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Environmental Laboratory

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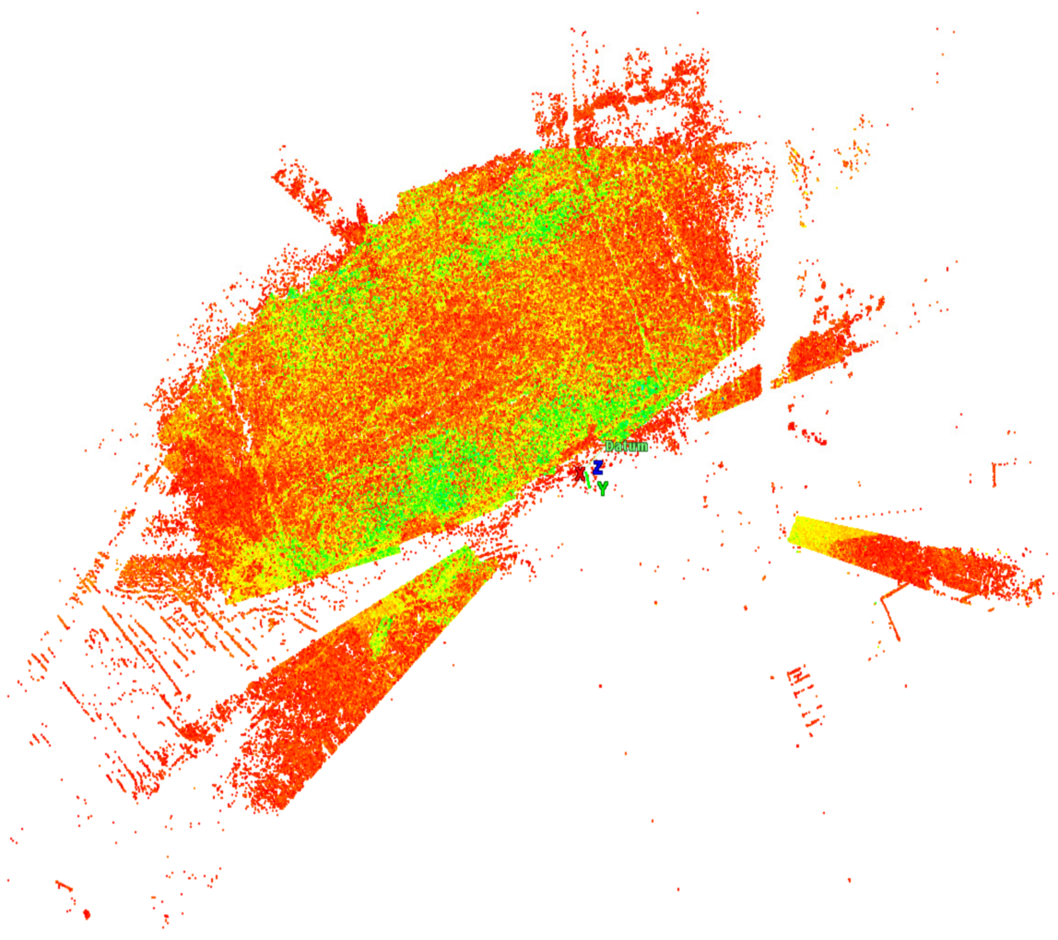
Engineer Research and Development Center

Countermine Phenomenology Program

Use of a High-Resolution 3D Laser Scanner for Minefield Surface Modeling and Terrain Characterization: Temperate Region

Sam S. Jackson and Michael J. Bishop

August 2005



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Use of a High-Resolution 3D Laser Scanner for Minefield Surface Modeling and Terrain Characterization: Temperate Region

Sam S. Jackson, Michael J. Bishop

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3909 Halls Ferry Road
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Final report

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ABSTRACT: The use of a high-resolution, ground-based 3D laser scanner was recently evaluated for terrestrial site characterization of variable-surface minefield sites and generation of surface and terrain models. The instrument used to conduct this research was a Leica HDS3000 3D laser scanner. The high-speed, highly accurate ranging system has a 360 deg horizontal × 270 deg vertical field of view that delivers positional, range, and angular (vertical and horizontal) single point accuracies (range 1 to 50 m) of 6 mm, 4 mm, and 60 micro-radians, respectively. The laser is a class 3R and is completely eye-safe with a wavelength of 523 nm and spot size of ≤6 mm at a distance of 50 m. The pulse rate is 1,000 points/sec with an optimal effective range up to 100 m which is capable of producing a maximum point cloud spacing of 1.2 mm in the horizontal and vertical direction. Two study sites located in the midwestern United States were used for this analysis. A very dense vegetation site (Grass Site) and a bare soil site with intermittent rocks and sparse vegetation (Dirt Site) were selected for data collection to simulate both obscured and semi-obscured minefield sites. High-density scans (range 0.2 to 2.0 cm spacing) were utilized for Cyra target acquisition and were commensurate with size and distance to target from scanner location. Medium-density scans (range 2.0 to 5.0 cm spacing) were chosen for point cloud generation of the entire site(s) with approximately 10 percent edge overlap between field scans. In order to provide equivalent, unobstructed viewing perspectives from all scan locations at each site, the scanner was positioned on a trailer-mounted, chain-driven lift and raised to an approximate scan height of 7.6 m above the ground. Final registration to UTM projected coordinate system of the multiple scan locations for the Dirt Site and Grass Site produced mean absolute errors of 0.014 and 0.017 m, respectively. The laser scanner adequately characterized surface roughness and vegetation height to produce contour and terrain models for the respective site locations. The detailed scans of the sites, along with the inherent natural vegetation characteristics present at each site, provide real-time discrimination of minefield site components under contrasting land surface conditions.

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Preface

This report was prepared for the U.S. Army Engineer Research and Development Center's (ERDC) Countermine Phenomenology Program. The technical monitor at the time of publication was Mr. Jerrell R. Ballard, Jr., Environmental Laboratory (EL), ERDC.

The work was performed under the direction of the Ecosystem Evaluation and Engineering Division (EE), EL, and was funded under the Site Characterization work unit with Mr. Thomas E. Berry as the EE Principal Investigator. The EL Principal Investigator for this analysis was Mr. Sam S. Jackson, EE, and coinvestigator was Mr. Michael J. Bishop, EE. Program Manager for the ERDC Countermine Phenomenology Program was Dr. Larry N. Lynch of the Geotechnical and Structures Laboratory, ERDC.

Many individuals contributed to the support of this project, including the following: Messrs. Ballard and Berry; Mr. David L. Leese, Information Technology Laboratory, ERDC; Ms. Elizabeth Lord, Computer Sciences Corporation; and Mr. R. Eddie Melton, Jr., JAYA Corporation. Dr. Edwin A. Theriot was Director, EL, and Dr. David J. Tazik was Chief, EE.

At the time of publication, COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Purpose

This measurement and analysis effort was conducted to support specific key objectives of the Engineer Research and Development Center's (ERDC) Countermine Phenomenology Program. The objectives addressed through this research primarily include the development of an improved knowledge of geo-environmental phenomenology factors impacting both mine and minefield detection in various operational environments and help support the development of algorithms using these factors to improve detection capability of both surface and buried mines and minefields.

The use of a high-resolution 3D ground-based laser scanner was evaluated and assessed for characterizing and capturing terrestrial site characteristics of variable-surface minefields to aid in surface model generation and ground surface contour mapping. This research tool is one of many being implemented by the ERDC Countermine Phenomenology Program to evaluate potential methods for characterizing and delineating background features within minefields. This effort is intended to support and improve the understanding of background phenomenology with respect to minefields (Jackson et al. 2005).

Background

The highly accurate and dense point data (or point clouds) captured by terrestrial 3D laser scanners, such as the Leica HDS3000 system, allow for the development of robust datasets for GIS modeling efforts and dynamic landscape visualization. The ground-based instrument is closely akin to its airborne light detection and ranging (LIDAR) counterpart. However, terrestrial LIDAR is acquired with more efficiency at a much higher resolution from a more stable platform. Eliminating the need to correct for orientation errors common with airborne sensors, terrestrial 3D laser scanners produce accuracy measured in millimeters as opposed to centimeters, but for obvious reasons are not as effective as airborne LIDAR at extracting data in the vertical dimension, such as vegetation height and ground surface elevation. Other limiting factors of ground-based LIDAR are its restriction to small geographic areas and the requirement of numerous scans, which can become labor-intensive for large area acquisitions.

Multiple laser scanner setups, analogous to airborne LIDAR swaths, are required for data acquisition when implementing terrestrial LIDAR and must be coregistered to form a cohesive point cloud representative of the sampled area. Laser scanning, in general, is a rapid non-invasive form of data acquisition that is suitable for characterizing areas with restricted or limited access or where environmental conditions exist that may limit one's ability to gain physical access to the area.

Airborne laser scanner systems are abundant on the market today and the technology is considered to be in a mature state. These laser systems are very complex, being more a geodetic system for data acquisition and more a photogrammetric system for data processing (Axelsson 1999). What is lacking, however, is the development and refinement of algorithms and data interpretation methods to provide various surface representations of the scanned area. Likewise, little is known about the implications for surface modeling from the use of terrestrial laser systems.

Terrestrial LIDAR — being active sensing devices that emit electromagnetic energy either in the visible or near infrared part of the spectrum — records the amount of reflectance and laser beam return time from the scanned feature. The surveyor can define the area of interest and specify the angular resolution value, with no further attendance required during the scanning phase, which takes only minutes to complete. Linear resolution over the object depends on distance, azimuth, and elevation of the laser beam, as well as terrain surface morphology. The accuracy of point positioning is a function of distance, the number of scanning repetitions, and laser spot-size (Colombo 2003).

Johansson (2002) documented undesirable artifacts in resulting point cloud data generated from various ground-based laser scanners. Strange effects along edges of objects and difficulty in capturing points on certain surfaces were noted. The author emphasizes small spot size, good range capabilities, and high positional accuracy of the chosen scanner to minimize or resolve these issues.

Guarnieri et al. (2004) described the insufficient use of natural objects as control points for model georeferencing and emphasized common error sources when using ground-based LIDAR. Detected errors were directly related to the scanner's accuracy, intensity response from the reflected laser beam, and the operator's ability to identify model control points. The authors advise the use of artificial reference targets[1] whenever possible to increase the accuracy of control point selection. These fixed targets can be surveyed and will therefore lend proper fitting procedures during the point cloud registration.

[1] Targets defined herein as scanner reference targets (Cyra targets) used for control point acquisition during laser data registration. These are not the same as landmine targets.

2 Study Methods and Data Processing

Site Description

Two variable-surface minefield sites located in the mid-western United States were selected as study site locations to conduct this research effort. A very densely vegetated site (Grass Site) and a mostly bare soil site[1] (Dirt Site), with intermittent rocks and sparse vegetation, allowed for characterization efforts to be employed for obscured and semi-obscured minefields. Each site is approximately rectangular having four-sided, right-angled polygons with opposite sides equal and parallel to each other. The dimensions of the Grass Site and Dirt Site are 40 × 160 m and 40 × 320 m, respectively. Both minefield sites serve as test beds for deployed mines and contain M20, M19, and RAAM buried and surface emplaced mines with top hat and Electro-Optical Infrared (EOIR) red board fiducial markers spaced at various intervals.

The Grass Site has about a 5 to 10 percent grade with a northwest-facing slope. It is comprised mostly of thick grass with varying density and distribution over the field. In contrast, the Dirt Site is relatively flat, with the exception of a drainage ditch oriented north and south across the center of the field on the east side. The Dirt Site has been plowed several times and consists mainly of large boulders and smaller rocks with sparse patches of grass vegetation. The basic capability to derive contour and terrain models from a high-density laser data point cloud was evaluated for these two geophysically different sites.

Laser Data Collection

Data acquisition took place during late July and early August 2004. A Leica HDS3000 3D laser scanner manufactured by Leica Geosystems HDS, Inc. (formerly Cyra Technologies) was used to provide a high-definition survey of both sites. The SmartScan Technology™ of this unit provides a maximum 360 deg horizontal field of view and a maximum 270 deg vertical field of view. The scanner emits rapid pulses of green (523 nm) laser light that sweeps across the landscape and sends back numerous measurements with precise x, y, and z coordinates, each having an associated RGB color and intensity value. The sophisticated design of the scanner enables point clouds to be captured that

[1] Named “Dirt Site” by Army test bed sponsor.

correspond to true point positions where the laser pulse hits the object. The point cloud represents the shape and position of the objects scanned relative to the position of the scanner (Leica Geosystems HDS, Inc. 2004). See Table 1 for a complete summary of the scanner specifications.

Table 1
Specifications for the Leica HDS3000 3D Laser Scanner

Field of View	360 deg H × 270 deg V
Positional Accuracy	6 mm at 50 m
Wavelength	523 nm
Spot Size	≤ 6 mm at 50 m
Pulse Rate	1,000 points/sec effective to 100 m
Maximum Sample Density (spacing)	1.2 mm

The operating software used in conjunction with the laser scanner during data acquisition was Cyclone Version 5.0. The Cyclone software assists the surveyor in capturing point cloud data, visually interpreting and processing these data, then integrating the collected information into useful geospatial formats.

When feasible, the scanner was positioned at approximately one-quarter length intervals along each field's long side in an effort to provide uniform scan coverage of the entire site. Also, to obtain an unobstructed viewing angle from all scanner locations, the scanner was positioned on a trailer-mounted, chain-driven lift and raised to a scan height of 7.62 m above the ground. At each initial fixed scanner position, a high-resolution picture image of the viewing area was captured using the scanner's built-in camera. This allowed the surveyor to easily view and depict areas to be scanned, making Cyra target acquisition and site/minefield scans much more efficient.

Cyra target acquisition

After a suitable image was acquired at each scanner setup, all corresponding Cyra targets within the effective scan range (< 100 m) were probed with the scanner prior to acquisition to determine the approximate distance to the target. High-density laser scans (range 0.2 to 2.0 cm spacing) were used for Cyra target acquisition and were commensurate with size and distance to the target from each scanner setup. The tie points generated from each target acquisition (Figure 1) established a set of constraints that were used to register, or geometrically align, all of the scanner locations into a single, fitted point cloud representing each site. Each tie point was labeled with a unique registration ID.

To obtain a tie point with minimal deviation from the center of the target, the target must be scanned with a sufficient density of postings in the object's center. Once a post point is manually selected that is close to the target's center, the scanner performs a coarse scan to locate the center circle then proceeds with a fine scan (~1.2 mm spacing at 50 m) using an algorithm to locate the exact center.

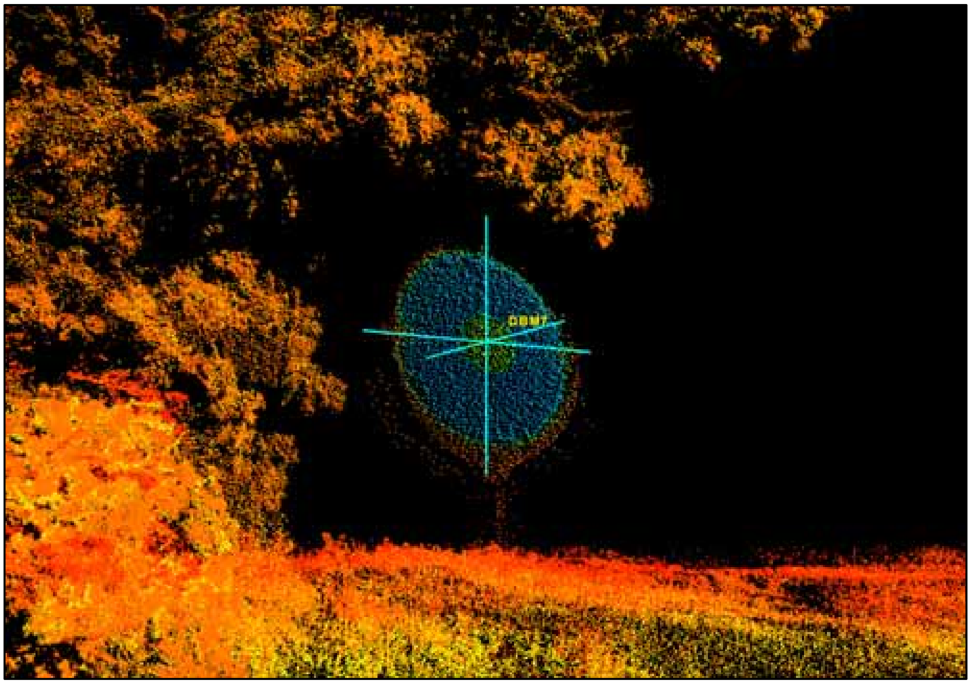


Figure 1. Tie point generated from precise Cyra target acquisition. Posting color represents multi-hue intensity of each laser return. High intensity appears blue and low intensity appears red

A vertex is placed at the perceived center of the Cyra target, representing the tie point. A minimum of three Cyra targets was placed at each scanner setup to produce sufficient tie points to be used as constraints in the registration process. Each Cyra target was strategically positioned at opposite extents of the minefield site and served as common targets to additional scanner setups in order to successfully reference each point cloud together.

Site/minefield scans

After target acquisition was complete at each scanner setup, the sites were scanned. The laser scanner was positioned at four locations at the Grass Site, two on the western-most side and two on the eastern-most side of the minefield. Restricted access on the north side of the Dirt Site prevented laser scan setups on this side. As a result, the scanner was positioned only on the south side and provided six total setups on the Dirt Site. Moderate-density scans were chosen for point cloud generation of each site with approximately 10 percent edge overlap at each field extent to capture the entire area of interest. Also, a 10 percent scan overlap between site scans ensured sufficient point cloud data collection for each site. The Grass Site and the Dirt Site were scanned at approximate post spacings of 5 and 2 cm, respectively, in the horizontal and vertical direction. Figure 2 depicts a small portion of the scanned Dirt Site and illustrates the point cloud representation of the various mines and fiducial markers in the minefield.

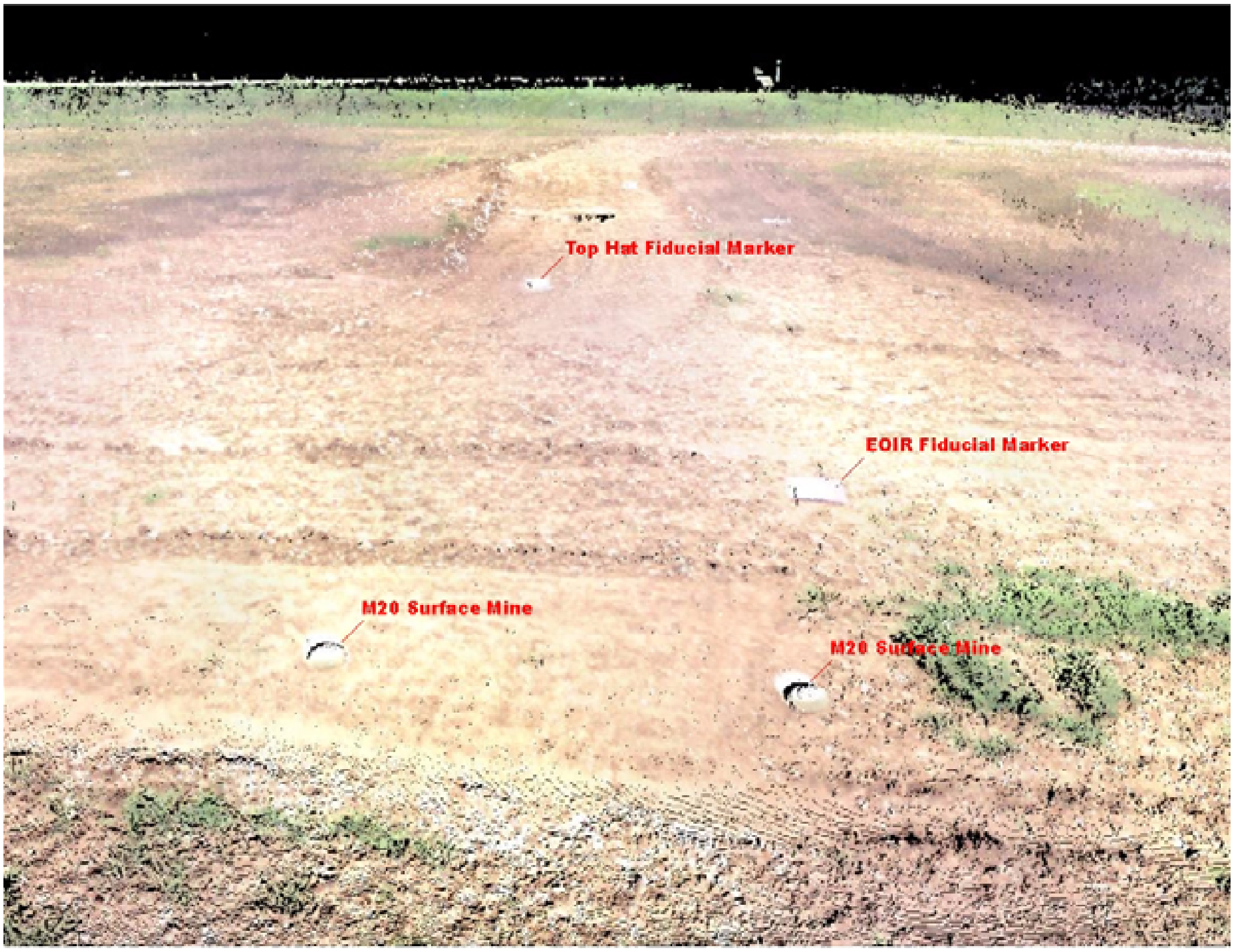


Figure 2. Graphical depiction of scanned Dirt Site showing M20 surface mines and fiducial markers. True-color laser postings are spaced every 2 cm

Data Analysis

Once data acquisition was completed for both sites, processing of the laser data began. To generate a three-dimensional, continuous point cloud representation of each site, each scanner setup location's point cloud, or ScanWorld, had to be coregistered with one another (interim registration) and referenced to a common coordinate system (georegistration) for use with other spatial datasets and to perform additional analyses. A ScanWorld can be defined as a collection of scanned point clouds that are derived from consecutive scans at the same scanner location. The ScanWorlds were aligned together to form a referenced dataset representative of a particular site. The fully georegistered scan data were then processed to produce digital elevation and terrain models applicable to each site. Further descriptions of these post-processing techniques are detailed below.

Laser data registration

Registration is a method that aligns many individual ScanWorlds into a single georeferenced ScanWorld to represent the entire area of interest, in this case each minefield site. The registration process makes use of various mathematical algorithms that compute the optimal alignment transformations for each ScanWorld in the registration such that the constrained objects or point clouds are aligned as closely as possible in the resulting ScanWorld (Leica Geosystems HDS, Inc. 2004). Because sufficient Cyra targets were acquired for all ScanWorlds at each site, target-based registration was used for interim point cloud alignment. The Cyra targets placed at the extent of each minefield served as control or tie points in the registration process. These tie points that were common to adjacent ScanWorlds, appearing to be in the same Cartesian location (x, y, and z position), were fitted together to establish an accurate relationship between each of the ScanWorld point clouds. During this initial registration process, the Cyclone software added tie points as constraint objects to be paired with corresponding tie points in other ScanWorlds. The software performs a constraint-searching algorithm that locates objects with the same registration ID, or tie points that are geometrically consistent, to find the optimal solution.

After the ScanWorlds were registered together for each site, the single point cloud was georegistered to the Universal Transverse Mercator (UTM) projection on the basis of the North American Datum 1983 (NAD83). Surveyed coordinates of specific Cyra targets used in the registration process were collected to millimeter accuracies with a Real Time Kinematic (RTK) Global Positioning System (GPS) at each site and were used to register the existing point cloud data to the UTM projected coordinate system. Each target's Cartesian position was identified to minimum accuracies of 10 mm horizontal and 15 mm vertical. At least four surveyed Cyra targets with known coordinates were used for each site, and these corresponded to all relative ScanWorlds. A text file containing the Northing, Easting, and Elevation measurements associated with each surveyed Cyra target was imported into the Cyclone software. The imported survey coordinates served as a new survey control ScanWorld to which all others ere then georegistered. The surveyed Cyra targets were positioned to achieve a large aspect ratio and thus provide an optimal geometric solution in the registration process. After successful georegistration was completed for both sites, surface analysis techniques were employed to further characterize the sites and their associated backgrounds.

Surface/terrain analysis

Topographic derivatives were generated for each site to effectively relate the scanned laser data to terrain features. The abundance of data points generated from the laser scanner allowed for the production of detailed digital terrain and elevation model representations of each site. These terrain models not only provide 3D visualization of the background phenomenology but also enable analysts to measure topographic variations within the minefield.

The georegistered data points representing the area of interest at each site were extracted and unified as a single point cloud for processing. Scan data outside the fence area, or beyond the extent of each minefield, were discarded from the data set prior to processing to remove trees and other superfluous background data. Tall vegetation within the Dirt Site was manually extracted by similar means for generation of a bare earth model. Subsequent generation of a contour map from the bare earth model was produced for the Dirt Site as well. In addition, a vegetation height model was produced from the laser point cloud representing the Grass Site.

The Cyclone software was used to select five to nine individual laser data points representative of relatively flat, bare ground from a centralized area within the Dirt Site point cloud. Data for these sites were used as input for a region grow, surfacing algorithm. The surface-smoothing algorithm segments the point cloud to form a horizontally expanded, planar point cloud indicative of the terrain geometry. The algorithm operates based on fit calculation parameters that are user-specified and continues until all assumed non-ground data points are effectively isolated from the remaining ground points. The primary surface parameters involved in this process include (a) region thickness threshold, which defines the range of data points to be surfaced as ground, (b) surface angle tolerance to account for areas of high relief, and (c) gap distance, which defines the maximum distance allowed between parts of the same smooth surface. The region grow algorithm did not properly identify certain points within the Dirt Site. Therefore, these point data were manually edited until satisfactory results were obtained.

After all assumed vegetation was removed and the ground surface points were identified for the Dirt Site, the points representing bare ground were used to create a Triangulated Irregular Network (TIN) or mesh. By producing a TIN of the assumed ground, a coherent modeled surface can be easily visualized. An elevation contour map was subsequently produced from the TIN for the Dirt Site. Major contours were specified at 0.5-m intervals, and the number of minor intervals per major contour was set at five. As a result, this produced index contours at half-meter intervals and a contour interval of 10 cm, effectively yielding a highly detailed, micro topographical profile of the Dirt Site. A regularly spaced sample grid was then generated from the original TIN layer to provide a digital terrain model of the Dirt Site.

Due to the dense vegetation present at the Grass Site, a vegetation height map was produced to better quantify the background component of the site. The laser data points representative of the Grass Site were exported from the Cyclone software as an x, y, and z text file. This text file was imported into a custom, proprietary application written specifically for this vegetation height extraction (personal communication, R. E. Melton, Jr., Senior Programmer, JAYA Corporation 2004). The application was designed to distinguish and isolate assumed ground hits and maximum vegetation height points. The application extracts laser data from the lowest 10 percentile using each point's elevation (z) value and then averages those within a one square meter cell size. This is the assumed ground. Likewise, laser data from the top 10 percentile were extracted by z value, averaged, and then output as a single point representing the average maximum vegetation height for that 1-sq-m cell. The output, x and y values for the center of each cell and an average elevation value, were uploaded into an

ESRI point shapefile. Vegetation height was calculated by subtracting the assumed ground elevation points from the assumed vegetation elevation points. These new elevation point values were the representative vegetation height value for each one-meter cell center, which were used to generate a 1-m grid of the entire Grass Site.

3 Results and Discussion

Laser Data Registration

Mean Absolute Error (MAE) was used to measure the accuracy of the point cloud registrations for each site (Table 2). Point cloud alignment error was evaluated for both the interim registration and georegistration to the UTM projected coordinate system using the RTK-GPS collected survey coordinates.

Table 2
MAE Values for Interim Point Cloud Registration and Georegistration for Both Sites

Minefield Site	Registration Error (MAE)		# ScanWorlds
	Interim	Geo (UTM)	
Dirt Site	0.008 m	0.014 m	6
Grass Site	0.014 m	0.017 m	4

MAE can be defined as the weighted average of the absolute errors, with the relative frequencies as the weight factors. Additionally, the minimum MAE value can be interpreted as the mean absolute deviation among data points. All tie point constraints were equally weighted during the registration process. One constraint pair, a target tie point (DBM1) and its corresponding survey coordinate, was disabled in the final georegistration of the Dirt Site because of the inordinate error compared to all other constraints (Figure 3). See Appendix A for complete registration diagnostics for both minefield sites.

The Positional error of the Leica scan data alone is generally around 6 mm (Leica Geosystems HDS, Inc. 2004). However, the overlap measurements are often imprecise, especially for scans of complex geometry such as grass and other vegetation. Various reasons exist that could explain this intricacy. Overlapping laser points are often not always from the same surface, or blade of grass. Multiple viewpoints from different, surrounding ScanWorlds generate a somewhat convoluted perspective of the same spatial area, particularly for grass or vegetation scans, therefore increasing the point-to-point deviation or error. Other reasons may exist including environmental factors such as wind or sun angle, which may cause vegetated surfaces to be more spatially variable between consecutive scans, contributing to a higher MAE. Moderate winds during a portion of the Grass Site data capture contributed to lift platform and scanner

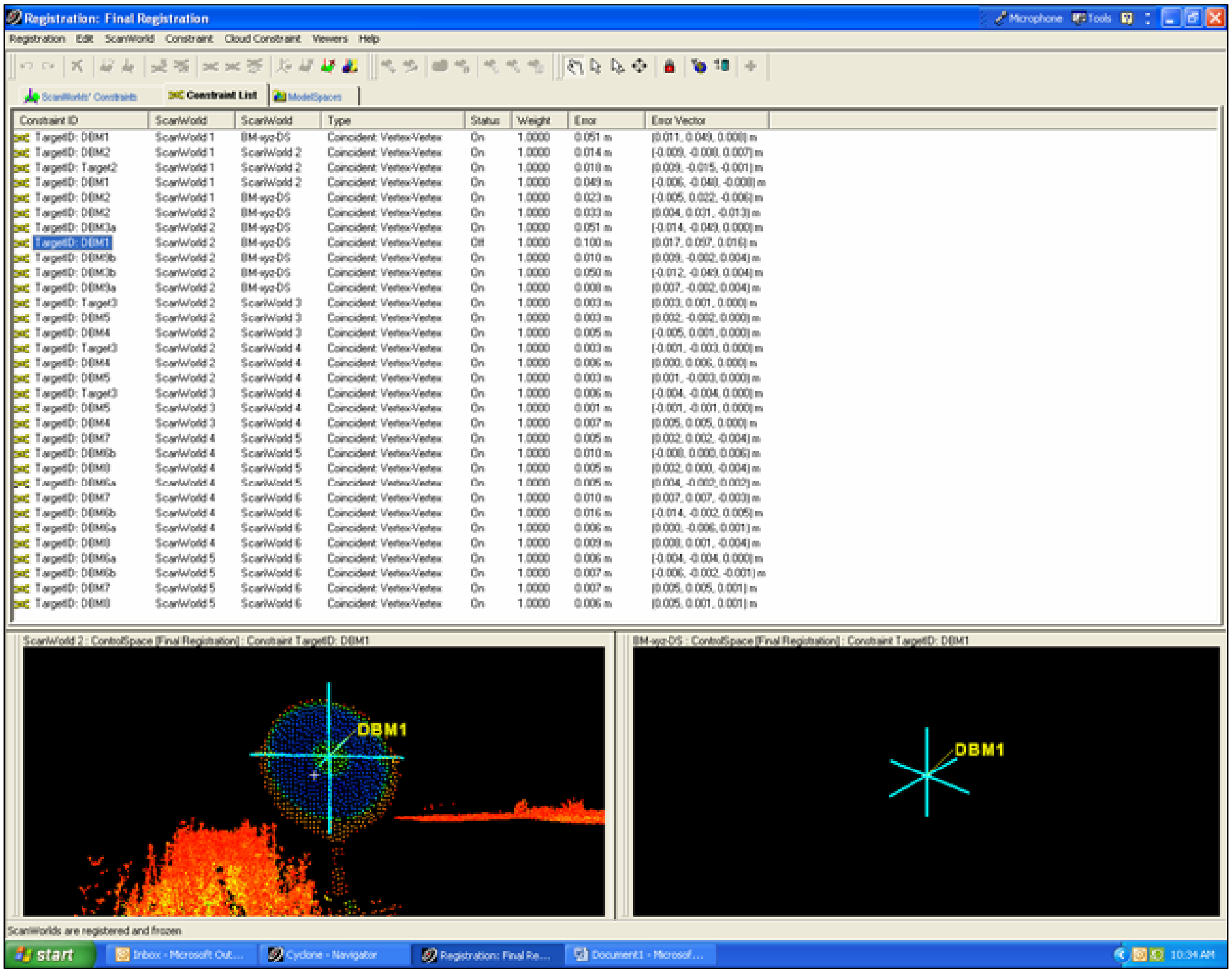


Figure 3. Illustration of Cyclone georegistration process for Dirt Site depicting synchronized windows of corresponding ScanWorlds with disabled tie point constraint (DBM1)

sway, making precise tie point acquisition much more difficult. Also, radiant heat energy from the intense mid-day sun during the same scanning operation produced an evident “wavy” pattern in a portion of the scan data. It is speculated, therefore, that these were the primary known causes of the higher error for the Grass Site (0.017 m) when compared to the Dirt Site (0.014 m).

Surface/Terrain Analysis

Terrestrial 3D laser characterization efforts of the variable-surface sites yielded an elevation contour map and vegetation height model of the Dirt Site and Grass Site, respectively. Figure 4 illustrates the resulting ground surface elevation contour map, with contour intervals of 10 cm.

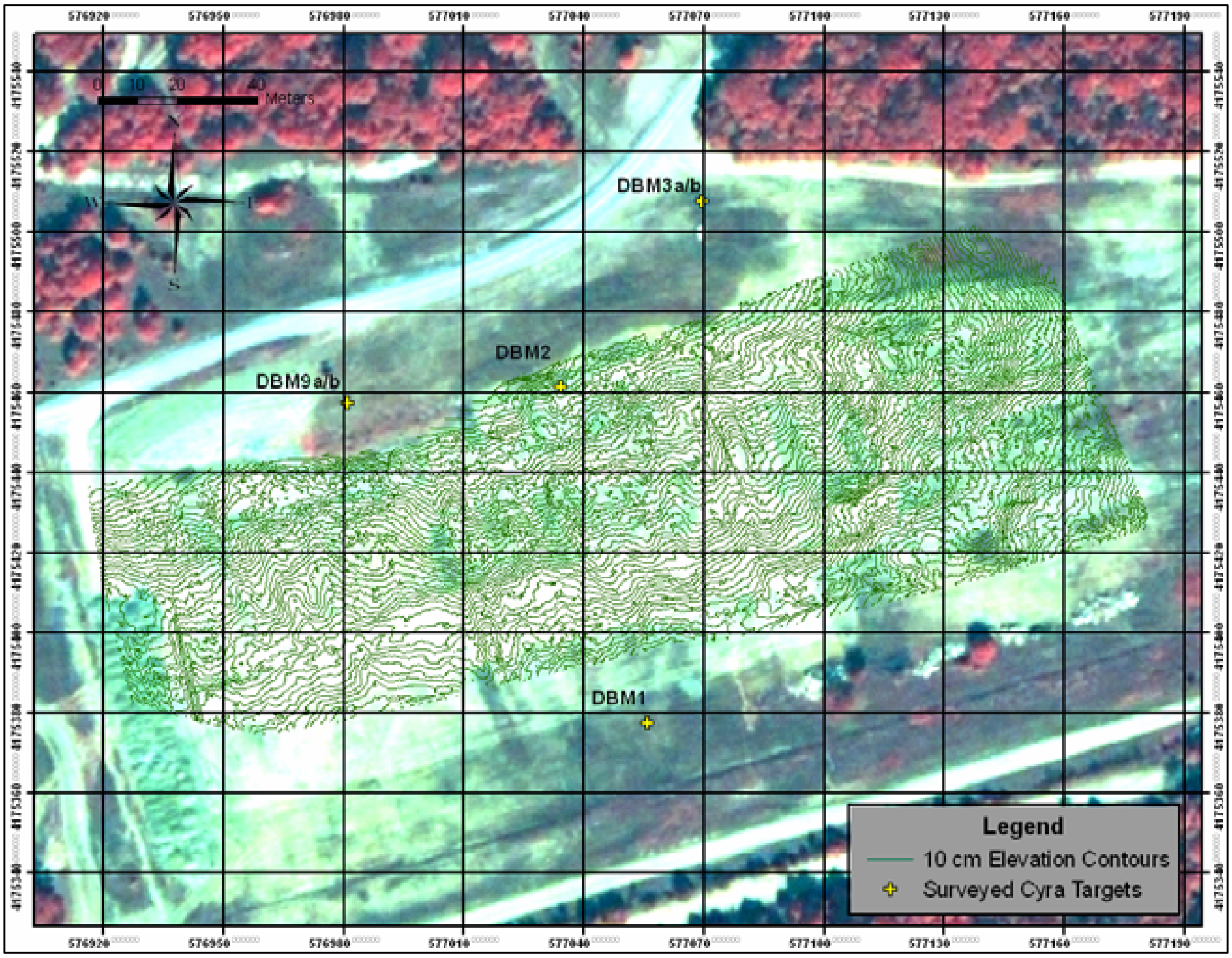


Figure 4. Gound elevation contour map (10-cm Interval) detailing the micro topography representative of the Dirt Site

The abundance of data points generated from the laser scanner provided a very rich data set from which to produce a very detailed micro topographical contour map of the Dirt Site. By producing a 10-cm contour interval map, the vertical relief and landscape profile of the site were accurately depicted. The contour interval measurement chosen produced a minimum vertical distance between adjacent contour lines, allowing for precise modeling capabilities of the terrain surface.

A vegetation height model, generated from the closely spaced laser data points, effectively characterized the very dense vegetative component of the Grass Site (Figure 5). Notice the high tree crown tops represented in red on the extreme northern and southwestern parts of the Grass Site. Inspection of the resulting vegetation surface revealed the variation in vegetation height differences across the site.

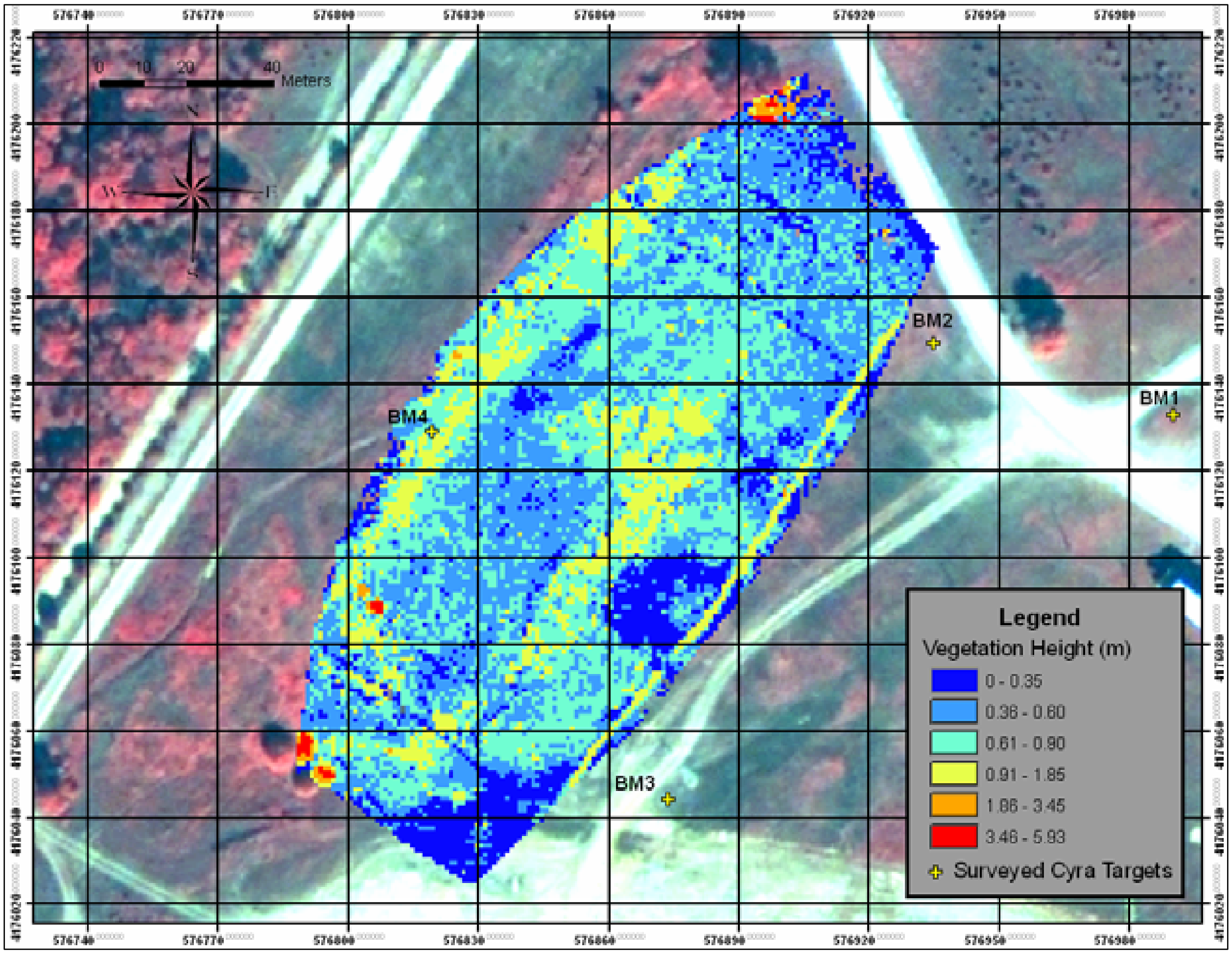


Figure 5. Vertical view of Grass Site depicting vegetation height in meters. The image portrays a chromatic sequence with lower vegetation heights appearing blue and higher vegetation heights appearing red

4 Future Considerations

A primary objective of this research was to characterize various backgrounds (sand, rock, grass, soil, etc.) typically present in a minefield and evaluate the effectiveness of utilizing a laser scanning device to accomplish this task. It may be apparent with additional research that a smaller area can be scanned to produce similar results and satisfy program objectives while minimizing registration error. If successful, this would significantly reduce the amount of data collected and save a great amount of time. Registration error could also be reduced by restricting Cyra target and laser measurement acquisitions to within 75 m, well within the stated effective range of the scanner (100 m).

Due to the oblique, off-nadir measurement angle of the elevated scanner, vertical measurements of scanned objects are not effectively obtained. To better determine the terrestrial scanner's ability to accurately extract vegetation heights in a minefield, a ground-truth exercise should be implemented to develop a control measurement of vegetation heights to compare to the scanner data estimates. In addition, the related estimation of assumed "ground" at a vegetated site using an average of z values in the lowest tenth percentile of points for a unit area is a methodology that should be field validated.

References

Axelsson, P. (1999). “Processing of laser scanner data—algorithms and applications,” *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2-3), 138-147.

Colombo, L. (2003). “Terrestrial laser imaging: A technique in progress,” *Geomatics World* 11, 5.

Guarnieri, A., Vettore, A., and Remondino, F. (2004). “Photogrammetry and ground-based laser scanning: Assessment of metric accuracy of the 3D model of Pozzoveggiani Church,” FIG Working Week, May 22-27, Athens, Greece.

Jackson, S., Bishop, M., Leese, D., and Lord, E. (2005). “High-Resolution 3D laser imaging of various surfaces in minefields and implications for surface modeling.” *Detection and Remediation Technologies for Mines and Minelike Targets*. Proceedings of the SPIE Defense and Security Symposium, Orlando, FL, March 28 - April 1.

Johansson, M. (2002). “Explorations into the behavior of three different high-resolution ground-based laser scanners in the built environment.” *Close Range Imaging-Long Range Vision*. Proceedings of the ISPRS Commission V Symposium, Corfu, Greece, 1-2 September 2002.

Leica Geosystems HDS, Inc. (2004). Cyra Technologies HDS training manual.

Appendix A
Registration Diagnostics

```
                                                 Final Registration Diagnostics_UTMxyzDS.txt
Status: VALID Registration
Mean Absolute Error:
   for Enabled Constraints = 0.014 m
   for Disabled Constraints = 0.100 m
Date: 2004.09.10 09:00:10
Database name : Dirt_Site

ScanWorlds
ScanWorld 1
ScanWorld 2
ScanWorld 3
ScanWorld 4
ScanWorld 5
ScanWorld 6
BM-xyz-DS

Constraints
Name               ScanWorld     ScanWorld     Type                           On/Off  Weight  Error    Error Vector
TargetID: DBM1     ScanWorld 1   ScanWorld 2   Coincident: Vertex-Vertex      On      1.0000  0.049 m  (-0.048, -0.006, -0.008) m
TargetID: DBM2     ScanWorld 1   ScanWorld 2   Coincident: Vertex-Vertex      On      1.0000  0.014 m  (-0.008, -0.009, 0.007) m
TargetID: Target2  ScanWorld 1   ScanWorld 2   Coincident: Vertex-Vertex      On      1.0000  0.018 m  (-0.015, 0.009, -0.001) m
TargetID: Target3  ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex      On      1.0000  0.003 m  (0.001, 0.003, 0.000) m
TargetID: DBM4     ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex      On      1.0000  0.005 m  (0.001, -0.005, 0.000) m
TargetID: DBM5     ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex      On      1.0000  0.003 m  (-0.002, 0.002, 0.000) m
TargetID: Target3  ScanWorld 2   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.003 m  (-0.003, -0.001, 0.000) m
TargetID: DBM4     ScanWorld 2   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.006 m  (0.006, 0.000, 0.000) m
TargetID: DBM5     ScanWorld 2   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.003 m  (-0.003, 0.001, 0.000) m
TargetID: Target3  ScanWorld 3   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.006 m  (-0.004, -0.004, 0.000) m
TargetID: DBM4     ScanWorld 3   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.007 m  (0.005, 0.005, 0.000) m
TargetID: DBM5     ScanWorld 3   ScanWorld 4   Coincident: Vertex-Vertex      On      1.0000  0.001 m  (-0.001, -0.001, 0.000) m
TargetID: DBM6a    ScanWorld 4   ScanWorld 5   Coincident: Vertex-Vertex      On      1.0000  0.005 m  (-0.002, 0.004, 0.002) m
TargetID: DBM6b    ScanWorld 4   ScanWorld 5   Coincident: Vertex-Vertex      On      1.0000  0.010 m  (0.000, -0.008, 0.006) m
TargetID: DBM7     ScanWorld 4   ScanWorld 5   Coincident: Vertex-Vertex      On      1.0000  0.005 m  (0.002, 0.002, -0.004) m
TargetID: DBM8     ScanWorld 4   ScanWorld 5   Coincident: Vertex-Vertex      On      1.0000  0.005 m  (0.000, 0.002, -0.004) m
TargetID: DBM6a    ScanWorld 4   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.006 m  (-0.006, 0.000, 0.001) m
TargetID: DBM6b    ScanWorld 4   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.016 m  (-0.002, -0.014, 0.005) m
TargetID: DBM7     ScanWorld 4   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.010 m  (0.007, 0.007, -0.003) m
TargetID: DBM8     ScanWorld 4   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.009 m  (0.001, 0.008, -0.004) m
TargetID: DBM7     ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.007 m  (0.005, 0.005, 0.001) m
TargetID: DBM8     ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.006 m  (0.001, 0.005, 0.001) m
TargetID: DBM6a    ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.006 m  (-0.004, -0.004, 0.000) m
TargetID: DBM6b    ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex      On      1.0000  0.007 m  (-0.002, -0.006, -0.001) m
TargetID: DBM1     ScanWorld 1   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.051 m  (0.049, 0.011, 0.008) m
TargetID: DBM2     ScanWorld 1   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.023 m  (0.022, -0.005, -0.006) m
TargetID: DBM1     ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      Off     1.0000  0.100 m  (0.097, 0.017, 0.016) m
TargetID: DBM2     ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.033 m  (0.031, 0.004, -0.013) m
TargetID: DBM3a    ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.051 m  (-0.049, -0.014, 0.000) m
TargetID: DBM3b    ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.050 m  (-0.049, -0.012, 0.004) m
TargetID: DBM9a    ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.008 m  (-0.002, 0.007, 0.004) m
TargetID: DBM9b    ScanWorld 2   BM-xyz-DS     Coincident: Vertex-Vertex      On      1.0000  0.010 m  (-0.002, 0.009, 0.004) m

ScanWorld Transformations
ScanWorld 1
translation: (4175364.153, 577001.415, 342.135) m
rotation: (-0.0043, 0.0047, -1.0000):71.050 deg
ScanWorld 2
translation: (4175402.145, 577100.966, 342.303) m
rotation: (-0.0073, 0.0047, -1.0000):69.085 deg
ScanWorld 3
translation: (4175430.434, 577218.713, 340.909) m
rotation: (0.0009, 0.0074, -1.0000):168.915 deg
ScanWorld 4
translation: (4175431.397, 577219.363, 340.954) m
rotation: (0.0023, -0.0032, 1.0000):77.021 deg
ScanWorld 5
translation: (4175451.473, 577313.238, 346.698) m
rotation: (-0.0079, 0.0115, -0.9999):92.921 deg
ScanWorld 6
translation: (4175498.617, 577303.640, 347.103) m
rotation: (-0.0079, 0.0111, -0.9999):122.630 deg
ScanWorld BM-xyz-DS
translation: (0.000, 0.000, 0.000) m
rotation: (0.0000, 1.0000, 0.0000):0.000 deg

Unused ControlSpace Objects
ScanWorld 1:
    Vertex : TargetID : Target1
ScanWorld 3:
    Vertex : TargetID : DBM4
ScanWorld 4:
    Vertex : TargetID : Target 4
```

Figure A1. Final Registration Diagnostics_UTMxyzDS.txt

```
                                                                    Interim Registration Diagnostics_DS.txt
Status: VALID Registration
Mean Absolute Error:
        for Enabled Constraints = 0.008 m
        for Disabled Constraints = 0.000 m
Date: 2004.08.19 13:50:10
Database name : Dirt_Site

ScanWorlds
ScanWorld 1
ScanWorld 2
ScanWorld 3
ScanWorld 4
ScanWorld 5
ScanWorld 6

Constraints
Name               ScanWorld    ScanWorld    Type                          On/Off  Weight  Error    Error Vector
TargetID: DBM1     ScanWorld 1  ScanWorld 2  Coincident: Vertex-Vertex     On      1.0000  0.024 m  (0.024, -0.004, -0.002) m
TargetID: DBM2     ScanWorld 1  ScanWorld 2  Coincident: Vertex-Vertex     On      1.0000  0.017 m  (-0.016, -0.005, 0.001) m
TargetID: Target2  ScanWorld 1  ScanWorld 2  Coincident: Vertex-Vertex     On      1.0000  0.012 m  (-0.007, 0.009, 0.001) m
TargetID: Target3  ScanWorld 2  ScanWorld 3  Coincident: Vertex-Vertex     On      1.0000  0.003 m  (0.000, 0.003, 0.000) m
TargetID: DBM4     ScanWorld 2  ScanWorld 3  Coincident: Vertex-Vertex     On      1.0000  0.005 m  (-0.003, -0.004, 0.000) m
TargetID: DBM5     ScanWorld 2  ScanWorld 3  Coincident: Vertex-Vertex     On      1.0000  0.003 m  (0.003, 0.001, 0.000) m
TargetID: Target3  ScanWorld 2  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.003 m  (0.002, -0.002, 0.000) m
TargetID: DBM4     ScanWorld 2  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.006 m  (-0.006, 0.002, 0.000) m
TargetID: DBM5     ScanWorld 2  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.003 m  (0.003, 0.000, 0.000) m
TargetID: Target3  ScanWorld 3  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.006 m  (0.002, -0.005, 0.000) m
TargetID: DBM4     ScanWorld 3  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.007 m  (-0.003, 0.006, 0.000) m
TargetID: DBM5     ScanWorld 3  ScanWorld 4  Coincident: Vertex-Vertex     On      1.0000  0.001 m  (0.001, -0.001, 0.000) m
TargetID: DBM6a    ScanWorld 4  ScanWorld 5  Coincident: Vertex-Vertex     On      1.0000  0.005 m  (0.003, 0.003, 0.002) m
TargetID: DBM6b    ScanWorld 4  ScanWorld 5  Coincident: Vertex-Vertex     On      1.0000  0.010 m  (-0.003, -0.008, 0.006) m
TargetID: DBM7     ScanWorld 4  ScanWorld 5  Coincident: Vertex-Vertex     On      1.0000  0.005 m  (-0.001, 0.002, -0.004) m
TargetID: DBM8     ScanWorld 4  ScanWorld 5  Coincident: Vertex-Vertex     On      1.0000  0.005 m  (0.001, 0.002, -0.004) m
TargetID: DBM6a    ScanWorld 4  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.006 m  (0.006, -0.002, 0.001) m
TargetID: DBM6b    ScanWorld 4  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.016 m  (-0.003, -0.014, 0.005) m
TargetID: DBM7     ScanWorld 4  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.010 m  (-0.004, 0.009, -0.003) m
TargetID: DBM8     ScanWorld 4  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.009 m  (0.001, 0.008, -0.004) m
TargetID: DBM7     ScanWorld 5  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.007 m  (-0.003, 0.006, 0.001) m
TargetID: DBM8     ScanWorld 5  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.006 m  (0.001, 0.006, 0.001) m
TargetID: DBM6a    ScanWorld 5  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.006 m  (0.002, -0.005, 0.000) m
TargetID: DBM6b    ScanWorld 5  ScanWorld 6  Coincident: Vertex-Vertex     On      1.0000  0.007 m  (0.000, -0.007, -0.001) m

ScanWorld Transformations
ScanWorld 1
translation: (0.000, 0.000, 0.000) m
rotation: (0.0000, 1.0000, 0.0000):0.000 deg
ScanWorld 2
translation: (-3.629, 106.503, 0.952) m
rotation: (-0.0673, -0.0666, 0.9955):1.980 deg
ScanWorld 3
translation: (7.843, 227.063, 0.485) m
rotation: (-0.0007, 0.0117, -0.9999):97.860 deg
ScanWorld 4
translation: (7.142, 227.990, 0.535) m
rotation: (0.0027, -0.0049, 1.0000):148.077 deg
ScanWorld 5
translation: (18.621, 323.252, 7.015) m
rotation: (-0.0297, 0.0179, -0.9994):21.872 deg
ScanWorld 6
translation: (-29.086, 329.476, 7.388) m
rotation: (-0.0173, 0.0111, -0.9998):51.577 deg

Unused ControlSpace Objects
ScanWorld 1:
    Vertex : TargetID : Target1

ScanWorld 2:
    Vertex : TargetID : DBM3a
    Vertex : TargetID : DBM3b
    Vertex : TargetID : DBM9a
    Vertex : TargetID : DBM9b

ScanWorld 3:
    Vertex : TargetID : DBM4

ScanWorld 4:
    Vertex : TargetID : Target 4
```

Figure A2. Interim Registration Diagnostics_DS.txt

```
Status: VALID Registration
Mean Absolute Error:
   for Enabled Constraints = 0.017 m
   for Disabled Constraints = 0.000 m
Date: 2004.09.10 09:11:26
Database name : Grassy_Site_Tallveg

ScanWorlds
ScanWorld 2
ScanWorld 3
ScanWorld 5
ScanWorld 6
BM-xyz-GS

Constraints
Name            ScanWorld     ScanWorld     Type                          On/Off   Weight   Error     Error Vector
TargetID: BM1   ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex     On       1.0000   0.022 m   (-0.016, 0.010, 0.012) m
TargetID: BM2   ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex     On       1.0000   0.025 m   (0.011, -0.013, -0.018) m
TargetID: BM3   ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex     On       1.0000   0.012 m   (-0.001, 0.011, -0.005) m
TargetID: Targ5 ScanWorld 2   ScanWorld 3   Coincident: Vertex-Vertex     On       1.0000   0.008 m   (0.006, -0.003, 0.005) m
TargetID: BM1   ScanWorld 2   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.008 m   (-0.006, 0.000, 0.005) m
TargetID: BM2   ScanWorld 2   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.005 m   (-0.003, -0.001, -0.004) m
TargetID: BM3   ScanWorld 2   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.015 m   (0.005, 0.014, 0.002) m
TargetID: Targ5 ScanWorld 2   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.011 m   (0.003, -0.007, -0.007) m
TargetID: BM1   ScanWorld 2   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.007 m   (0.003, 0.002, -0.006) m
TargetID: BM2   ScanWorld 2   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.009 m   (-0.006, -0.002, 0.007) m
TargetID: BM3   ScanWorld 2   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.007 m   (-0.007, -0.004, 0.000) m
TargetID: Targ5 ScanWorld 2   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.014 m   (0.013, 0.004, 0.003) m
TargetID: BM3   ScanWorld 3   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.010 m   (0.007, 0.002, 0.008) m
TargetID: BM2   ScanWorld 3   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.023 m   (-0.014, 0.012, 0.014) m
TargetID: BM1   ScanWorld 3   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.016 m   (0.010, -0.010, -0.008) m
TargetID: BM4   ScanWorld 3   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.005 m   (0.001, -0.001, -0.004) m
TargetID: Targ5 ScanWorld 3   ScanWorld 5   Coincident: Vertex-Vertex     On       1.0000   0.013 m   (-0.003, -0.004, -0.012) m
TargetID: BM3   ScanWorld 3   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.016 m   (-0.005, -0.015, 0.005) m
TargetID: BM2   ScanWorld 3   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.032 m   (-0.017, 0.011, 0.025) m
TargetID: BM1   ScanWorld 3   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.027 m   (0.018, -0.009, -0.018) m
TargetID: BM4   ScanWorld 3   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.015 m   (-0.002, 0.008, -0.013) m
TargetID: Targ5 ScanWorld 3   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.010 m   (0.007, 0.007, -0.002) m
TargetID: BM3   ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.021 m   (-0.012, -0.017, -0.002) m
TargetID: BM2   ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.011 m   (-0.003, -0.001, 0.011) m
TargetID: BM1   ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.014 m   (0.009, 0.002, -0.010) m
TargetID: BM4   ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.013 m   (-0.003, 0.009, -0.009) m
TargetID: Targ5 ScanWorld 5   ScanWorld 6   Coincident: Vertex-Vertex     On       1.0000   0.019 m   (0.010, 0.012, 0.011) m
TargetID: BM1   ScanWorld 2   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.024 m   (-0.017, -0.013, -0.012) m
TargetID: BM2   ScanWorld 2   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.021 m   (0.012, -0.010, 0.014) m
TargetID: BM3   ScanWorld 2   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.011 m   (0.002, 0.011, 0.003) m
TargetID: BM3   ScanWorld 3   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.009 m   (0.004, -0.001, 0.008) m
TargetID: BM2   ScanWorld 3   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.032 m   (0.000, 0.003, 0.032) m
TargetID: BM1   ScanWorld 3   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.033 m   (-0.001, -0.023, -0.024) m
TargetID: BM4   ScanWorld 3   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.030 m   (-0.003, 0.025, -0.015) m
TargetID: BM3   ScanWorld 5   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.004 m   (-0.003, -0.003, 0.001) m
TargetID: BM2   ScanWorld 5   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.025 m   (0.015, -0.009, 0.018) m
TargetID: BM1   ScanWorld 5   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.023 m   (-0.011, -0.013, -0.016) m
TargetID: BM4   ScanWorld 5   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.028 m   (-0.004, 0.026, -0.011) m
TargetID: BM3   ScanWorld 6   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.017 m   (0.009, 0.014, 0.003) m
TargetID: BM2   ScanWorld 6   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.021 m   (0.018, -0.009, 0.007) m
TargetID: BM1   ScanWorld 6   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.025 m   (-0.020, -0.015, -0.006) m
TargetID: BM4   ScanWorld 6   BM-xyz-GS     Coincident: Vertex-Vertex     On       1.0000   0.017 m   (-0.001, 0.017, -0.002) m

ScanWorld Transformations
ScanWorld 2
translation: (4176111.191, 576907.227, 351.818) m
rotation: (-0.0025, 0.0015, -1.0000):135.445 deg
ScanWorld 3
translation: (4176069.258, 576873.798, 349.791) m
rotation: (-0.0009, 0.0019, -1.0000):130.307 deg
ScanWorld 5
translation: (4176128.055, 576799.248, 343.859) m
rotation: (-0.0089, -0.0070, 0.9999):64.915 deg
ScanWorld 6
translation: (4176170.164, 576836.374, 345.654) m
rotation: (-0.0114, -0.0030, 0.9999):54.224 deg
ScanWorld BM-xyz-GS
translation: (0.000, 0.000, 0.000) m
rotation: (0.0000, 1.0000, 0.0000):0.000 deg
Unused ControlSpace Objects : none
```

Figure A3. Final Registration Diagnostics_UTMxyzGS.txt

Status: VALID Registration
Mean Absolute Error:
for Enabled Constraints = 0.014 m
for Disabled Constraints = 0.000 m
Date: 2004.08.19 12:04:00
Database name : Grassy_Site_Tallveg

ScanWorlds
ScanWorld 2
ScanWorld 3
ScanWorld 5
ScanWorld 6

Constraints

Name	ScanWorld	ScanWorld	Type	On/Off	Weight	Error	Error Vector
TargetID: BM1	ScanWorld 2	ScanWorld 3	Coincident: Vertex-Vertex	On	1.0000	0.020 m	(0.004, 0.017, 0.009) m
TargetID: BM2	ScanWorld 2	ScanWorld 3	Coincident: Vertex-Vertex	On	1.0000	0.024 m	(0.002, -0.018, -0.015) m
TargetID: BM3	ScanWorld 2	ScanWorld 3	Coincident: Vertex-Vertex	On	1.0000	0.012 m	(-0.006, 0.009, -0.006) m
TargetID: Targ5	ScanWorld 2	ScanWorld 3	Coincident: Vertex-Vertex	On	1.0000	0.010 m	(-0.001, -0.007, 0.007) m
TargetID: BM1	ScanWorld 2	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.006 m	(0.004, 0.003, 0.002) m
TargetID: BM2	ScanWorld 2	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.004 m	(0.004, 0.001, -0.001) m
TargetID: BM3	ScanWorld 2	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.014 m	(-0.013, 0.006, 0.003) m
TargetID: Targ5	ScanWorld 2	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.010 m	(0.004, -0.007, -0.004) m
TargetID: BM1	ScanWorld 2	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.009 m	(-0.002, -0.002, -0.009) m
TargetID: BM2	ScanWorld 2	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.012 m	(0.007, 0.002, 0.010) m
TargetID: BM3	ScanWorld 2	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.009 m	(0.008, 0.002, -0.001) m
TargetID: Targ5	ScanWorld 2	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.014 m	(-0.011, -0.006, 0.006) m
TargetID: BM3	ScanWorld 3	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.011 m	(-0.007, -0.003, 0.008) m
TargetID: BM2	ScanWorld 3	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.023 m	(0.001, 0.019, 0.014) m
TargetID: BM1	ScanWorld 3	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.016 m	(0.000, -0.014, -0.008) m
TargetID: BM4	ScanWorld 3	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.004 m	(0.000, -0.001, -0.004) m
TargetID: Targ5	ScanWorld 3	ScanWorld 5	Coincident: Vertex-Vertex	On	1.0000	0.013 m	(0.005, -0.001, -0.012) m
TargetID: BM3	ScanWorld 3	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.017 m	(0.015, -0.007, 0.005) m
TargetID: BM2	ScanWorld 3	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.032 m	(0.005, 0.020, 0.025) m
TargetID: BM1	ScanWorld 3	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.027 m	(-0.006, -0.019, -0.018) m
TargetID: BM4	ScanWorld 3	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.016 m	(-0.004, 0.007, -0.014) m
TargetID: Targ5	ScanWorld 3	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.010 m	(-0.010, 0.000, -0.002) m
TargetID: BM3	ScanWorld 5	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.022 m	(0.021, -0.004, -0.003) m
TargetID: BM2	ScanWorld 5	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.011 m	(0.003, 0.001, 0.011) m
TargetID: BM1	ScanWorld 5	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.013 m	(-0.007, -0.005, -0.010) m
TargetID: BM4	ScanWorld 5	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.013 m	(-0.004, 0.008, -0.010) m
TargetID: Targ5	ScanWorld 5	ScanWorld 6	Coincident: Vertex-Vertex	On	1.0000	0.018 m	(-0.015, 0.001, 0.010) m

ScanWorld Transformations
ScanWorld 2
translation: (0.000, 0.000, 0.000) m
rotation: (0.0000, 1.0000, 0.0000):0.000 deg
ScanWorld 3
translation: (53.235, 6.436, -2.173) m
rotation: (0.0052, 0.0313, 0.9995):5.141 deg
ScanWorld 5
translation: (65.086, -87.740, -8.533) m
rotation: (-0.0030, 0.0083, -1.0000):159.644 deg
ScanWorld 6
translation: (9.095, -91.707, -6.572) m
rotation: (-0.0008, 0.0076, -1.0000):170.336 deg

Unused ControlSpace Objects : none

Figure A4. Interim Registration Diagnostics_GS.txt

Appendix B
Cyra Scan Logs/Field Sketches

CYRA **Scan Log**

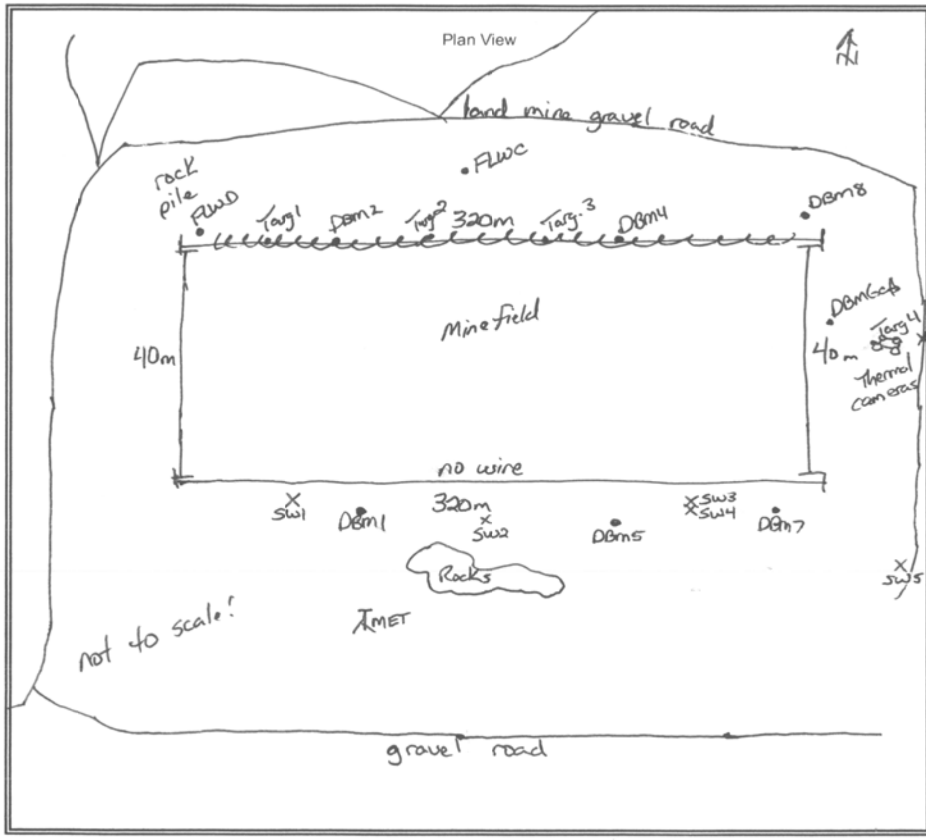
DBm = Dirt Bench Mark
have height data, will be surveyed
Target = used only for registration
will not be surveyed

DBm 3ab → FLW-C
(a)Top, bottom(b)
DBm 9ab → FLW-D

07/29/04 Start
Team: Jackson / Leese / Lord

Field Sketches

Scan Position Description: Dirt_Site



40°x 40° Perspective View

Notes:
SW3 interrupted on 7/31 due to radar over flight.
Finished scans with SW4 after flight on same day.
Targ.4 on Thermal camera trailer
SW 5 + 6 near thermal camera setup. SW6 on gravel road.

Scan Position #: ______ **ScanWorld ID:** ____________

Cyra_Scan_Log_FORM.doc Page 2 of 5 Rev 6/4/03 RA

Figure B1. Cyra scan logs/field sketches (Sheet 1 of 16)

- Small rainfall during 1st/2nd field scan
- found that it is best to use at least 0.5cm scan on targets (0.3cm works well on small ones over 100m)

CYRA **Scan Log**

Scan Log:

Data Base Name: Dirt_Site
Project Name: Dirt_Site

Project Leader:

Names of Crew: Jackson/Leese

Start Time: 0900

Temperature: Humidity:

Date: 07/29/04

Finish Time:

Atmospheric Pressure:

scanner Ht. 25

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DS	SW1	1	DBM1	no wire South Dirt site BM	Target Ht. 1.607m 1 cm scan	
DS	SW1	2	DBM2	wire fence North Dirt site BM	Targ. Ht. 1.708m 1 cm Scan	
DS	SW1	3	Target1	North-west Dirt site Target	0.5 cm Scan	
DS	SW1	4	Target2	North-center west Dirt site Target	0.3 cm Scan	
DS	SW1	5	none	1st Field scan from SW1	2 cm Scan	
DS	SW1	6	Target1, BM2	2nd Field scan from SW1	2 cm scan	
DS	SW1	7	Target2, BM2	3rd Field Scan from SW1	2 cm scan	
DS	SW1	8	none	4th Field scan from SW1	2 cm Scan	

Field Sketches

Scan Position Description: SW1, Dirt Site, Set-up on South-west side

Scan Log Form.doc Plan View Page 1 of 5 Rev 6/4/03 RA

Figure B1. (Sheet 2 of 16)

CYRA

DBm3
.95m bottom
2.15m Top

DBM4 } will be used as targets only,
DBM5 } no heights or survey is needed.

Scan Log

DBm3a
DBm3b FLW-C surveyed Bm.

Scan Log:

Data Base Name: Dirt Site
Project Name: Dirt Site

Project Leader:

Names of Crew: Jackson/Leese/Ballard.

Start Time: 1630
Temperature: Humidity:

Date: 7/30/04
Finish Time:
Atmospheric Pressure:

Scanner Ht: 25'

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DS	SW2	1	DBM1	South Dirt Site Bm	Ht 1.607m 0.5 cm scan	
DS	SW2	2	DBM2	North Dirt Site Bm	Ht 1.708m 0.5 cm	
DS	SW2	3	Target 2	North-center west target on fence	0.3 cm	
DS	SW2	4	DBM3a FLW-C?	North-center Cyra Bm top target	Ht. 2.15m 0.3 cm	
DS	SW2	5	DBM3b	north-center Cyra BM bottom target	Ht. 0.95m 0.3 cm	
DS	SW2	6	Target 3	North center east target on fence	0.3 cm	
DS	SW2	7	DBM4	North center east Bm Dirt site	0.5 cm	
DS	SW2	8	DBM5	South east Bm Dirt Site	0.5 cm	
DS	SW2	9	~~1st field scan from SW2~~ none	1st field scan from SW2	2 cm	
DS	SW2	10	DBM2	2nd field scan from SW2	2 cm	
DS	SW2	11	DBM2, T2, DBm3a,b, T3	3rd field scan from SW2	2 cm	
DS	SW2	12	DBM4	4th field scan from SW2	2 cm	
DS	SW2	13	none	5th field scan from SW2	2 cm	

Field Sketches

Scan Position Description: SW2, Dirt Site South Side center-west

DS	SW2	14	DBM6a FLW-D	Target scan, Bm surveyed	0.3 cm	Ht. 2.15m
DS	SW2	15	DBM6b - FLW-D	Target scan Bm surveyed	0.3 cm	Ht 0.95m

Scan Log Form.doc Plan View Page 1 of 5 Rev 6/4/03 RA

Figure B1. (Sheet 3 of 16)

CYRA

Scan Log

Scan Log:

Data Base Name: Dirt Site

Project Name: Dirt Site

Project Leader: ______

Names of Crew: Lord / Jackson

Start Time: 0800

Temperature: ______ Humidity: ______

Date: 07/21/04

Finish Time: ——

Atmospheric Pressure: ______

corner Ht. 25'

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DS	SW3	1	Target3	North-east center Dirt site - Fence	~~0.3 cm~~ Rescan - 0.2	
DS	SW3	2	DBM4	North-east center Dirt site	~~0.5 cm~~ Rescan - 0.3	
DS	SW3	3	DBM5	Southeast Dirt Site BM	0.5 cm	
DS	SW3	4	NONE	First Field Scan from SW3	2cm x 2cm Scan	
DS	SW3	5	NONE	Second Field Scan - SW3	2cm x 2cm Scan	
DS	SW3	6	TARGET 3 DBM4	Third Field Scan - SW3	2 cm^2 - did not finish due to Radar flight need to start SW4 and re-acquire targets and scan where left off.	

Field Sketches

Scan Position Description: SW3, Dirt site North east South side

Scan Log Form.doc

Plan View

Page 1 of 5

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Figure B1. (Sheet 4 of 16)

Same location as SW3, had to reacquire due to Radar Flight interruption

CYRA

Scan Log

Scan Log:

Data Base Name: Dirt Site

Project Name: Dirt Site

Project Leader:

Names of Crew: Jackson/Lease/Bellard/Hord

Start Time: 1700

Temperature: Humidity:

Date: 07/31/04

Finish Time:

Atmospheric Pressure:

camera Ht. 25'

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DS ~~SW4~~	SW4	1	Target 3	North-east center Dirt Site Fence	0.3 cm	
DS	SW4	2	DBM4	North east center Dirt site	0.3 cm	
DS	SW4	3	DBM5	Southeast Dirt Site BM	0.5 cm	
DS	SW4	4	DBM6a	East side of Dirt site Cyra top	0.2 cm	
DS	SW4	5	DBM6b	East side of Dirt site Cyra bottom	0.2 cm Ht. 2.15m	
DS	SW4	6	Target 4	East side dirt site Thermal camera trailer	0.2 cm	
DS	SW4	7	DBM4	1st Field scan from SW4	2 cm	
DS	SW4	9	NONE	2nd Field Scan from SW4	2 cm 1114 x 726 (31.931m)	
DS	SW4	10	Target 4 DBM7 DBM6A+6B	3rd Field Scan - East end of Field.	2cm x 2cm 1002 x 823 (26.915)	
DS	SW4	11	DBM7	Acquire newly placed TARGET South east corner BM under tree	2 x 2 ~~5x5~~ 83.437 98 x 147	
			DBM8	Acquire newly placed target Northeast corner BM	0.3 x 0.3 cm² ~~5x5~~	

Field Sketches

Scan Position Description: SW4, Southeast Dirt Field site

Scan Log Form.doc

Plan View

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Figure B1. (Sheet 5 of 16)

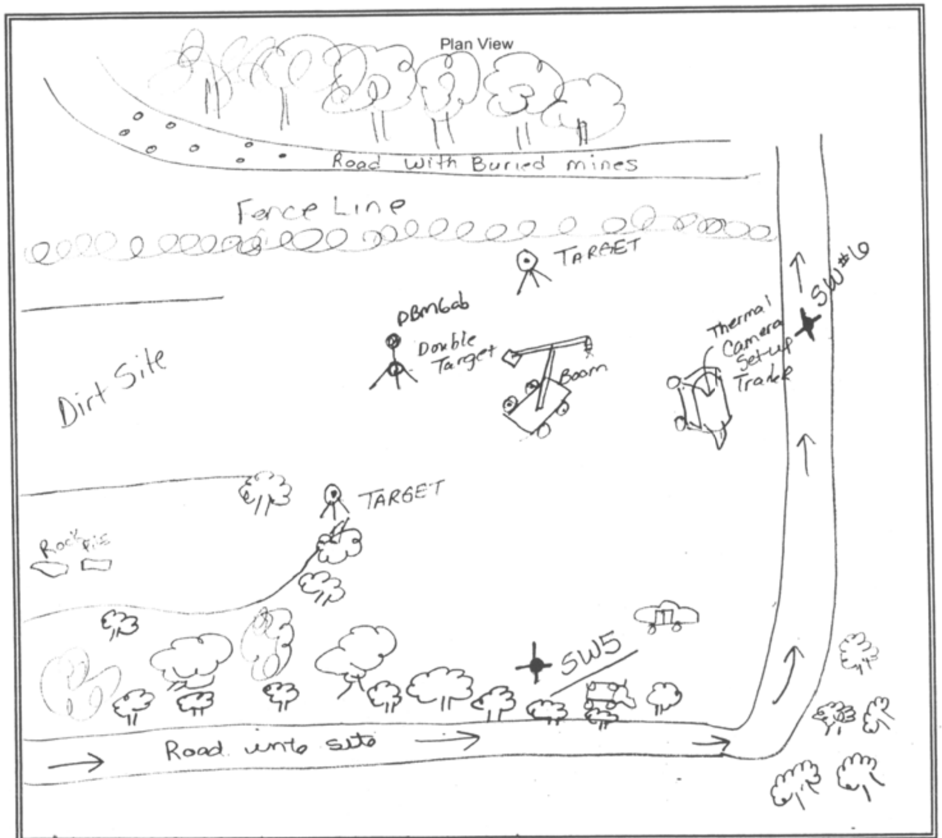
CYRA

Scan Log

Dirt Site Hill - SW#'s 5+6

Field Sketches

Scan Position Description: Eastern Side of Dirt Site / Trailer Area



40°x 40° Perspective View

Notes: To match Target names from yesterdays scan, I used the same names we used yesterday afternoon. There were only 3 targets on this scan (4 actually 6A+6B) one was the double cyra target.

Scan Position #: 5 **ScanWorld ID:** 5

Cyra_Scan_Log_FORM.doc Page 2 of 5 Rev 6/4/03 RA

Figure B1. (Sheet 6 of 16)

CYRA

Scan Log

Image 360 x 135 = High Resolution - Exposure 4.0

Scan Log:

Data Base Name: Dirt Site

Project Name: Dirt Site

Project Leader: Berry / Leese

Names of Crew: Leese / Lord

Start Time: 8:25

Temperature: ________ **Humidity:** ________

Date: 08-01

Finish Time: ________

Atmospheric Pressure: ________

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DSH	SW5	1	DBM7	East Side of DS Mine Site	34.988 m 202 x 266 pix $0.3 \times 0.3\ cm^2$	
		2	DBM8	East	79.055 m $0.3 \times 0.3\ cm^2$	
		3	DBM6A	Double Target on top of Hill near the Dirt Site Eastern Side.	59.242 412 x 472 pix $0.2 \times 0.2\ cm^2$	
		4	DBM6B	Double Target - on ~~top~~ top of Hill near the Sirt Site. Bottom part of target.	51.288 m 338 x 348 $0.2 \times 0.2\ cm^2$	
		5	DBM7	First Field Scan, Includes Eastern portion of DS.	1567 x 1539 $1.0 \times 1.0\ cm^2$ 26 minutes. Breezy at times Grassy area more.	
		6	NONE	2nd Field Scan. Hill Side. With small portion of Dirt Site.	1928 x 1784 1.0 x 1.0 35.40 min. Still Breezy Grass swaying	
		7	DBM6A + DBM6B DBM8	Top of Dirt Site ~~Field~~ on Hill Thermal camera mine set-up. 3rd Field Scan	2978 x 2284 1.0 x 1.0 65.0 minutes. - Still Breezy Varying greatly by area.	
		8	NONE	4th Field Scan on top of Hill mine Field Test Plots to the Thermal trailer side.	3177 x 2056 1.0 x 1.0 62.0 minutes Breeze has slacked up.	

Figure B1. (Sheet 7 of 16)

CYRA

Scan Log

Scan Log:

Acquired Image 7:25AM 360x135 Exposure 8.0 & 7.5 minutes
Only a very slight Breeze
Very sunny, with High Clouds then @ 9:30 overcast and Thunder.

Date: 08-02

Data Base Name: Dirt Site
Project Name: Dirt Site

Project Leader: Leese / Berry
Names of Crew: Leese / Lord

Start Time: 0715
Temperature:______ **Humidity:**______

Finish Time:______
Atmospheric Pressure:______

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
DSH SW6	SW6	1	DBM7	South east Brn Target Under Tree Acquire Target For North end of DS Hill Top.	Probe = 51.372 m 2.0 minutes 0.3x0.3 cm² 275 x 387 pixels	
DSH SW6	SW6	2	DBM6A	South Center of Hill Top near Dirt Site. Same as SW5	Probe = 34.284 3.3 min 0.3x0.3cm². 487x495 pixels	
DSH SW6	SW6	3	DBM6B	South Center of Hill Top near Dirt Site Same as SW5	Probe 28.735 2m 6sec 0.3x0.3cm² 325x330 pixels	
DSH SW6	SW6	4	DBM8	North end of Hill over DS Same of SW5	Probe 38.405m 1min 2 sec 0.3x0.3cm² 172x231	
DSH	SW6	5	START & STOP			
DSH	SW6	6	DBM7	3 Test Areas plus a little of the Hill Top	1.0cm x 1.0cm² 88 min. 3588x 2719	
DSH	SW6	7	DBM6A + 6B DBM8	Northern most end of hill near Dirt Site Include Road w/ mine + IED	2x2cm² scan 28min. 2183x1002 pixels 38 probe	
DSH	SW6	8	DBM7 + DBM6A+6B	Center of DS: Hill Top From DBM7 to DBM6A/B	20.261 Probe 18 min 2.0x2.0 1427x1066 cm	NOTE: Truck Bumped Trailer: approx 8:14-8:15 on the computer Clock. ≈ 10.0 minutes left in scan

Figure B1. (Sheet 8 of 16)

BM = Grass Site benchmarks, will be surveyed in (have height data)
Target = used only for point cloud registration, not surveyed

CYRA

Scan Log

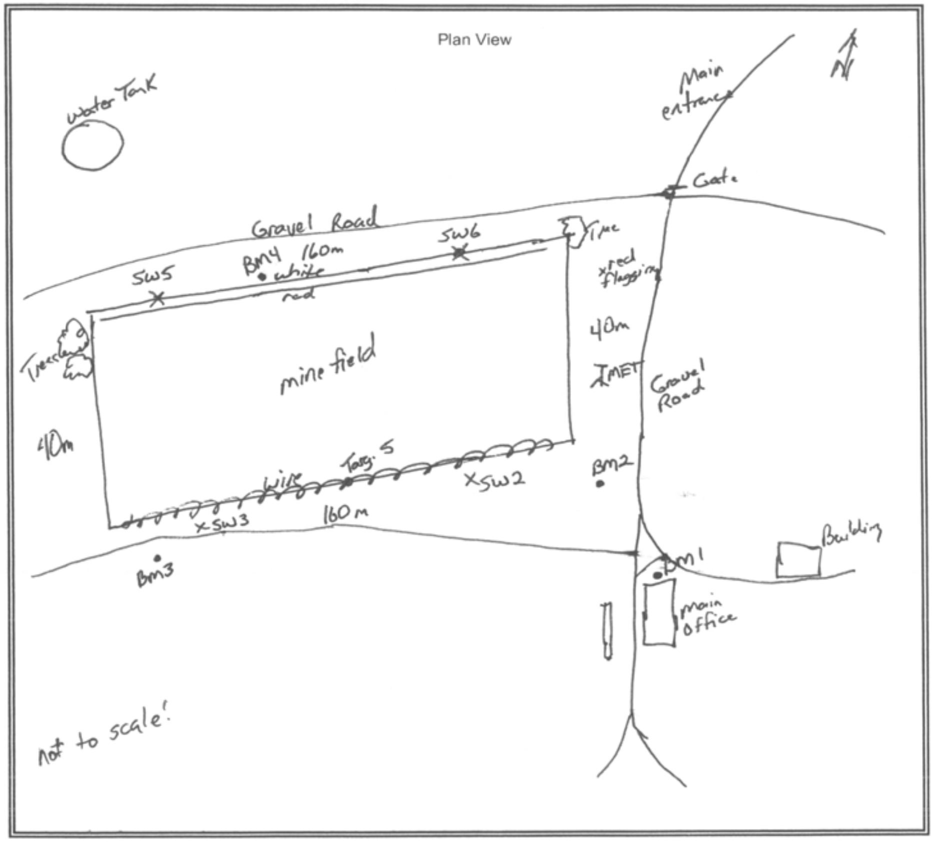
Try and place targets ≤100m, if possible

07/26/04 Start
Team: Jackson | Leese

Field Sketches

Scan Position Description: Grassy site - Tall Vegetation

Plan View



Scan Position #: ______ **ScanWorld ID:** ____________

40°x 40° Perspective View

Notes:

4 SW (2 on each, opposite end)
BM1 = FLWA - surveyed

Target 5 on Fence post.

Figure B1. (Sheet 9 of 16)

CYRA

~~SW1~~ wireless connection problem (w/ router)

Scan Log

Scan Log:

Data Base Name: Grassy Site-TallVeg

Project Name: Grassy Site

Project Leader: Jackson / Leese

Names of Crew:

Start Time: 13:20

Temperature: ________ Humidity: ________

Date: 07/26/04

Finish Time: ________

Atmospheric Pressure: ________

Ht.(m)	Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
7m30	GS	SW1	1	BM1-FLW-A	North West ~~South~~ Side of ~~[illegible]~~ Building (office)	range 95.95m to BM1 (had to re-do) Target Scan	
7m30	GS	SW1	2	BM2	grass pole (highest pt.)	range 8m to BM2 target scan	
7m30	GS	SW1	3	BM3	near gravel pile	range 83.77m to BM3 target scan	
7m62 25 feet	GS	SW2	1	BM4	center of North Side fence	range	

Field Sketches

Scan Position Description: Scanner at 7m above ground

Scan Log Form.doc Plan View Page 1 of 5 Rev 6/4/03 RA

Figure B1. (Sheet 10 of 16)

CYRA

Scan Log

Allow ~ 10% overlap b/t field scans

Scan Log:

Data Base Name: Grassy_Site_TallVeg

Project Name: Grassy Site

Project Leader: ________

Names of Crew: Dellard/Jackson/Leese

Start Time: 1430

Temperature: ________ **Humidity:** ________

Date: 07/26/04

Finish Time: ________

Atmospheric Pressure: ________

Scanner Ht.	Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
25 Ft.	GS	SW2	1	Bm 3	near gravel pile Target scan	$2 cm^2$ scan target 1.523m	
25 Ft.	GS	SW2	2	Bm2	grassy nole (highest elev.) target scan	$2 cm^2$ scan targ. Ht 1.533m	
25 Ft	GS	SW2	3	BM1-FLW-A	Bm near office target scan	$1 cm^2$ scan Targ Ht. 1.948 m	
25 Ft	GS	SW2	4	Bm4	North side (center) target scan	$1 cm^2$ scan Targ Ht. 1.505 m	did not acquire
25 Ft.	GS	SW2	5	Targ 5	South side fence (small mag target)	$1 cm^2$ scan	
25 Ft.	GS	SW2	6	none	1st field scan from SW2	$2 cm^2$ scan	
25 Ft.	GS	SW2	7	none	2nd field scan from SW2	$5 cm^2$ scan	
25 Ft.	GS	SW2	8	none	3rd field scan from SW2	$5 cm^2$ scan	
25 Ft.	GS	SW2	9	Targ 5	4th field scan from SW2	$5 cm^2$ scan	
25 Ft	GS	SW2	10	Targ 5	5th field scan from SW2	$5 cm^2$ scan	
25 Ft	GS	SW2	11	none	6th field scan from SW2 Filling in gap	$5 cm^2$ scan	
25 Ft	GS	SW2	12	none	7th field scan from SW2	$5 cm^2$ scan	

Field Sketches

Scan Position Description: SW2 South-East quarter-in, grassy mine field

Plan View

Figure B1. (Sheet 11 of 16)

CYRA

Scan Log

Scan Log:

Data Base Name: Grassy Site TallVeg
Project Name: Grassy-Site

Project Leader: ____________

Names of Crew: Leese/Jackson

Start Time: 9:35 am
Temperature: ________ Humidity: ________

Date: 07/27/04
Finish Time: ________
Atmospheric Pressure: ________

Scanner HT	Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
25 ft.	GS	SW3	1	Bm3	gravel pile target scan	2 cm² Targ Scan Ht. 1.523m	
25 ft.	GS	SW3	2	BM2	grassy nole (highest elev.) targ. scan	0.3 0.3 cm² Targ. Scan Ht. 1.533m	
25 ft.	GS	SW3	3	Bm1, FLW-A	BM near office targ. scan	0.3 cm² Targ. Scan Ht. 1.948m	did not acquire real good may need to reduce weight for registrat
25 ft	GS	SW3	4	Bm 4	North side (center) targ. scan	0.3 cm² Targ. Scan Ht. 1.505 m	
25 ft.	GS	SW3	5	Target 5	South side Fence post (small magnet)	1 cm² Targ. Scan	
25 ft	GS	SW3	6	none	1st field scan from SW3	5 cm² scan	
25 ft	GS	SW3	7	none	2nd field scan from SW3	5 cm² scan	
25 ft	GS	SW3	8	Bm4	3rd field scan from SW3	5 cm² scan	
25 ft	GS	SW3	9	none	4th field scan from SW3	5 cm² scan	
25 ft	GS	SW3	10	none	5th field scan from SW3	5 cm² scan	
25 ft	GS	SW3	11	Target 5	6th field scan from SW3	5 cm² scan	

Field Sketches

Scan Position Description: SW3 South-west quarter-in, grassy mine field

Plan View

Figure B1. (Sheet 12 of 16)

CYRA

Scan Log

Re-Do! as SW6

Scan Log:

Data Base Name: Grassy-Site-TallVeg
Project Name: Grassy Site

Project Leader:

Names of Crew: Leese/Jackson

Start Time: 1400/1500
Temperature:
Humidity:

Date: 07/27/04 / REDO 07/28/04 AS SW6
Finish Time: 1700
Atmospheric Pressure:

Scanner Height	Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
25 ft.	GS	SW4	1	Bm3	gravel pile - target scan	0.2 cm² target ht 1.523 m	
26 ft	GS	SW4	2	Bm2	grassy mole - highest elev	0.3 cm² targ ht. 1.533 m	
25 ft	GS	SW4	3	BM1-FLW-A	Bm near off fence	0.1 cm² targ ht 1.948 m	did not acquire
25 ft	GS	SW4	4	Bm4	North fence - center	0.5 cm² targ ht. 1.505 m	
25 ft	GS	SW4	5	target 5	South fence - center magnet target	0.3 cm² scan - target	
25 ft	GS	SW4	6	none	1st field scan from SW4	5 cm² scan	
25 ft	GS	SW4	7	none	2nd field scan from SW4	5 cm² scan	
25 ft	GS	SW4	8	none	3rd field scan from SW4	5 cm² scan	
25 ft	GS	SW4	9	none	4th field scan from SW4	5 cm² scan	
25 ft	GS	SW4	10	target 5/Bm3	5th field scan from SW4	5 cm² scan	
25 ft	GS	SW4	11	Bm3	6th field scan from SW4	5 cm² scan	
25 ft	GS	SW4	12	none	7th field scan from SW4	5 cm² scan	
25 ft	GS	SW4	13	Bm4	8th field scan from SW4	5 cm² scan	
25 ft	GS	SW4	14	none	9th field scan from SW4	5 cm² scan	

Field Sketches

Scan Position Description: SW4 North-east quarter in, grassy mixed field

Plan View → Lower NE corner

Scan Log Form.doc

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Figure B1. (Sheet 13 of 16)

CYRA

Scan Log

Wind affected scanner

Scan Log:

Data Base Name: Grassy_Site_TallVeg

Project Name: Grassy-Site

Project Leader: Re-Do

Names of Crew: Jackson / Leese

Start Time: 0815

Temperature: ________ Humidity: ________

Date: 7/28/04

Finish Time: ________

Atmospheric Pressure: ________

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
GS	SW5	1	BM3	gravel pile	cm² target scan Ht 1.523m	
GS	SW5	2	BM2	grassy mole	1 cm² target scan Ht. 1.533m	
GS	SW5	3	BM1-FLW-A	near office	1 cm² target scan Ht. 1.948m	could not acquire
GS	SW5	4	~~BM~~ 4	north-center fence	0.5 cm² target scan Ht. 1.505	
GS	SW5	5	Target 5	South-center fence small magnet	0.5 cm² target	

Field Sketches

Scan Position Description: ______________________

Scan Log Form.doc

Plan View

Page 1 of 5

Rev 6/4/03 RA

Figure B1. (Sheet 14 of 16)

CYRA

Scan Log

Scan Log:

Data Base Name: Grassy-Site_Tall_Veg

Project Name: Grassy Site

Project Leader:

Names of Crew: Jackson/Leese

Start Time: 1300

Temperature: ________ Humidity: ________

Date: 07/28/04

Finish Time: 1430

Atmospheric Pressure: ________

Scanner Ht.
25'

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
GS	SW5	1	Bm3	Gravel pile	0.5 cm² target Ht 1.523m	
GS	SW5	2	Bm2	grassy node (high elev.)	0.3 cm² target 0.3cm² Ht. 1.533m	
GS	SW5	3	BM1 FLW-A	near office	0.5 cm² target Ht. 1.948m	
GS	SW5	4	BM4	North Fence (center)	1cm² target Ht. 1.505m	
GS	SW5	5	Target 5	South fence post small magnet	0.5cm² scan target	
GS	SW5	6	none	1st field scan from SW5	5 cm² scan	
GS	SW5	7	none	2nd field scan from SW5	5 cm² scan	
GS	SW5	8	none	3rd field scan from SW5	5 cm² scan	
GS	SW5	9	Bm3 gravel pile T5	4th field scan from SW5	5 cm² scan	
GS	SW5	10	Bm4	5th field scan from SW5	5 cm² scan	
GS	SW5	11	Bm4, Bm1, Bm2	6th field scan from SW5	5 cm² scan	
GS	SW5	12	none	7th Field scan from SW5	5 cm² scan	

error!
software ackup

Field Sketches

Scan Position Description: SW5, North-west 1 quarter in, grassy mine field

Scan Log Form.doc

Plan View

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Figure B1. (Sheet 15 of 16)

CYRA

Scan Log

Scan Log:

Data Base Name: GRASS SITE

Project Name: GRASSY SITE - TALL VEG

Project Leader:

Names of Crew: JACKSON/LEESE

Start Time: 1500

Temperature: Humidity:

Date: 07/28/04

Finish Time: 1830

Atmospheric Pressure:

25'

Scanner Location	ScanWorld ID	Scan No.	Targets Included in Scan	Description of Area Scanned	Comments	ModelSpace View Name
GS	SW6	1	Bm3	GRAVEL PILE BM	0.5cm TARGET HT 1.523m	
GS	SW6	2	BM2	GRASSY KNOLL	0.5cm TARGET HT 1.533	
GS	SW6	3	Bm 1	APG 1 -	0.~~2~~ cm TGT HT 1.948	
GS	SW6	4	Bm 4	NORTH FENCE - CORNER	0.~~5~~cm TARGET HT 1.505	ACQUIRED BUT DID NOT DISPLAY CROSSHAIR (tie pt.)
GS	SW6	5	TARGET Bm 5	SOUTH FENCE - CENTER	TARGET 0.5cm -	~~0.3 Acquire~~ ACQUIRED BUT DID NOT DISPLAY CROSSHAIR
GS	SW6	6	none	1st field scan from SW6	5 cm² Scan	
GS	SW6	7	BM1, Bm2	2nd field scan from SW6	5 cm² Scan	
GS	SW6	8	Targ. 5	3rd field scan from SW6	5 cm² scan	
GS	SW6	9	BM3	4th field scan from SW6	5 cm² scan	
GS	SW6	10	BM 4	5th field scan from SW6	5 cm² scan	

error! (*) software locked up after selecting View; then couldn't acquire target as tie point
- software closed by itself.

Field Sketches

Scan Position Description: SW6 North East 1 quarter-in, grassy mine field

Scan Log Form.doc

Plan View

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Figure B1. (Sheet 16 of 16)

Appendix C
Scanner Setup Pictures

Figure C1. Trailer-mounted setup of Leica HDS3000 3D Laser Scanner elevated 7.62 m above Grass Site (viewed from southwest looking northeast, taken 26 July 2004)

REPORT DOCUMENTATION PAGE

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14. ABSTRACT

The use of a high-resolution, ground-based 3D laser scanner was recently evaluated for terrestrial site characterization of variable-surface minefield sites and generation of surface and terrain models. The instrument used to conduct this research was a Leica HDS3000 3D laser scanner. The high-speed, highly accurate ranging system has a 360 deg horizontal × 270 deg vertical field of view that delivers positional, range, and angular (vertical and horizontal) single point accuracies (range 1 to 50 m) of 6 mm, 4 mm, and 60 micro-radians, respectively. The laser is a class 3R and is completely eye-safe with a wavelength of 523 nm and spot size of ≤6 mm at a distance of 50 m. The pulse rate is 1,000 points/sec with an optimal effective range up to 100 m which is capable of producing a maximum point cloud spacing of 1.2 mm in the horizontal and vertical direction. Two study sites located in the midwestern United States were used for this analysis. A very dense vegetation site (Grass Site) and a bare soil site with intermittent rocks and sparse vegetation (Dirt Site) were selected for data collection to simulate both obscured and semi-obscured minefield sites. High-density scans (range 0.2 to 2.0 cm spacing) were utilized for Cyra target acquisition and were commensurate with size and distance to target from scanner location. Medium-density scans (range 2.0 to 5.0 cm spacing) were chosen for point cloud generation of the entire site(s) with approximately 10 percent edge overlap between field scans. In order to provide equivalent, unobstructed viewing perspectives from all scan locations

(Continued)

15. SUBJECT TERMS
Laser
LIDAR
Minefield
Modeling
Registration

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	44	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

14. (Concluded)

at each site, the scanner was positioned on a trailer-mounted, chain-driven lift and raised to an approximate scan height of 7.6 m above the ground. Final registration to UTM projected coordinate system of the multiple scan locations for the Dirt Site and Grass Site produced mean absolute errors of 0.014 and 0.017 m, respectively. The laser scanner adequately characterized surface roughness and vegetation height to produce contour and terrain models for the respective site locations. The detailed scans of the sites, along with the inherent natural vegetation characteristics present at each site, provide real-time discrimination of minefield site components under contrasting land surface conditions.