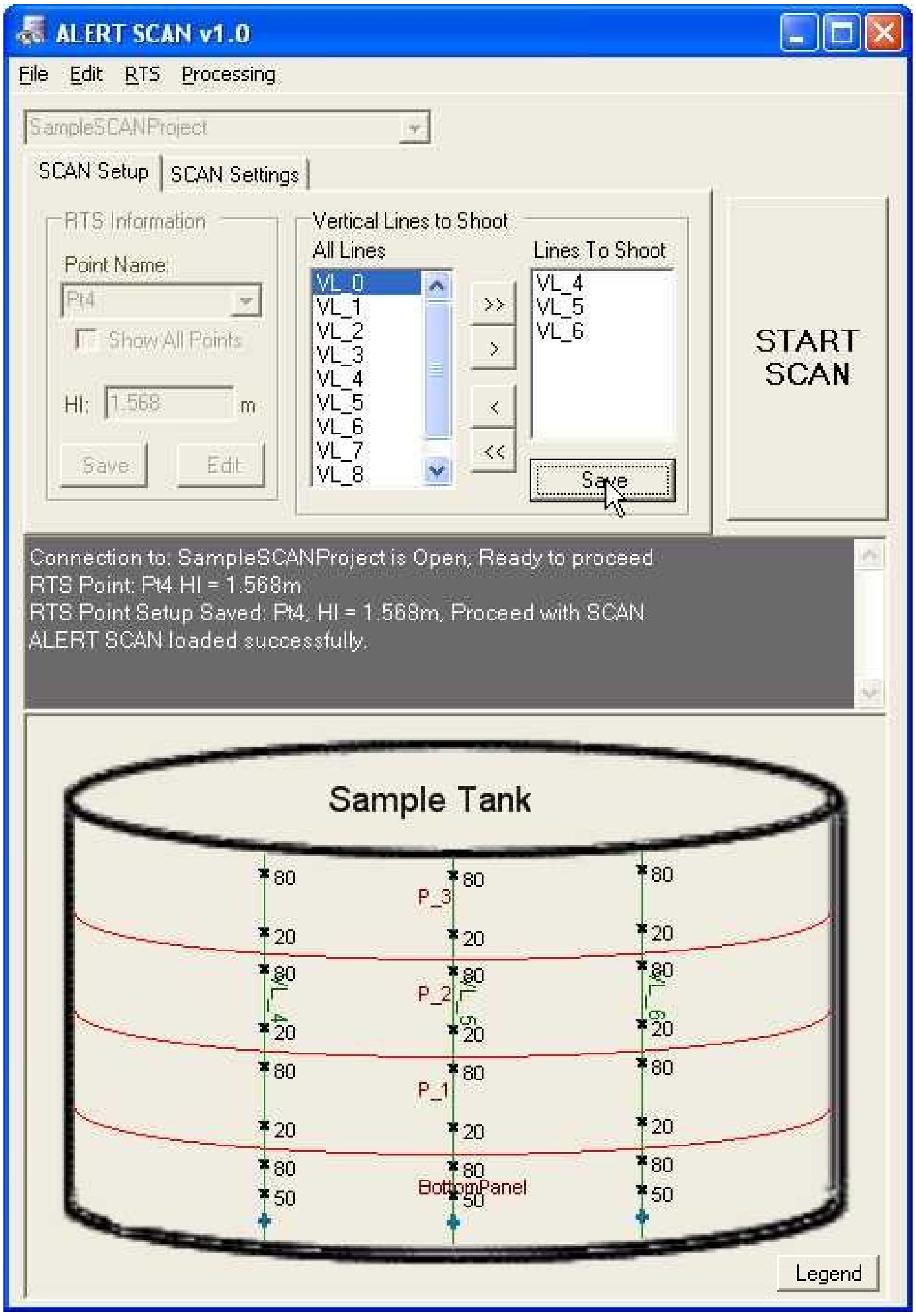
1. RTS setup on Pt4;
2. Perform Network observations from Pt4;
3. Launch ALERT SCAN and complete tank observations from Pt4 and;
4. Proceed to the next RTS point and repeat steps 1-3.

5.2.3.2 **Tank Points Observations (SCAN)**

Upon completion of the network point observation ALERT SCAN is used to proceed with the tank surface observations. Much like the previous section, there is a specific procedure to follow to perform these measurements correctly.

Selecting Vertical Lines to Measure

The first step is to select the VLs to observe from the current RTS point setup. The ALERT SCAN main window lists all the VLs configured for the tank (0), under "All Lines". The user must select the VLs from this list and add them to the "Lines To Shoot" list and save them to the DB. Upon that action, the VLs and Scan Points appear on the Tank Graphic (Figure 5.11). This is the easiest way for the user to verify that the percentage value for every Scanning Point is correct for each Panel and VL.



Connection to: SampleSCANProject is Open, Ready to proceed
RTS Point: Pt4 HI = 1.568m
RTS Point Setup Saved: Pt4, HI = 1.568m, Proceed with SCAN
ALERT SCAN loaded successfully.

Figure 5.11 Select vertical lines to be scanned

Training Vertical Lines

The second step in the data collection procedure is to “train” the VLs. Specifically, this means taking a manual measurement from the RTS setup to the physical

Cross points associated with each individual VL on the tank surface. The reason being that ALERT SCAN cannot compute the angles and distances (“seek” values) associated with every Scan point without these initial measurements (section 5.1.1.1). Specifically, SCAN needs horizontal and vertical angles and distance to each Cross point associated with each VL. Therefore, before each scan can be performed, each VL that is to be observed for that particular scan must be manually trained.

The user selects “Vertical Lines” then “Train from this RTS Setup”, from under the ”Edit” menu, which initiates the training sequence. SCAN begins the training with the first VL in the “Lines To Shoot” list and prompts the user to point the RTS to the Cross Point for that particular VL (Figure 5.12). SCAN then proceeds to the next Vertical Line in the list and repeats. This is done for all VLs to be observed. Upon completion of the training, SCAN automatically computes the required seek information for each individual SCAN Point.

Point the Instrument to the ' + ' (cross) on the tank for the Vertical Line:

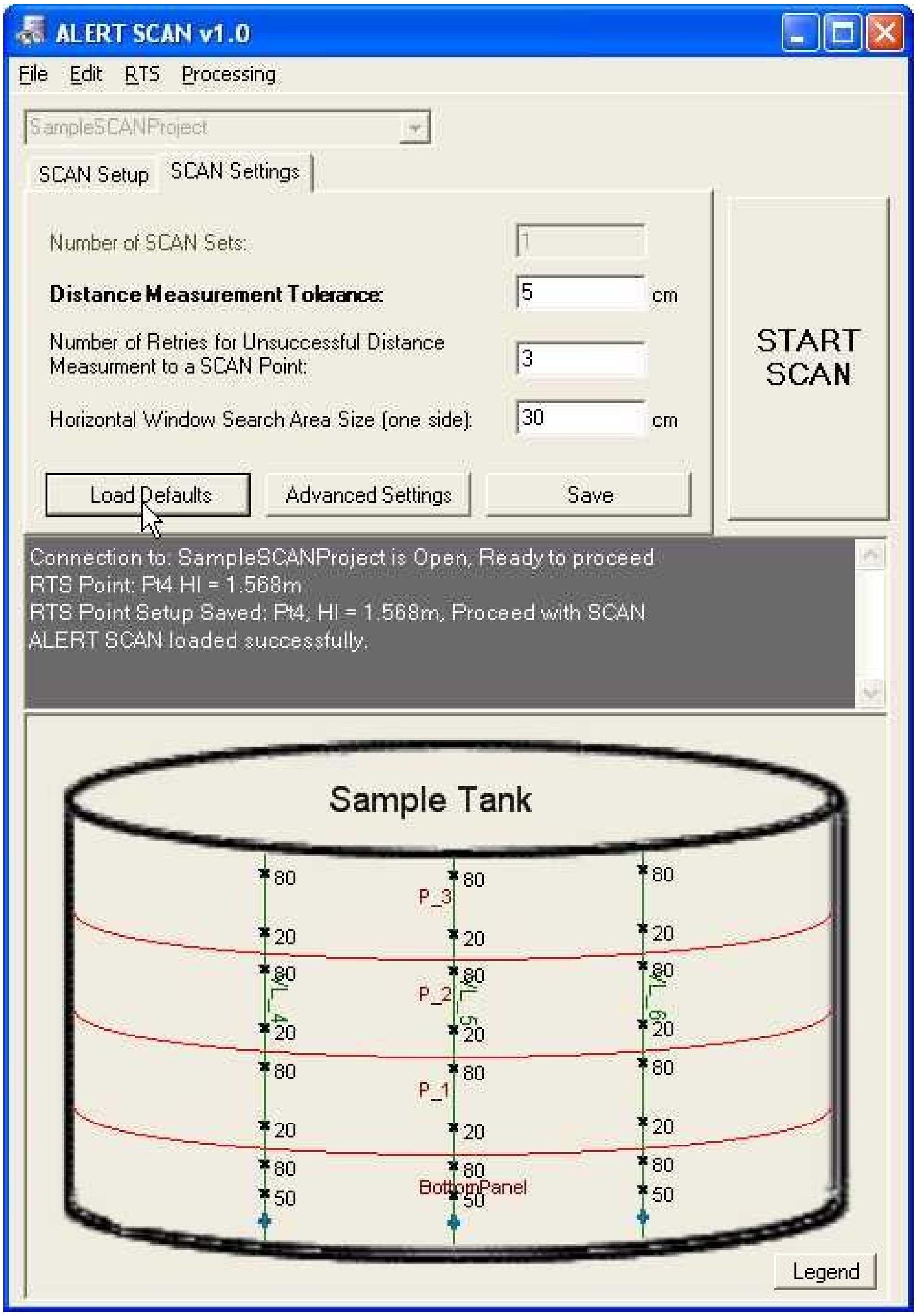
VL_4

Click 'OK' when sighted, 'Cancel' to Abort Scan.

Figure 5.12 Training a vertical line

Configuring SCAN Settings/Tolerances

The third step requires the user to configure the specific Scan settings and tolerances. The user must navigate to the “SCAN Settings” tab to display these settings (Figure 5.13). These settings control the behavior of SCAN and the data collection during the tank scanning process. The user must also select the “Advanced Settings” button to display the advanced SCAN settings (Figure 5.14). Each individual setting is outlined below.



Number of SCAN Sets: 1

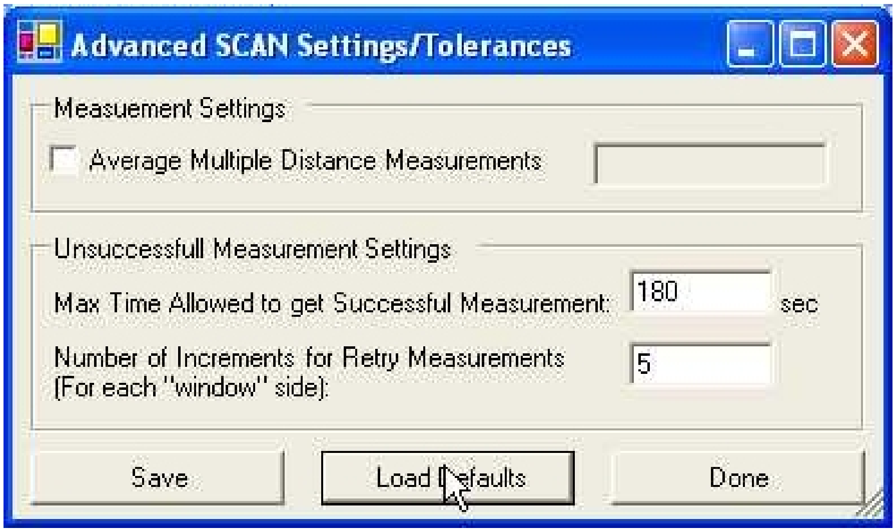
Distance Measurement Tolerance: 5 cm

Number of Retries for Unsuccessful Distance Measurment to a SCAN Point: 3

Horizontal Window Search Area Size (one side): 30 cm

```
Connection to: SampleSCANProject is Open, Ready to proceed
RTS Point: Pt4 HI = 1.568m
RTS Point Setup Saved: Pt4, HI = 1.568m, Proceed with SCAN
ALERT SCAN loaded successfully.
```

Figure 5.13 SCAN settings



Advanced SCAN Settings/Tolerances

Measurement Settings

☐ Average Multiple Distance Measurements

Unsuccessfull Measurement Settings

Max Time Allowed to get Successful Measurement: 180 sec

Number of Increments for Retry Measurements (For each "window" side): 5

Figure 5.14 Edit advanced SCAN settings

Distance Measurement Tolerance

This value defines the distance tolerance value (in centimetres) to which the measured distance to a Scan point must meet the computed expected distance. If the measurement does not meet this distance tolerance then ALERT SCAN initiates a horizontal search sequence (described below) to attempt to find a point near the original Scan point that does meet the tolerance.

Number of Retries for Unsuccessful Measurement

This value defines the number of times SCAN will attempt to obtain a measurement to a point if it is unsuccessful on the first attempt. This is not the same as a distance measurement not “meeting the tolerance”. Here, an “Unsuccessful Measurement” refers to the RTS being unable to obtain a distance measurement value.

SCAN automatically retries observations until a measurement is achieved or the total number of specified attempts has been met. If a successful measurement is not achieved, a search sequence is initiated (see Horizontal Window Search Area Size).

Horizontal Window Search Area Size

This value defines the maximum size, located on the surface of the tank (in centimetres), of the horizontal search window. The value defines only the size to one side of the SCAN point therefore, the total horizontal search area is twice this value. This value is only used if a measurement is obtained but does not meet the required tolerance (see “Distance Measure Tolerance”). In this case SCAN attempts to search for point in close vicinity to the original. Specifically, the RTS moves horizontally to the user’s left, along a constant VCR value, and retries the measurement. If that fails, then it attempts a measurement to a point to the right of the original point. This continues, with increasing horizontal spacing, until an acceptable distance measure (i.e., meets the tolerance) has been obtained or the maximum window size has been exhausted. This search sequence was designed to mimic the way in which the Venezuelan surveyors adjust for obstacles located on the VL, as was described to the author during an on-site visit.

If a successful measurement is not obtained, then SCAN automatically flags this point as “unsuccessful” and proceeds to the next Scan point. Upon completion of the total scan process, SCAN manually attempts to obtain a measurement to all unsuccessful points. This is achieved by orienting the RTS to the seek values associated with each Scan point and prompting the user to chose the best location for the observation for that point (e.g., to the side of a ladder).

The horizontal search sequence is best explained with an example. For instance, a ladder may be situated precisely on top of a Scan point. When the RTS makes an observation to the ladder, the measured distance value will most likely not meet the distance tolerance. Thus, the RTS is pointed side-to-side (alternating left and right) attempting to “sight” around the ladder. The maximum value (on the surface of the tank, in metres) by which the RTS will move to each side is specified with this value.

Average Multiple Distance Measurements

For greater accuracy, it is possible to take the average of any specified number of successful distance measurements. This setting value simply indicates the number of repeated distance measurements to obtain before being averaged. The averaged values are the ones tested against the tolerance values and stored in the DB.

Maximum Time Allowed to get Successful Measurement

In the instance of an “unsuccessful” measurement (i.e., distance value does not meet the tolerance), a search sequence is initiated. This search may take minutes to complete and, if repeated many times, can significantly lengthen the total scan time. For this reason, the user can define a maximum time allowance to attempt to locate a measurement that meets the distance tolerance. This time value, in seconds, is defined here. If the maximum time allowed to obtain a measurement is reached, then SCAN automatically marks this point as “unsuccessful” and proceeds to the next Scan point.

Number of Increments for Retry Measurements

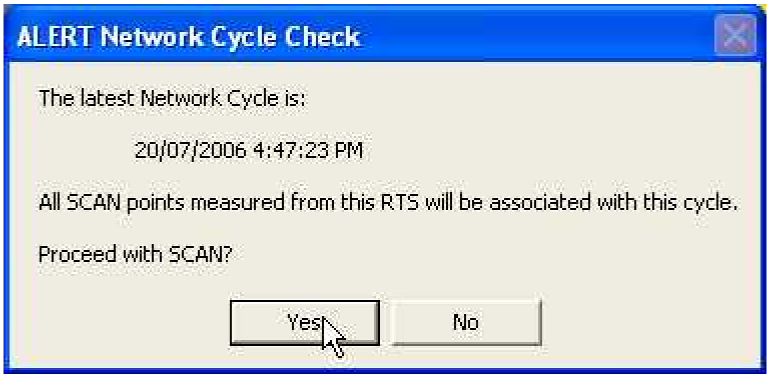
This value represents another parameter the user can use to modify the automated successful measurement search sequence. This value defines the number of divisions (per side) of the horizontal search window. For example, a search window size of 0.5 m with five increments would result in individual search intervals at every 10 cm.

5.2.3.3 **Initiate Tank Scanning**

Once the previous three steps have been competed, a full tank surface scan performed from this RTS station. The user simply clicks the “START SCAN” button to initiate the scanning process. There are three automatic checks performed internally by SCAN as the scan is initiated. If any scan settings or steps have not been configured correctly, a message is displayed and the scan will not continue.

These checks also help maintain the data integrity within the ALERT DB by verifying the ALERT observations cycles. The reason is that the scan observations must be integrated into the network observations to enable proper data processing. In further detail, a series of network observations from a RTS point locations are placed in a “cycle”. In order to include the scan observations with the network observations, they must be included in that same cycle.

The first check is a verification of the previously completed Network Measurement Cycle. SCAN searches through the ALERT database and locates the most recent set of network point measurements made from the current RTS setup point. This is critical to ensure correct data processing later, as the upcoming SCAN observation data is linked to these network measurements. The user is prompted with a message box shown in Figure 5.15. If the user selects “No”, the Scan is aborted.


ALERT Network Cycle Check

The latest Network Cycle is:

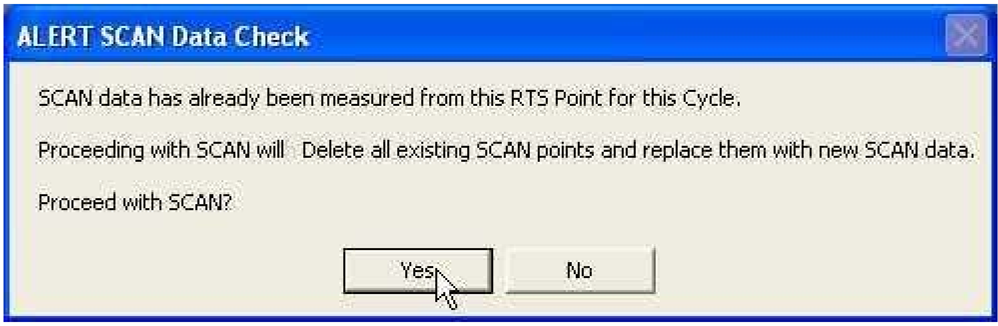
20/07/2006 4:47:23 PM

All SCAN points measured from this RTS will be associated with this cycle.

Proceed with SCAN?

Figure 5.15 Confirm ALERT cycle

The second check is used as a data-overwrite confirmation. SCAN locates any previous SCAN data associated with this RTS Setup for this Network Cycle. If any data has been found, then the user is prompted to overwrite this data with the new SCAN data (Figure 5.16). This may occur if a scan had been aborted at any time during the scanning process or a completed scan is to be re-done.


ALERT SCAN Data Check

SCAN data has already been measured from this RTS Point for this Cycle.

Proceeding with SCAN will Delete all existing SCAN points and replace them with new SCAN data.

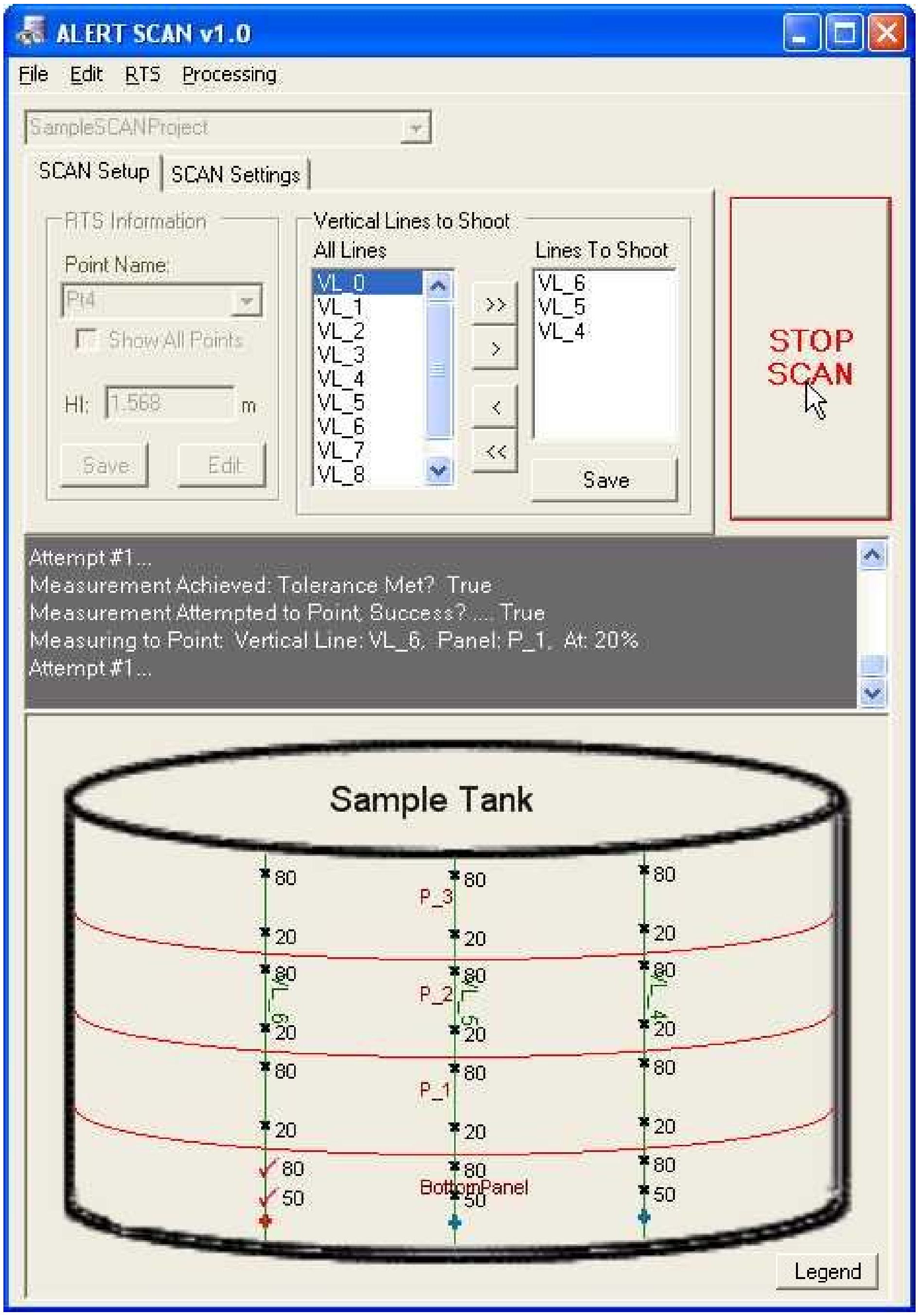
Proceed with SCAN?

0.

Figure 5.16 Confirm overwrite of previous SCAN data

The third check is a verification of VL training from this RTS setup. If the VLs have not been trained from this RTS setup prior to clicking the “START SCAN” button, the user is prompted to do so before the scan would begin.

Successful completion of the three checks allows ALERT SCAN to initiate the scanning procedure. All RTS and SCAN actions are seen in real-time on the Status Bar and on the Tank Graphic. As SCAN measures to a Scan point, updates are displayed in the Status Bar and the Tank Graphic gives a visual representation (Figure 5.17). When a Scan point has been successfully measured (i.e., met tolerance), the Scan point image on the Tank Graphic changes to a red check mark.



Point Name: Pt4

HI: 1.568 m

```
Attempt #1...
Measurement Achieved: Tolerance Met?  True
Measurement Attempted to Point, Success? .... True
Measuring to Point:  Vertical Line: VL_6,  Panel: P_1,  At: 20%
Attempt #1...
```

Figure 5.17 Tank Graphic during SCAN

During the scan, the “START SCAN” button changes to “STOP SCAN”. If at anytime during the course of the scan the user needs to abort the scan, they simply click that button and a message box appears to confirm the cancellation. All scan data collected up to that point, in that scan, are then deleted from the DB.

Unsuccessful Measurements

As discussed earlier, at any time during the scan process if, for some reason, the first measurement attempt to a Scan point is unsuccessful (either didn't meet tolerance or a measurement not achieved at all) a search protocol is initiated. SCAN communicates with the RTS and attempts to locate an observation that does meet the tolerance for this particular SCAN point. This search procedure is also shown, in real time, on the Tank Graphic during the scan. For each attempted measurement, as a small black "x" is shown on the Tank Graphic at each attempted point (Figure 5.18).

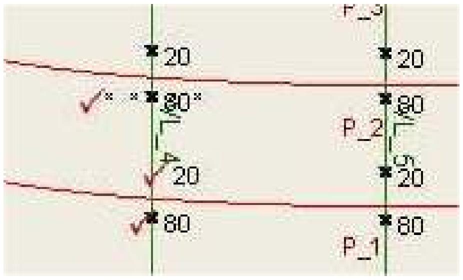


Figure 5.18 Successful measurements

It can also be seen in Figure 5.18 that SCAN obtained a successful measurement (indicated by the red check mark) after numerous unsuccessful attempts (black "x"). As SCAN proceeds through the entire tank scanning process, Scan points that have not been successfully measured are automatically flagged. The points are referred to as "Unsuccessful" points and dealt with individually upon completion of the scan. These points can be identified on the Tank Graphic since there is no red check mark associated with the point (Figure 5.19).

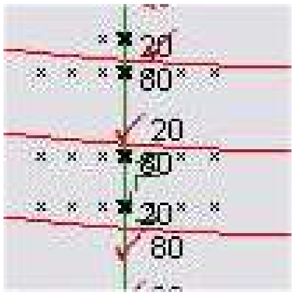
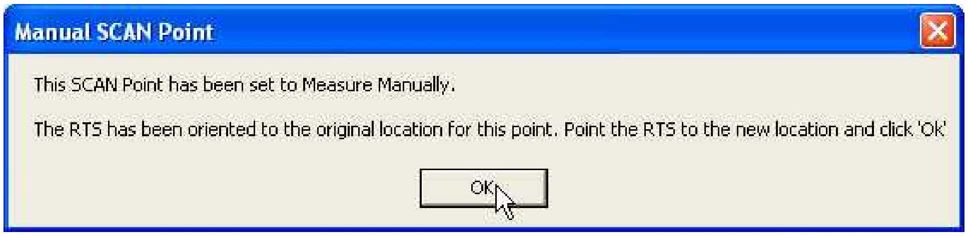


Figure 5.19 Unsuccessful measurements

Upon completion of the full tank scan, the user is prompted to manually point to each Unsuccessful point (similar to “Manual Points”, section 0) and measurements can be re-done. If a successful measurement still cannot be obtained then the point can be excluded from the SCAN data.

Manually Scanned Points

As mentioned earlier, some Scan points can be configured to be observed manually. When measurements are to be made to one of these points, during the scan process, a message box appears and the automatic data collection is temporarily halted. The user is prompted to manually point the RTS to the desired point location (Figure 5.20), where upon measurements can be made and the automatic data collection is continued. All data quality checks are still enforced and the user is prompted to re-measure if the observation does not meet the tolerance or was unsuccessful.



This SCAN Point has been set to Measure Manually.

The RTS has been oriented to the original location for this point. Point the RTS to the new location and click 'Ok'

Figure 5.20 Manually scanned point

This option very is useful if it is known that a particular point will not meet the tolerance (e.g., ladder situated in the line-of-sight). This function saves time and increases accuracy by allowing the user to measure to the closest possible point to the original.

5.2.4 Data Processing

This section outlines the steps required to process the data collected with the ALERT PTS utility (network points) and the ALERT SCAN utility (tank points). A combination of ALERT data processing utilities and manual traverse calculations are used to derive adjusted coordinates for each Scan point. The following steps outline the procedure used to process both the Network and Scan observations through the ALERT Processor. For the purposes of this report, only a brief description of each step is given. More information about ALERT is available on the CCGE website [CCGE, 2007b] or in the ALERT manual [CCGE, 2006].

The first step in the data processing procedure is to design, within ALERT, the control network around each oil tank (i.e., the control points). This is done to configure ALERT to process the observation as a multi-station network adjustment [CCGE, 2006].

All RTS setups that were used as control points for the reference network must be added to the project “network”. This is done in the ALERT Project Manager.

The second step in the data processing procedure cannot be done automatically by ALERT. The evolution of the ALERT system is an on-going process, and at the time of this report, the automated network processing module was not fully completed. For this reason, some calculations must be done “by-hand” and requires basic surveying knowledge. In order to facilitate the network processing, ALERT must have a basic idea of the configuration of the network. This requires approximate coordinates to be computed within a common coordinate system for the survey points observed in the control network. This step must only be done once for each tank project.

The easiest way to perform these coordinate calculations is to use raw direction observation measurements between control points and traverse “around” the control network computing azimuths and coordinates for each point. This requires some hand calculations and a sketch of the points and directions is helpful. The raw observation data (directions and distances) required for these computations is gathered by using the ALERT Data Browser [CCGE, 2006].

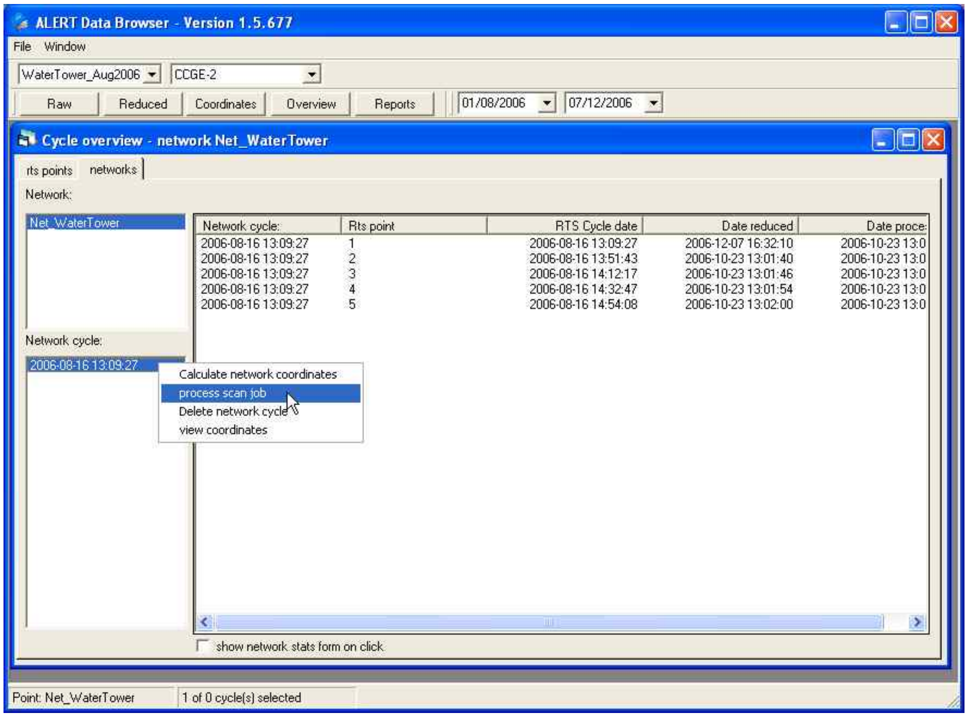
The third step in the data processing procedure is to configure the way in which the network data is processed. The manually calculated approximate coordinates and azimuths for the RTS control network points are used to configure the network processing. This is done by using the ALERT Processing Manager [CCGE, 2006].

The fourth step in the data processing procedure is to process the network observations. Before the Network and Scan observations can be processed together, the individual RTS setup observations must be processed. The user must process the data for each RTS setup and the associated observation cycles. This is done using the ALERT Data Browser. Upon successful observation reduction, coordinates are computed for each observed point and can be viewed in the Data Browser [CCGE, 2006].

The fifth step in the data processing procedure is to "build" the network within ALERT. The processed individual RTS setup observations coordinates, computed for each point, must be combined into a single "control network". The user must connect all the RTS setups that are to be used in creating the control network by using the ALERT Network Builder [CCGE, 2006].

The final step in the data processing procedure is to reduce the raw scan observations data. As discussed in section 5.1.2, the existing ALERT system was modified to accommodate some SCAN functions and data. This is an instance of one of those modifications.

Once the user has "built" the network, within ALERT, the network and Scan observation data can be processed together. In the ALERT Data Browser, the user must select the network cycle and select "process scan job" (Figure 5.21). This action computes coordinates for every observed Scan point and may take several minutes to complete (depending on computer processing speed).



WaterTower_Aug2006 CCGE-2 01/08/2006 07/12/2006

Net_WaterTower

2006-08-16 13:09:27

Network cycle:	Rts point	RTS Cycle date	Date reduced	Date proce:
2006-08-16 13:09:27	1	2006-08-16 13:09:27	2006-12-07 16:32:10	2006-10-23 13:0
2006-08-16 13:09:27	2	2006-08-16 13:51:43	2006-10-23 13:01:40	2006-10-23 13:0
2006-08-16 13:09:27	3	2006-08-16 14:12:17	2006-10-23 13:01:46	2006-10-23 13:0
2006-08-16 13:09:27	4	2006-08-16 14:32:47	2006-10-23 13:01:54	2006-10-23 13:0
2006-08-16 13:09:27	5	2006-08-16 14:54:08	2006-10-23 13:02:00	2006-10-23 13:0

Point: Net_WaterTower 1 of 0 cycle(s) selected

Figure 5.21 ALERT Data Browser process SCAN data

5.2.5 Coordinate Plotting

This section outlines the process of using the existing ALERT graphing and plotting functions to create a graphical representation of all the observed points. This is another module of ALERT that is not fully developed at the time of printing, but useful information can still be gathered from it. For that reason, it is briefly shown here.

Using the ALERT Network Plotter, two-dimensional coordinate plots can easily be created [CCGE, 2006]. As with the ALERT Data Browser, this ALERT module had to be modified to accommodate SCAN measurements. The user selects the “tank scan plot” option and chooses the network cycle from the list to be plotted [CCGE, 2006].

Plots of the sample tank simulation observations can be seen in both the X-Y (Figure 5.22) and X-Z (Figure 5.23) views. The cylindrical outline of the tank is obvious and plainly visible in the XY plot and the VLs are seen in the XZ view. These plots are of little technical use but provide a useful tool to provide the user with reassurance that the data was collected and processed.

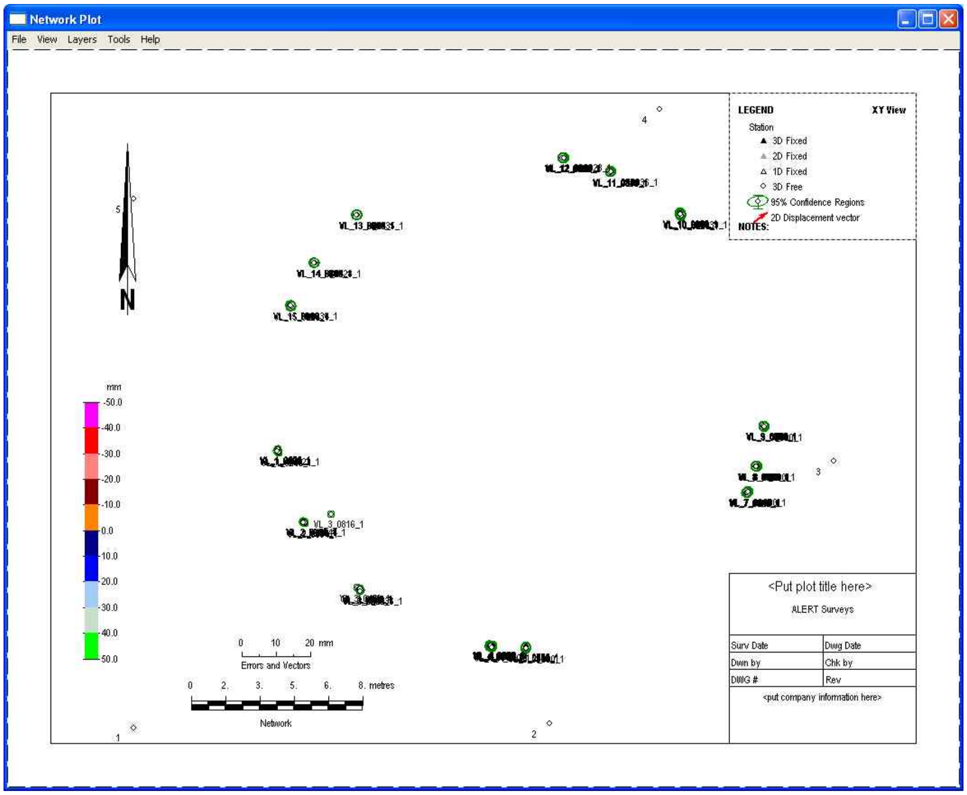


Figure 5.22 Tank coordinate XY plot

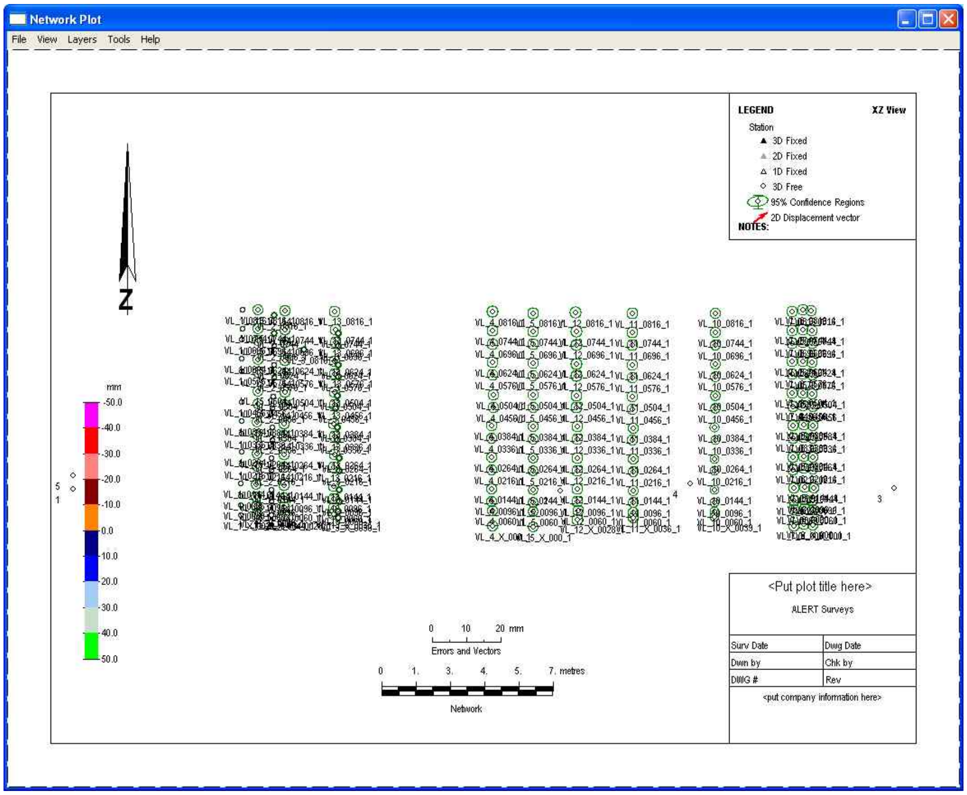


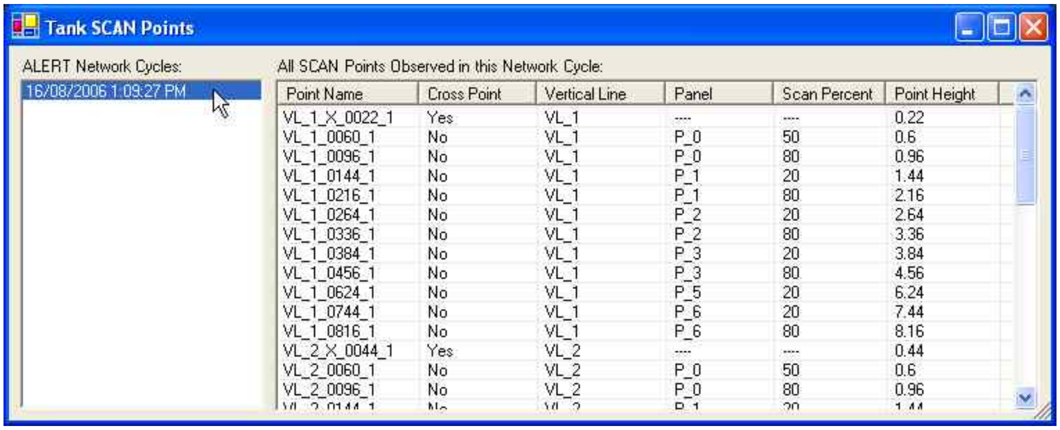
Figure 5.23 Tank coordinate XZ plot

5.2.6 Viewing SCAN Points

The automatic naming scheme for the Scan points is designed to give information on the location of each Scan point. The point name conveys the VL name, the physical point height on the tank (based on the VL Cross height), whether the point is a Cross point, and the overall number of times this point has been scanned (at any time in the project). For example, the name for a SCAN point located in VL "VL1" at a height of 1.6 metres being measured for the first time would be "VL1_0160_1". However, this point information may be very difficult to decipher on a condensed network plot (Figure

5.22 and Figure 5.23). It also may be difficult to remember or understand the naming scheme associated with each Scan point when viewing such a network plot. Therefore, a function has been built into ALERT SCAN to ease this frustration. This function displays each Scan point, processed in an ALERT network cycle, and the Panel, VL, and Scanning Percentage value associated with that point. Used in combination with the ALERT Plotter, a user can easily note information regarding each or a series of Scan points.

To view the Scan Points for a particular processed network cycle, the user must launch ALERT SCAN, chose the ALERT Project, and select "View SCAN Points" from the "Processing" menu. This displays a window listing the processed ALERT Network cycles in this project on the left. The user selects the desired network cycle from the list. This displays all the Scan points observed and processed in that cycle in the right window. Information can be seen for each individual Scan Point, including the VL, Panel, Scanning Percent, and Point Height (Figure 5.24). This is advantageous when analyzing the network plots and coordinate point data. It is essential to know the location on the tank of any Scan points that may be deforming at a dangerous rate.



16/08/2006 1:09:27 PM

Point Name	Cross Point	Vertical Line	Panel	Scan Percent	Point Height
VL_1_X_0022_1	Yes	VL_1	----	----	0.22
VL_1_0060_1	No	VL_1	P_0	50	0.6
VL_1_0096_1	No	VL_1	P_0	80	0.96
VL_1_0144_1	No	VL_1	P_1	20	1.44
VL_1_0216_1	No	VL_1	P_1	80	2.16
VL_1_0264_1	No	VL_1	P_2	20	2.64
VL_1_0336_1	No	VL_1	P_2	80	3.36
VL_1_0384_1	No	VL_1	P_3	20	3.84
VL_1_0456_1	No	VL_1	P_3	80	4.56
VL_1_0624_1	No	VL_1	P_5	20	6.24
VL_1_0744_1	No	VL_1	P_6	20	7.44
VL_1_0816_1	No	VL_1	P_6	80	8.16
VL_2_X_0044_1	Yes	VL_2	----	----	0.44
VL_2_0060_1	No	VL_2	P_0	50	0.6
VL_2_0096_1	No	VL_2	P_0	80	0.96
VL_2_0144_1	No	VL_2	P_1	20	1.44

Figure 5.24 All Scan Points

6 FIELD VERIFICATION: WATER TANK

The functionality, reliability, and accuracy of the ALERT SCAN software had to be tested on an actual test object before the system could be implemented in actual tank monitoring situations in Venezuela. Specifically, a water tank located in Fredericton, NB, which has comparable physical surface dimensions to a Venezuelan oil tank, was used to simulate conditions (Figure 6.1). The total time required to configure, perform, and process data from a full surface scan and associated control network points was used to test the performance and efficiency of the system.

Figure 6.1 Water Tank in Fredericton, NB

Two epochs were completed (one in May and the other in August) using the ALERT SCAN module and data was processed through the slightly modified ALERT

Processor (section 5.2.4). Using the final computed scan point coordinates output from ALERT, comparisons of individual VLs between the two epochs were done. From these computations a basic idea of the overall shape of the tank was investigated. For the purposes of this thesis, which is centered primarily in the design and development of the SCAN system, the main focus of the field test is to test the configuration and performance of efficient and accurate data collection. For that reason, a very limited investigation into the structural integrity of the tank is examined based upon SCAN measurements.

6.1 Procedure

Prior to any observations or project setup, reconnaissance was performed on the tank and surroundings areas. Approximate positions for the network control points and VL cross points were located. The location for the VLs cross points were associated to graffiti on the outer surface of the tank and were placed around the surface of the water tank to ensure complete scanning coverage. Graffiti was used because it was preserved on the surface of the tank between the two epochs and ensured repeatability of the same VL Cross points.

Prior to field measurements, an ALERT project was created and the project settings, outlined in section 5.2.2, were configured. SCAN was used to configure the tank parameters and the desired scanning process. Once in the field, the height of each cross point was measured from the base of the tank and input into SCAN. The tripods were setup on the artificial network points where they would remain for the duration of the field observations. The control points were not physical monuments fixed in the ground and the locations were not kept consistent between epochs. The reason being, that the location of the water tank was in a public park and the security of the monuments could not be maintained. The author decided that the use of potentially falsely stable reference points to compute absolute positions of tank points, would have introduced unneeded uncertainty into the precision and reliability of the SCAN system. Because the cross points were chosen as permanent markings on the surface of the tank, they could be maintained between sessions, and relative positions of the scan points were sufficient.

With the tripods setup on the artificial control points, observations were performed. The RTS was placed on control point “1” and two reflectors were placed on points “2” and “5”. The locations of network point reflectors were trained with ALERT from the RTS and the ALERT Portable Task Setup (section 5.2.3.1) was used to perform the automatic control network measurements. This process takes only one or two minutes.

Upon completion of the network point measurements, SCAN was initiated and surface scanning to the water tank could commence. As described in section 5.2.3.2 when SCAN is launched from the ALERT PTS, the network control point which the RTS is situated is automatically “passed” into SCAN. Because of this, when SCAN is loaded, it has automatically configured the user-defined scan settings (i.e., the VLs and the positions of the surface points to scan) from this “RTS Point”. After SCAN is loaded, the user is only required to train the VLs (three, in this case) manually with the RTS. This only takes about a minute and then SCAN can be initiated. The user can watch the RTS as it moves automatically to each pre-configured scan point location and performs a measurement. Figure 6.2 shows the RTS and SCAN during the scan process. ALERT SCAN can be seen on the laptop screen in real time as it controls the RTS to measure to each scan point.

Figure 6.2 ALERT SCAN and the RL RTS collecting data of the water tank

This process was repeated for each control point and a complete scan of the tank was performed. The total time required to scan the entire surface of the tank took only one half-day, with the author being the only person in the field.

6.2 Results

As mentioned at the beginning of this chapter, this thesis is not focused on the way in which the processed results (coordinates) are analyzed, but in the manner in which the data is gathered efficiently and precisely. However, this section outlines and gives an example of some preliminary analysis that can be gathered from the ALERT SCAN measurements and the overall performance of the system.

The first verification was done to ensure that the coordinates of the reference network points were computed to meet the required relative precision of 1:100000 (as specified in section 4.1). The final network coordinates for point "1" were taken from the ALERT DB and compared with the initial fixed coordinates given to this point. During network processing, the Easting and Northing coordinate values for point "1" were set 0 (i.e., the origin of the coordinate system). After the ALERT network processing (discussed in section 5.2.4) was completed, these coordinate values were slightly different, 0.0005 m (Easting) and -0.0004 m (Northing). The absolute variation from the original coordinates was 0.0007 m, computed from the square root of the sum of squares of the Easting and Northing coordinates. The total distance of the perimeter of the network was 108 m, computed from a simple summation of the distances between network points. From these values, the relative precision of the network is determined to be 1: 154000, which meets the tolerance of 1:100000.

A basic idea into the structural integrity of the water tank can be done using the adjusted point coordinates output from the ALERT Processor, which are manipulated to determine the "verticality" of each individual VL. In other words, the horizontal "offset" of each Scan point in a particular VL is computed with respect to an artificial vertical axis projected from the Cross Point for that VL, as shown in Figure 6.3. The "horizontal offset" from the true vertical axis is referenced to a plane between the vertical axis and the computed center of the tank. Therefore, the amount by which each VL is "leaning" either "inward" or "outward" with respect to the tank center is calculated. This value is computed for each Scan point in that VL which results in a cross sectional view of each VL. By comparing epochs, the user can see any trends in the movement, if any, of each VL over time.

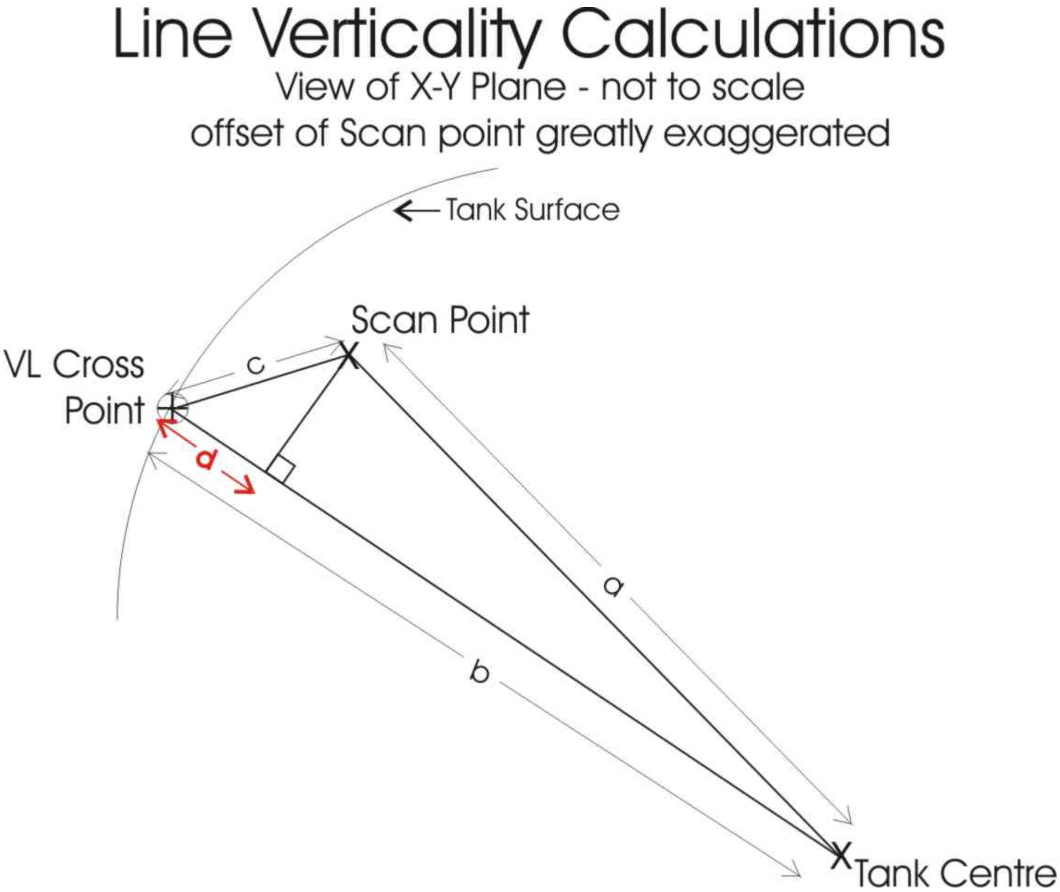


Figure 6.3 Line verticality calculations

In Figure 6.3, "d" represents the horizontal offset of a Scan point from the artificial vertical axis projected from the VL Cross point. The values for "c" (which will be almost zero in most cases), “a”, and “b” can easily be computed using basic trigonometry using the easting and northing coordinate values of the VL Cross and Scan point (retrieved from the ALERT DB) and approximate coordintaes of the centre tank point (computed using an algortihm borrowed from Tom [2007]). This simple algortihm computes approximate easting and northing coordinate values for the centre of a circle given three points located on the circle (surface of the tank). From these computed values, the horizontal offset can be derived using equation (6.1).

$$d = \frac{b^2 + c^2 - a^2}{2b} \tag{6.1}$$

However, because the value of “c” is very close to zero, the geometry of the problem is poorly conditioned and this equation should not be used. From Figure 6.3, note that as “c” approached zero, “a” and “b” will lie virtually on the same line. Therefore, the simple difference between “a” and “b” can be used to compute the value of “d”. The height of each Scan point is simply calculated by taking the difference between the given height value of the said point with that of the VL Cross point (retrieved from the ALERT DB).

In order to properly compare the verticality computations from two separate epochs of measurements, the VLs must be referenced into the same coordinate frame. Because the verticality values of each VL are relative to that VL Cross point and the fact that the physical Cross point on the tank is the same between epochs, only the height values of each Scan point in one epoch require translation. This was accomplished by artificially creating a benchmark height on the Cross point for one epoch and referencing the height values of the other epoch to it.

For the purposes of testing the reliability of the SCAN system in its entirety, the absolute differences in the two epochs were calculated. Because there were no repeated measurements to any one point on a VL, direct offset values could not be compared. Therefore, a linear trend line using least squares methods was computed for each epoch as a function of height versus horizontal offset. Arbitrary height values of 0 to 8 metres, at 0.5 metre increments, were chosen and used with this linear trend to compute the corresponding offset values. In this manner, direct comparisons between offset values for separate epochs could be done.

The following plots (Figure 6.4, Figure 6.5, and Figure 6.6) show the verticality of three VLs ("VL_13", "VL_14", and "VL_15") from the two separate epochs ("May" and "August"). Both the computed horizontal offset values and computed trend lines are shown. The plots are essentially cross sections of the tank at each VL with the center of the tank located on the right side of the plot. A positive offset value indicates that the Scan point is nearer to the centre of the tank than the Cross point for that VL.

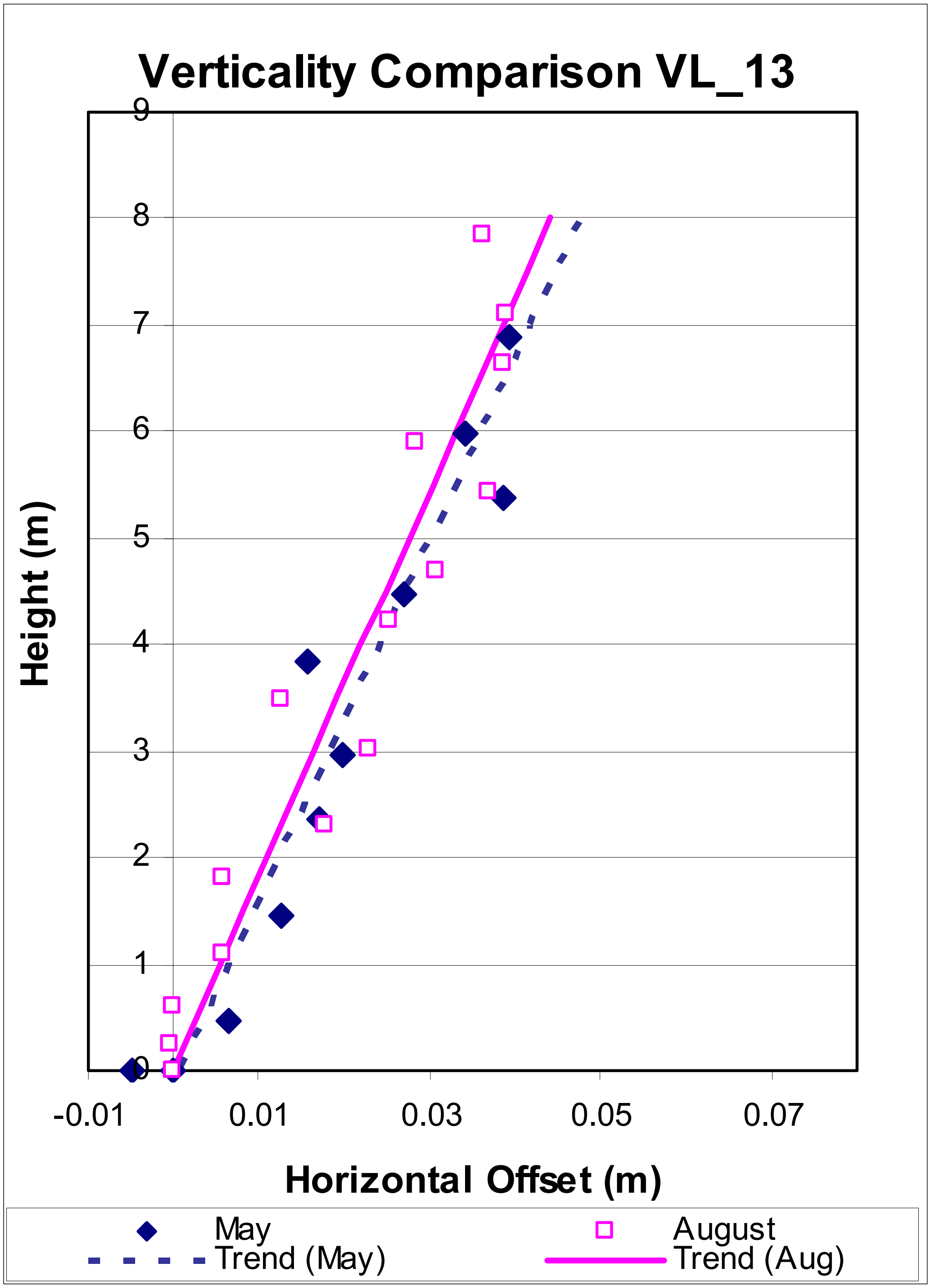


Figure 6.4 Trend Lines for vertical line "VL_13"

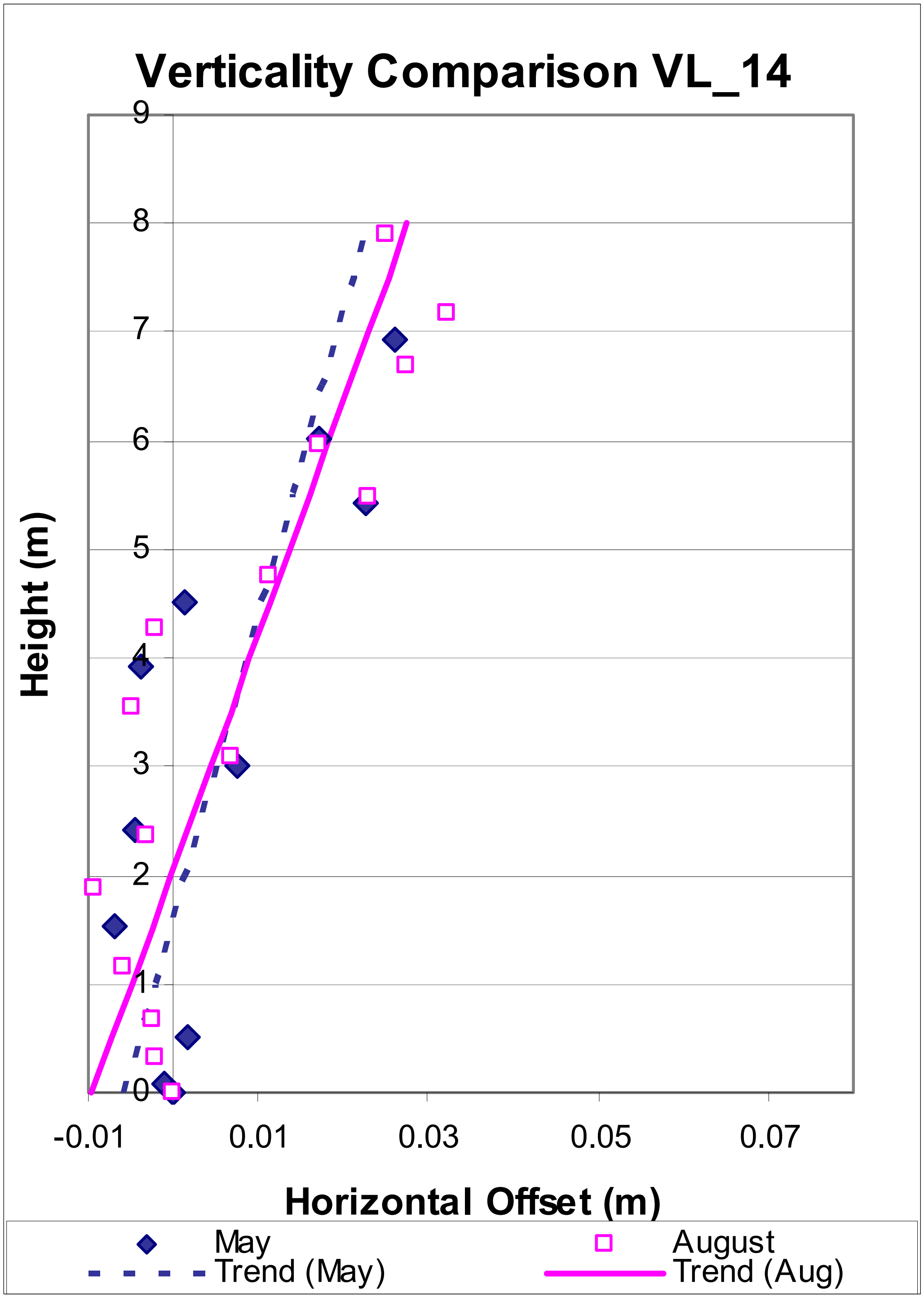


Figure 6.5 Trend Lines for vertical line “VL_14”

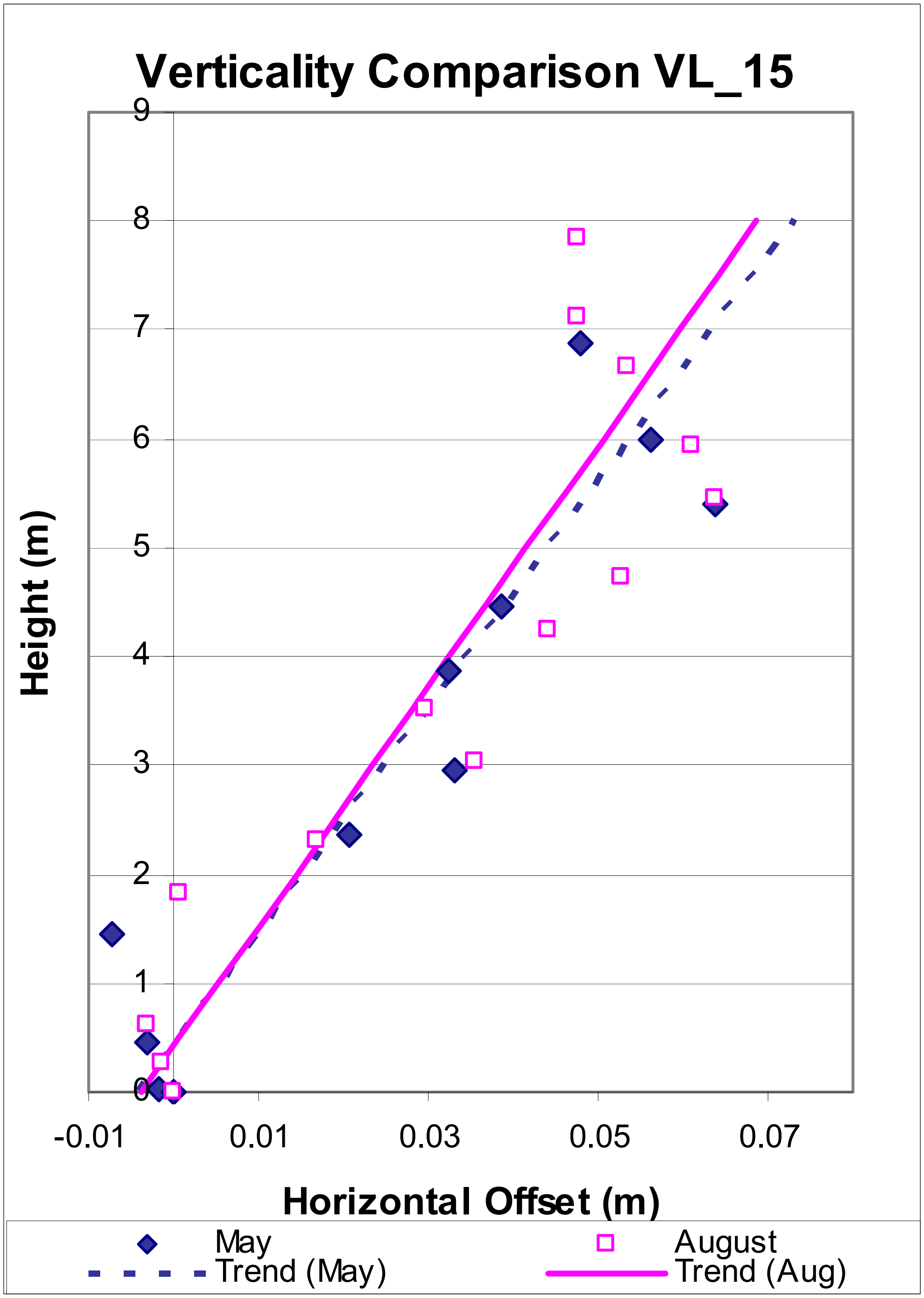


Figure 6.6 Trend Lines for vertical line “VL_15”

A quick visual comparison of the graphs indicates that the trend lines of the computed horizontal offset values are very similar between the two epochs for all VLs, but there is some discrepancy. However, there is no way of determining whether those discrepancies are due to the system used to gather the data or from actual physical deformations of the tank surface detected by the system.

It was later discovered that the water levels within the tank are constantly changing and even during the course of the measurements (only a few hours), the water levels varied considerably [Larlee, 2008]. Theses varying water levels were present during both epochs, therefore, it can be assumed that the tank conditions were similar between epochs and that measurements were made to the same physical structure. However, because this is an assumption, any precision values computed from the following statistically tests cannot definitively state the precision of the system, but only indicate that the system is a reliable method to gather data.

A ratio of the variances of the two sets of data (e.g., two epochs for one VL) can be used to determine whether there is a significant difference in the precisions of the two sets, as described in Holscher [1971, p. 136-145]. This ratio, F, is then compared to the theoretical value (based on confidence level and degrees of freedom) to determine whether the two variances differ significantly [Holscher, 1971]. For example, using the data for "VL_13", the variance of the data from both the "May" and "August" epochs were 0.0002 m, thus a ratio value of 1. The theoretical value, taken from Holscher [1971, table 10.3], of the variance ratio at a 95% confidence level, using degrees of freedom of 15 for "August" and 10 for "May", is 2.84. Therefore, since the computed variance ratio is less than the theoretical value, there is no significant difference in the precision of the two sets of data. It was also computed that there was no significant difference in the precisions of the data for “VL_14” and “VL_15”.

Computations could be done to determine the statistical significance of the discrepancies between the two trend lines, since there was no significant difference in the precision of the data between the two epochs. This was done using a t-test to compare the two sets of data (i.e., the horizontal offset values from “May” and “August”) at a 95% confidence level as described in Holscher [1971, p. 120]. The results from this analysis indicate that the two trend lines for each individual VL are not significantly different at a 95% confidence level (i.e., the trend lines for “May” and “August” are statistically similar at a 95% confidence level for each VL). This test indicates that the ALERT SCAN system is a reliable method to perform measurements to the surface of the tank.

7 RECOMMENDED METHODOLOGY TO PERFORM VENEZUELAN OIL TANK MONITORING

During an on-site visit to Venezuela, the author realized that there was a more efficient method by which to perform their oil tank monitoring surveys. However, this recommendation was not utilized because the Venezuelan company required that the collected observation data meet their current specifications (i.e., scan points in the form of percentage values of a panel within a vertical line). This chapter outlines the author's recommended methodology to simplify and improve upon the current oil tank monitoring specifications (which ALERT SCAN was designed to meet).

This method would include a grid scan made to the surface of the tank from the existing control points at a user-defined density (similar to the program described in chapter 3). This would eliminate the hassle of configuring measurements to fit individual vertical lines, percentages of panels, and cross points while still providing an effective, reliable method to collect observation data. Utilizing this method would require fewer user-inputs values and increase the surface scan efficiency.

Another way to streamline this monitoring method is to maximize the surface coverage of the scan from each station and minimize the total number of stations required to get complete surface coverage. Given the typical tank parameters and the location of the existing control points, the minimum number of RTS setups locations could be calculated (Figure 7.1). This alone would save time, because the current specifications require measurements to be made from every control point in the reference network [PDVSA, 2003]. By eliminating unnecessary RTS setups, the data collection would be more efficient, saving both time and money. Another advantage by having fewer RTS setups is the elimination of additional random error (from instrument centering, leveling, and pointing) and thus less uncertainty propagated throughout the network [Secord, 2003a].

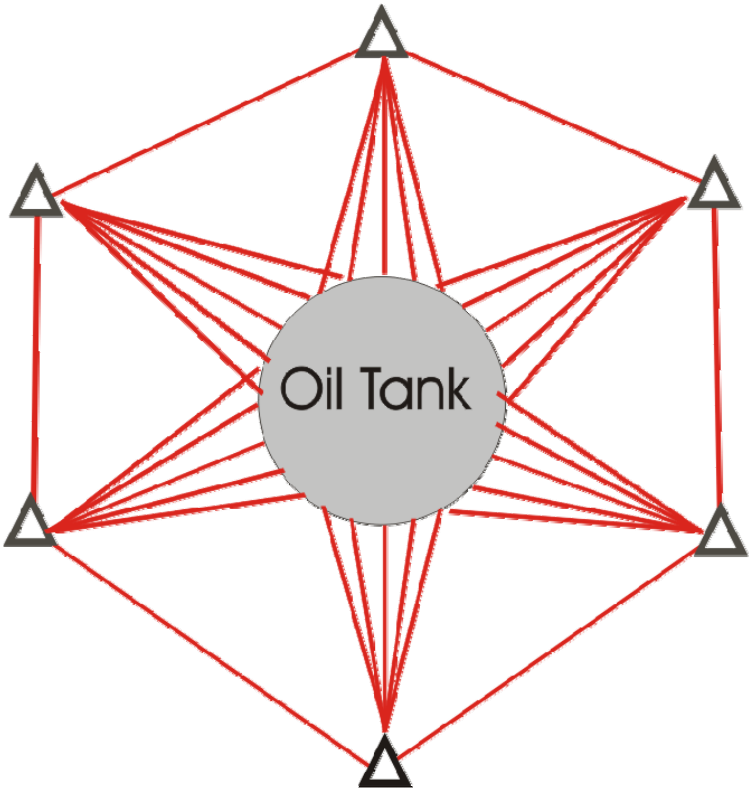


Figure 7.1 Minimum number of RTS setups

7.1 Computing the Minimum Number of RTS Setups

Incidence angles for any observation must be kept within an acceptable value to ensure measurements meet specified accuracy tolerances. From the feasibility test in the previous section, at an incidence angle of approximately 45 degrees at a distance of roughly 40 m from the object will result in distance measurements to a repeatability of better than 1 mm (at standard confidence level). Given the parameters of the tank (radius and height), the distance of the control points to the tank surface, and the value of the maximum allowed incidence angle, the minimum number of RTS stations required to ensure a full tank scanning coverage can be computed. The 2D case is shown in Figure 7.2.

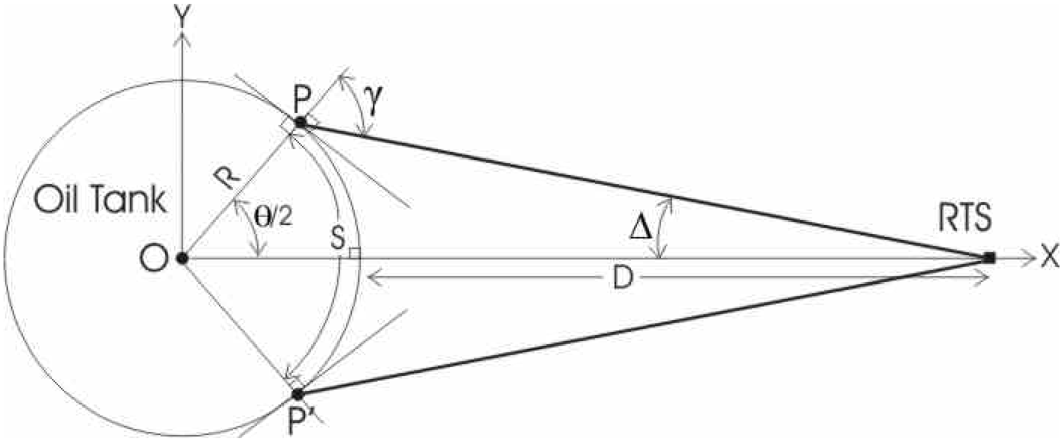


Figure 7.2 Oil tank XY plane

Where:

γ: incidence angle;

θ/2: half of the internal angle inscribed by the arc from P to P';

Δ: angle between the line from the RTS point (RTS) to the tank centre (O) and the line from the RTS point to the tank surface point (P);

R: tank radius;

D: distance from the tank to the RTS point; and

S: arc length between the two outer most tank surface points (P and P').

These values are computed using the equations 7.1 (all angular values are measured in radians):

$$\Delta = \sin^{-1}\left(\frac{R\sin(\pi-\gamma)}{R+D}\right) \text{ (from Sine Law)}$$

$$\theta/2 = \gamma - \Delta \quad \text{(from sum of interior angles} = \pi\text{)}$$

$$\mathrm{S} = \mathrm{R}\theta$$

$$\mathrm{C} = 2\pi\mathrm{R}$$

$$\mathrm{N} = \frac{\mathrm{C}}{\mathrm{S}}$$

(7.1)

Where:

C: tank circumference; and

N: Number of setups.

The total number of setups is rounded up to the next whole number (e.g., a value of 6.2 indicates 7 required setups). The 2D coordinate values for point P are computed using equation 7.2:

$$Xp = R\cos\left(\frac{\theta}{2}\right)$$

$$Yp = R\sin\left(\frac{\theta}{2}\right)$$

(7.2)

However, in the real-life situation, when the height component is also a factor, the solution becomes much more involved (Figure 7.3). Three-dimensional (3D) coordinate geometry must be used to determine the relationship between the line-of-sight vector from RTS to the tank surface and the incidence angle created with the tank surface at that point. To visualize this relationship in 3D, start at the horizontal case in the previous figure and note the changes to the incidence angle as the surface point (P) is moved “up” the tank (from P to P_H in Figure 7.3).

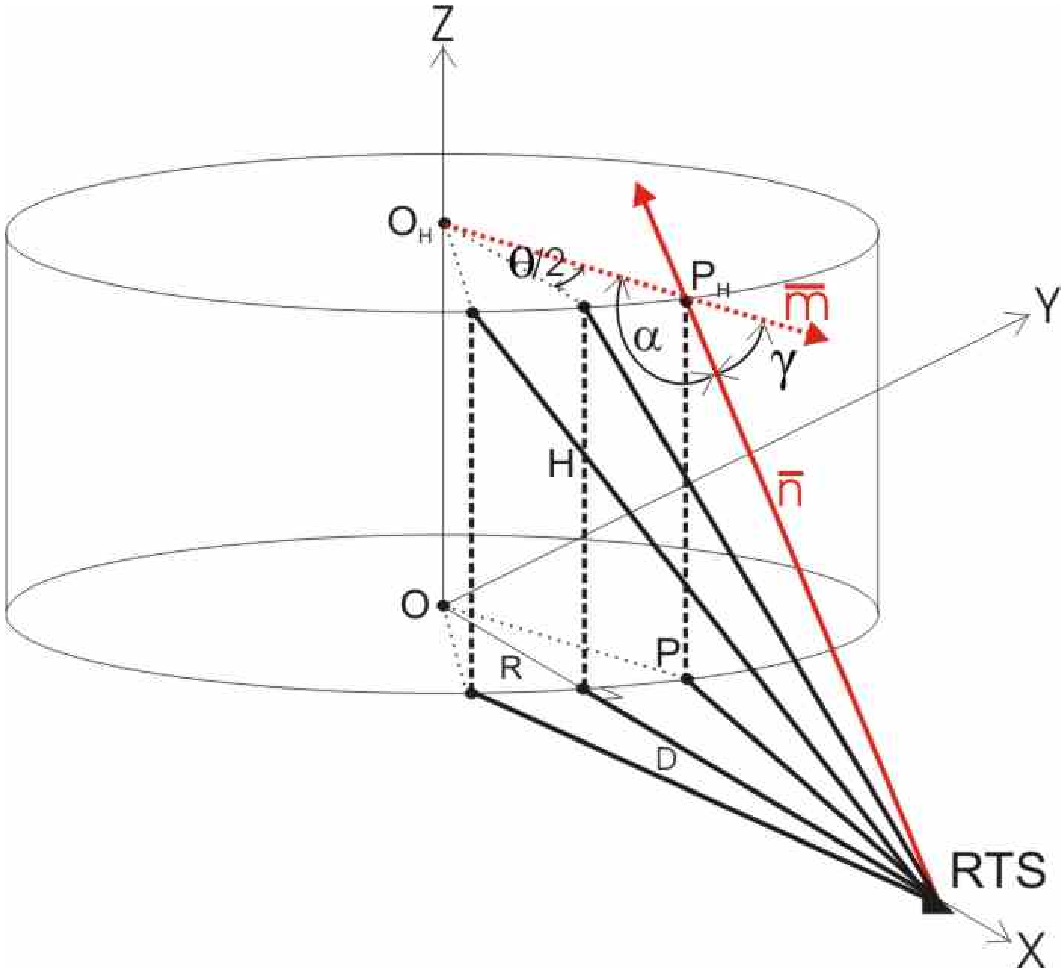


Figure 7.3 Oil tank-RTS 3D view

Where:

γ: spatial incidence angle;

$\vec{n}$: vector from the RTS point (RTS) to the point on the tank surface (P_H);

$\vec{m}$: vector from the centre of the tank, at height H (O_H), to the tank surface point (P_H);

α: angle created by the intersection of vectors $\vec{n}$ and $\vec{m}$ in the O_H-P_H-RTS plane; and

H: height of the tank with respect to the RTS.

The following equations (7.3), taken from Stewart [1995] and Thomas [2007], are used to compute these values:

$$\begin{aligned}
&\gamma = \pi - \alpha \\
&\alpha = \cos^{-1}\left(\frac{\vec{n}\cdot\vec{m}}{\|\vec{n}\|\|\vec{m}\|}\right) \quad \text{[Stewart, 1995, eqn. (11.3.6)]} \\
&\text{Where:} \\
&\vec{n} = \left\langle X_{PH} - X_{RTS}, Y_{PH} - Y_{RTS}, Z_{PH} - Z_{RTS} \right\rangle \\
&\vec{m} = \left\langle X_{PH} - X_{OH}, Y_{PH} - Y_{OH}, Z_{PH} - Z_{OH} \right\rangle
\end{aligned} \tag{7.3}$$

Where:

$\vec{n}\cdot\vec{m}$: dot product between the two vectors;

$\|\vec{n}\|$: length of *n* vector; and

$\|\vec{m}\|$: length of *m* vector (equal to R).

These equations require 3D coordinate values for the points RTS, O_H, and P_H. A constraint can be placed on the Z coordinate for point P_H when using a tank as the monitored structure. Since it is known that the full height of the tank must be scanned from the RTS station, it can be assumed that the Z coordinate of the point P_H is the height of the tank (minus the height of instrument), which is also the Z coordinate of the point O_H. A number of other coordinated values can be easily be derived. The X and Y coordinate values for O_H are zero, as are the Y and Z coordinates for point RTS. The X coordinate for point RTS is simply the sum of R and D. The 3D coordinates are as follows:

$$\begin{aligned}
&\mathrm{RTS} : (\mathrm{R}+\mathrm{D}, 0, 0)\\
&\mathrm{P_H} : (\mathrm{X_{PH}}, \mathrm{Y_{PH}}, \mathrm{H})\\
&\mathrm{O_H} : (0, 0, \mathrm{H})
\end{aligned}$$

The only unknown values are the X and Y coordinates for the point P_H. Substituting these coordinate values into equations 7.3 results in equations 7.4:

$$\begin{aligned}
&\vec{n} = \left\langle \mathrm{X_{PH}} - (\mathrm{R}+\mathrm{D}), \mathrm{Y_{PH}}, \mathrm{H} \right\rangle\\
&\vec{m} = \left\langle \mathrm{X_{PH}}, \mathrm{Y_{PH}}, 0 \right\rangle\\
&\vec{n}\cdot\vec{m} = \mathrm{X_{PH}}^2 - \mathrm{X_{PH}}(\mathrm{R}+\mathrm{D}) + \mathrm{Y_{PH}}^2\\
&\|\vec{n}\| = \sqrt{(\mathrm{X_{PH}} - (\mathrm{R}+\mathrm{D}))^2 + \mathrm{Y_{PH}}^2 + \mathrm{H}^2}\\
&\|\vec{m}\| = \mathrm{R}\\
&\Rightarrow \alpha = \cos^{-1}\left(\frac{\mathrm{X_{PH}}^2 - \mathrm{X_{PH}}(\mathrm{R}+\mathrm{D}) + \mathrm{Y_{PH}}^2}{\mathrm{R}\sqrt{(\mathrm{X_{PH}} - (\mathrm{R}+\mathrm{D}))^2 + \mathrm{Y_{PH}}^2 + \mathrm{H}^2}} \right)
\end{aligned}$$

(7.4)

To solve for the unknown values of X_{PH} and Y_{PH} given an incidence value (α) involves extremely complex formula manipulation (one that the author could not solve). To alleviate this problem, an alternate approach was conceived, which involved estimating the coordinate values for P_H and computing the incidence angle and ensuring this value is less than the maximum allowed (e.g., 45 degrees).

However, coordinate values must be chosen to ensure that the point is still located on the tank surface (i.e., on the circle). This is done by using the 2D case (equations 7.1 and 7.2) and selecting an initial incidence angle which results in acceptable coordinate values (i.e., coordinates of point P). Substitute these values into equation 7.4 results in an incidence angle in the 3D case. Selecting the correct incidence angle in the 2D case will produce the desired 3D incidence angle (e.g., 45 degrees). This 2D angle can them be used in equations 7.1 to produce the minimum number of required setups. This process is best described using an example.

7.2 Example Using Typical Tank Values

For this example, typical Venezuelan tank parameters, a maximum allowable incidence angle of 45 degrees, and a height of instrument of 1.5 m are used. The tank parameters include a tank radius of 18 m, a tank height of 15 m, and distance of 40 m perpendicular from the surface of tank to the RTS point.

First, using only the 2D case (equations 7.1), the number of required setups is six (rounded up from 5.6). The value for θ is 64.6 degrees, the arc length (S) is 20.3 m, and the circumference is 113 m. The computed (X, Y) coordinates for point P are (15.2, 9.6), from equation 7.2.

Substituting these coordinate values (for P) into equation 7.4 results in a 3D incidence angle of 47.5 degrees. This is greater than the 45 degree limit, therefore a smaller incidence angle in the 2D case must be chosen. An acceptable initial starting 2D value would be 42 degrees, which is computed from subtracting 2.5 degrees (the difference of 47.5 and 45 degrees) from 45 degrees, and rounding down to the nearest integer value. Using 42 degrees as the 2D incidence angle results in a 3D incidence angle of 44.8 degrees, which is less than the 45 degree limit. Using this incidence angle of 42 degrees in equations 7.1, again results in 6 required setups to ensure full tank coverage (however, this time it is rounded up from 5.9).

This method could be designed to be automated for the user by simply accepting the tank parameters and maximum allowable incidence angle and built into a semi-automated monitoring system.

8 CONCLUSIONS

This report has outlined the research, design, development, and testing of a software system ("SCAN") to perform semi-automated structural monitoring of large oil tanks. The chosen approach was to utilize a robotic total station with reflectorless electronic distance measurement technology in combination with an existing software system designed to perform fully automated deformation monitoring surveys ("ALERT").

The "ALERT SCAN" software system has been designed to meet the needs and specifications of a Venezuelan oil company to improve upon a previous method to conduct routine structural monitoring of their hundreds of large oil storage tanks. The major weakness of the previously existing monitoring method, utilized by the Venezuelan surveyors, was the amount of time required to perform the data collection for each tank.

The ALERT SCAN system has been proven to reduce the time required to perform all field measurements from two weeks (with 2-3 persons) to one half-day (by a single person). The system was also showed to meet the required relative precision of the reference network measurements of 1:100000 as the final coordinates from the field test resulted in a relative precision of 1:154000. Tests on the quality of the data collected by the system indicate that it is a reliable method to perform oil tank deformation surveys. Further improvements to the monitoring scheme, to increase data collection efficiency, were proposed, in the form of a new, alternative methodology.

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APPENDIX I

List of Acronyms

2D	Two-dimensional
3D	Three-dimensional
ALERT	Name of software program to perform fully automated deformation monitoring, developed by the CCGE
ATR	Automatic Target Recognition
BL	Bottom Left
BR	Bottom Right
CCGE	Canadian Centre for Geodetic Engineering
DB	Database
DCM	Data Collection Manager, a module of ALERT
DLL	Dynamic Link Library
EDM	Electronic Distance Measurement
GPS	Global Positioning System
GUI	Graphical User Interface
HCR	Horizontal Circle Reading
HI	Height of Instrument
ISO	International Organization for Standardization
MS	Microsoft
PTS	Portable Task Setup, a module of ALERT
RL	Reflectorless

RL3DScanning	Name of software program to scan a planar surface, developed by the author
RTS	Robotic Total Station
SCAN	Name of software program to scan the surface of an oil tank, developed by the author
SD	Standard Deviation
TL	Top Left
TR	Top Right
UNB	University of New Brunswick
VB	Visual Basic
VCR	Vertical Circle Reading
VL	Vertical Line

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