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**Application of Statistically-Based Site Characterization
Tools to the Pueblo Precision Bombing and Pattern
Gunnery Range #2 for the ESTCP Wide Area
Assessment Demonstration**

ESTCP Project # 200325



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1. Introduction

This report provides results of a subset of the larger wide area assessment project established by ESTCP to field test a number of UXO site characterization technologies. Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) have developed statistical algorithms to create transect designs based on desired Data Quality Objectives (DQO) and identify potential target areas. The transect design tools provide a statistically defensible method to use transect survey data that covers only a small proportion of the total study area (i.e. 1% to 3%) to identify target areas of a desired size, shape and anomaly density. Target area density estimates, probability estimates, and density flagging routines are applied after the data are gathered from the established transect design to separate potential target areas from areas that require no further remediation. These tools, combined with the other components of the wide area assessment (WAA) project, can provide methods to correctly and efficiently aide in the transfer of formerly used defense sites (FUDS) to the public or private domain.

This report documents the application of statistically-based site characterization tools developed by PNNL and SNL to the Pueblo Precision Bombing and Pattern Gunnery Range #2 as part of the ESTCP WAA. Specifically, these tools are used to accomplish: 1) geophysical transect design to locate potential target areas with an agreed upon confidence; 2) anomaly density estimation across the site using the geophysical transect data collected along the transect design; and 3) target area boundary delineation. These activities are conducted for several different conceptual site models accounting for multiple types of munitions thought to be used at the site.

2. Pueblo WAA Site Information and Munition Use

This WAA study area is a small part of the larger Pueblo Precision Bombing and Pattern Gunnery Range #2 as shown in Figure 1. It covers approximately 7300 acres and is located about 20 miles south of La Junta, Colorado, in Otero County. The entire training range encompasses 67,769 acres and consists of a bombing camp with two runways and nine precision bombing targets, a suspected 75mm air-to-ground target, along with an air-to-ground pattern gunnery range. The ranges were issued a Certificate of Clearance (surface only) in 1946 for a land use of cattle grazing. The WAA study area includes two known targets, Bomb Target 3 and Bomb Target 4, a suspected 75mm air-to-ground target, and the range area between these. Based on the Archival Search Report (ASR), the study area is most likely to contain the following munitions.

- Bomb, General Purpose (GP), 100-pound High Explosive, AN-M30 and AN-M30-A1
- Bomb, Practice, 100-pound, M38A2
- Bomb, Practice, 100-pound, Mk 15 Mod 3
- Bomb, Incendiary, 4-pound, AN-M50A1
- Shot, Armor-Piercing (AP), M72 (75mm)

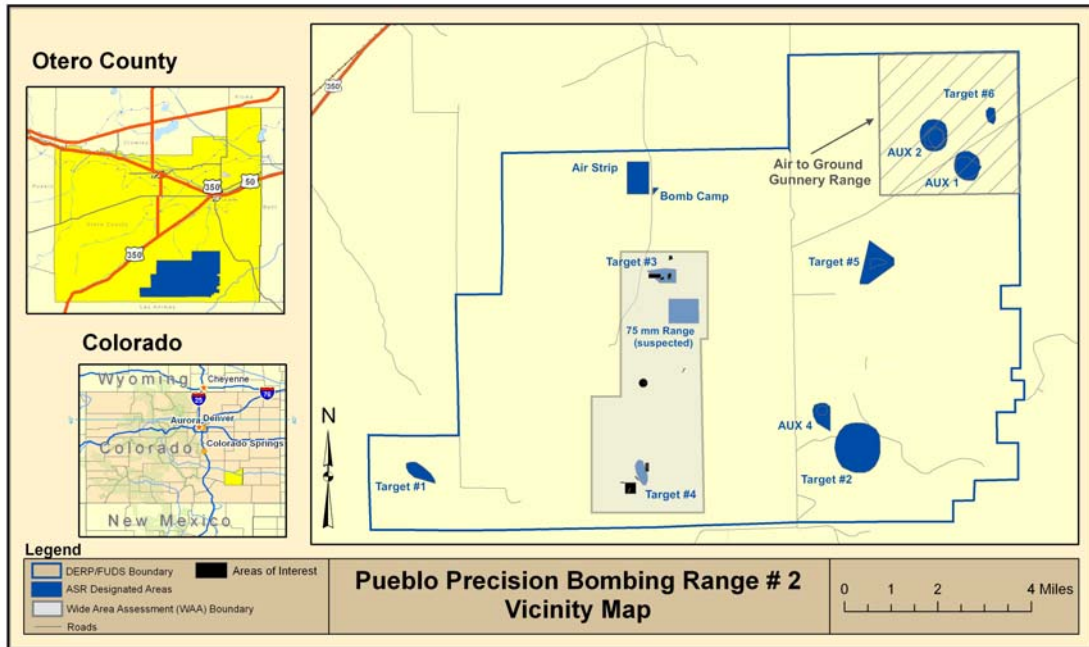


Figure 1: Vicinity map of the WAA Pueblo study area with identified features of interest.

3. Transect Design and Analysis Approach

Visual Sample Plan (VSP) is a statistical sampling software package designed by PNNL through funding from multiple government agencies to provide the site investigators a simple to use defensible method of gathering and analyzing their respective data. Through funding from SERDP and ESTCP, VSP has been developed to aid in transect sampling to identify areas where the likelihood of UXO presence is elevated. Given the design parameters, VSP will compute the required spacing of transects to achieve the specified probability of traversing the critical target area, calculate the probability of both traversing and detecting the critical target zone if it exists, display the proposed transects on the site map and will output the x,y coordinates of the proposed transects. The user can then conduct a sensitivity analysis by evaluating the effects of the input parameters and their required DQO parameters. These methods and tools allow the project team to balance DQO objectives against costs and other site constraints.

VSP's target identification algorithm uses a circular window to calculate the density of anomalies within a certain distance from the center of the window. This window, centered on a transect, systematically moves along each transect of the site and flags the center point of the window located on the transect as an area of high density when the window has more anomalies than expected for background anomalies alone. Because there is often no prior estimate of background anomaly density, VSP provides the capability of examining the distribution of densities based on the user defined window diameter. The user can then determine an optimum critical value or background density based on this window size. With the optimum window size and appropriate background

density determined, cells along the transects belonging to potential target areas are identified. When these “flagged” areas are identified the user can then manually encompass these areas with a polyline and export the vertex points for other use.

The choice of window diameter and critical density is currently left to the VSP user. During this analysis many different window sizes and critical densities were examined. The choice of window size depends on the transect spacing and the assumed target area size and shape. The size of the circular window used in this report was close to the assumed 1000 ft diameter target area and was a 300m diameter window. With this window size different threshold critical densities were considered and different critical densities between 45 and 60 anomalies per acre seemed reasonable. Figure 2 shows a histogram of the window densities based on the CSM-0 transect design. The final critical density of 53 anomalies per acre (red line in Figure 2) is approximately where the histogram shows an inflection point which identifies the transition region between densities associated with background and those associated with potential target areas. This figure is similar to the histograms for the other transect designs which resulted in the same critical density for each design.

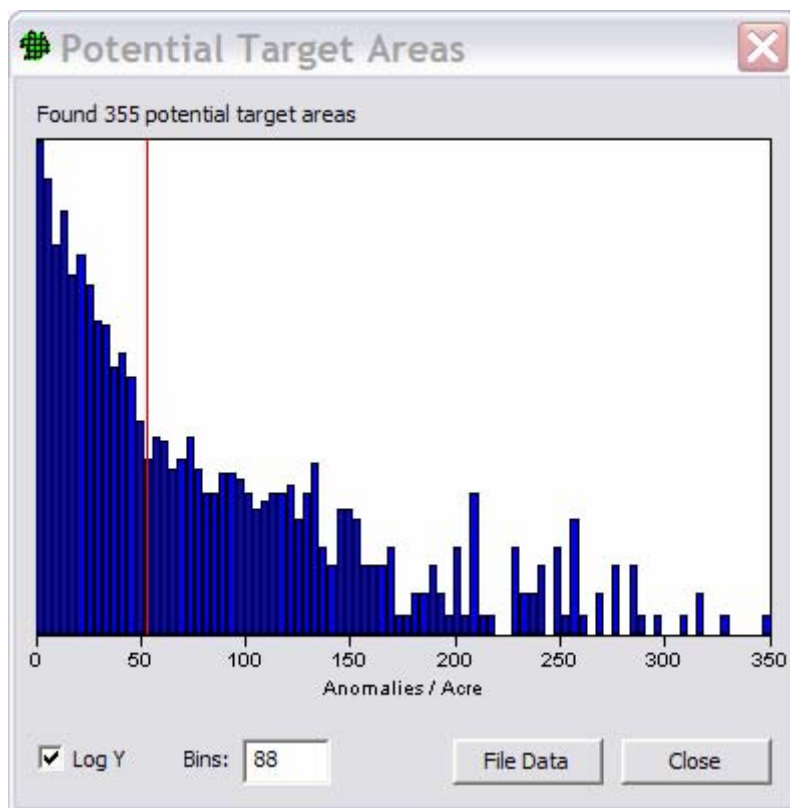


Figure 2: Example histogram of the window densities based on CSM-0 transect design with a 300m diameter window.

Geostatistical estimation using the kriging algorithm was used to extrapolate information away from the transect locations to unsurveyed locations of the site domain. Both the probability of being within a target area and the anomaly density were estimated using the indicator kriging (IK) and ordinary kriging (OK) approaches to estimation.

Indicator kriging allows for the direct mapping of the probability of exceeding a critical density threshold across the site. The resulting probability map defines the probability of being within a target area and can be used as part of the target identification and delineation process. Target areas can be defined as those regions where the probability of being within the target exceeds a probability contour (e.g., 5 percent) as specified by the site characterization team. These probability maps are also useful for locating additional sampling transects and allowing the regulator to define the reliability of the characterization decisions made from the available data. Probability values near 0.50 indicate areas of maximum uncertainty with respect to the threshold being considered. Probability mapping can be completed using only the information obtained from the transects as designed using VSP and the appropriate design parameters (see above), or the geostatistical algorithms can be used to merge both the transect data and more subjective information on the location and extent of target areas as obtained from Archival Search Reports (ASR's), aerial imagery and/or simulations of UXO locations based on the conceptual site model (CSM).

Similar to the probability mapping, estimates of geophysical anomaly density can be made across the site based on limited transect data. Density estimation provides additional information for target area boundary delineation. A density contour is selected and areas of the site where the estimated density exceeds this contour are defined as being within the target area. While this target area delineation approach is more straightforward than the probability mapping approach, it is a deterministic approach and does not allow the decision maker any direct consideration of reliability in setting the extent of the target boundary.

The initial geostatistical analysis applied to the anomaly density data as part of identifying potential areas of interest was indicator kriging (IK). For this process the anomaly density data were transformed to indicator values of one or zero. The indicator variable was set to one for all locations where the anomaly densities were above a chosen threshold; zeros are recorded for all other locations. The indicator variable anomaly data were then used to produce kriging estimate maps showing probabilities of exceeding the indicator threshold. These maps were then used in delineating AOI for the Pueblo site.

As part of the data pre-processing prior to geostatistical analyses (kriging), an averaging procedure was applied to the raw magnetic anomaly data. This procedure was similar to that used within the VSP flagging routines, but operates on a grid-cell basis. This process operates by computing the average anomaly density for each grid cell crossed by a sampling transect. Average density values are only computed for those cells actually crossed by a sampling transect.

The anomaly density average is computed using a user specified rectangular window around the cell of interest. Typically this window has its greatest dimension parallel to the transect direction. The average density is computed using the number of anomalies and total sampled area falling within the averaging window. The resulting anomaly density distribution is much smoother than the original raw or unsmoothed magnetic anomaly data. The smoothed, more continuous grid cell values of anomaly densities

resulting from this process are then used in the subsequent kriging estimates. All anomaly density averaging used square grid cells 25 m in each dimension. This is the same grid cell size employed in the subsequent kriging analyses. For all the kriging estimations presented in this report an averaging window of 125 m in the X direction (East-West), and 325 m in the Y direction (North-South) was used. The window size in the Y direction (parallel to the majority of transects) was chosen similar to the expected target size of 1000 feet (305 m). The X direction window size was chosen large enough to include field sampling deviations from the original straight-line transect design, but small enough to not include adjacent transects.

4. Pueblo WAA Transect Design and Target Area Identification

This study area had three potential target areas that guided the transect design process. Two of the target areas had identified precision bomb aiming circles based on aerial photography. From the archival search report (ASR) and the conceptual site model (CSM-0) it is probable that high explosive 100 lb (HE) bombs were used on at least one of the two bomb target areas. Generally, the HE bombs would have a much larger impact area than the 100 lb practice bombs due to the frag dispersion. If the dispersed frags were detectable and the use were significant, the allowed spacing between transects may increase for the HE bomb target areas. However due to uncertainties about fragmentation patterns, use and fragment size for the two types of bombs, the CSM-0 transect designs were based on the smaller probable impact area of the 100 lb practice bombs. This demonstration had two conceptual site models where the CSM-1 contained additional information based on the Ortho-imagery and LIDAR obtained at the site and CSM-0 relied primarily upon the ASR and previous site visits. The PNNL/SNL team did not have CSM-1 available to them while designing the CSM-0 transect designs. The process of creating each design and obtaining the data from each transect design is depicted in Figure 3. The dense and sparse transect designs are named to identify the amount of information in each and are explained in more detail in the following sections. The dense transects were collected all at once and the additional transects were requested based on results of this dense transect design. The sparse transect design was separated from the dense transects later for comparison purposes. There were two stages of additional transects that were requested during the geophysical surveying. The first stage of additional transects was based on findings from the dense transect design. The second stage of additional transects (CSM-1) was based on the dense with additional transects and the addition LIDAR imagery provided to the PNNL/SNL team.

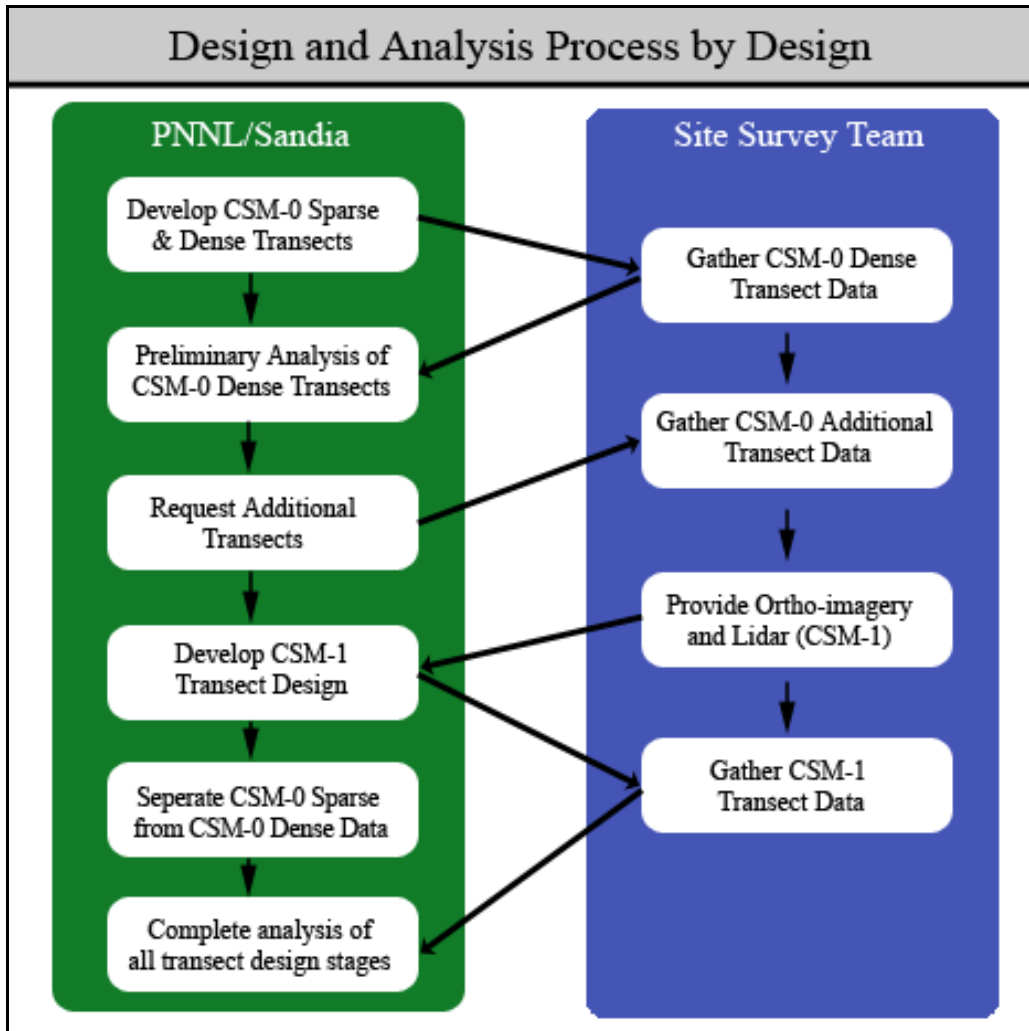


Figure 3: Diagram of how each transect design was created and the subsequent data was obtained and analyzed.

The process of delineating Areas of Interest (AOI) from the magnetic anomaly data for each sampling scenario was performed via the VSP and Kriging analysis as discussed above. The results from each of these processes were incorporated into the final AOI delineations and the AOI boundaries were manually constructed taking into consideration these results, the sampling transect geometry, topography and local anomaly densities.

4.1. CSM-0 Bombing Target Transect Designs and Analysis

4.1.1. CSM-0 Bombing Target Sparse Transect Design

Based on analysis Versar (email on 08/17/2005), CSM-0 and available high resolution aerial images of each of the known bomb target areas, 1000 ft. diameter target rings were identified and formed the basis for establishing the sparse transect designs. To identify potential 100 lb bomb circular 1000 ft. (305m) diameter target areas, a 2 meter wide parallel transect pattern spaced appropriately to ensure a 99% probability of traversal was designed. The resulting 14 transects are oriented north-south 310 meters apart on center

and cover 0.65% of the study area, as shown in Figure 4. These transects are a subset of the transects from the dense transect design explained in section 0.

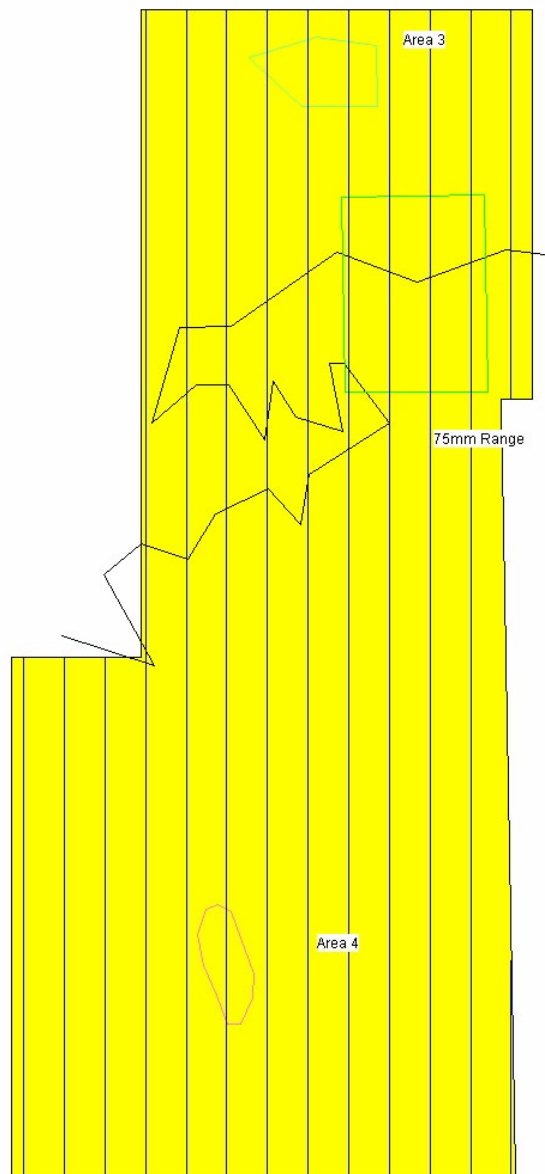


Figure 4: Sparse transect design for CSM-0 spaced 310 m apart on centers.

4.1.2. CSM-0 Bombing Target Sparse Transect Design Analysis

The actual course traversed by the geophysical survey team is depicted in Figure 5. This figure shows the inaccessible areas where the survey team could not obtain transects and where they had to circumvent obstacles in their path. Table 1 is a summary comparison of the proposed design to the actual data obtained from the transect survey.

	Transect Coverage (sq. meters)	Percent Coverage	Anomaly Count
Proposed	195361.17	0.654%	-
Actual	192150.87	0.643%	672

Table 1: Summary of CSM-0 Bombing Target Sparse Transect Data.

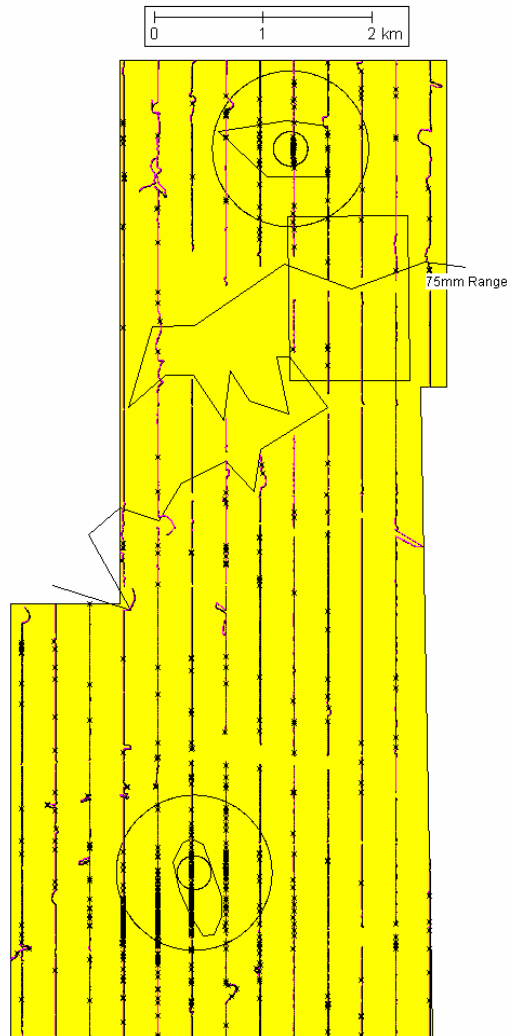


Figure 5: The lines represent the actual course over ground (COG) data based on the proposed bombing target sparse transect design with the identified anomalies (black dots).

4.1.2.1. Target Area Identification and Delineation

Figure 6 shows the flagged areas of high density for a 300 m diameter window with a critical density of 53 anomalies per acre (APA). The identified areas of interest (AOI) are identified by the blue shaded regions. This figure shows the information used to

identify AOI-B and AOI-C which are the two small areas flagged by VSP that were identified as AOI.

Figure 7 shows the indicator kriging probability levels for the CSM-0 Sparse transect design using an indicator kriging threshold of 60 APA. Areas with a probability of 0.05 or greater of being above the 60 APA threshold are indicated by color-filled probability contours. These areas were included as part of the information used in determining the final boundaries for the AOI. The indicator kriging threshold value of 60 APA was chosen based on the spatial pattern resulting from the implementation of different threshold values. The 60 APA value was selected as the minimum value which did not generate a spatial pattern of the indicator variable which contained many small isolated clusters in the smoothed anomaly data. The 60 APA threshold value generated indicator variable spatial patterns with large contiguous areas which would be most like what would be expected for former target areas. This choice of threshold value is reinforced in the results of the density kriging shown below. A similar process in choosing the IK threshold value was applied to all the sampling transect designs presented in this report.

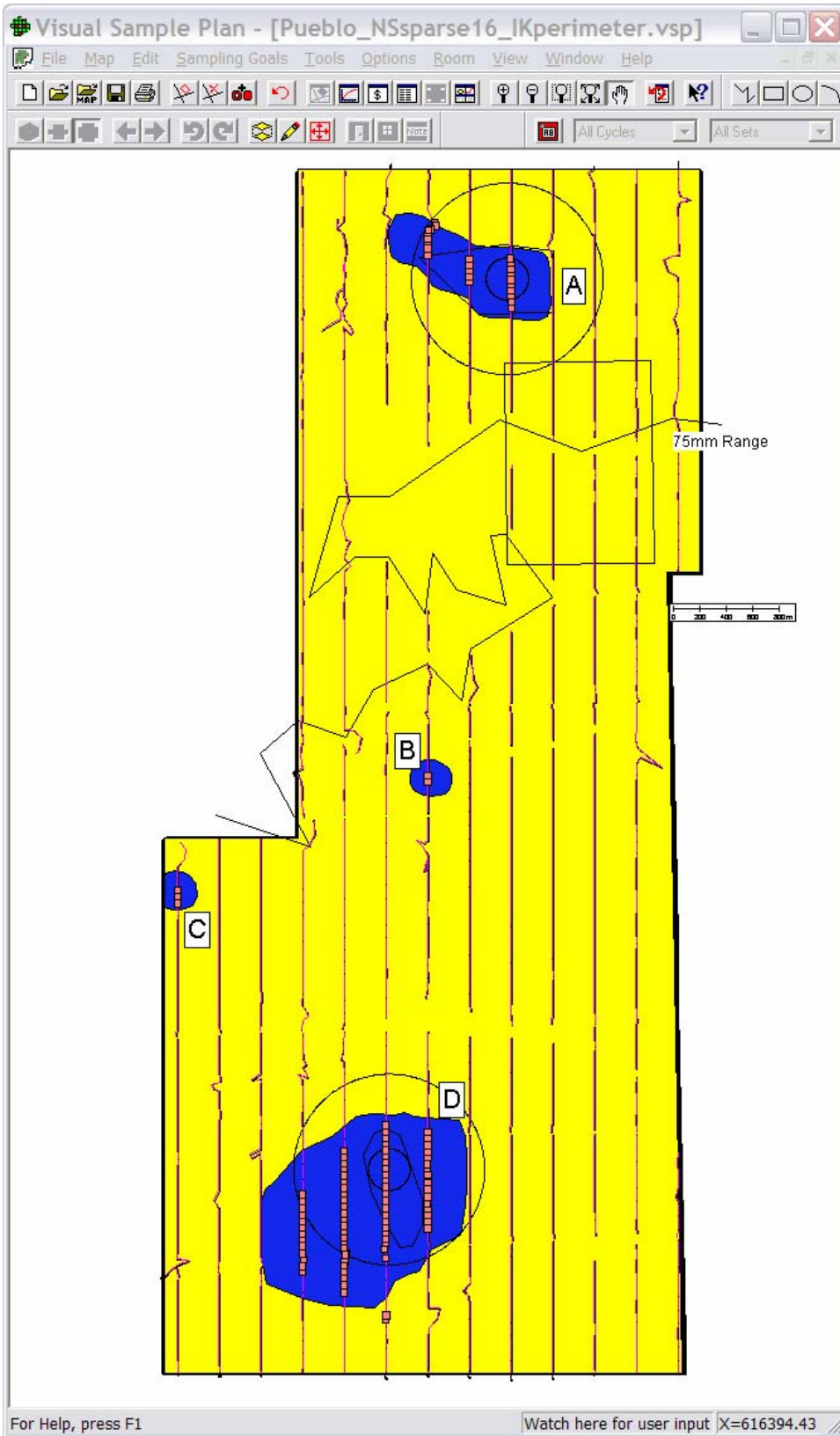


Figure 6: VSP CSM-0 Sparse flagged high density areas (red squares) based on a 300 m diameter window and a critical density of 53 anomalies per acre with delineated AOI boundaries (blue areas).

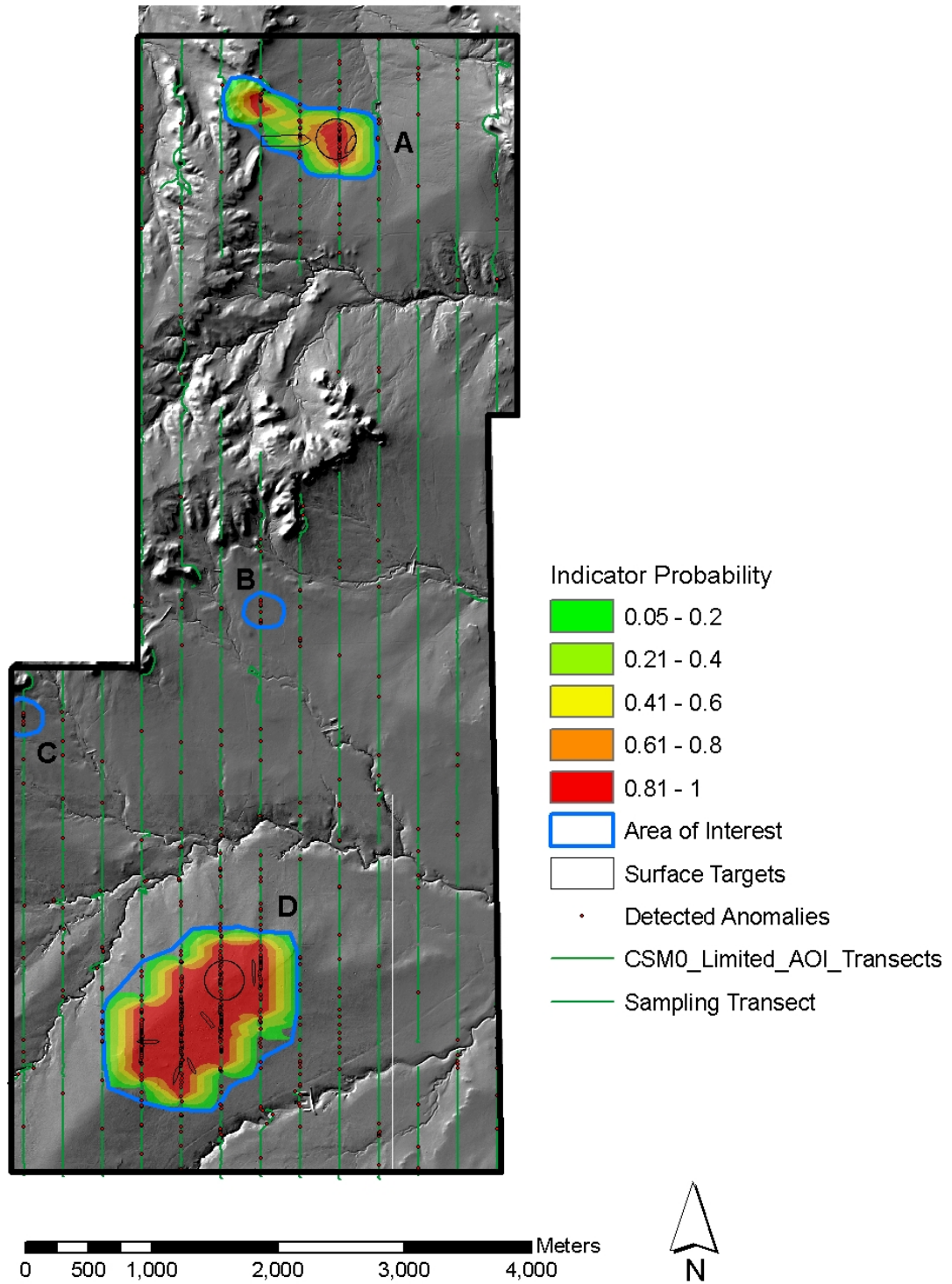


Figure 7: Indicator Kriging results and delineated AOI developed from CSM-0 Sparse transect anomaly data.

As part of the kriging process, it was necessary to model the spatial variability of the anomaly density data. This spatial variability was represented using variograms of the anomaly density data. Variograms model how the variance between data points changes as the spatial distance between any two points increases. Typically the variance increases as the distance between points increases. Figure 8 presents the indicator variogram developed using the transect data from CSM-0 Sparse design. The points in this figure represent the variance values computed at specific lag distances. The solid line represents the analytic model fit to the data points. It is these model curves that are used during the kriging procedures. The parameters describing these curves for all of the Pueblo data variograms are provided in Appendix A.

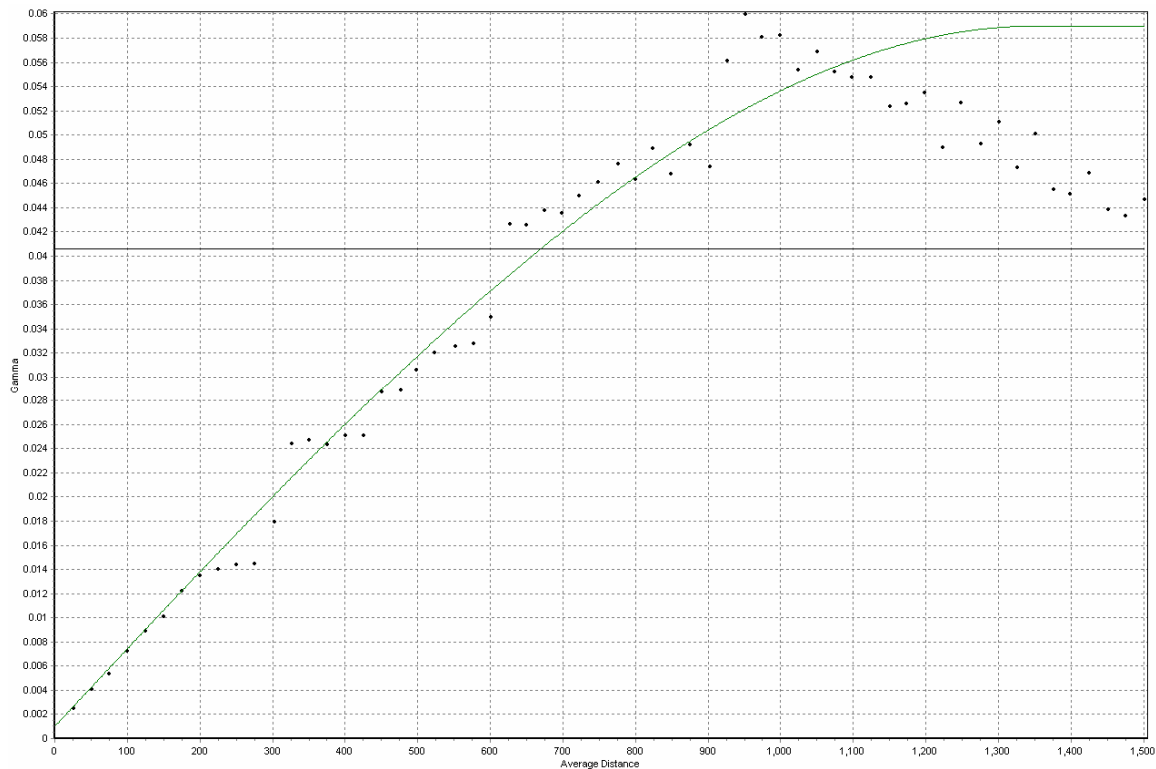


Figure 8: Variogram model and observational data for CSM-0 Sparse transect design IK analysis. Units of X-axis are in meters.

There are four individual AOI identified in Figures 6 and 7. Basic statistics for these AOI, which are identified by alphabetic designators, are provided in Table 2. Two of these areas (AOI B and C) did not contain anomaly densities above the criteria (60 anomalies/acre) specified for the IK. Delimitation of these areas was based on the VSP flagging results and validated by the anomaly density kriging estimates shown in Figure 9. There are some cases where small, isolated areas were flagged during the VSP analysis but were not included as AOI's. The photography and topography of the site was

investigated in these areas and they were considered too small and isolated to be associated with site munitions use and/or were deemed to be a sampling artifact and hence were not included in the delineation of the AOI's.

AOI		Sample Transects Crossing AOI			Anomaly	
ID	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
A	555,704	3	1,409	2,818	53	75
B	68,673	1	267	534	8	59
C	58,970	1	289	578	8	55
D	1,724,288	4	5,032	10,064	285	113

Table 2: Basic statistics of AOI identified from CSM-0 Sparse transect design. Anomaly density based on transect sample area and magnetic anomaly count.

The two largest AOI (A and D) fall in areas containing identified terrain target features (i.e. target circles and ship outlines). AOI A and D correspond to the previously identified locations of Target 3 (T3) and Target 4 (T4) respectively; AOI B and C do not correspond to any previously identified target areas.

As shown in Table 2, AOI D has the highest transect anomaly density (unsmoothed) at 113 anomalies per acre. AOI A has the next highest density at 75 anomalies per acre. AOI B and C have lower transect anomaly densities at 59 and 55 anomalies per acre respectively. The anomaly densities shown in Table 2 represent average, unsmoothed densities computed strictly from the AOI sample transect area and the number of anomalies detected in that AOI.

It is interesting to note that the two largest identified target areas, A and D, have dimensions that are 3 to 4 times larger than those expected based on the conceptual site model used to design the transect survey (100lb bombs with a target diameter of 1000 ft or 305 meters). This large difference can be due to multiple smaller individual target areas coalescing into the two large target areas (e.g. AOI D). The result of this merging of smaller target areas into target areas that can be considerably larger than the areas used in the conceptual model is that multiple transects intersect these large target areas.

4.1.2.2. Target Area Density Estimates

Ordinary Kriging (OK) was used to develop continuous anomaly density maps for the entire Pueblo WAA site. The Kriging estimates were computed using 25 m by 25 m square grid cells using the smoothed anomaly density values computed from the CSM-0 Sparse transect sample data. A variogram model specific to this data set was developed for use in the OK. The details of this model are provided in Appendix A.

Figure 9 presents a map of the anomaly densities (anomalies per acre) estimated from the OK analysis. The color-filled contours indicate anomaly densities; areas without a color overlay have estimated densities below 20 APA. As shown in this figure, the identified AOI enclose the highest anomaly density locations and correspond with the IK results presented above. Additional AOI locations not identified in the IK analysis but flagged during the VSP analysis (AOI B and C) appear as isolated areas with relatively high density values. As shown by Figure 9, those areas at 60 APA and above form compact features with steep density gradients, whereas areas below 40 APA tend to be irregular and more spatially dispersed. This result likely indicates a transition from a background anomaly regime to a target anomaly regime occurring at or near the 60 APA threshold.

Figure 10 shows a graph of the total area above various anomaly density levels for the entire Pueblo WAA site. As shown by this graph, there are substantial changes in the slope of the graph for those segments in the 20 to 60 anomalies per acre range. The graph assumes a more uniform slope for density levels above 60 anomalies per acre indicating the transition to a different density regime. This substantial change in the graph occurring around the 60 APA level adds support to the selection of a critical density level in the neighborhood of 60 anomalies per acre as used in the IK analysis discussed above.

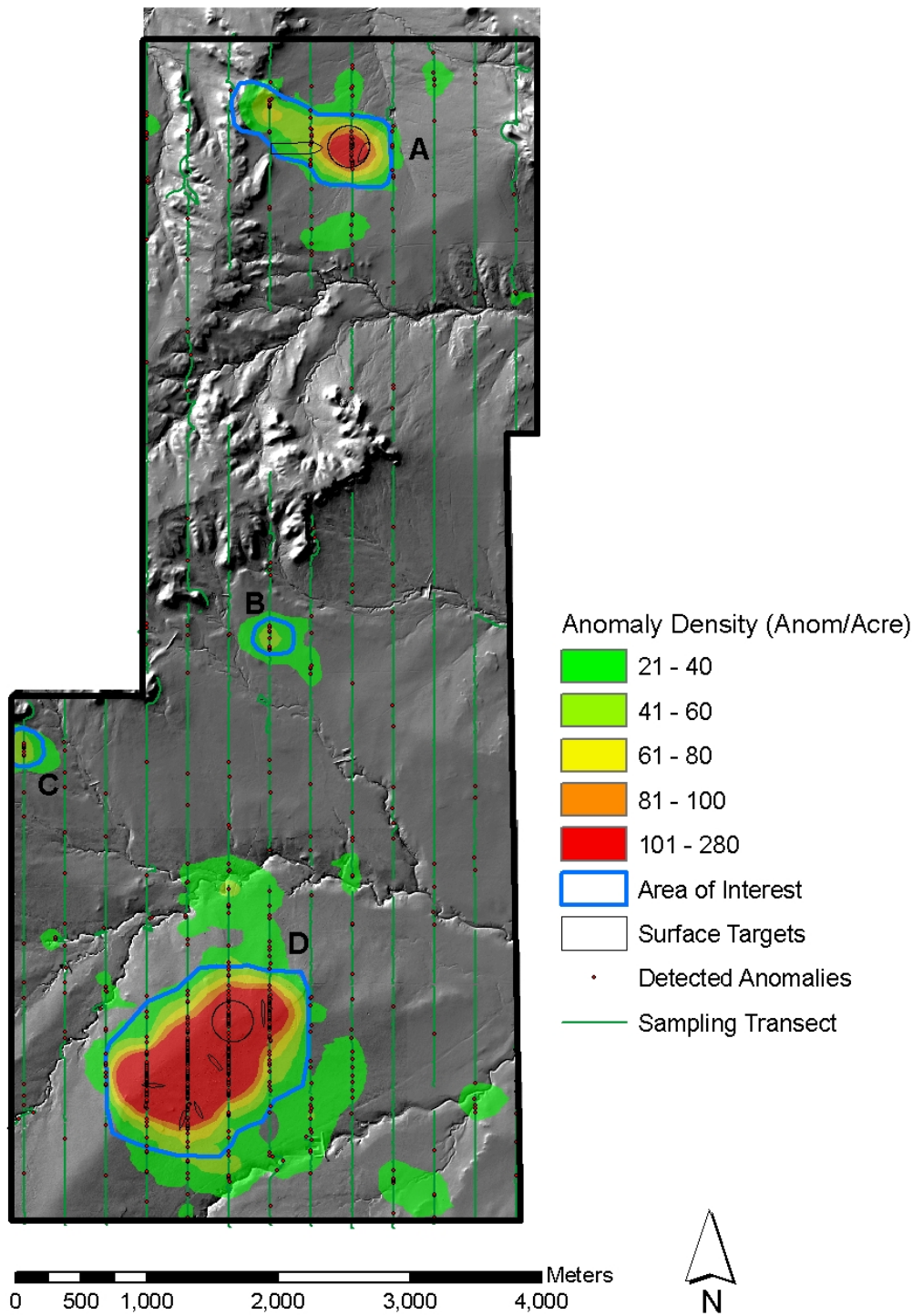


Figure 9: OK developed anomaly density estimates for the CSM-0 Sparse transect design.

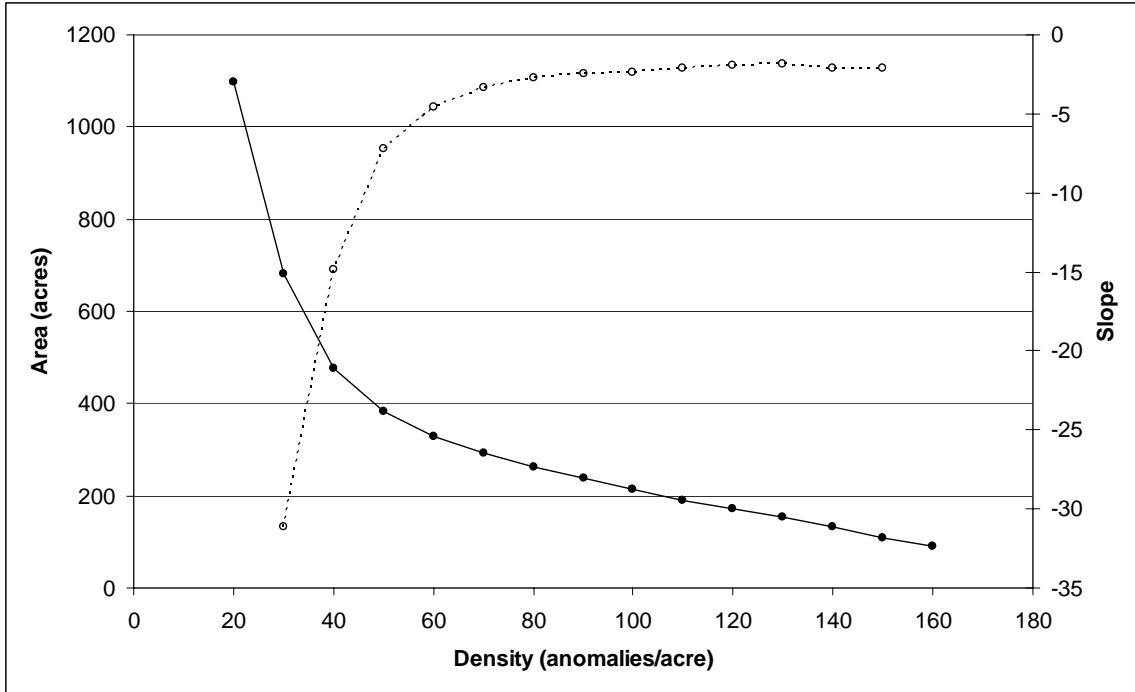


Figure 10: Graph showing amount of area (solid line) at or above specified anomaly density levels for OK estimates computed from CSM-0 Sparse transect design sample data. Dashed line shows the slope of the solid line for that density level.

4.1.3. CSM-0 Bombing Target Dense Transect Design

The CSM-0 sparse transect design presented in section 4.1.2 was based on the desire to identify 1000 ft diameter target areas based on the observed target circles. However, target areas could have been smaller if the bombers were quite accurate and they were using 100 lb practice bombs. Therefore, a more dense transect design was developed to ensure a high probability of traversing a 500 ft diameter target area. Of course this dense design has twice as many transects as the sparse design.

To identify potential 100 lb bomb circular 500 ft. diameter target areas, a 2 meter wide parallel transect pattern spaced appropriately to ensure a 99% probability of traversal was used. The resulting 27 transects are oriented north-south 155 meters apart on center and covered 1.3% of the study area, as shown in Figure 11. Note that 14 of the transects are the same as those used for the sparse transect design explained previously.

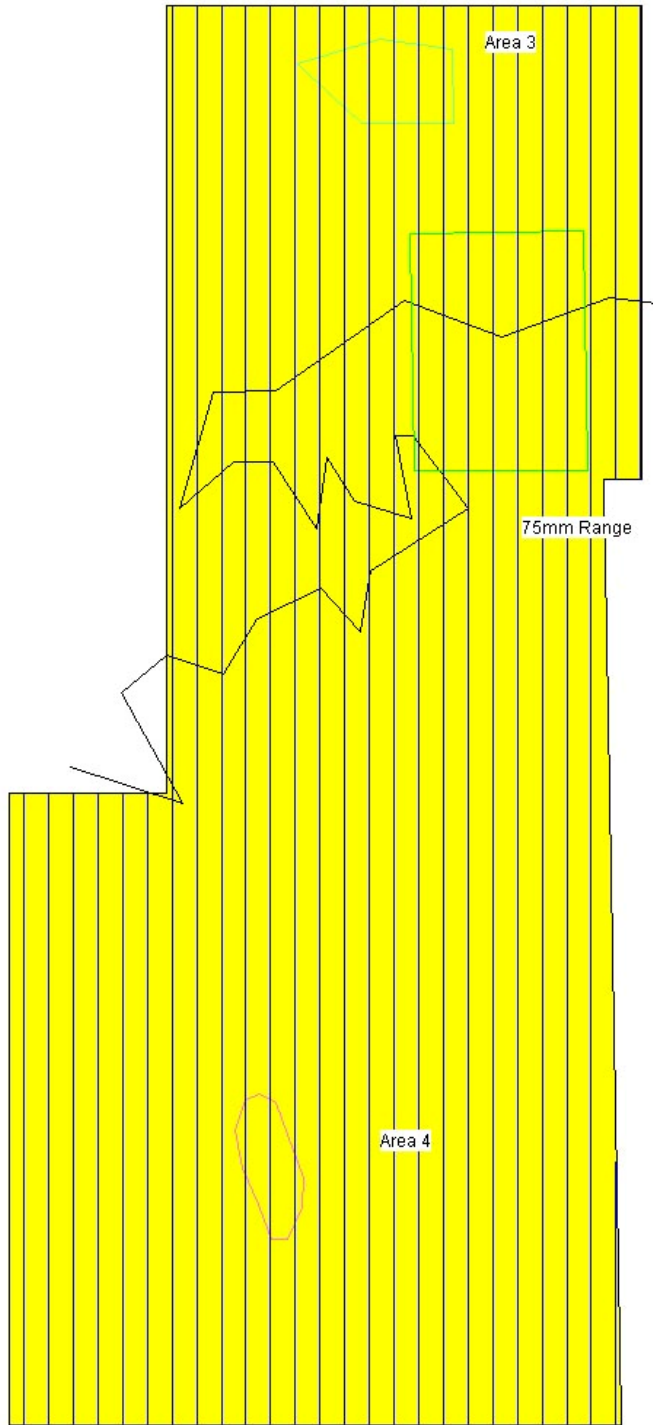


Figure 11: Dense CSM-0 transect designs spaced 155 m apart on centers.

4.1.4. CSM-0 Bombing Target Dense Transect Design Analysis

The actual traversed area for this transect design, depicted in Figure 12 and summarized in Table 3, was the main design surveyed. This actual coverage was used to identify any potential areas for the additional transects request as a part of CSM-0.

	Transect Coverage (sq. meters)	Percent Coverage	Anomaly Count
Proposed	387374.63	1.296%	-
Actual	378681.97	1.267%	1447

Table 3: Summary of CSM-0 Bombing Target Dense Transect Data.

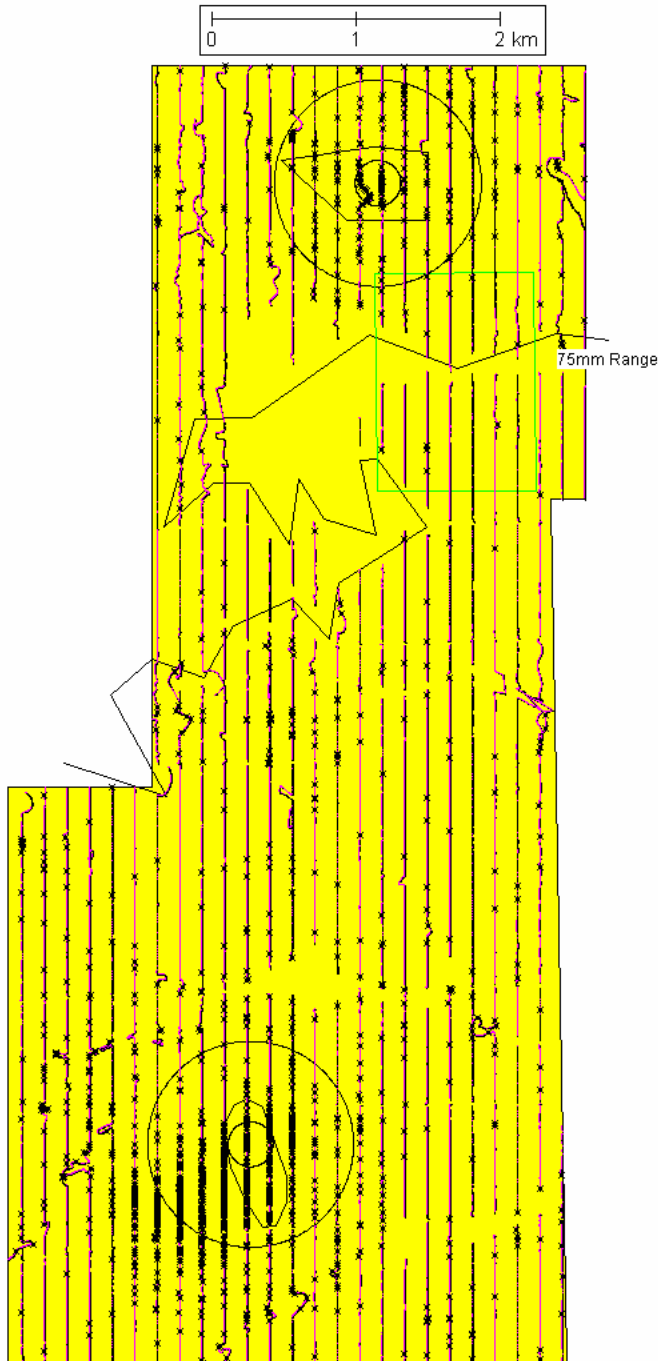


Figure 12: The lines represent the actual course over ground (COG) data based on the proposed bombing target dense transect design with the identified anomalies (black dots).

4.1.4.1. Target Area Identification and Delineation

As explained in Section 3, the VSP target area flagging methods were used and various combinations of window sizes and critical densities were explored. Figure 13 shows the flagged areas based on the CSM-0 Dense transect design and the VSP flagging routine with a 300 m window diameter and a critical density of 53 APA. The blue shaded areas represent the delineated boundaries of the identified AOI.

In a manner similar to that used for the CSM-0 Sparse transect design, IK estimation was applied to the CSM-0 Dense transect design data for target area identification and delineation. The data preprocessing was identical to that used for the CSM-0 Sparse transect data using an averaging window of 125 m in the X direction (East-West), and 325 m in the Y direction (North-South). The kriging grid used cells that were 25 m by 25 m in size. A threshold level of 60 APA was used for the indicator variable. This threshold level was selected in the same manner as used in the CSM-0 Sparse transect design. IK of this variable was then used to produce a map showing the probability of exceeding the threshold level. This map was part of the information used in identifying and delineating AOI for the Pueblo site. The variogram model used for the IK is listed in Appendix A and is similar to that used in the CSM-0 Sparse transect scenario

Figure 14 shows the indicator kriging probability levels for the CSM-0 Dense transect design using an indicator kriging threshold of 60 APA. Only areas with a probability of 0.05 or greater of being above the 60 APA threshold are indicated by color-filled contours. These areas were included as part of the information used in determining the final boundaries for the AOI.

There are six individual AOI identified in Figures 13 and 14. This is an increase in the number of AOI identified compared to CSM-0 Sparse transect design. Basic statistics for the AOI, which are identified by alphabetic designators, are provided in Table 4. One of the areas (AOI C) did not contain anomaly densities above the criteria (60 APA) specified for the IK. Delineation of this area was based on the VSP flagging results and anomaly density estimates. There are some cases where small, isolated areas were flagged during the VSP analysis. Further investigation of the sample transect area, local topography, and anomaly distribution in these areas indicated that these were likely flagged due to sampling artifacts. These artifacts are typically the result of a discontinuity in the sample transect, or abrupt terrain changes such as occurs when sampling transects cross drainage features. These areas were not included in the delineation of the AOI's.

The two largest AOI (A and D) fall in areas containing identified terrain target features (i.e. target circles and ship outlines). AOI A and D correspond to the previously identified locations of Target 3 (T3) and Target 4 (T4), respectively. AOI F and E fall adjacent to, but removed from, T3 and T4 respectively. The other delineated AOI do not correspond to any previously identified target areas.

As shown in Table 4, AOI D has the highest transect anomaly density (unsmoothed) at 120 anomalies per acre. This area corresponds to T4. AOI A has the next highest density at 77 anomalies per acre and corresponds to T3. The anomaly densities shown in Table 4 represent average, unsmoothed densities computed strictly from the AOI sample transect area and the number of anomalies detected in that AOI. The AOI areas and densities in Table 4 can be compared directly with those calculated from the sparse transect design shown in Table 2. For both of the largest AOI's (A and D), the estimated areas decrease with additional transects, and the estimated densities increase slightly.

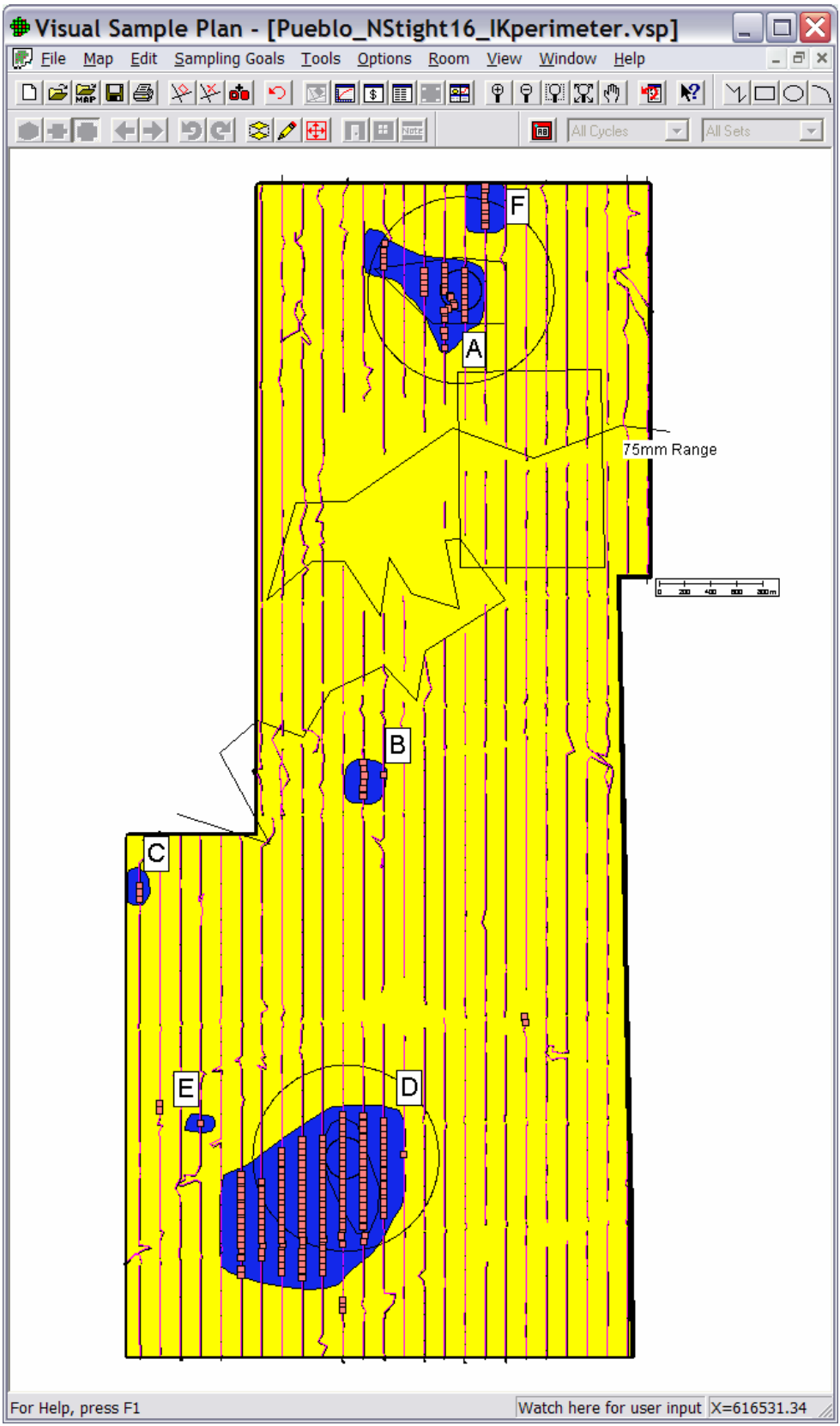


Figure 13: VSP CSM-0 Dense flagged high density areas (red squares) based on a 300 m diameter window and a critical density of 53 anomalies per acre with delineated AOI boundaries (blue areas).

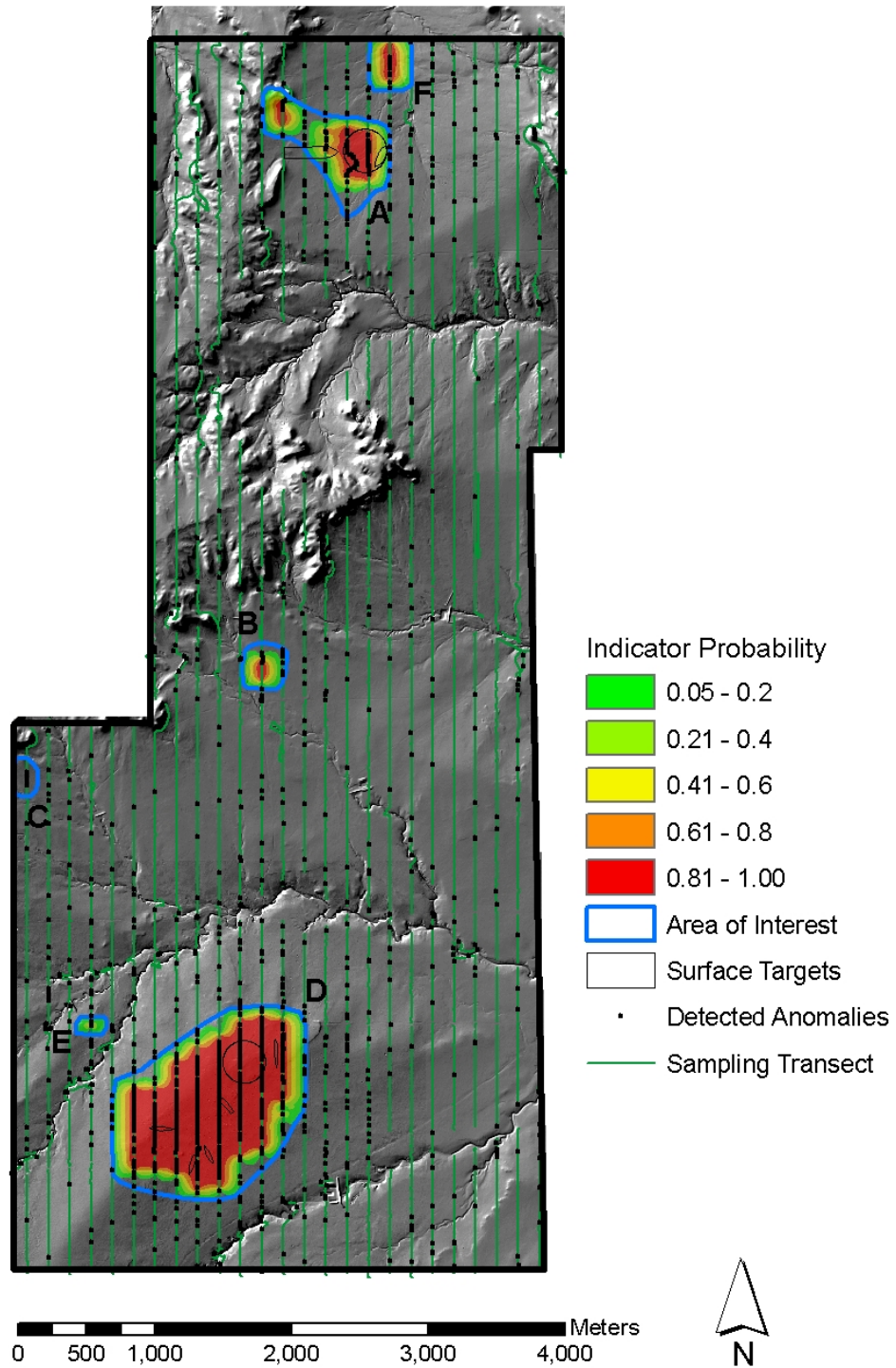


Figure 14: Indicator Kriging results and delineated AOI developed from CSM-0 Dense transect anomaly data.

AOI		Sample Transects Crossing AOI			Anomaly	
ID	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
A	424,335	6	2,476	4,952	95	77
B	95,386	2	563	1,126	19	67
C	41,697	1	278	556	8	58
D	1,534,685	10	10,027	20,054	602	120
E	26,954	1	133	266	3	45
F	112,520	2	640	1,280	12	38

Table 4: Basic statistics of AOI identified from CSM-0 Dense transect design. Anomaly density based on transect sample area and magnetic anomaly count.

4.1.4.2. Target Area Density Estimates

Ordinary Kriging (OK) was applied to the CSM-0 Dense transect anomaly data to develop continuous anomaly density maps for the entire Pueblo WAA site. The Kriging estimates were computed using 25 m by 25 m square grid cells and using the smoothed anomaly density values computed from the transect sample data. A variogram model specific to this data set was developed for use in the OK. This model is similar to that developed for the CSM-0 Sparse scenario. The details of this model are provided in Appendix A.

Figure 15 presents a map of the anomaly densities (anomalies per acre) estimated from the OK analysis. The color-filled contours indicate anomaly densities; areas without a color overlay have estimated densities below 20 anomalies per acre. As shown in this figure, the identified AOI enclose the highest anomaly density locations and correspond with the IK results presented above. One additional AOI location not identified in the IK analysis but flagged during the VSP analysis (AOI C) shows as an isolated area with relatively high density values. As shown by Figure 15, those areas at 60 APA and above form compact features with steep density gradients, whereas areas below 40 APA tend to be irregular and more dispersed. This result likely indicates a transition from a background anomaly regime to a target anomaly regime between densities of 40 and 60 APA.

Figure 16 shows a graph of total area above various anomaly density levels for the entire Pueblo WAA site. As shown by this graph, there are substantial changes in slope of this graph for those segments in the 20 to 60 anomalies per acre range. The total area enclosed above the critical density level decreases by a factor of 3 from 1200 acres to 400 acres as the critical density level increases from 20 to 60 APA. The graph assumes a more uniform slope for density levels above 60 APA indicating the transition to a different density regime. This substantial change in the graph occurring around the 60 APA level adds support to the selection of a critical density level in the neighborhood of 60 APA.

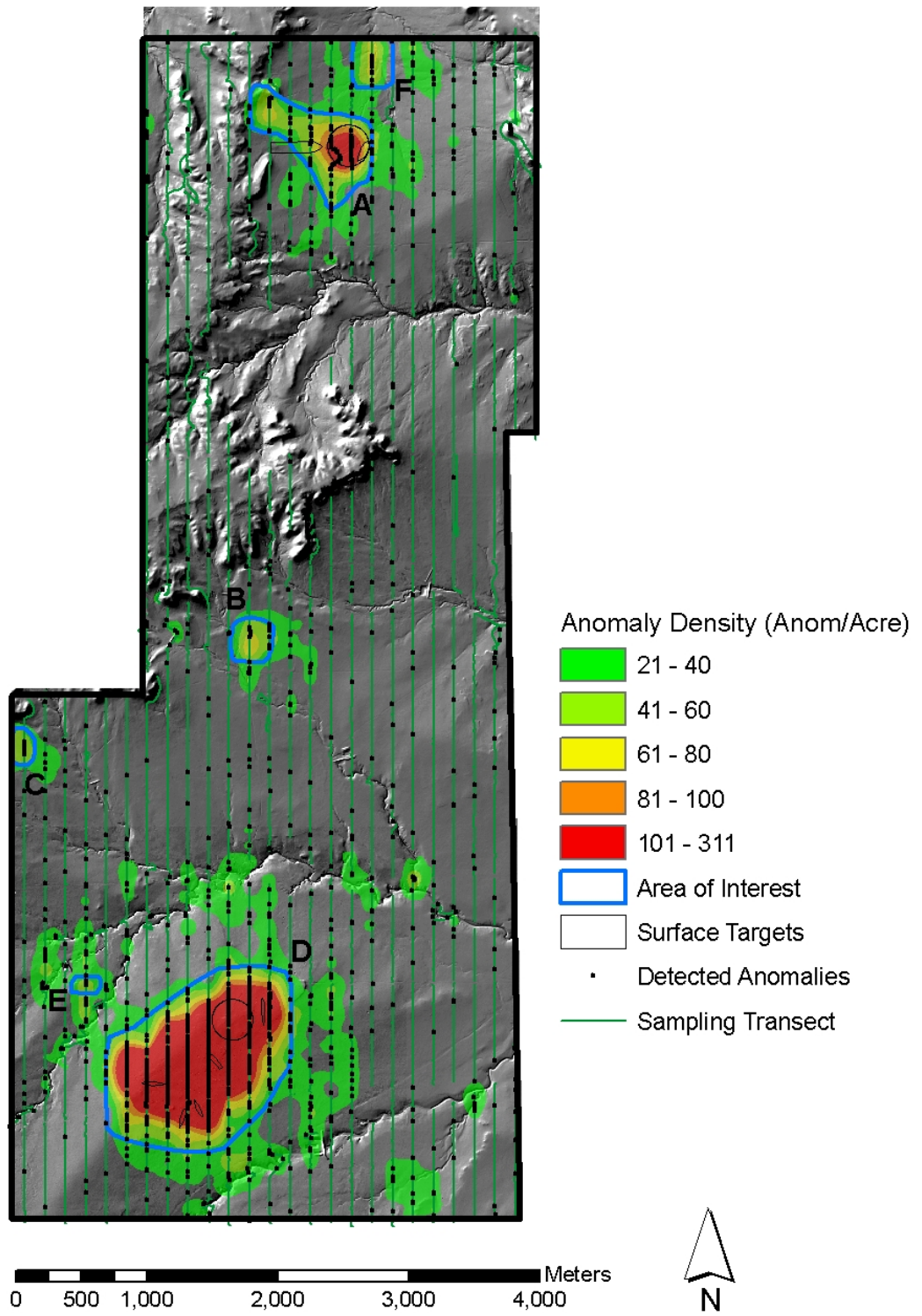


Figure 15: OK developed anomaly density estimates for the CSM-0 Dense transect design.

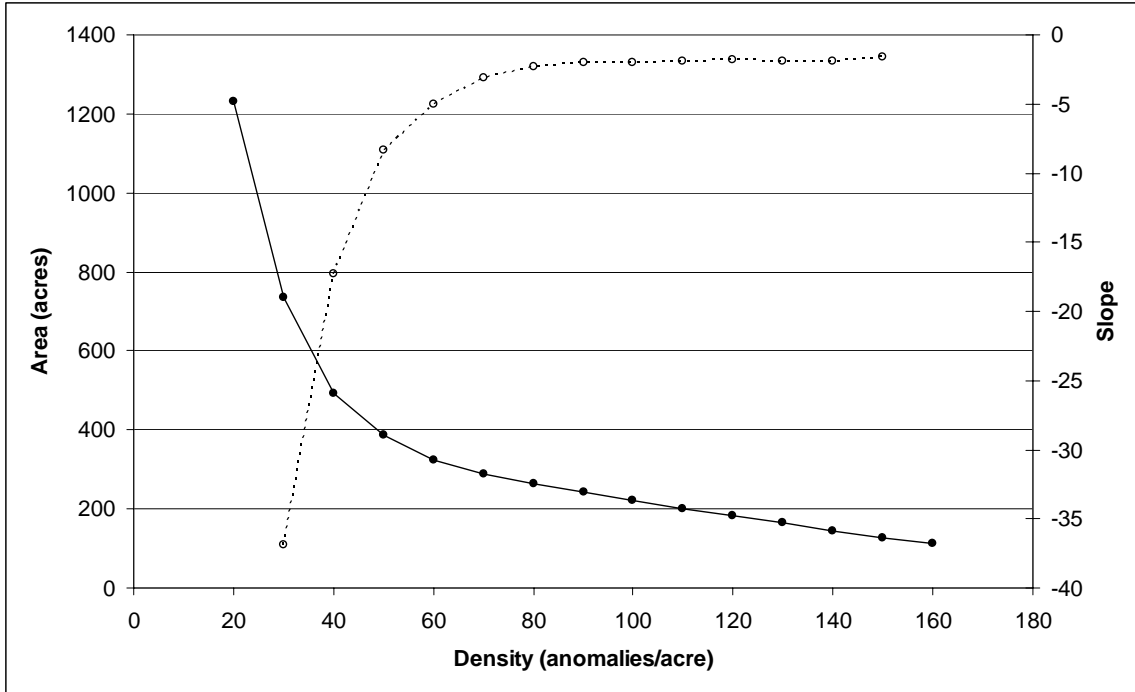


Figure 16: Graph showing amount of area (solid line) at or above specified anomaly density levels for OK estimates computed from CSM-0 Dense transect design sample data. Dashed line shows the slope of the solid line for that density level.

4.1.5. CSM-0 Bombing Target Dense with Additional Transect Design

Additional transects within the study were requested after the initial analysis of the full transect design data to better delineate and identify suspected target areas. These additional transects were located to further investigate some of the smaller AOI's identified from the Sparse and Dense CSM-0 transect designs and they were requested while the geophysical survey team were on site completing the CSM-0 transects. Figure 17 shows the full transect design with the additional requested transects that run east west.

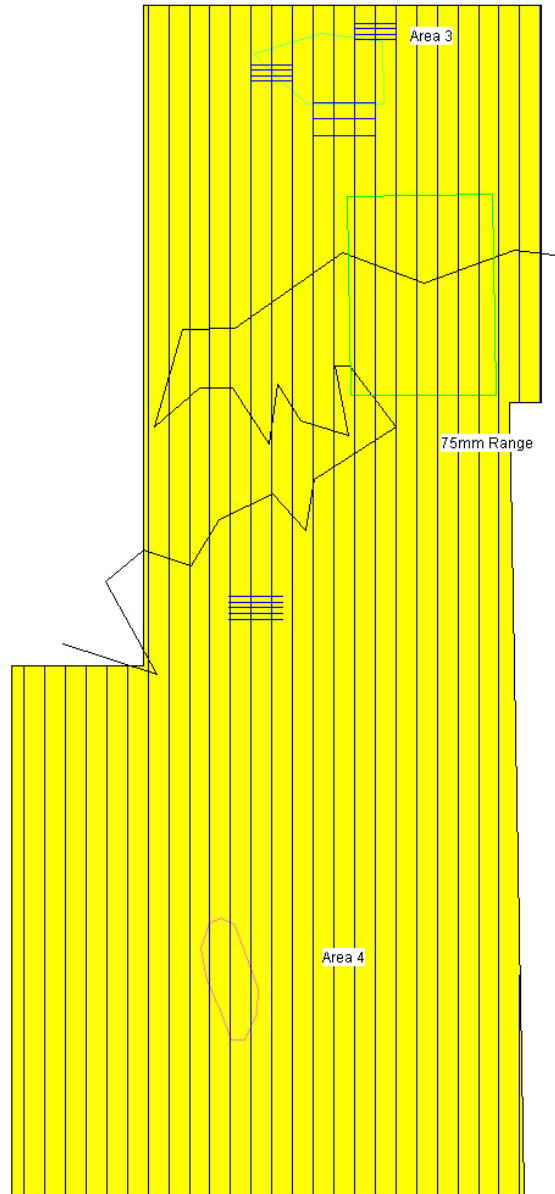


Figure 17: Dense bombing target transect design with additional transects requested in four areas of uncertainty

4.1.6. CSM-0 Bombing Target Dense with Additional Transect Design Target Identification

The actual surveyed area for this scenario only changed due to the four additional areas in which extra transects were requested. The four areas were identified as potential target areas but there was enough uncertainty about these areas that the additional transect requests were made. The survey team actually surveyed a little more area than proposed with the additional transects (Shown in Figure 18) which reduced the difference in coverage as compared to the CSM-0 Dense design (Table 3) and is summarized in Table 5.

	Transect Coverage (sq. meters)	Percent Coverage	Anomaly Count
Proposed	399283.64	1.336%	-
Actual	392608.37	1.313%	1596

Table 5: Summary of Dense CSM-0 Dense with Additional Transect Data.

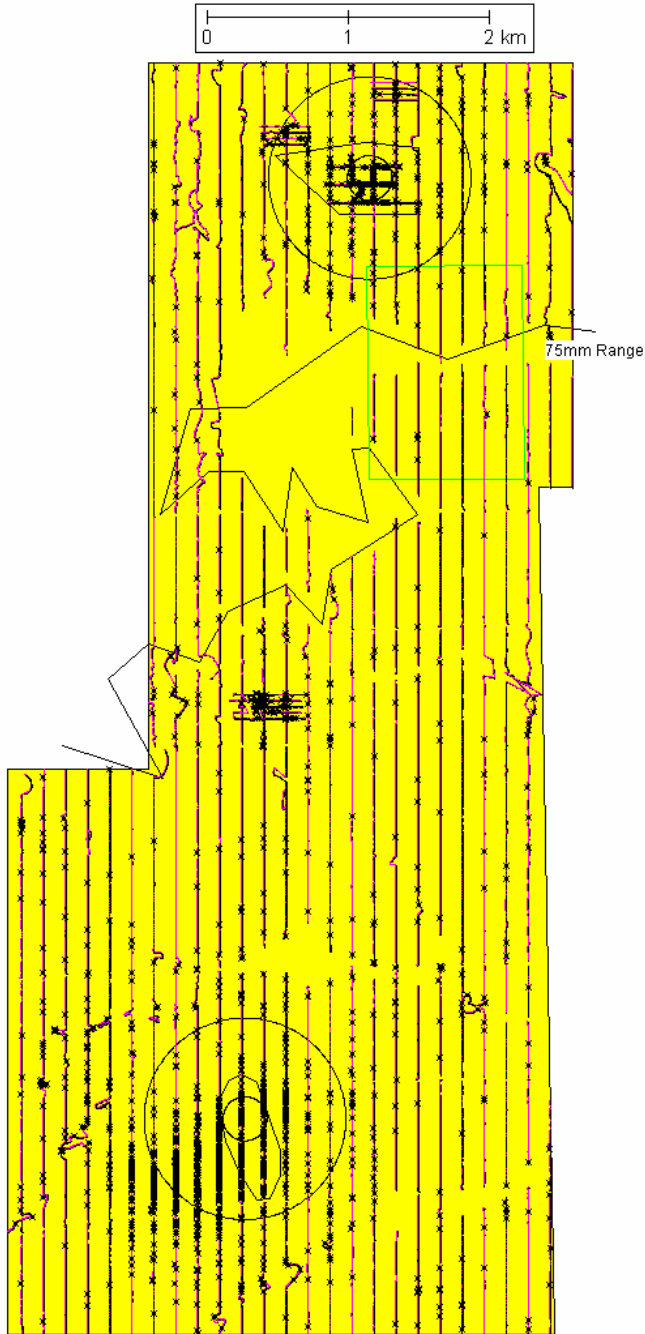


Figure 18: The lines represent the actual course over ground (COG) data based on the proposed bombing target dense plus additional transect design with the identified anomalies (black dots).

4.1.6.1. Target Area Identification and Delineation

Figure 19 depicts the flagged high density areas from the VSP flagging routine with a 53 anomalies per acre critical density based on a 300 m diameter window. The blue shaded areas are the delineated AOI defined by the PNNL and SNL team.

Figure 20 shows the indicator kriging probability levels for the CSM-0 Dense with Additional transect design using an indicator kriging threshold of 60 APA. This threshold level was selected in the same manner as used in the previously presented transect designs. Only areas with a probability of 0.05 or greater of being above the 60 APA threshold are indicated by color-filled contours. The data preprocessing was identical to that discussed previously, using an averaging window of 125 m in the X direction (East-West), and 325 m in the Y direction (North-South). The kriging grid cells were 25 m by 25 m in size. The variogram model developed from the transect data and used for the IK analysis is listed in Appendix A. The addition of the east-west transects resulted in only small changes in the variogram model compared to prior CSM-0 Dense variogram model. The range changed slightly, and the sill value for the model increased by 7%.

There are five individual AOI identified in Figures 19 and 20. This is a decrease in the number of AOI identified compared to CSM-0 Dense transect design. The additional transects served to eliminate AOI F by providing additional sample data which showed that this area had a lower anomaly density than initially estimated. The additional transects also tightened the boundaries of the remaining AOI.

Basic statistics for the identified AOI, which are identified by alphabetic designators, are provided in Table 6. One of the areas (AOI C) did not contain anomaly densities above the criteria (60 anomalies/acre) specified for the IK. Delineation of this area was based on the VSP flagging results and anomaly density estimates. There are some cases where small, isolated areas were flagged during the VSP analysis. Further investigation of the sample transect area, local topography, and anomaly distribution in these areas indicated that these were likely flagged due to sampling artifacts. These artifacts are typically the result of a discontinuity in the sample transect, or abrupt terrain changes such as occurs when sampling transects cross drainage features. These areas were not included in the delineation of the AOI's.

The two largest AOI (A and D) fall in areas containing identified terrain target features. AOI A and D correspond to the previously identified locations of T3 and T4 respectively. AOI E falls adjacent to, but removed from, T4. The other delineated AOI (B and C) do not correspond to any previously identified target areas

As shown in Table 6, AOI D (T4) has the highest transect anomaly density (unsmoothed) at 120 anomalies per acre. This is exactly the same as the CSM-0 Dense transect results, as this area did not receive any additional transects. Similarly, the results from AOI's B and C did not change from the previous scenario as no additional transects were added in these areas. AOI A has the second highest density at 82 anomalies per acre and

corresponds to T3. This area did receive additional transect coverage for this scenario. The addition of these transects reduced the number of AOI around T3, and tightened the AOI boundary. The AOI associated with T3 was reduced in area from 424,335 m² to 361,226 m², a reduction of 15%. The additional transects for AOI B provided information which assisted in refining the boundaries for this area expanding it by 28%.

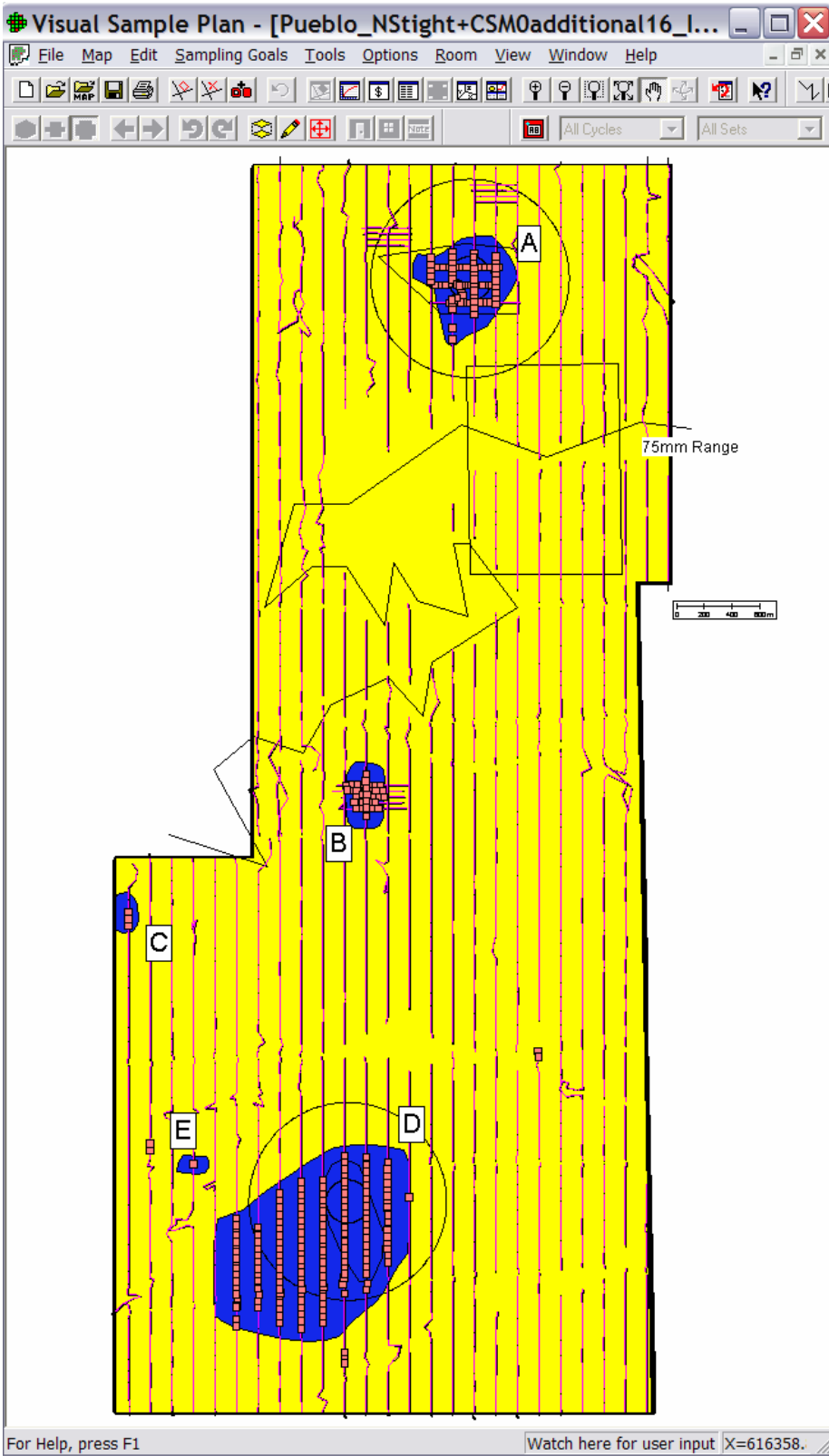


Figure 19: CSM-0 Dense with Additional flagged high density areas (red squares) based on a 300 m diameter window and a critical density of 53 anomalies per acre with delineated AOI boundaries (blue areas)

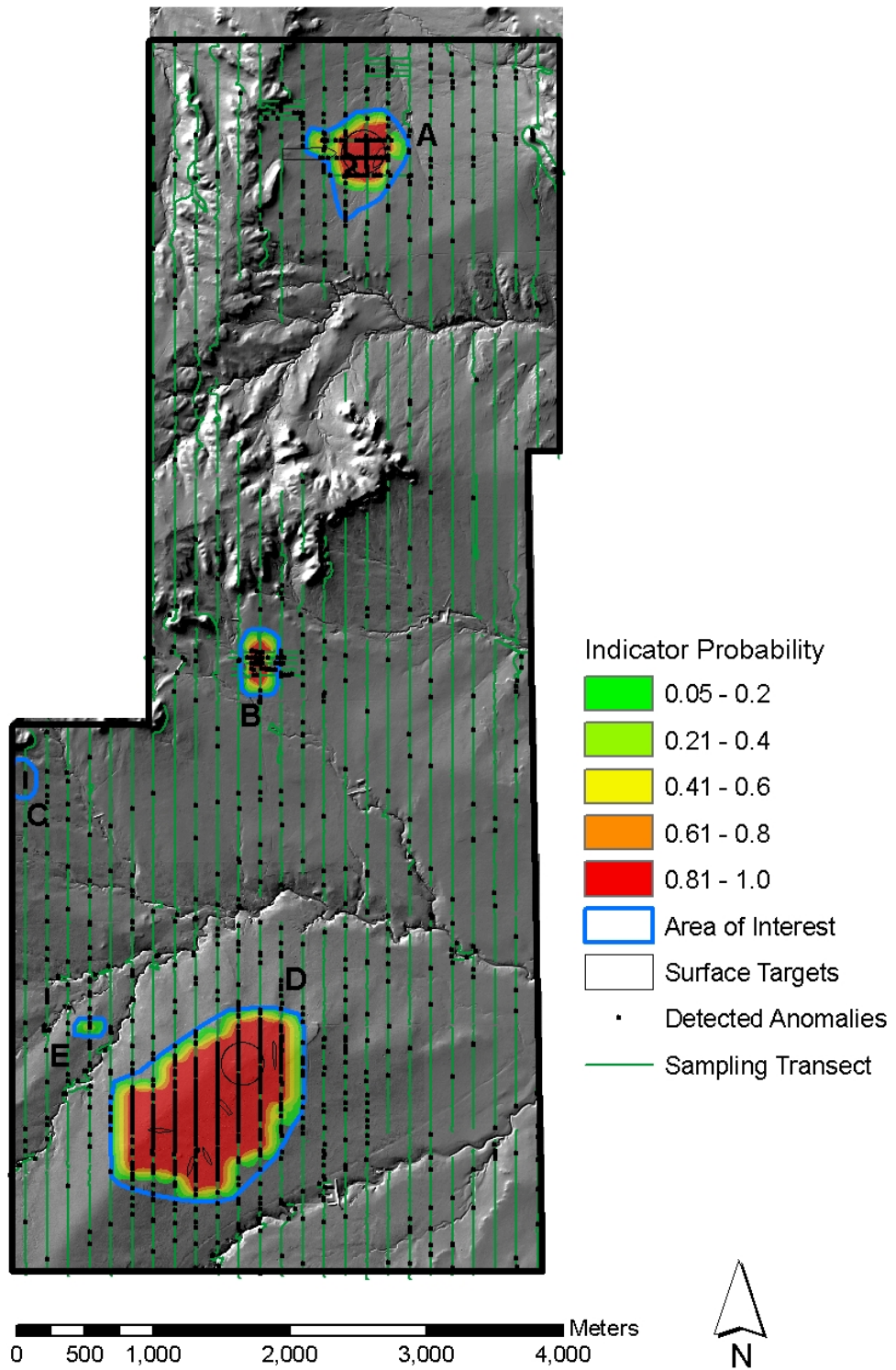


Figure 20: Indicator Kriging results and delineated AOI developed from CSM-0 Dense with Additional transect anomaly data.

AOI		Sample Transects Crossing AOI			Anomaly	
ID	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
A	361,226	7	3,761	7,522	155	82
B	122,080	6	1,918	3,836	57	59
C	41,697	1	278	556	8	58
D	1,534,685	10	10,027	20,054	602	120
E	26,954	1	133	266	3	45

Table 6: Basic statistics of AOI identified from CSM-0 Dense with Additional transect design. Anomaly density based on transect sample area and magnetic anomaly count.

4.1.6.2. Target Area Density Estimates

Ordinary Kriging (OK) was applied to the CSM-0 Dense with Additional transect anomaly data to develop continuous anomaly density maps for the entire Pueblo WAA site. The Kriging estimates were computed using 25 m by 25 m square grid cells and using the smoothed anomaly density values computed from the transect sample data. A variogram model specific to this data set was developed for use in the OK. The details of this model are provided in Appendix A. The addition of the east-west additional transects resulted in only small changes in the variogram model compared to prior CSM-0 Dense variogram model. The functions employed in the model remained the same although their ranges changed slightly, and the overall sill value for the model decreased by 2%.

Figure 21 presents a map of the anomaly densities (anomalies per acre) estimated from the OK analysis. The color-filled contours indicate anomaly densities; areas without a color overlay have estimated densities below 20 anomalies per acre. As shown in this figure, the identified AOI enclose the highest anomaly density locations and correspond with the IK results presented above. One additional AOI location not identified in the IK analysis but flagged during the VSP analysis (AOI C) appears as an isolated area with relatively high density values. As in the previous analyses, those areas at 60 APA and above form compact features with steep density gradients, whereas areas below 40 APA tend to be irregular and more dispersed, likely indicating a transition from a background to a target anomaly regime between values of 40 and 60 APA.

Figure 22 shows a graph of total area above various anomaly density levels for the entire Pueblo WAA site based on the OK density estimates. As in previous graphs, there are substantial changes in the slope of this graph for those segments in the 20 to 60 anomalies per acre range while the enclosed area drops from more than 1200 acres to less than 400 acres. The graph assumes a more uniform slope for density levels above 60 APA indicating the transition to a different density regime. This result is consistent with the results from previous sampling scenarios, and adds support to the selection of a critical density level in the neighborhood of 60 APA.

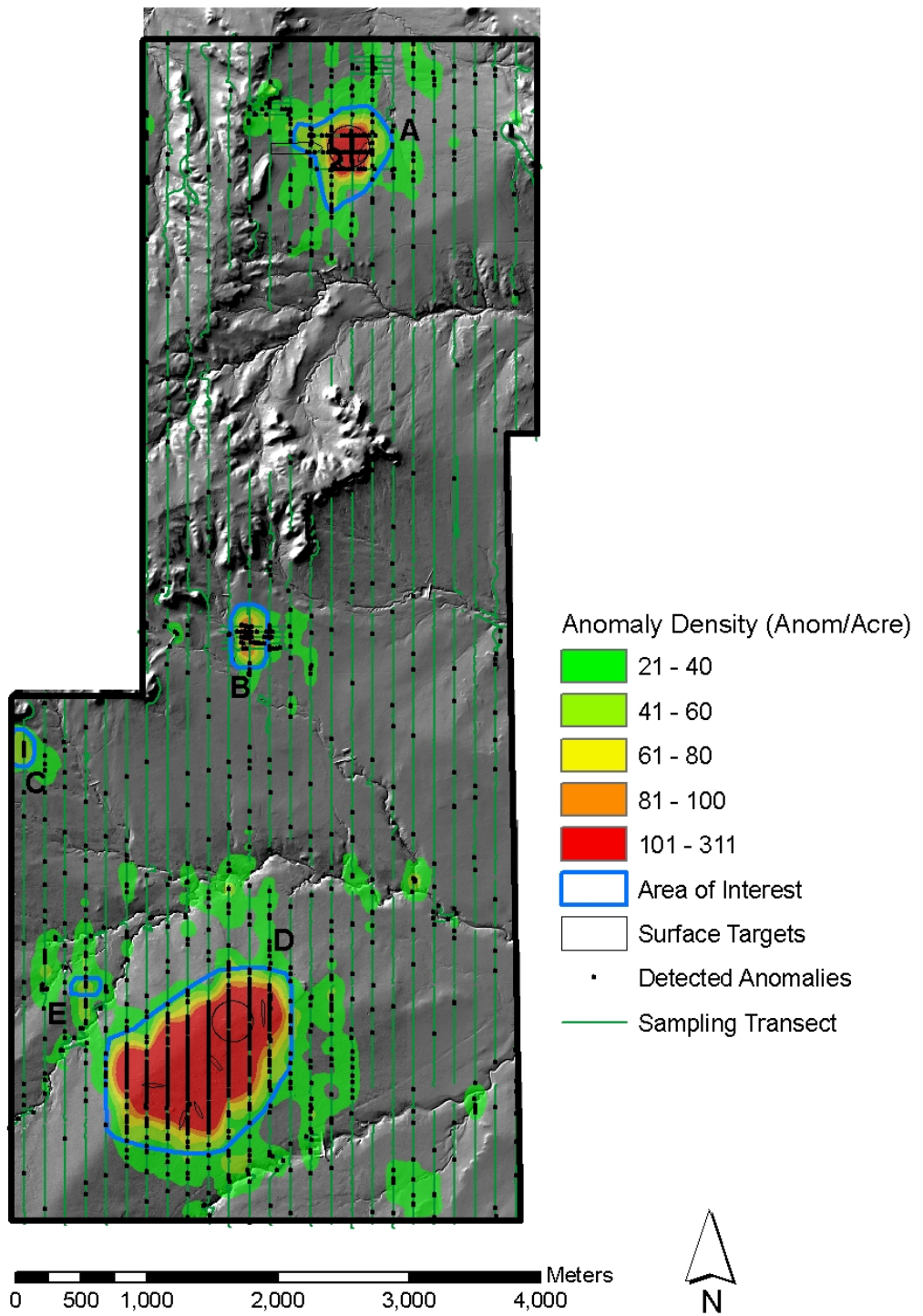


Figure 21: OK developed anomaly density estimates for the CSM-0 Dense with Additional transect design.

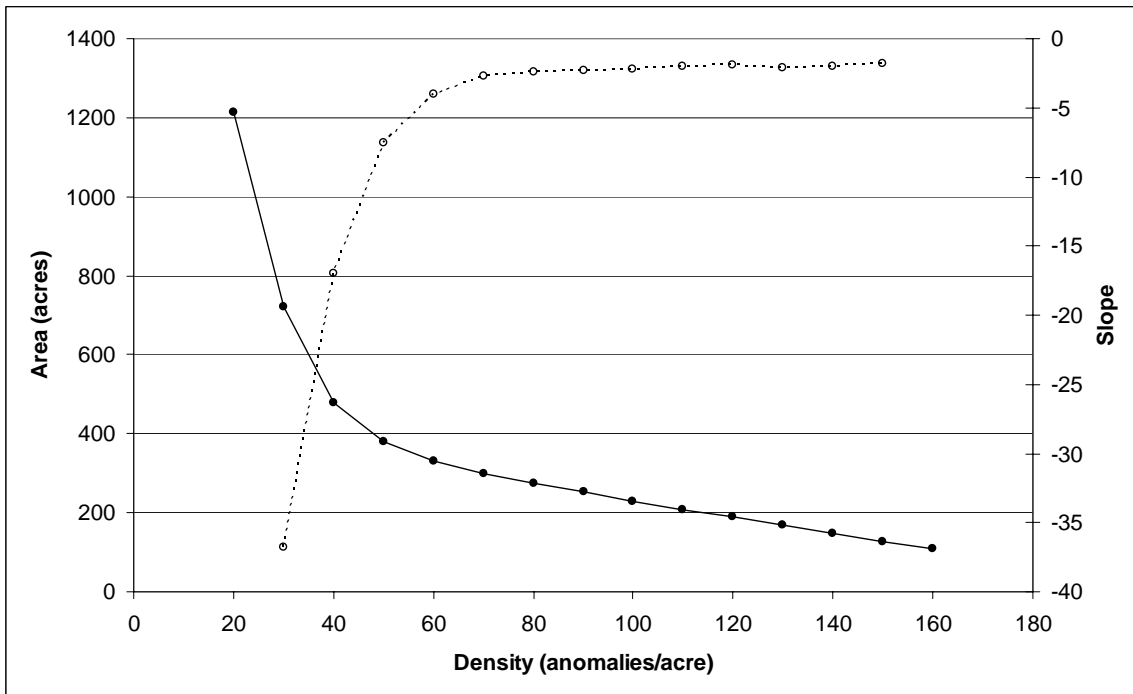


Figure 22: Graph showing amount of area (solid line) at or above specified anomaly density levels for OK estimates computed from CSM-0 Dense with Additional transect design sample data. Dashed line shows the slope of the solid line for that density level.

4.2. CSM-1 Bombing Target Transect Design and Analysis

4.2.1. CSM-1 Bombing Target Additional Requests Transect Design

The CSM-1 transect design was intended to be an entirely separate design from the previous designs based on the additional information gained from the high altitude ortho-photography and LIDAR imagery. The PNNL/SNL team received this imagery upon completion of the CSM-0 transect design surveys. Based on the initial target identification routines from the CSM-0 transects and the high altitude imagery the original site wide transect design proved adequate. However, this joint use of the initial transect design and the high altitude imagery did identify areas where additional transects were desired as shown in Figure 23. Future work at other sites may begin with the imagery and use that to direct the initial transect design. For the Pueblo site, this exercise allows for exploration and testing of techniques used to integrate wide-area imagery with geophysical transects.

From the imagery/lidar data, four additional potential areas of interest were identified. The two largest areas (blue lines) with additional transect requests lie on the perimeter of the southern target area as shown in Figure 24. Some isolated flagged areas appeared in each of these regions. The northern region of additional transects showed possible crater like terrain disturbances (some identified with arrows on Figure 24). Figure 25 depicts

the small area of interest on the western edge of the site. This area did get flagged as a potential high density area but was much smaller than the defined target area of interest. With the flagging, the additional lidar information that identified a potential crater feature (identified by the arrow) provided enough evidence to warrant the additional transects requested in this area. Figure 26 shows the additional transects by the northern target area requested due to the potential ship target identified with the lidar (shape identified by yellow lines). In Figures 24, 25, and 26 the red lines represent the existing transects gathered based on the CSM-0 transect design, the blue lines represent the additional transects requested based on added information from CSM-1, and the green boxes represent identified anomalies from CSM-0.

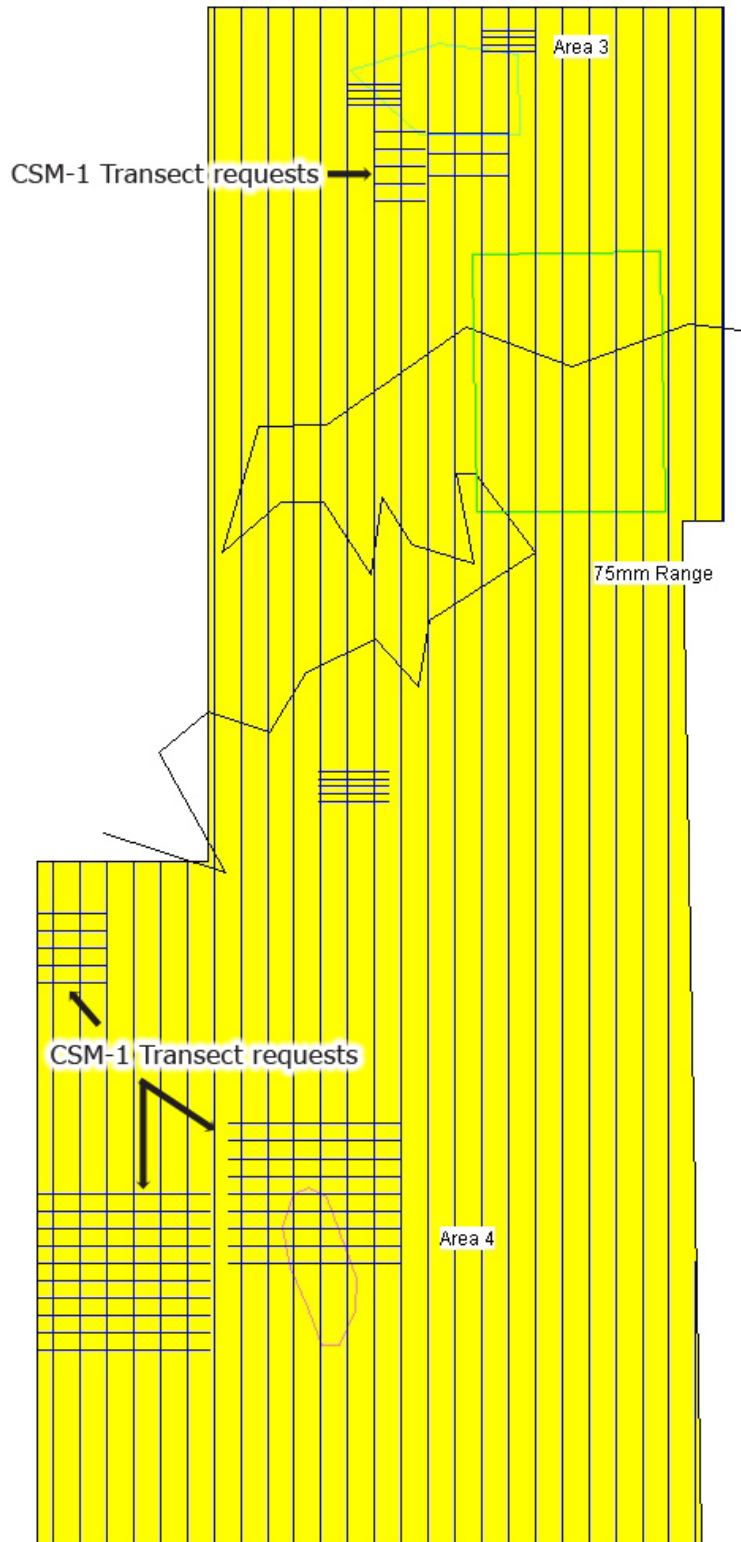


Figure 23: CSM-1 design with additional transects requested based on joint use of CSM-0 findings and high altitude imagery.

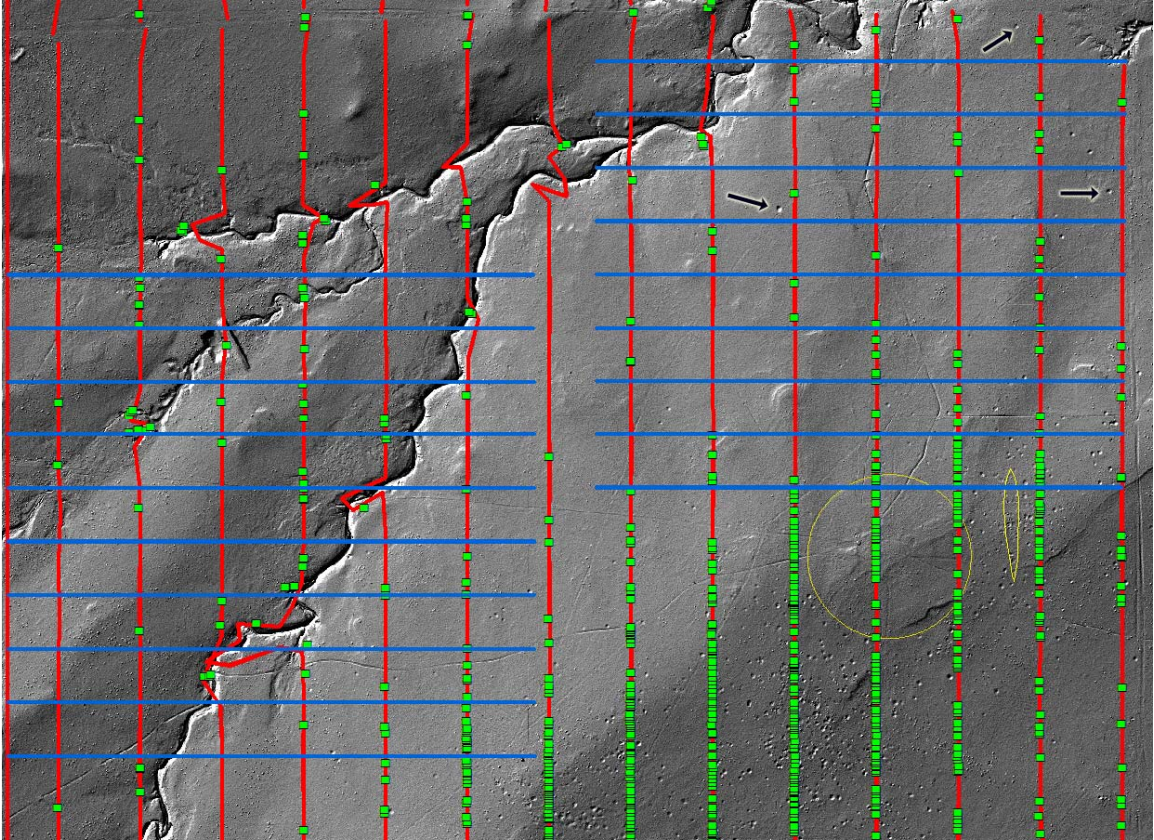


Figure 24: Southern Target Area with some of the CSM-1 transect requests

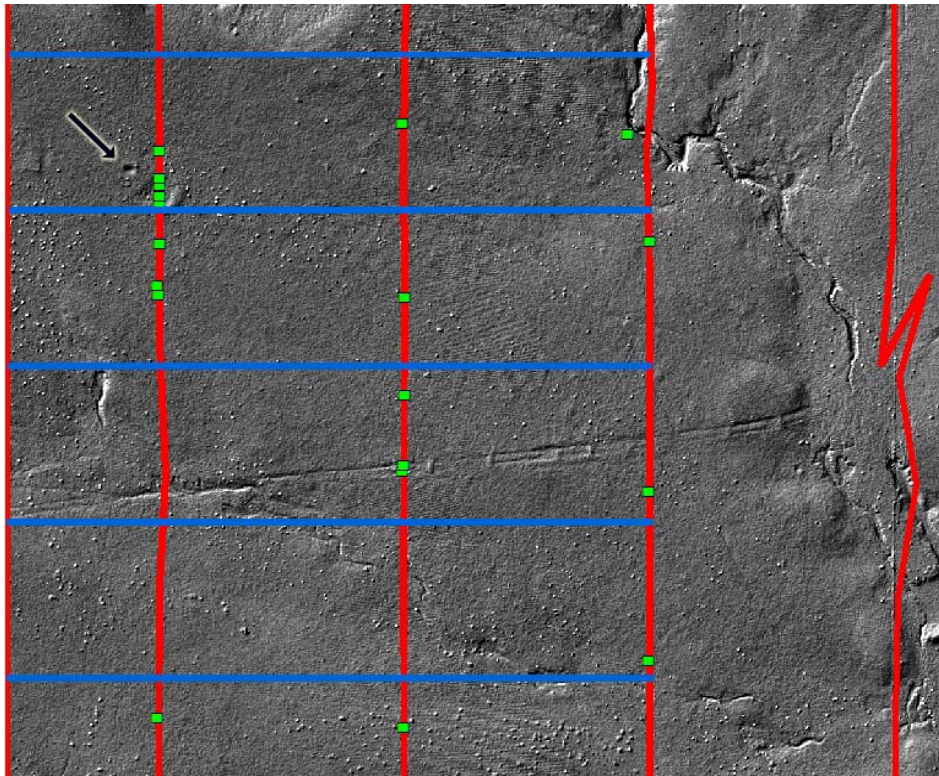


Figure 25: Additional transects requested along the western edge of the study area

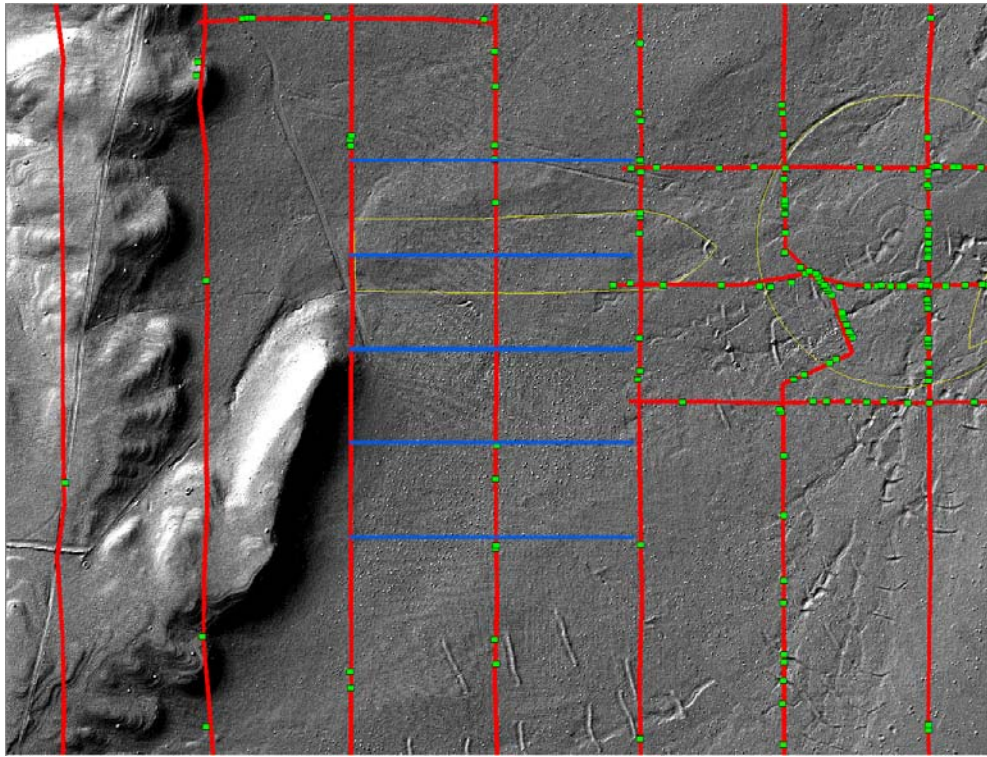


Figure 26: Additional transects requested by the Northern target area as a part of CSM-1

4.2.2. CSM-1 Bombing Target Transect Design Analysis

As described in section 4.2.1, these extra transects were requested as a result of the additional information supplied by the ortho-photography imagery and LIDAR data. The actual traversed transects based on the four requested areas, shown in Figure 27, covered more area than requested. Thus, the actual completed transect coverage slightly exceeded the total requested transect coverage, as shown in Table 7.

	Transect Coverage (sq. meters)	Percent Coverage	Anomaly Count
Proposed	444607.67	1.487%	-
Actual	445990.65	1.492%	1853

Table 7: Summary of CSM-1 Bombing Target Transect Data.

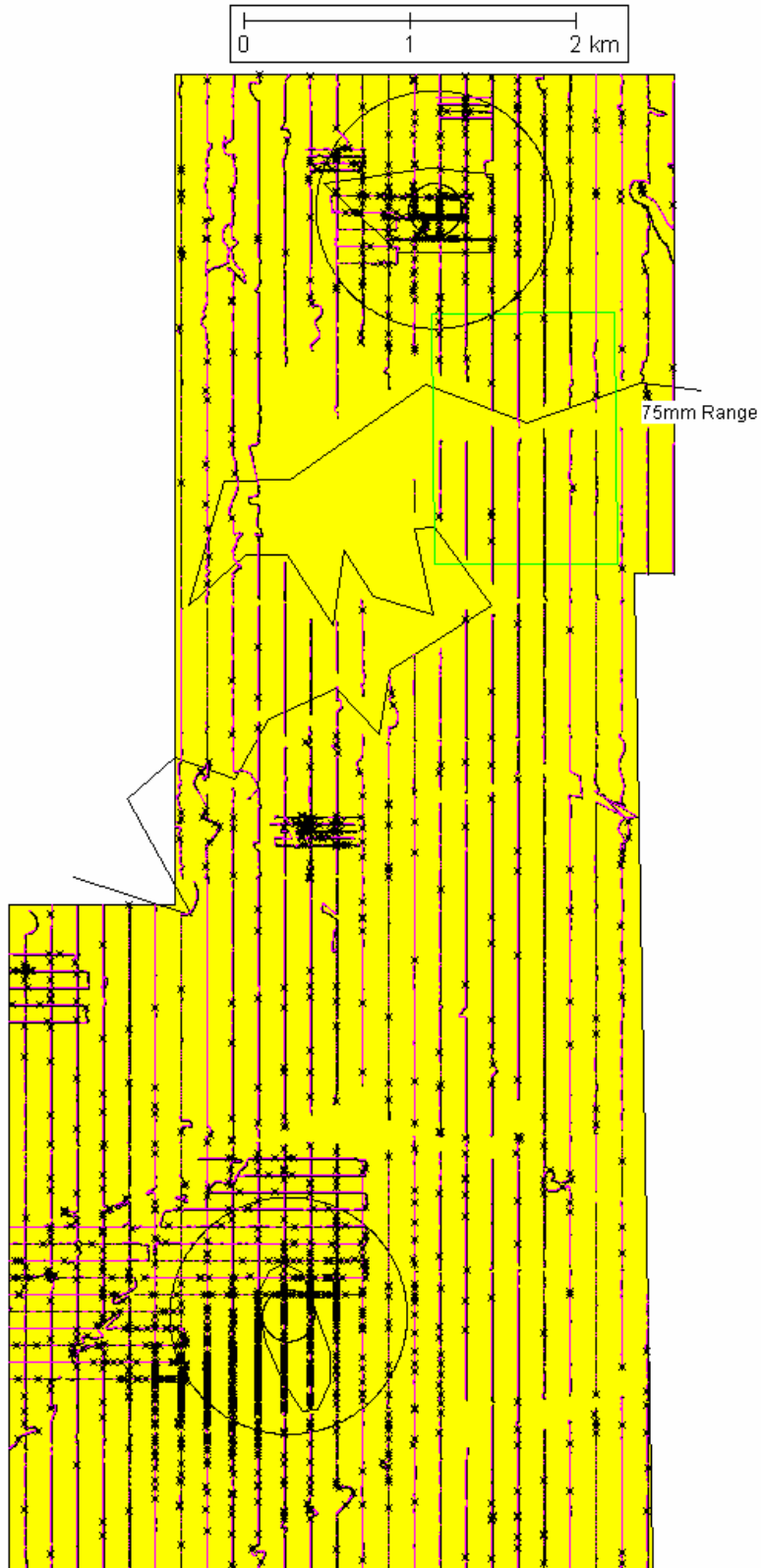


Figure 27: Actual course over ground (COG) data based on the proposed CSM-1 bombing target transect design with the identified anomalies.

4.2.2.1. Target Area Identification and Delineation

The flagged high density areas based on a 300 m diameter window and a critical density of 53 anomalies per acre along with the AOI defined by PNNL and SNL are shown in Figure 28. Figure 29 shows the indicator kriging probability levels for the CSM-1 transect design using an indicator kriging threshold of 60 APA. This threshold level was selected in the same manner as used in the previously presented transect designs. Only areas with a probability of 0.05 or greater of being above the 60 APA threshold are indicated by color-filled contours. The data preprocessing was identical to that discussed previously, using an averaging window of 125 m in the X direction (East-West), and 325 m in the Y direction (North-South). The kriging grid cells were 25 m by 25 m in size. The variogram model developed from the transect data and used for the IK analysis is listed in Appendix A and is similar to the model used in the prior analyses.

There are three individual AOI identified in Figures 28 and 29. This result is a decrease in the number of AOI identified compared to CSM-0 Dense with Additional transect design. The additional transects added for the CSM-1 design served to eliminate two previously listed AOI by providing additional sample data indicating these areas had lower anomaly density than initially estimated. Specifically, these additional transects eliminated the small AOI along the western margin of the site, and the small AOI to the west of T4. The additional transects also tightened the boundaries of the AOI associated with T3 and T4.

Basic statistics for the identified AOI, identified by alphabetic designators, are provided in Table 8. There are some cases where small, isolated areas were flagged during the VSP analysis. Further investigation of the sample transect area, local topography, and anomaly distribution in these areas indicated that these were likely flagged due to sampling artifacts. These artifacts are typically the result of a discontinuity in the sample transect, or abrupt terrain changes such as occurs when sampling transects cross drainage features. These areas were not included in the delineation of the AOI's.

As in previous sampling scenarios, the two largest AOI (A and D) fall in areas corresponding to target features T3 and T4 respectively. AOI B does not correspond to any previously identified target area.

As shown in Table 8, AOI D (T4) has the highest transect anomaly density (unsmoothed) at 117 APA. AOI A has the second highest density at 94 anomalies per acre and corresponds to T3. Additional transect coverage in this scenario added further refinement for AOI A, reducing its area by 30% compared to the previous sampling design. The additional transects for AOI D provided information which assisted in refining the boundaries for this area reducing it by 7%.

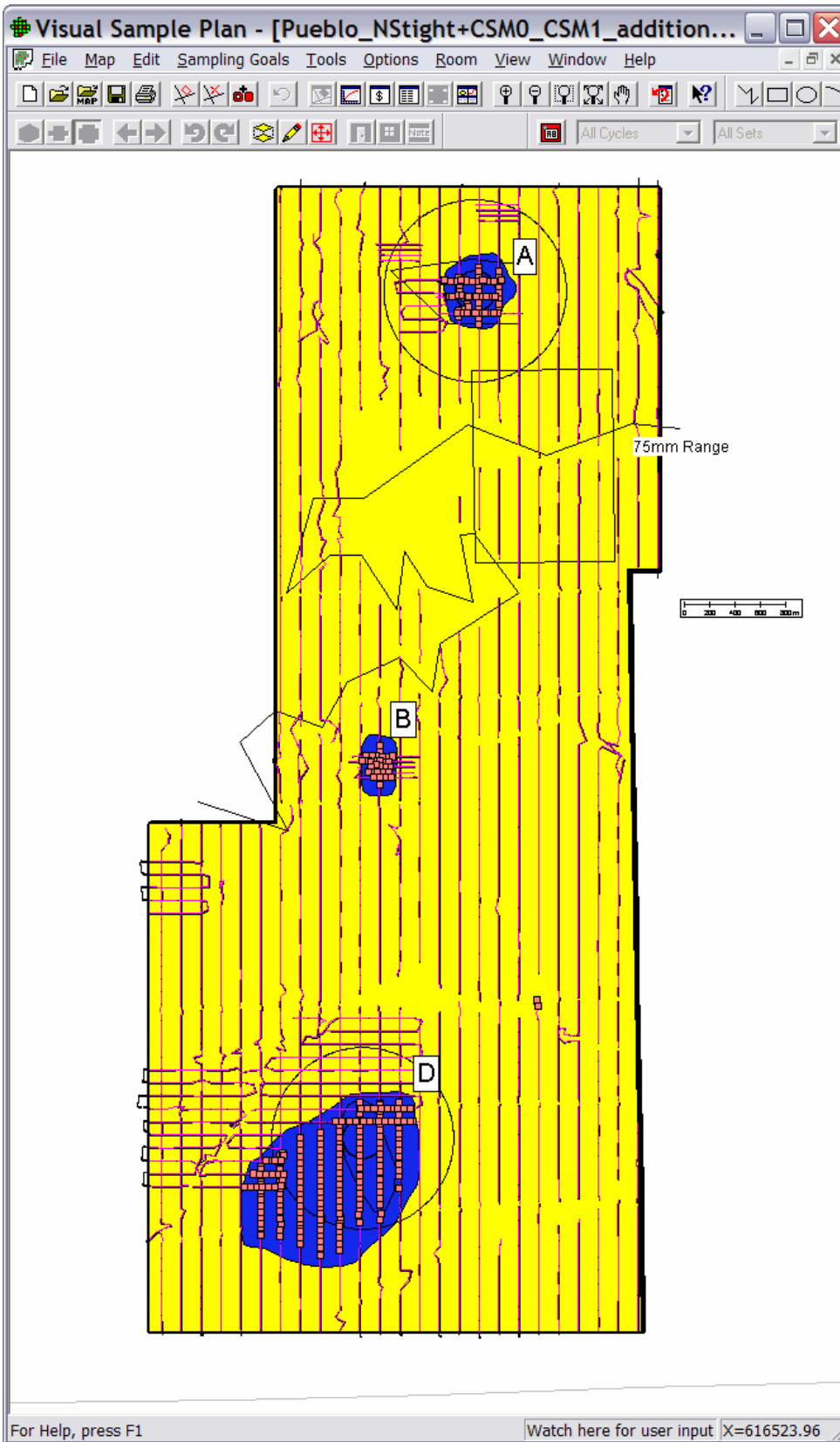


Figure 28: VSP flagged high density areas (red squares) based on a 300 m diameter window and a critical density of 53 anomalies per acre with delineated AOI boundaries (blue areas)

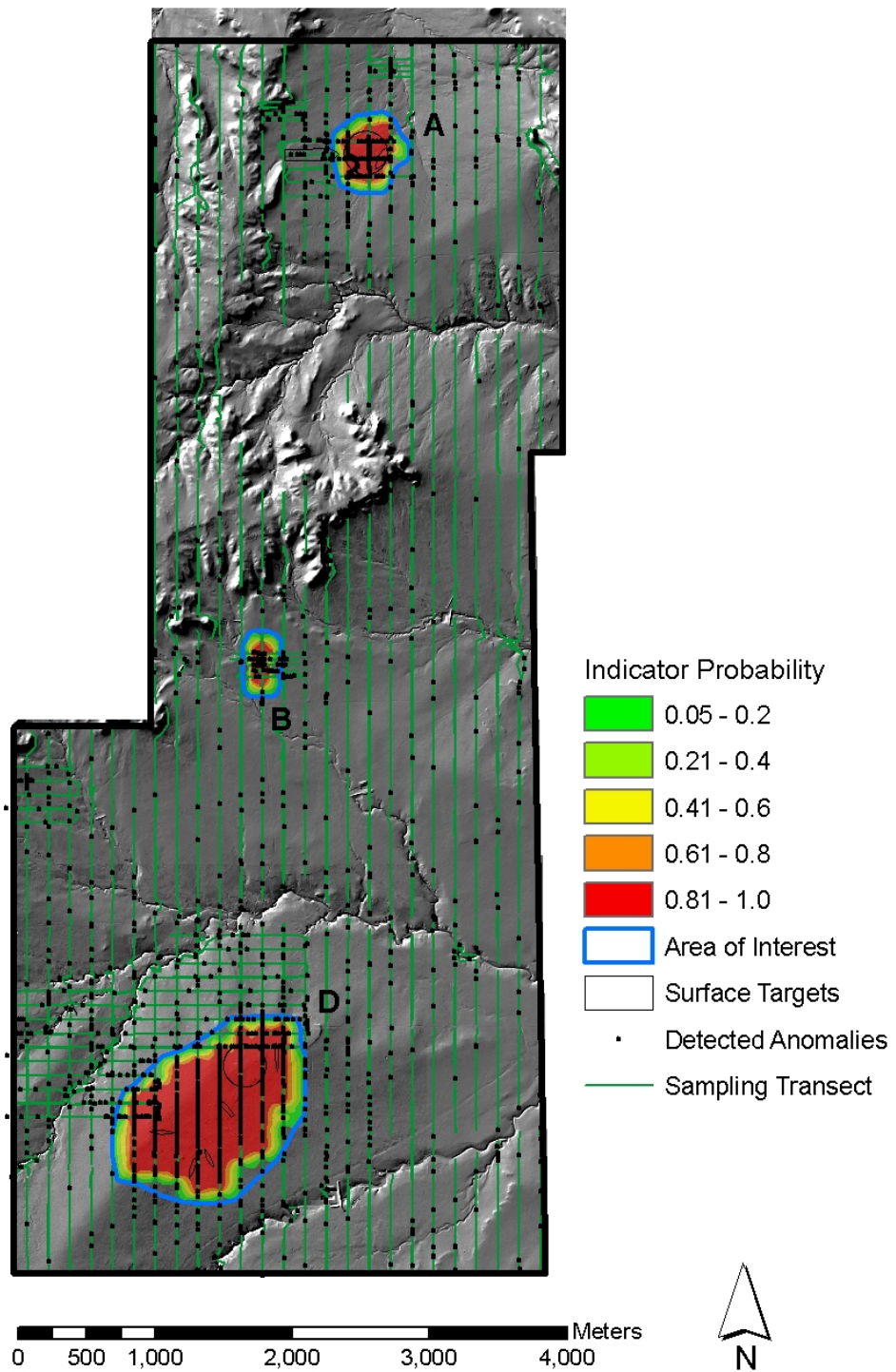


Figure 29: Indicator Kriging results and delineated AOI developed from CSM-1 transect anomaly data.

AOI		Sample Transects Crossing AOI			Anomaly	
ID	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
A	253,596	6	2,895	5,790	136	94
B	122,080	6	1,918	3,836	57	59
D	1,434,419	17	11,963	23,926	699	117

Table 8: Basic statistics of AOI identified from CSM-1 transect design. Anomaly density based on transect sample area and magnetic anomaly count.

4.2.2.2. Target Area Density Estimates

Ordinary Kriging (OK) was applied to the CSM-1 transect anomaly data to develop continuous anomaly density maps for the entire Pueblo WAA site. The Kriging estimates were computed using 25 m by 25 m square grid cells using the smoothed anomaly density values computed from the transect sample data. A variogram model specific to this data set was developed for use in the OK and it is similar to previous variogram models. The details of this model are provided in Appendix A.

Figure 30 presents a map of the anomaly densities (anomalies per acre) estimated from the OK analysis. The color-filled contours indicate anomaly densities; areas without a color overlay have estimated densities below 20 APA. As shown in this figure, the identified AOI enclose the highest anomaly density locations and correspond with the IK results presented above. As in the previous analyses, those areas at 60 APA and above form compact features with steep density gradients, whereas areas below 40 APA tend to be irregular and more dispersed, likely indicating a transition from a background to a target anomaly regime. In Figure 28 there are several small, isolated, low density regions removed from the identified AOIs. These areas tend to occur in steep terrain adjacent to drainage features. This is most notable near AOI D. This curious correlation between terrain and anomaly density may indicate an artifact of the sampling system interacting with steep topography.

Figure 31 shows a graph of total area above various anomaly density levels for the entire Pueblo WAA site based on the OK density estimates. As in previous graphs, there are substantial changes in slope of this graph for those segments in the 20 to 60 APA range corresponding to an enclosed area of nearly 1200 acres to less than 400 acres. The graph assumes a more uniform slope for density levels above 60 APA indicating the transition to a different density regime. This is consistent with the results from previous sampling scenarios, and adds support to the selection of a critical density level in the neighborhood of 60 APA.

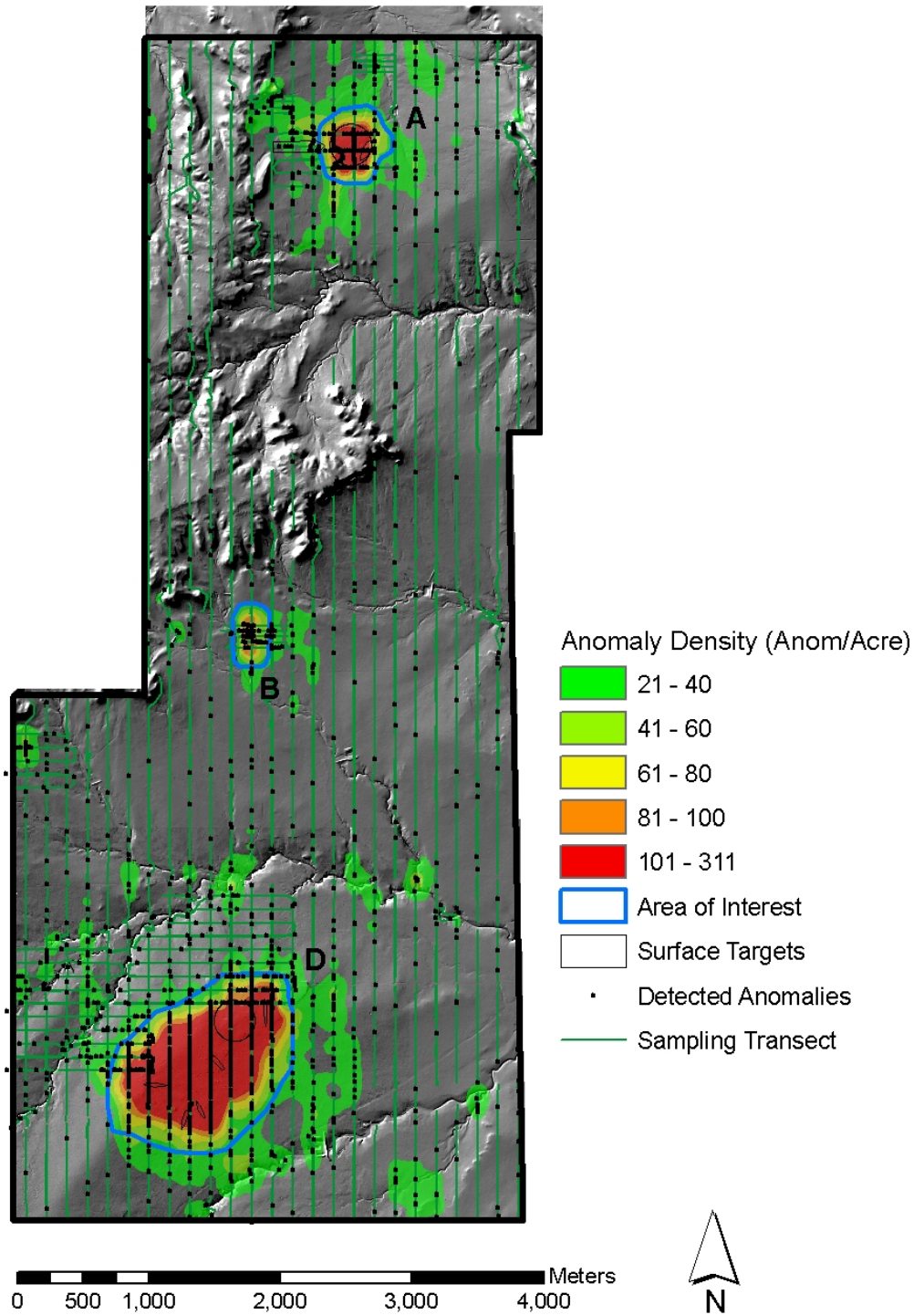


Figure 30: OK developed anomaly density estimates for the CSM-1 transect design.

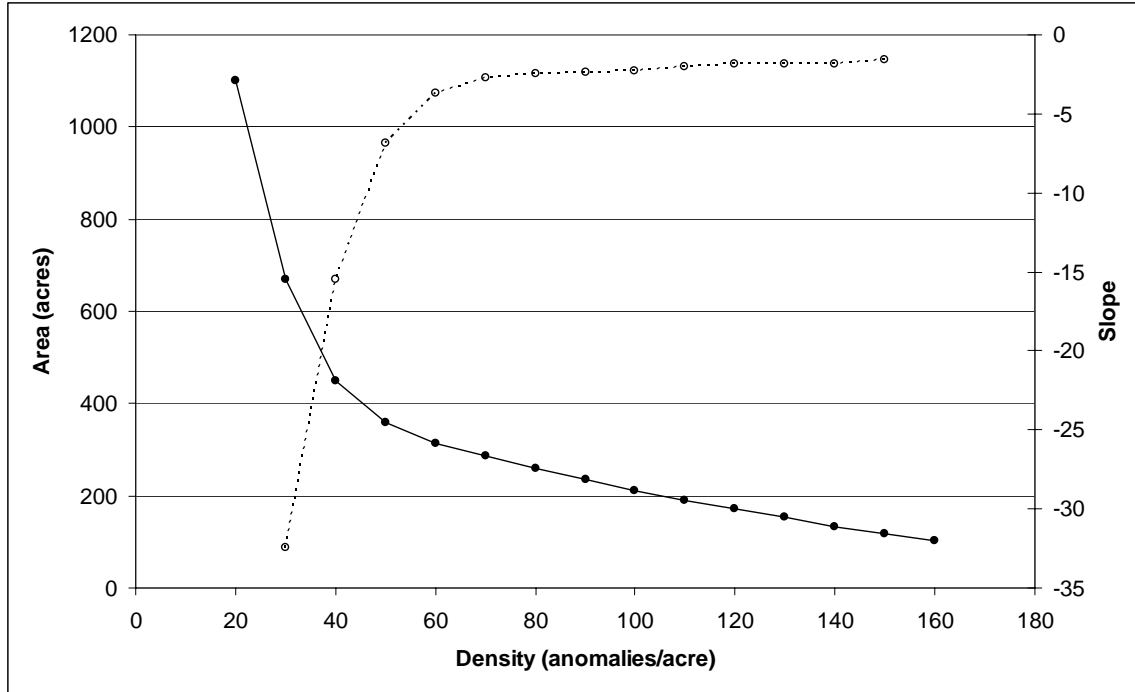


Figure 31: Graph showing amount of area (solid line) at or above specified anomaly density levels for OK estimates computed from CSM-1 transect design sample data. Dashed line shows the slope of the solid line for that density level.

4.3. 75 mm Suspect Area Transect Designs

4.3.1. 75 mm Suspect Area Dense Transect Design

Based on the finding of 75 mm munitions by a rancher, a subset of the entire site was identified as a suspect 75mm bombing area and a survey design was developed to detect a target area if one indeed existed. Based on the CSM-0 and the ASR, the suspected 75 mm air-to-ground range, which is 1,660,128 square meters in size, was probably used by a T13E1 75 mm cannon which was placed in the nose of a B-25 bomber. It is suspected that the rounds used in the cannon were armor piercing munitions which did not contain high explosives. Using the CSM, the uncertainty associated with this target area is very high and the potential target area was assumed to be elliptical (perhaps 100 m wide by as much as 8000 m long). While the potential length is extremely large, the sparse and dense transect designs are based on the suspected width of 100 meters. The sparse transect design was dropped for analysis and will not be presented in this document because very little metallic activity was identified in this area.

Since the flight approach pattern and therefore the orientation of a potential target area ellipse was unknown, a conservative circular 100 meter target area was assumed for this 75 mm Dense transect design. For the dense transect design to identify all potential 100 meter circular 75mm target areas, a 2 meter wide rectangular grid transect pattern spaced

appropriately to ensure a 100% probability of traversal was developed. The 15 east-west transects are 102 meters apart on center and cover 2.0% of the suspected 75mm range and the 7 north-south transects, used from the CSM-0 Dense 100 lb bomb target area designs, are 155 meters apart on center and cover 1.1% of the suspected 75 mm range. Figure 32 shows the locations of the rectangular grid transects on the suspected 75 mm air-to-ground impact area.

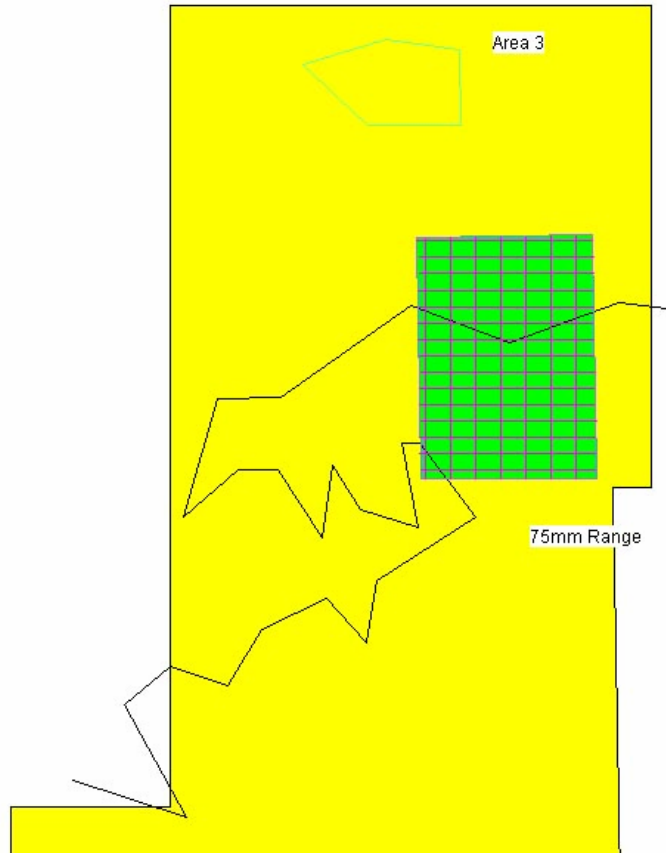


Figure 32: 75 mm Dense transect design located in the northern portion of the study area

4.3.2. 75 mm Suspect Area Full Transect Design Analysis

Because of a large wash and small grouping of trees, some of the requested transects could not be obtained. Figure 33 shows the actual areas that were covered by the transects. As Table 9 details, there were only 28 identified anomalies in this area. As a result of this limited anomaly detection, the 75 mm transect design analysis shown in Figure 34 was analyzed as a part of the CSM-0 Dense with Additional transect survey design. Figure 35 shows a window density histogram, from VSP, based on the identified 75 mm suspect area. No high density areas were flagged and this histogram shows a distribution that is most likely associated with background alone. Based on the results shown in Figures 34 and 35 no potential target areas were identified within the suspected 75mm munitions range. During the study, findings indicated that this area did not exist in the Pueblo WAA site.

The additional transects added to the site study were incorporated into the CSM-1 transect data and used in generating OK density estimates similar to the previously presented sampling scenarios. The results from this estimation confirm that there are no high anomaly density areas within the suspect 75 mm area. No density estimates above the 20 APA background level were created within the suspect 75 mm area. Figure 34 shows the density estimate results.

	Transect Coverage (sq. meters)	Percent Coverage	Anomaly Count
Proposed	54112.96	3.260%	-
Actual	45254.23	2.726%	28

Table 9: Summary of CSM-0 75mm Dense Transect Data. The differences in proposed and actual coverage were largely a result of a wash and a grouping of trees in this area. All accessible areas were surveyed at the proposed coverage density.

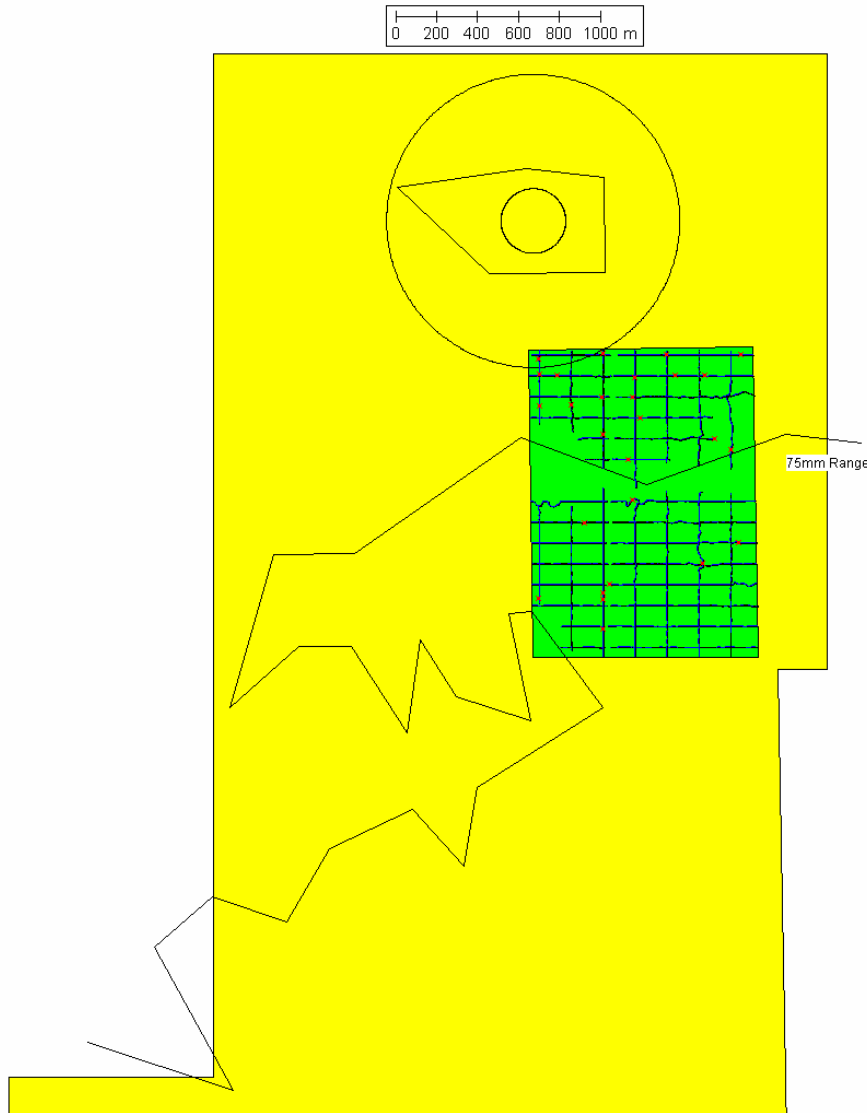


Figure 33: Actual course over ground (COG) data based on the proposed CSM-0 75mm transect design with the identified anomalies.

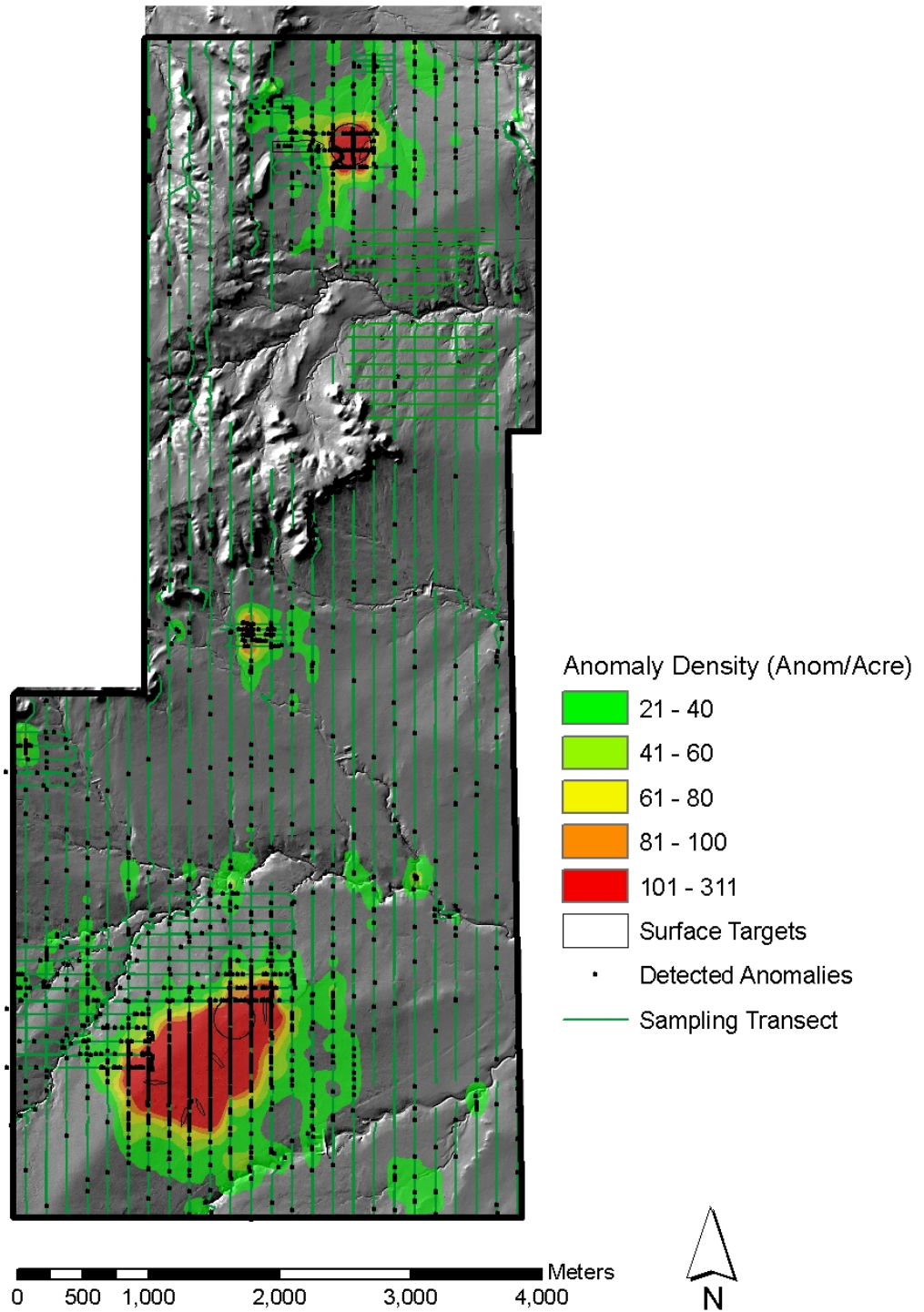


Figure 34: OK anomaly density estimates for the CSM-0 75 mm transect design.

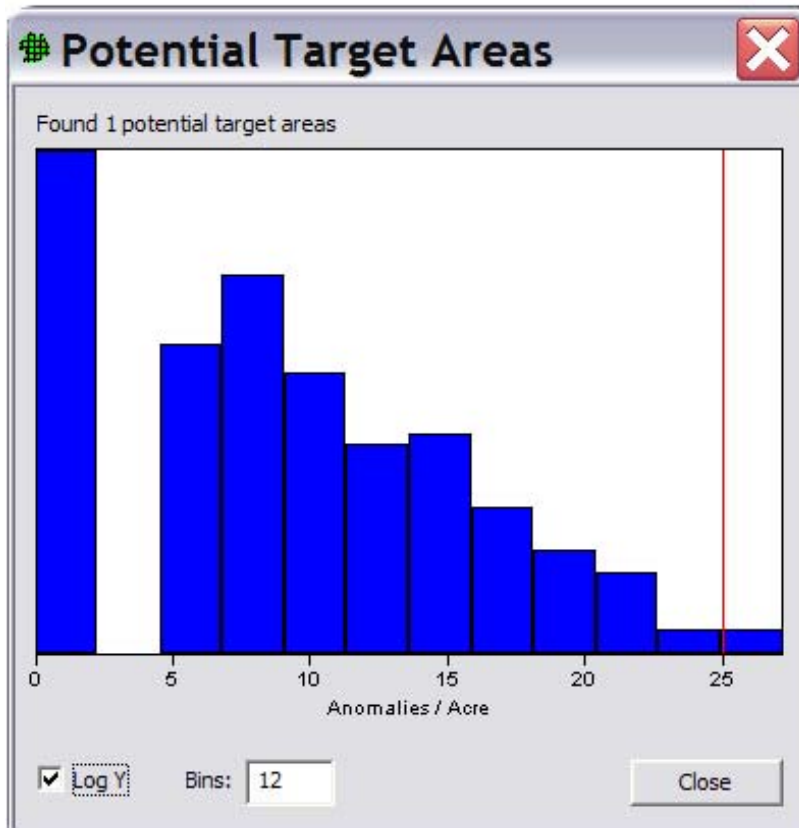


Figure 35: Histogram of the window densities based on the VSP routine for the identified 75 mm suspect area.

The estimated anomaly density within this 75 mm suspect area is 2.5 anomalies/acre. Figure 36 shows the probability of detecting a 100 m diameter target area as a function of target area density when background is 2.5 anomalies per acre and the transect spacing is as described above. The estimate of 2.5 anomalies/acre makes the assumption that all anomalies identified in this area are associated with background. This assumption may make the background estimate too high if potential target areas were actually traversed. Using a higher estimate for background will result in conservative estimates for different probabilities of detection shown in Figure 36. Thus, this figure can be used to show how well this transect design would perform based on the assumed target area density. During the study, additional and clarified facts about the 75mm munition found indicated that this area did not exist in the Pueblo WAA site.

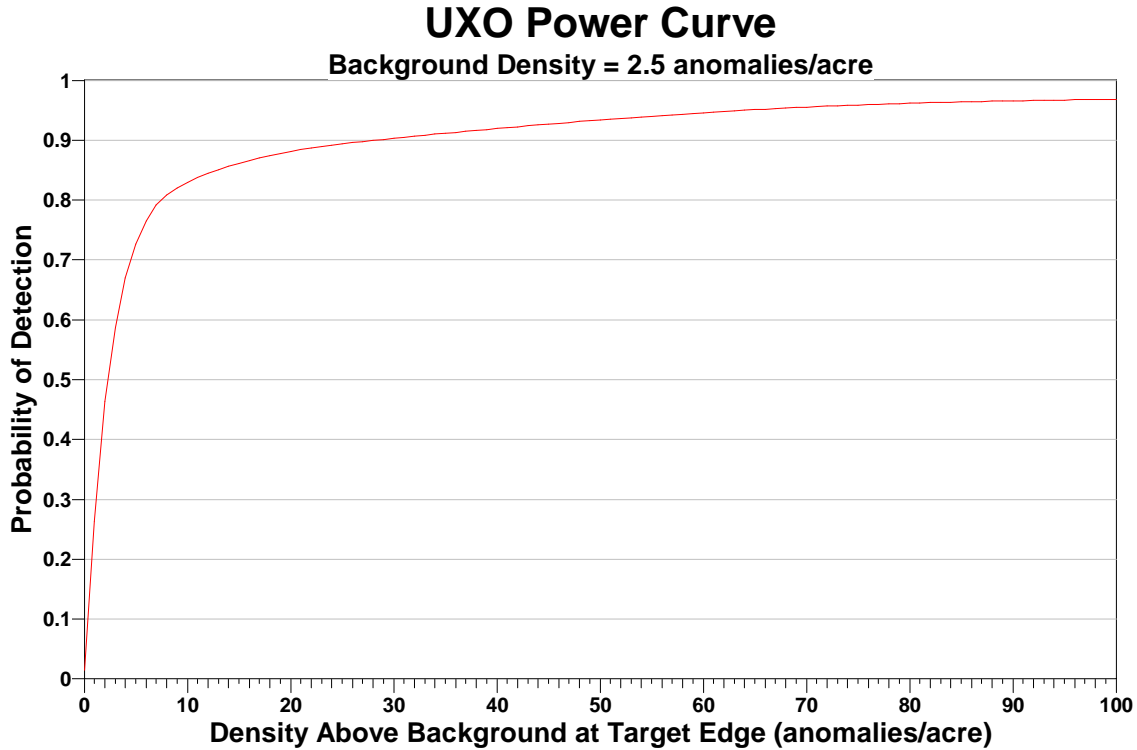
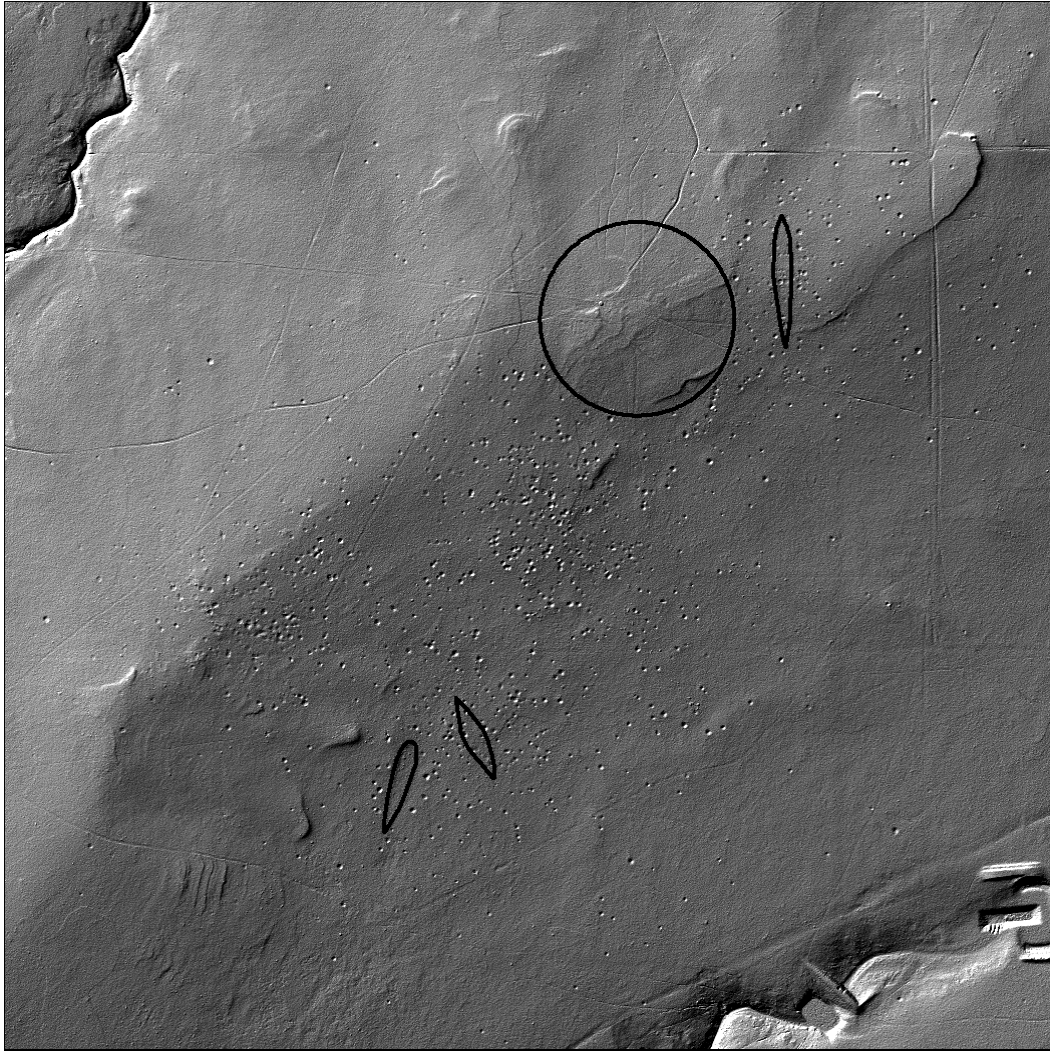


Figure 36: Probability of detection a 100 m diameter target area with a rectangular transect spacing of 102 x 155 m on centers and a 2.5 anom/acre background level as a function of target area density.

4.4. Crater Density Analysis for Target Area 4

Target 4 (T4) located in the southern portion of the Pueblo WAA site is surrounded by a large number of topographic depressions. Their proximity to T4, size, shape, and lack of any other likely formative process, strongly suggest that these depressions are munitions related craters. Figure 37 shows a shaded relief image created from the available LIDAR data of the terrain around T4. Figure 38 shows a detailed view of the craters around two surface target features. Figure 39 shows a photograph of a crater located near T4.



0 125 250 500 750 1,000 Meters


 Surface Target Feature



Figure 37: Shaded relief image of topographic LIDAR data showing crater features around T4. Previously identified target circle and ship outlines also shown.

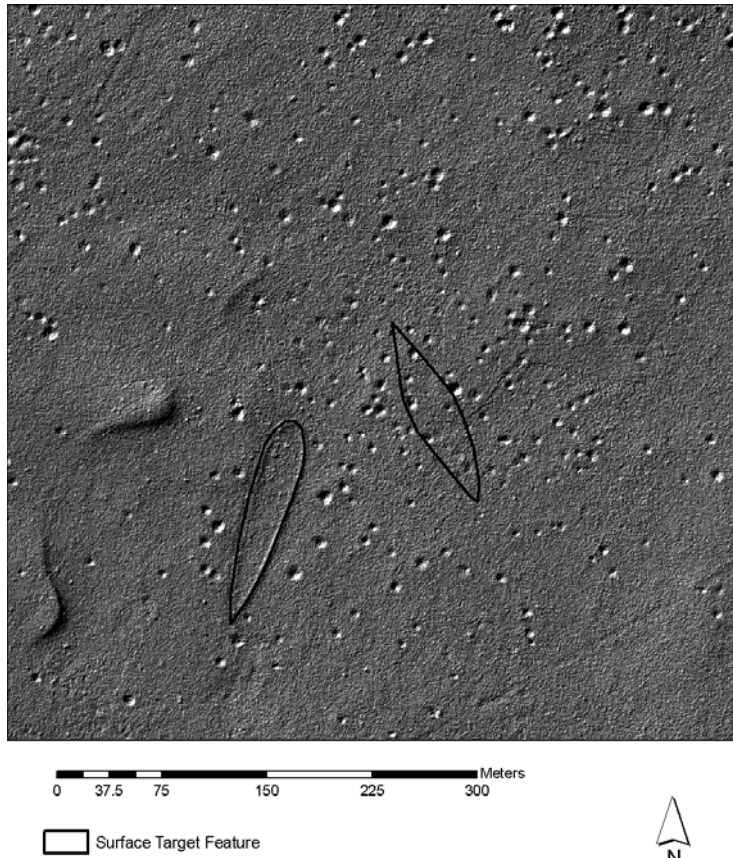


Figure 38: Shaded relief image of topographic LIDAR data showing details of crater features around previously identified ship target outlines.



Figure 39: Photograph of crater feature near T4

Closer examination of the spatial distribution of craters in the T4 area indicates some clustering. Clustering of the craters may indicate the locations of individual target features. To examine this aspect more thoroughly, a data set of crater locations was created by digitizing the location of each crater using a geographic information system (GIS). Craters were identified through visual examination of the LIDAR images. These locations were then used in an Average Nearest Neighbor Analysis using Euclidean distance within the GIS. The result from this analysis indicates that there is less than 1% likelihood that the pattern of points representing the crater locations could be the result of a random process and that there is a strong indication of clustering of the crater locations.

A relative density map of the craters was also created from the digitized location data and is shown in Figure 40. In this map, areas with a relatively high density of craters are indicated with red shading; areas with relatively low density are shown by green shading. Examination of the density map reveals several areas with relatively high crater densities. Four individual clusters of high crater density have been identified and are labeled “A” through “D” (Figure 40).

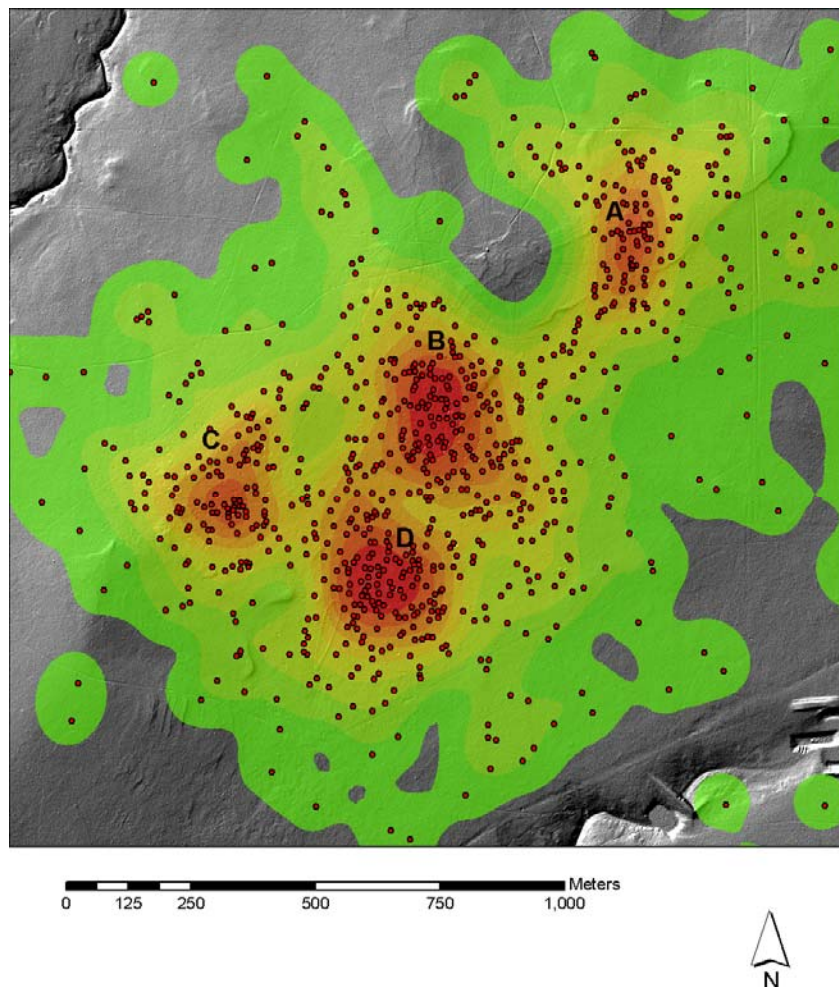


Figure 40: Crater density map; high density areas are shaded red, low density areas are shaded green. Individual craters shown as filled circles. Alphabetic labels identify high density clusters.

Two of the identified clusters, A and D, are coincident with previously identified surface targets (ship outlines) and indicate heavy usage of these surface targets (Figure 41). Conversely, clusters B and C, which map as distinct clusters separate from A and D, do not have any previously identified surface target nearby. This may indicate that clusters B and C are associated with unidentified target features. Curiously, the circular terrain target feature has a very low crater density. This may indicate that this area was re-graded at some time subsequent to target use.

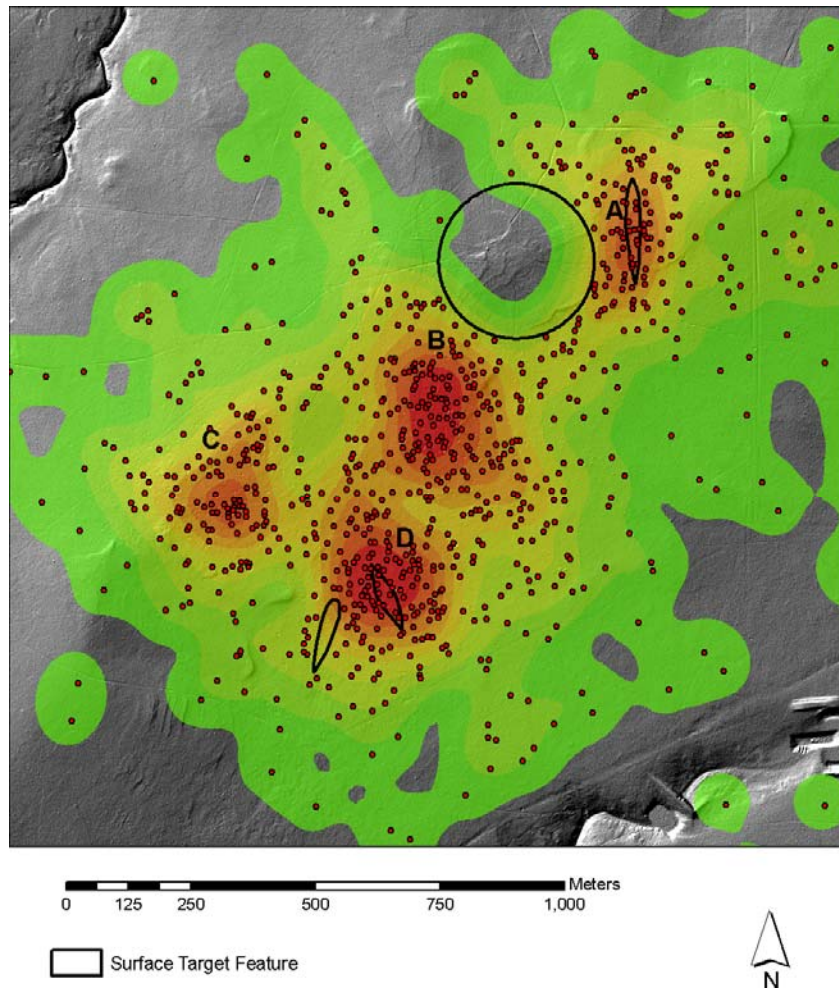


Figure 41: Crater density map with surface target features; high density areas are shaded red, low density areas are shaded green. Individual craters shown as filled circles. Alphabetic labels identify high density clusters.

Guided by the locations of clusters B and C, further analysis of the LIDAR topography data was performed to determine if there was any evidence of historic surface target features in those areas. This processing did reveal faint surface target features centered at the B and C cluster locations that were not visible in the original LIDAR data rendering (Figure 42). Plotting the newly identified surface target features in conjunction with the crater density data reveals a consistent pattern between the ship target outlines and the high crater density locations (Figure 43). The full spatial coverage of the topographic LIDAR data provides a means to leverage geomorphic indicators, such as craters, to

assist in bridging the gaps between the limited coverage transect data. These indicators can then be used as a guide to direct target specific sampling as necessary and used as additional information in site characterization.

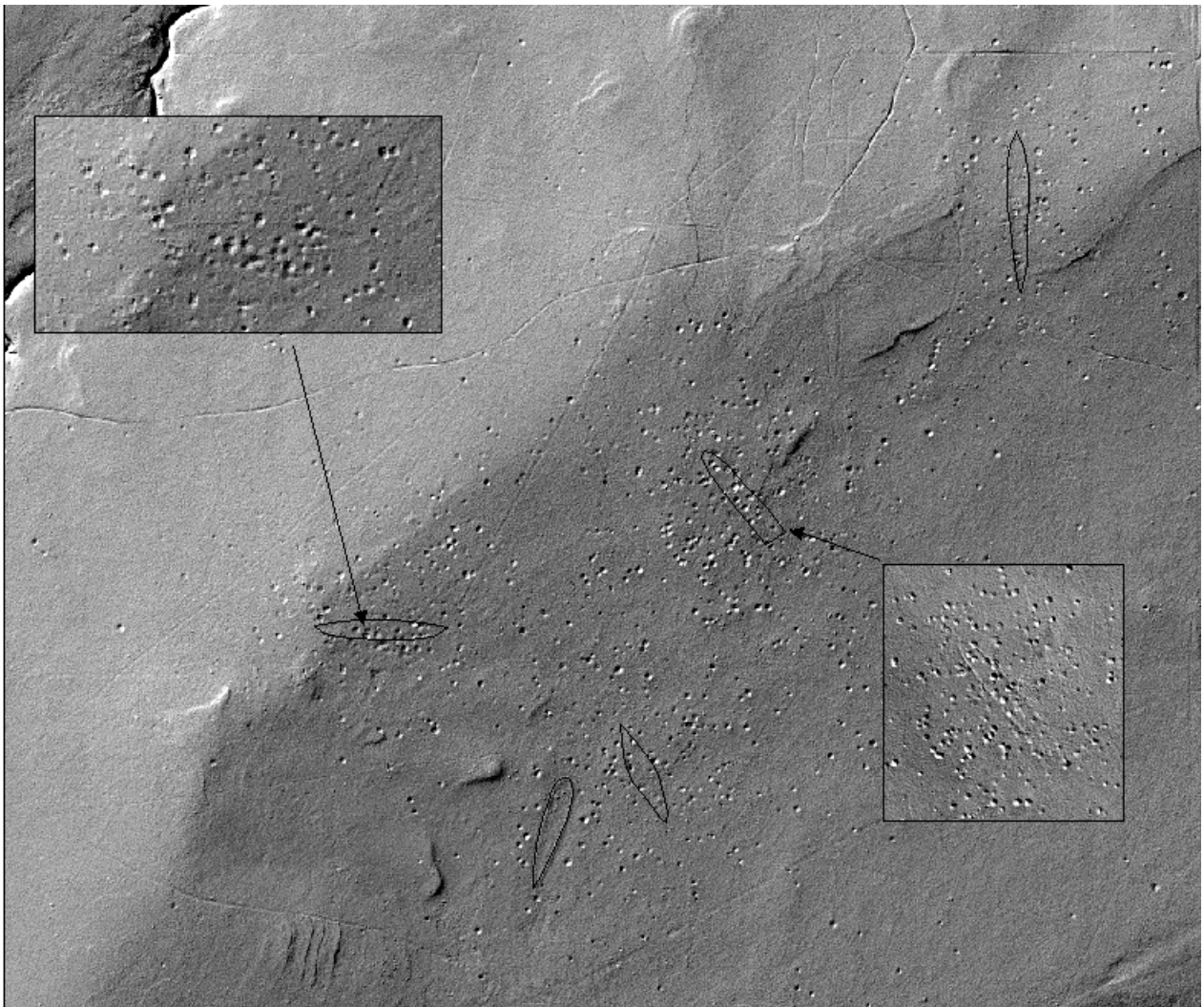


Figure 42: Locations of newly identified surface target features. Inset figures show detailed views of the processed LIDAR data with evidence of newly identified ship outline targets. Previously identified ship outline targets also shown.

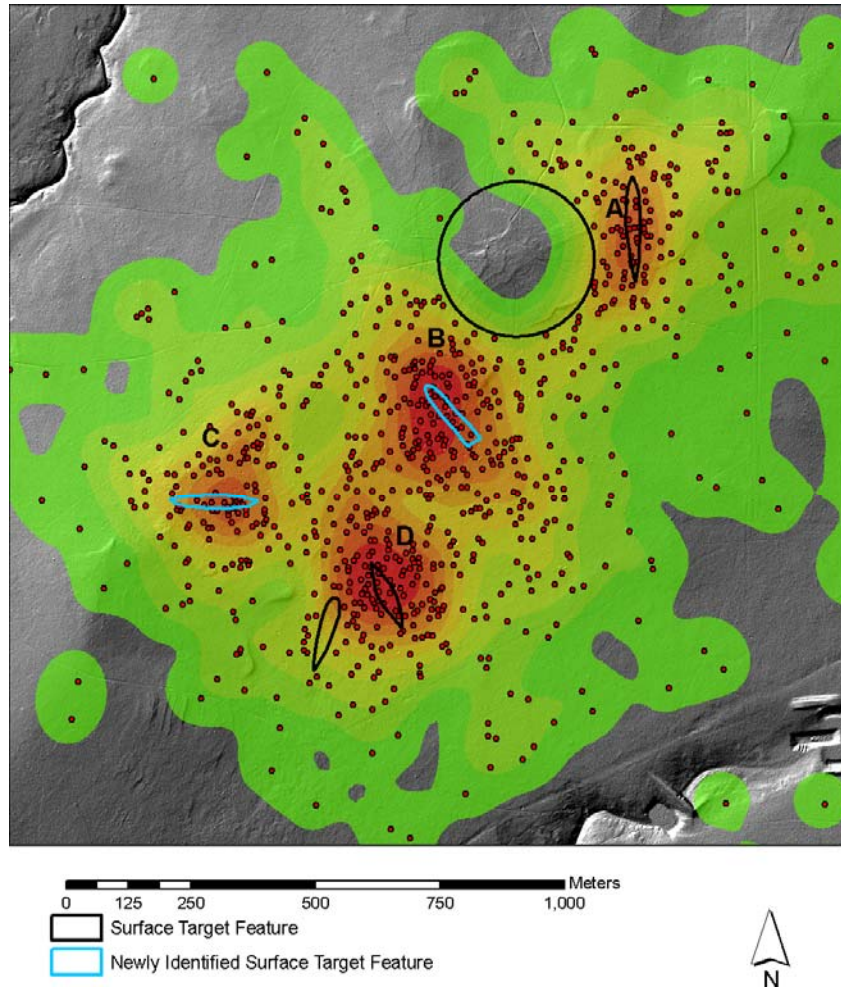


Figure 43: Crater density map with newly identified surface target features; high density areas are shaded red, low density areas are shaded green. Individual craters shown as filled circles. Alphabetic labels identify high density clusters.

4.4.1. Use of Crater Density as Prior Information

Because the crater features occurring around T4 are likely related to site munitions use, their distribution can provide information regarding the historic use of the site and aid in site characterization. Using the crater distribution as prior information during anomaly density kriging can augment the magnetometer transect data and be used to fill in information between the sample transects. Because of the complexities of crater formation, fragment dispersal, and historic site clean-up, the crater density data will be treated as ‘soft’ information in relation to the magnetometer transect data for this analysis.

The crater density information will be used to augment anomaly density estimates using the CSM-0 Sparse transect data in the area around T4. Using the CSM-0 Sparse transects will test how much information the prior data add in estimating magnetic anomaly

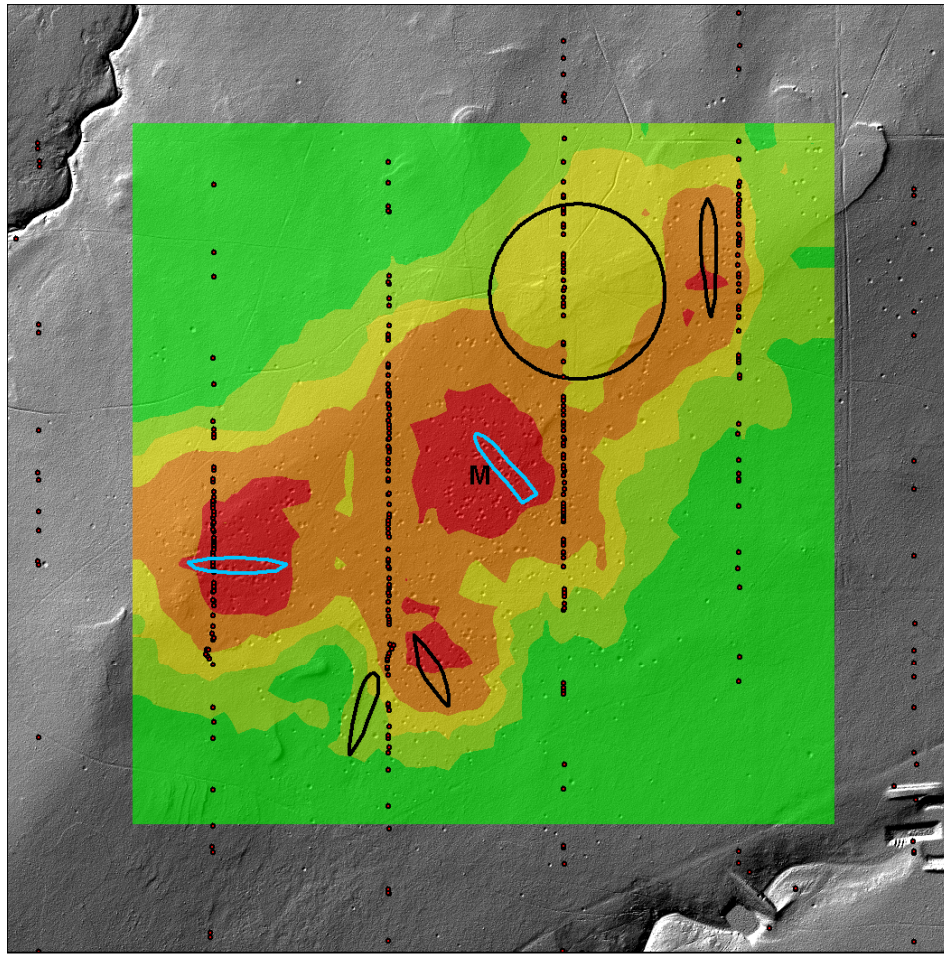
densities using the sparse transect data. The results from this will then be compared against the CSM-1 density estimates which were developed from the most dense transect data.

In order to use the crater density information in conjunction with the magnetic anomaly data, the gridded crater density data were scaled to have the same range of values as the magnetic anomaly data from the CSM-0 Sparse transects in the vicinity of T4. The residuals between the rescaled crater density information and the CSM-0 Sparse transect data were then computed. These residuals were then used with Ordinary Kriging to produce a grid of residual estimates for the T4 area. The kriged residuals were then added to the rescaled grid of crater densities to obtain a final estimate of anomaly densities.

Figure 44 shows the final estimate of anomaly densities developed using the CSM-0 Sparse transect data and the crater densities as prior information. The map shows high estimated anomaly densities around the ship outline targets. Several of these higher density areas occur in areas removed from the sampling transects; this result would not be possible without the influence of the crater density information.

Figure 45 shows the anomaly density estimates for the same area as Figure 44, but developed only using the CSM-0 Sparse transect data.

Figure 46 shows the anomaly density estimates developed using the dense CSM-1 transect data. Comparison of Figures 44, 45 and 46 shows that the addition of the prior information based on crater densities significantly improved the CSM-0 Sparse transect anomaly density kriging estimate. Incorporation of the prior information into the kriging process adds additional refinement to the spatial pattern in the density estimate. The resulting pattern more closely resembles the CSM-1 results which were developed using many more transects. In addition, the location of the maximum anomaly density estimate, shown in each figure by the symbol “M”, shifts away from the CSM-0 Sparse transect to a location very close the maximum location for the CSM-1 estimates. This indicates improved accuracy in the prior information results compared to the CSM-0 Sparse transect results.



0 125 250 500 750 1,000 Meters

Anomaly Density using Prior Information (Anom/Acre)



6 - 80
81 - 120
121 - 160
161 - 240
241 - 389

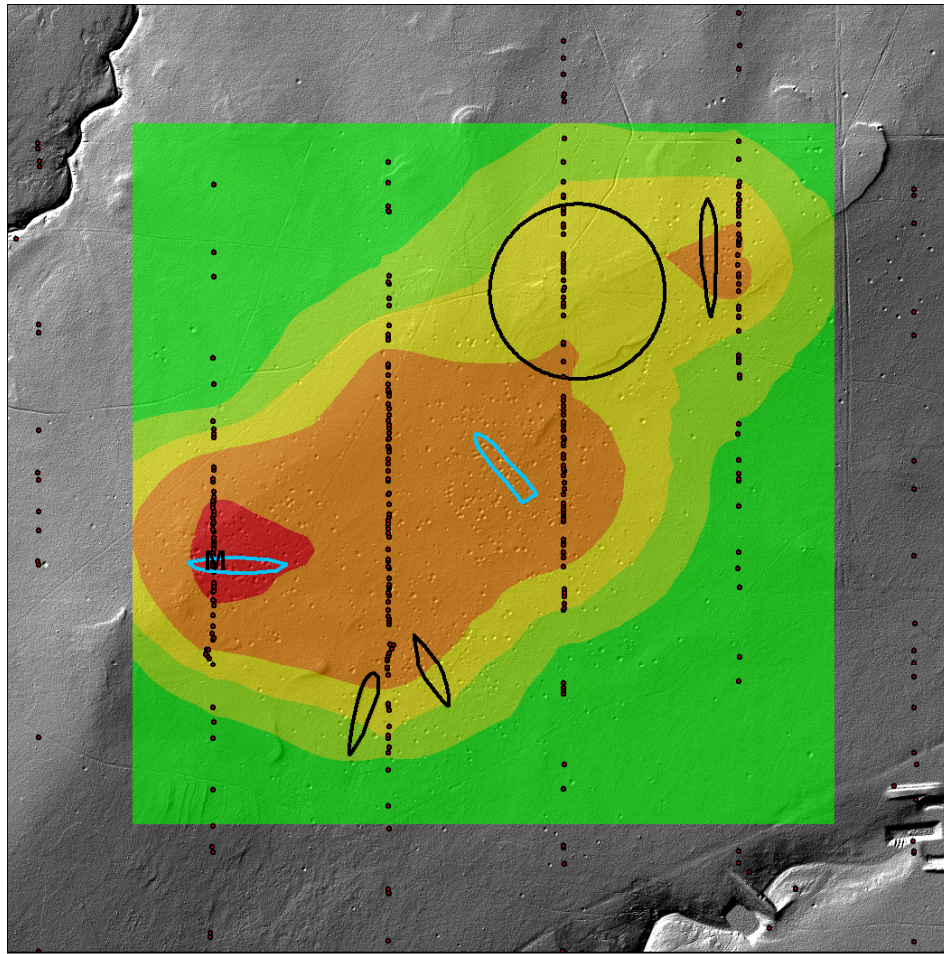
• CSM-0 Limited Detected Anomalies

□ Surface Target Feature

□ Newly Identified Surface Target Feature



Figure 44: Magnetic anomaly density estimated using CSM-0 Sparse transect data and prior information derived from impact crater distribution. Symbol “M” indicates location of maximum anomaly density value.



0 125 250 500 750 1,000 Meters

CSM-0 Limited Anomaly Density (Anom/Acre)



0 - 80
81 - 120
121 - 160
161 - 240
241 - 280

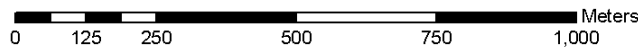
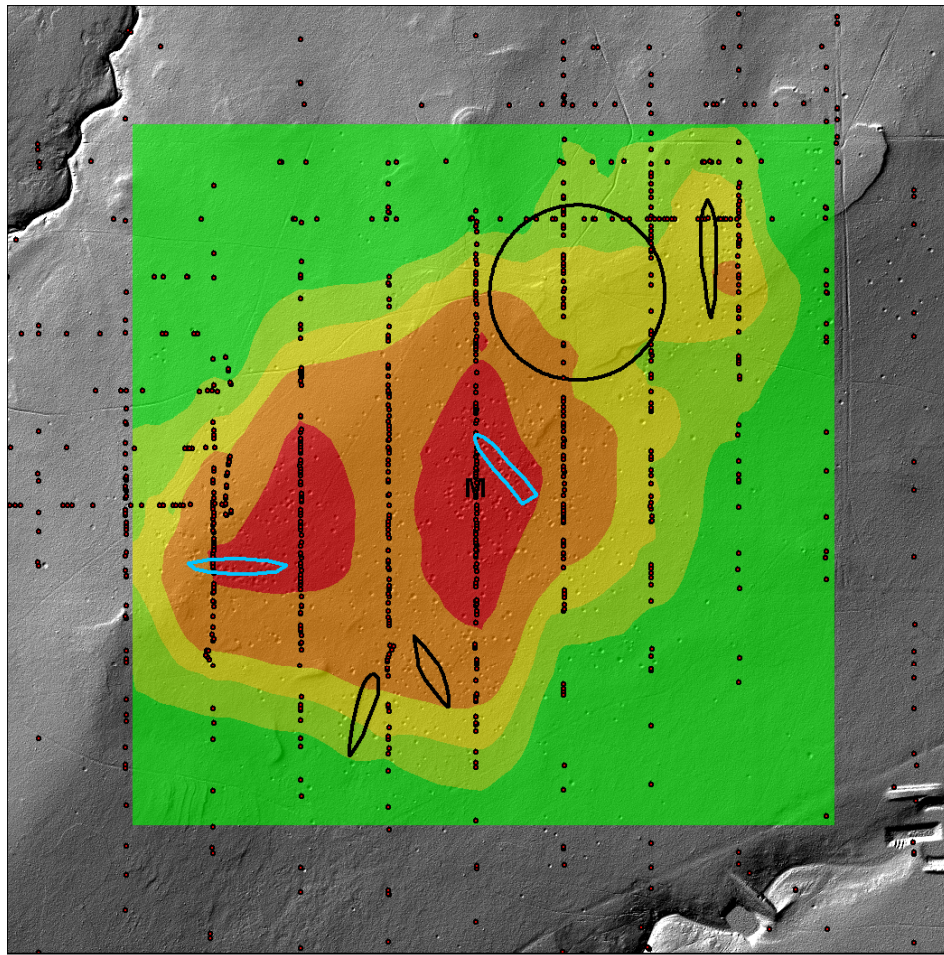
• CSM-0 Limited Detected Anomalies

□ Surface Target Feature

□ Newly Identified Surface Target Feature



Figure 45: Magnetic anomaly density estimated using CSM-0 Sparse transect data only. Symbol “M” indicates location of maximum anomaly density value.



CSM-1 Anomaly Density (Anom/Acre)



0 - 80
81 - 120
121 - 160
161 - 240
241 - 311

• CSM-1 Detected Anomalies

▭ Surface Target Feature

▭ Newly Identified Surface Target Feature



Figure 46: Magnetic anomaly density estimated using CSM-1 transect data only. Symbol “M” indicates location of maximum anomaly density value.

As shown above, the inclusion of prior information can be used to help refine magnetic anomaly density estimates. When secondary prior information, such as crater density distribution, is available, it can significantly improve anomaly density estimates developed from limited transect data. A significant advantage of this approach is that the “hard” data coming from the transects always overrides the “soft” prior information, and

therefore, if the two data sets are inconsistent, the final estimate will be more consistent with the, presumably, more reliable transect data.

5. Comparison of Transect Design Estimates and Delineations

This section demonstrates the change in delineation of identified AOI based on the different amount of transect data available at each stage of the analysis process. As stated previously, the CSM-0 Sparse transect design was created and analyzed after all the other transect designs were collected and analyzed. The CSM-0 Dense, CSM-0 Dense with Additional, and CSM-1 transect designs were gathered in that order and the preliminary analyses were done in that order (See Figure 3). The AOI identified using the combination of transect data and crater density maps as estimated from the LIDAR data are not part of this comparison.

The CSM-1 design was the most comprehensive and is used as the baseline to compare the other three designs accuracy and coverage statistics. This comparison is for explanation purposes in regards to this document. Future work with the land based MTADS 100% coverage areas and the Helicopter MTADS data could prove to be an improved baseline. There is also future work planned to return to the site and do some validation excavation and identification. This future work will provide a better understanding of the Pueblo WAA study area and provide an improved overall understanding of the performance of the surveyed transect designs.

5.1. Target Area Detection and Delineation

Table 10 shows the differences in misclassification between different scenarios as compared the CSM-1. This is done on a cell-by-cell basis using the kriging cells (25m square). A cell was considered within an AOI if the center of the cell was situated within an AOI delineating boundary (Figure 47). A test AOI cell was considered misclassified if it was not common to the CSM-1 AOI. Misclassifications include cells identified as inside the test AOI but falling outside of the CSM-1 AOI (false positives), and cells that were not identified as inside the test AOI but fall inside of the CSM-1 AOI (false negatives). The last column shows the amount of area sampled as a percentage of the CSM-1 sampled transect area.

Transect Design	Cells in AOI	Misclassified Cells	Total Surveyed Area (m²)	Percent of CSM-1 Surveyed Area
CSM-0 Sparse	3,852	1,344	192150.87	43%
CSM-0 Dense	3,559	969	378681.97	85%
CSM-0 w/ add.	3,322	428	392608.37	88%
CSM-1	2,894	N/A	445990.65	100 %

Table 10: Summary of each transect design’s coverage and the combined AOI as compared to CSM-1.

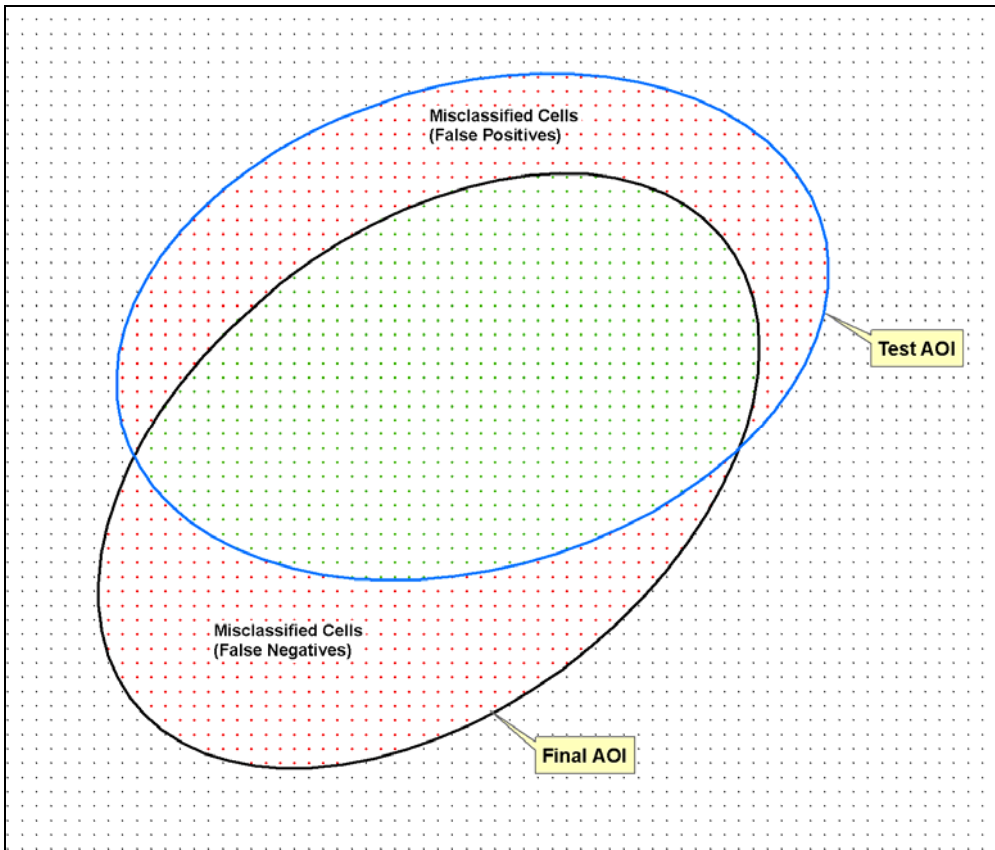


Figure 47: Map view schematic showing definition of misclassified cells as used in testing AOI delineations. Black oval represents final AOI determination, blue oval represents the AOI being compared to the final. Dots represent center of kriging grid cells. Red dots show cell centers misclassified for this test AOI; green dots show properly classified grid cells.

Figures 48 and 49 show a portion of the Pueblo WAA study area with the identified AOI for each of the transect designs. Each of these figures has each transect design and the corresponding AOI delineation coded by colors. The CSM-0 Dense transect design includes the CSM-0 Sparse transects also but are the blue transects that are unique to the CSM-0 Dense design and provided additional information beyond the CSM-0 Sparse transects.

Figure 48 focuses on the northern target area and shows how the additional transect requests in this area condensed the final delineation to an area just under half the size of the delineated target area based on the CSM-0 Sparse transect design. As additional transects are requested, the delineation of the target area consistently shrinks to the final delineation shown in red.

Table 11 provides a numerical summary of what is shown in Figure 48. The CSM-0 Dense design shows two separate areas and they are presented as one in Table 11. The smaller area to the north has a lower density per acre which influences the overall density per acre of the delineated areas for the CSM-0 Dense design.

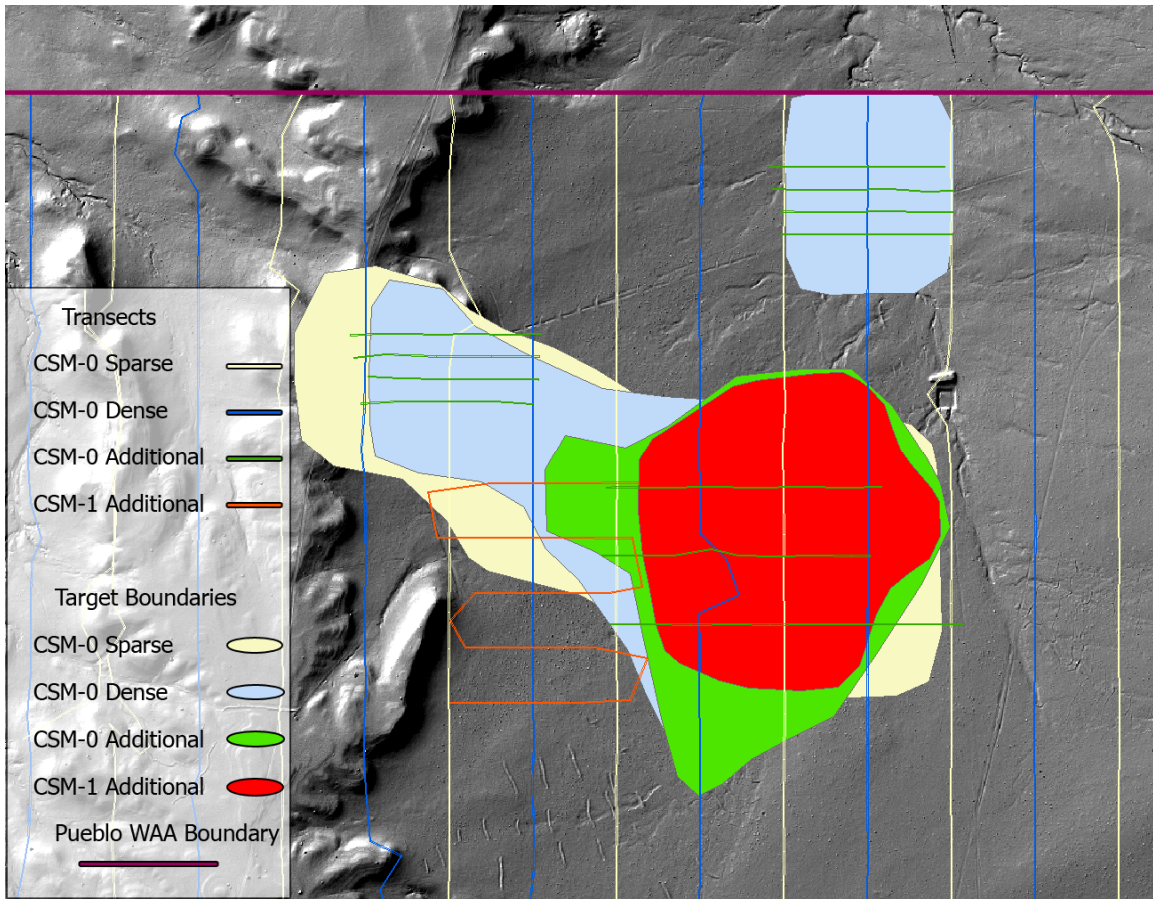


Figure 48: The northern portion of the Pueblo WAA study area with the target area delineations and corresponding traversed transects for each of the different designs.

Northern Region		Sample Transects Crossing AOI			Anomaly	
CSM	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
CSM-0 Sparse	555704	3	1409	2818	53	75
CSM-0 Dense	536855	8	3116	6232	107	69
CSM-0 D. w/ Add.	361226	7	3761	7522	155	82
CSM-1	253596	6	2895	5790	136	94

Table 11: Summary of delineated target area coverage based on each of the identified transect designs for the northern target area.

The main target area located in the southern portion of the study area provides another example of how delineation improves with each additional transect coverage increase. Figure 49 and Table 12 show how the target area boundaries shrunk with each additional transect request. There were no additional transects requested in this area as a part of CSM-0. Thus, the CSM-0 Dense with Additional and CSM-0 Dense target area delineations are identical. The additional transects gathered as a part of CSM-1 demonstrated that the smaller possible high density area to the west of the main target

area was not as dense as previously estimated. The decrease in area of the CSM-1 AOI (1434419 m²) from CSM-0 Sparse AOI (1724288 m²) for the southern target area shown in Figure 49 was not as large as the decrease for the same comparison of the northern target area AOI shown in Figure 48. The change in delineated area was an approximate 17% decrease in size for the southern AOI as compared to an approximate decrease of 54% for the northern target area. The difference in size of the northern and southern target areas and the shape of the northern target that has a limb extending to the west which disappears as more transect data are added to the design are potential factors in explaining this difference

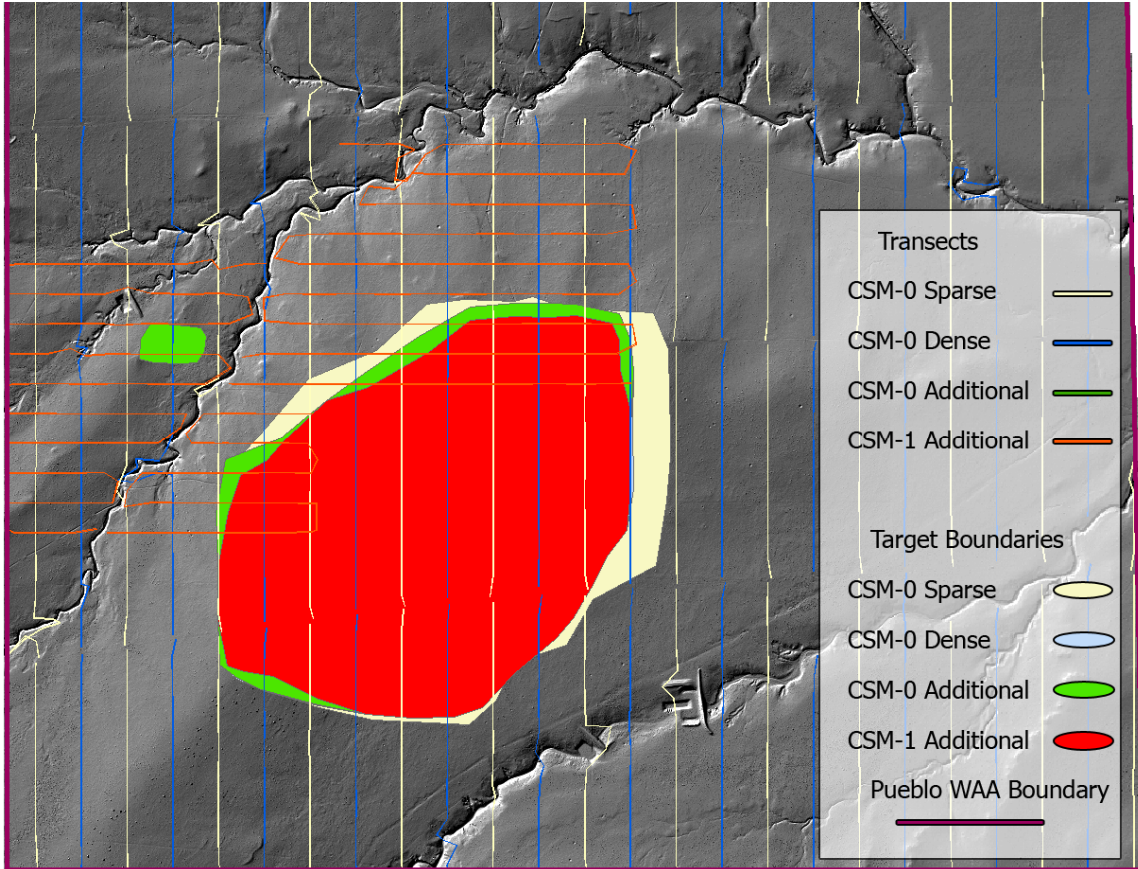


Figure 49: The southern portion of the Pueblo WAA study area with the target area delineation and corresponding traversed transects for each of the different designs. The CSM-0 Dense design is identical to the CSM-0 Dense with Additional design.

Southern Region		Sample Transects Crossing AOI			Anomaly	
Design	Area (m ²)	Number	Total Length (m)	Total Area (m ²)	Count	Density (per Acre)
CSM-0 Sparse	1724288	9	5032	10064	285	113
CSM-0 Dense	1534685	10	10027	20054	602	120
CSM-0 w/ Add.	1534685	10	10027	20054	602	120
CSM-1	1434419	17	11963	23926	699	117

Table 12: Summary of delineated target area coverage based on each of the identified transect designs for the southern target area.

6. Summary and Proposals

6.1. Summary of Transect Designs and Target Area Assessment

This report documents the application of statistically-based UXO site characterization tools to the WAA conducted at the Pueblo Precision Bombing and Pattern Gunnery Range #2. The applications demonstrated here include geophysical transect design, target area flagging, target area boundary delineation and anomaly density mapping using transect data only as well as transect data coupled with prior information in the form of crater density maps. These tools were applied to the Pueblo site under four different conceptual models in order of increasing data density denoted as CSM-0 Sparse, CSM-0 Dense, CSM-0 Dense with Additional and CSM-1. All data were collected along nominally parallel and/or orthogonal transects of 2m width. The amount of the site surveyed under each conceptual model ranged from less than one percent to nearly three percent. In addition to the data collected across the whole site, a separate analysis was done for a sub-region of the site suspected of containing 75mm munitions. Very few anomalies were found in this sub-region and target boundary delineation and anomaly density mapping were not conducted for this sub-region. Assuming that a traversed target area would be detectable in the 75mm sub-region, in areas where the proposed transects were gathered, there are no potential circular target areas of a 100m diameter or greater.

Transect designs used in these analyses are based on the probable ordnance used at the site, 100 lb. bombs, and the conceptual model of how these ordnance were targeted at features on the ground as well as aiming variation and the fragmentation patterns of these ordnance. These considerations resulted in parallel north-south transects with a 310 meter spacing for the CSM-0 Sparse design and a more conservative 155m spacing for the CSM-0 Dense design. Additional east-west transects were added to the Dense design and then another set of additional transects were added based on examination of the Ortho-photography and LIDAR data to create the CSM-1 data set.

For all levels of data collection, surveyed cells exceeding a threshold value of 53 APA were flagged as potentially belonging to a target area. Using a slightly higher threshold of 60 APA and a slightly different means of calculating the average anomaly density within a moving window, the transect data were transformed to [0,1] indicator values and the probability of being within the target area was mapped across the site using IK. Additionally, the anomaly density was also mapped across the site using OK. For all levels of data collection, the spatial correlation of the indicator or anomaly density data was strong and relatively easy to identify and model using variograms. The variogram models did not change drastically with the collection of additional data.

Using all the available transect survey data based on CSM-1 results, the identified potential target areas and boundaries are shown in Figure 50.

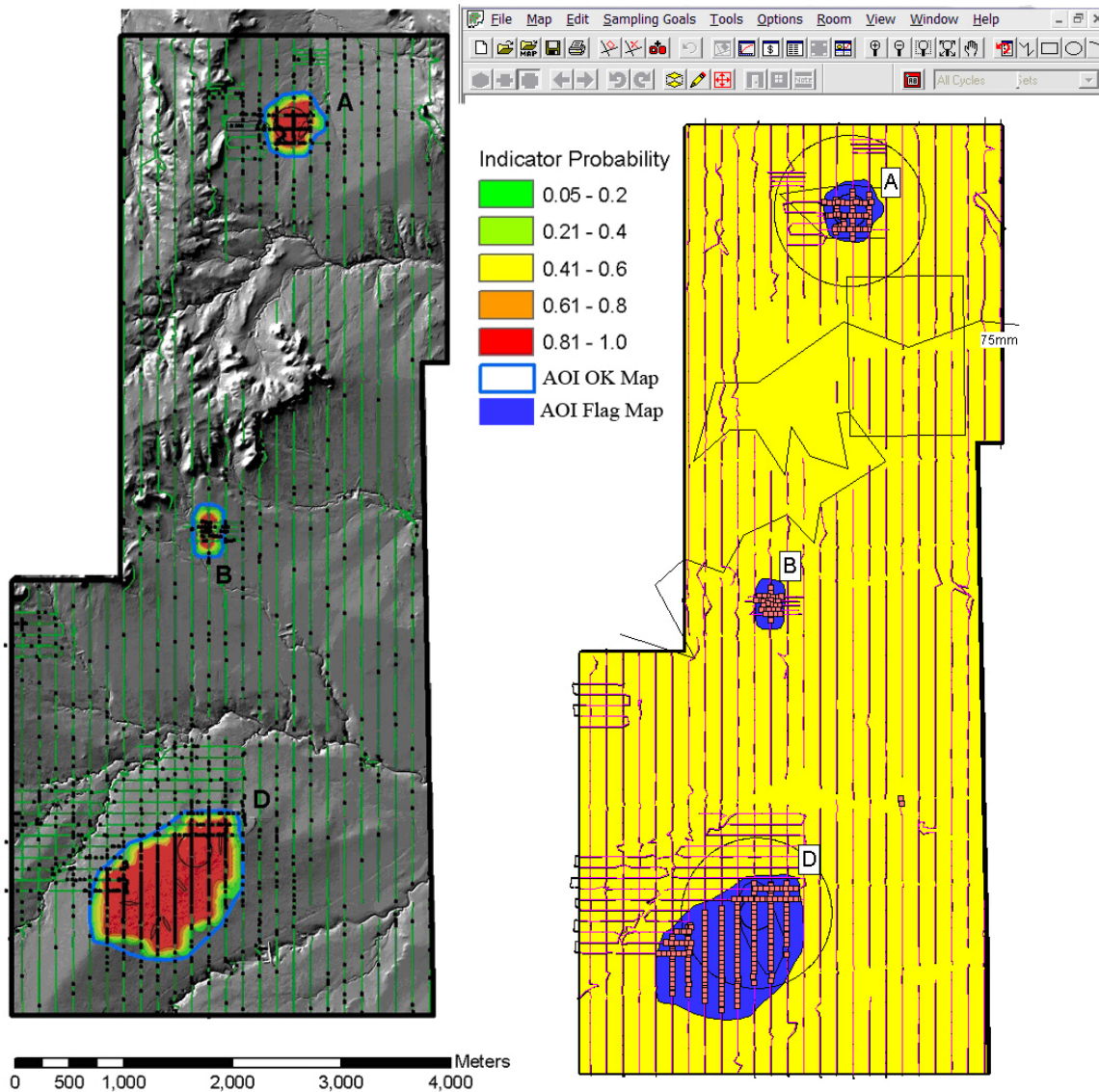


Figure 50: Final delineated boundaries based on the CSM-1 data. As shown in Figures 28 and 29.

6.2. Summary of Transect Coverage Comparisons

The overall effect of increasing the number of transects in the different conceptual models is to decrease the areas within the identified target boundaries. The number of identified target areas associated with the 100 lb. bombs does change from one data set to the next with small target areas appearing in some regions. These smaller areas are not flagged when additional transect sampling is obtained and the final data set identifies the same main target areas as identified by the original transect data. These results indicate that the original CSM-0 Sparse transect design was dense enough to find all significant 100 lb. bomb target areas on the site and the more conservative transect designs were not necessary. The main reason for this result is that the target areas identified are not the result of ordnance being aimed at a single location, but at multiple locations in relatively close proximity that together form a relatively connected region of higher anomaly

density. The multiple ship targets identified at the southern target area confirm the presence of multiple target locations. Two other factors that contribute to the conservatism of the transect designs used here, at least for the southern target area, are the dimensions of the ship targets themselves and the apparent use of HE bombs. The conceptual model used to determine the transect spacing considered ordnance aimed at a single point, not at a ship shape that is roughly 150 meters long by 30 meters wide. Also, the transect spacing was developed assuming the fragmentation of 100 lb practice bombs and the fragmentation of 100 lb HE bombs have a much larger impact area. This larger potential target area contributes to the larger than expected regions of higher anomaly density. If these larger target sizes had been part of the conceptual model used to develop the transect spacing, fewer transects may have been proposed.

This WAA provides the first opportunity to field test the data integration capabilities of the kriging algorithm. Results here show that the limited transect data obtained for the CSM-0 Sparse design integrated with the crater density map created from the LIDAR data through the kriging process was capable of identifying similar anomaly density patterns in the southern region as the CSM-1 conceptual model that required considerably more transect data. These results indicate that other secondary data streams, such as crater density, that can support the primary transect data need to be identified and used to advantage as early as possible in the site characterization process. Another advantage of using the crater density data at the Pueblo site was the identification of two more ship outlines within the southern target area. Identification of these other aiming locations provides more backing for the conceptual model of ordnance distribution developed during this site characterization.

Finally, this WAA site provided the first opportunity to conduct iterative analyses in near real time with the geophysical survey team. Geophysical survey data were delivered daily to the PNNL/SNL team and quickly analyzed using VSP. This allowed real-time discussions regarding flagged areas and even identified some quality assurance issues early enough to permit corrections. These iterative interactions proved very valuable in the process of interpreting flagged areas, especially some of the very isolated areas.

6.3. Proposals for Future Analyses

An additional evaluation of the results presented in this analysis can be done by comparing the results herein to the results of the 100 percent site coverage by helicopter surveying. However, to make this evaluation meaningful, it will be necessary to determine the consistency between the ground-based magnetometer data and the helicopter magnetometer data. Differences in measured anomaly densities between the ground and helicopter data will result from the differences in height above the ground of the magnetometers in the two different platforms. Other differences in the processing of the geophysical data between the two platforms may also result in differences of the measured anomaly densities. While it will most likely be possible to compare the shapes and areas of target area boundaries, the same boundaries may or may not result from

different anomaly density thresholds applied to the transect and helicopter data. If time and funding permits, the PNNL/SNL team requests to

- Compare estimates from helicopter data based on the COG obtained by the land based MTADS.
- Compare both target area delineation and estimated anomaly densities from this report to the helicopter data.
- Use same transect design assumptions (spacing and width) developed in this report based on different locations of the transects to identify the variability of estimates and delineation due to transect location.
- Compare target area identification and delineation using “transects” from helicopter data against the results from this report.
- Similar comparisons requested above with the other WAA sites.

Appendix A

Variogram Parameters

This appendix presents the analytical model parameters used during the kriging analyses. Variograms from observational data were computed using a lag of 25 m and a lag tolerance of 12.5 m. Observational data consisted of anomaly densities in anomalies per acre.

Variogram model parameters for density estimates developed using Ordinary Kriging.

Transect Design	Nugget	Model Type^{1,2}	Sill¹	Range¹ (m)
CSM-0 Sparse	0.0	Sph. / Gau.	38 / 1200	140 / 1650
CSM-0 Dense	0.0	Sph. / Gau.	45 / 1400	140 / 1750
CSM0-0 Dense AR	0.0	Sph. / Gau.	65 / 1350	120 / 1650
CSM-1	0.0	Sph. / Gau.	65 / 1550	120 / 1700
75mm Area	0.0	Sph. / Gau.	65 / 1450	120 / 1700

¹Two nested models were used, parameters for first and second model listed respectively.

²Spherical model abbreviated Sph; Gaussian model abbreviated Gau.

Variogram model parameters used in Indicator Kriging analyses.

Transect Design	Nugget	Model Type	Sill	Range (m)
CSM-0 Sparse	0.001	Spherical	0.058	1350
CSM-0 Dense	0.0005	Spherical	0.055	1100
CSM0-0 Dense AR	0.002	Spherical	0.059	950
CSM-1	0.002	Spherical	0.069	920
75mm Area	0.002	Spherical	0.063	1000