Geospatial Research Laboratory

US Army Corps of Engineers®
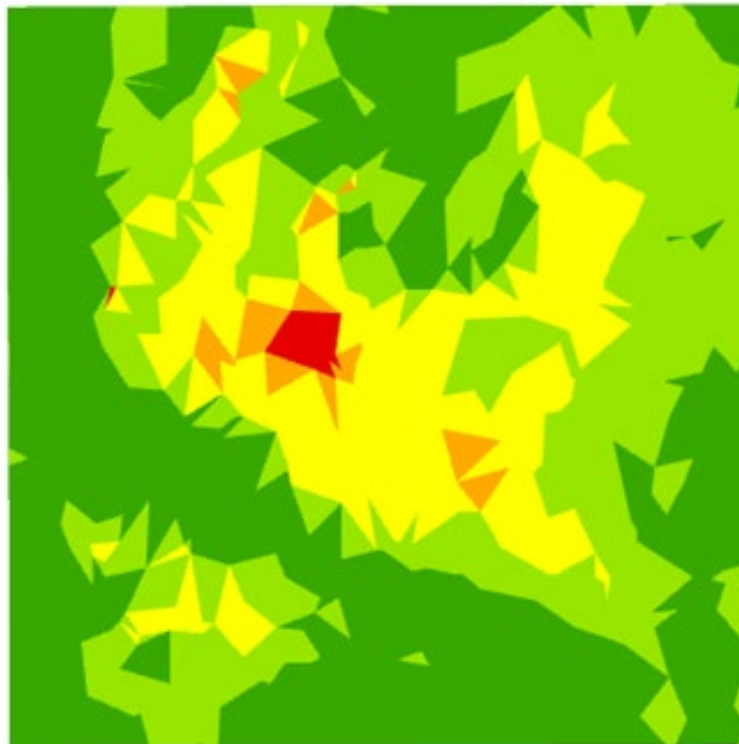Engineer Research and Development Center

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

Tactical Geospatial Information Capabilities

Cross Country Mobility (CCM) Modeling Using Triangulated Irregular Networks (TIN)

Sarah Rehrer, Andrew Griffin, and Matthew Renner   November 2022

Cross Country Mobility (CCM) Modeling Using Triangulated Irregular Networks (TIN)

Sarah Rehrer, Andrew Griffin, and Matthew Renner

US Army Engineer Research and Development Center (ERDC)
Geospatial Research Laboratory (GRL)
7701 Telegraph Road
Alexandria, VA 22315-3864

Final report

Abstract

Cross country mobility (CCM) models terrain that has insufficient or unavailable infrastructure for crossing. This historically has been done with either hand-drawn and estimated maps or with raster-based terrain analysis, both of which have their own strengths and weaknesses. In this report the authors explore the possibility of using triangulated irregular networks (TINs) as a means of representing terrain characteristics used in CCM and discuss the possibilities of using such networks for routing capabilities in lieu of a traditional road-based network. The factors used to calculate CCM are modified from previous methods to capture a more accurate measurement of terrain characteristics. Using a TIN to store and represent CCM information achieves comparable results to raster cost analysis with the additional benefits of an integrated network useful for visualization and routing and a reduction in the number of related files. Additionally, TINs can in some cases more accurately show the contours of the landscape and reveal feature details or impediments that may be lost within a raster, thus improving the quality of CCM overlays.

Contents

Figures and Tables

Figures

Tables

Preface

This page intentionally left blank.

1   Introduction

The goal of this project is to demonstrate the feasibility of TINs as a more efficient and comprehensive medium for storing terrain data and for generating CCM model outputs. Analog and digitized cost analysis formulas currently utilized by the US Army were evaluated, and a modified version was incorporated into a custom Java interface. A series of vector TINs were then produced and compared to raster-based CCM models.

1.1   Background

Cross country mobility (CCM) is understanding the best way to traverse areas without roads or over open natural terrain (US Army 2017). This is a calculated estimate based on expected averages for assumed terrain conditions rather than an exact projection. Parameterizing vehicle characteristics and underlying terrain classifications including waterbodies, soil moisture, slope changes, and land cover is vital to estimating traversal time over a given area. Efficient and accurate calculation of CCM terrain products is essential for military planning to move people and equipment in undeveloped areas.

Routing is a network problem wherein travel is conducted along linear segments between points with an associated traversal cost. Roads, cart tracks, trails, and other transportation pathways combine into a complex system of routes and corridors. Many studies describe potential solutions for these systems that are conceptually identical to computer and other network spaces. CCM is routing without an explicitly existing network; the challenge for CCM algorithms is to calculate an optimal vehicle terrain path independent of any transportation system network.

Currently the most utilized solution for non-network routing is cost analysis. This method is based on specific factors that determine through a measurable value the difficulty of traversing a given terrain (US Army 2017). Raster data are useful for this analysis as individual square grid cells are assigned an individual cost value, creating a continuous surface over the area of interest (AOI). A cost analysis algorithm, such as Dijkstra's algorithm or A* (Hart 1968), is then utilized to determine the added costs

of cells from a starting grid cell and progressing in the direction of a chosen destination cell.

The cost analysis method, however, requires significant computational resources and is often inefficient and time consuming depending on the specific algorithm. All acceptable cells in the direction of the destination are queried until an impassable area is reached, then analysis is resumed from the next closest unimpeded area. Additionally, processing time is further increased by practical considerations such as raster file size and the number of files an end user may need to fully cover an AOI. Advances in computational capacity have largely mitigated these inefficiencies, but mobile/handheld devices and other systems with limited processing power cannot efficiently apply raster-based cost analysis algorithms.

An alternative method for storing and processing terrain information is a triangulated irregular network (TIN). The TIN data format creates irregularly shaped triangles that represent the underlying terrain morphology and elevation. Overall geospatial trends and topology are maintained without needing to retain every gridded raster data point, and required terrain parameters are stored together in each triangle. To accomplish this, a TIN is generated from a digital elevation model (DEM) with each triangle facet attributed with information conflated from the raster input (i.e., elevation values). The populated triangles represent larger areas of like type, which are used to calculate the cost to traverse that triangle in the network. While the TIN generation process may introduce minor errors in the final elevation model, it decreases file size and computation time for many geospatial algorithms. These characteristics are the motivation for using TINs to perform geospatial analysis, particularly in the mobile/handheld and mounted computing environments. Exploiting a TIN format thus overcomes the inefficiencies of raster cost analysis and creates an easily understood network reflecting the terrain of an area.

1.2 Objectives

The goal of this project is to demonstrate the feasibility of TINs as a more efficient and comprehensive medium for storing terrain data and for generating CCM model outputs. More specific tasks include:

- Evaluation and comparison of existing CCM formulas to that developed by the MEGATIN project.
- Demonstration of the efficacy of the MEGATIN formula in creating TIN-based CCM models and storing of the required factors required for CCM modeling.
- Comparison of MEGATIN CCM models to SAGE-generated CCM models over a shared AOI.

1.3 Approach

Analog and digitized cost analysis formulas currently utilized by the US Army were evaluated, and a modified version was incorporated into a custom Java interface. A series of vector TINs were then produced and compared to raster-based CCM models.

1.4 Scope

Prior work conducted by the Multi-Exploitation for Geospatial Analysis on Triangular Irregular Networks (MEGATIN) team provided an argument for utilizing TINs as a method for CCM modeling. This project seeks to further expand on the initial concept, and provide analytical evidence in comparison to similar methods.

2 Methodology

2.1 Cross-country mobility technical approach

2.1.1 Factors

CCM calculations for this project were based on formulas utilized by both the Defense Mapping School (Defense Mapping School 1993) and Situational Awareness Geospatially Enabled (SAGE) (Khona 2016). Both approaches use calculations detailed in FM 5-33: Terrain Analysis (US Army 1990), which remains the Army's authoritative document regarding CCM. Originally these calculations were performed manually via pen-and-paper methods, but SAGE digitized the full process for incorporation into that toolset. Likewise, for this project a custom Java tool was developed to automate the vehicle selection, CCM calculation, and TIN creation process utilizing the same formulas.

The standard method for calculating CCM determines the relative suitability of a given area for mobility expressed by the maximum obtainable speed of a chosen vehicle. This suitability is derived from constituent factors representing the impact of a given terrain characteristic. Here the Defense Mapping School and SAGE factors can be compared (Table 1).

Table 1. CCM factors. Asterisks (*) represent secondary factors mathematically derived from one or more other factors as described in this section.

Factor	Defense Mapping School	SAGE
F1	Speed/Slope	Slope
F2	Slope Intercept Frequency (SIF)	Terrain Roughness (slope, aspect, elevation)
F1/2*	F1 x F2	N/A
F3	Vegetation (type, spacing, roughness)	Vegetation (type, spacing)
F4	Soil (type, moisture)	Soil (type, moisture)
F5*	Surface Roughness	N/A

Speed/Slope as the first factor (F1) represents the "average optimum operational off-road speed … on a firm, smooth surface with a specific slope" for a select vehicle (Defense Mapping School 1993). This is derived from analog calculations finding the slope of the area and averaging it

against standard tabular information for maximum on- and off-road gradability and maximum road speed for the vehicle. SAGE utilizes this factor as is but renames it to simply "Slope."

The slope intercept frequency (SIF) factor (F2) is an estimation of the number of times slope changes between positive and negative slope in a given area. When multiplied with F1, the result is the average speed the vehicle can move reliant on the shape and variability of the terrain; this combined factor is then renamed "F1/2" for the final calculation. In SAGE, SIF is replaced with terrain roughness, which is a measure of "terrain ruggedness as the variation in three-dimensional orientation of grid cells within a neighborhood" and "effectively captures variability in slope and aspect into a single measure" (Khona 2016). F1/2 is thus made redundant and excluded from the final calculation in SAGE.

Vegetation as the third factor (F3) determines how variations in land cover slow vehicle speed. The original technique requires manual identification of forest versus non-forest plant types followed by analog calculation of vehicle maneuverability against tabular average stem spacing and roughness values (see Appendix A). SAGE simplifies this process by including land use land cover (LULC) raster surfaces as an end user input; however, it also eliminates the use of roughness as a sub-factor.

The soil factor (F4) identifies how soil type and moisture affect vehicle speed. As with vegetation, identification of soil type is completed manually and comparison made to standardized tables prior to analog calculation of vehicle maneuverability over wet or dry soil types (see Appendix B). SAGE again simplifies this process by including soil raster surfaces as an end user input.

Surface roughness as the final factor (F5) represents the degree of surface degradation and its impact on vehicle speed. These values are manually estimated in terms of percentage of speed lost versus surface materials and vehicle characteristics. SAGE excludes this factor, explaining that its terrain roughness module covers small-enough distances (i.e., measurements are calculated over 3×3 pixel neighborhoods rather than kilometers) to account for much more granular irregularities. Equation 1 presents the mathematical formula for normalizing values onto a common 0 to 1 scale:

$$Xn = (X - X\min) / (X\max - X\min) \tag{1}$$

The factors are then multiplied together to express the proportion of full speed that a vehicle can travel through the area. If any factor is 0 or less, that area is deemed non-traversable. The equations for the original Defense Mapping School and SAGE methods for calculating maximum traversal speed of a homogeneous area for a specific vehicle are expressed in Equations 2 and 3, respectively:

$$\text{Speed(kph)} = F1 / 2 \times F3 \times F4 \times F5 \tag{2}$$

$$\text{Speed(kph)} = F1 \times F2 \times F3 \times F4 \tag{3}$$

2.1.2 Normalization and final calculation

After each factor is calculated, the raw values are normalized on an interval between 0 and 1, with 0 indicating no possibility of traversal and 1 indicating no impediment to speed. More generally speaking, normalization allows for the factors to be expressed on a common scale with the same values. This is represented mathematically in Equation 1.

For this project slight modifications were made to several of the factors in order to produce more precise values and provide a more readily comparable final product. Given high resolution digital data and increased availability of digital computation methods for calculation, SIF was reevaluated to find a more accurate measurement for F2. In the original Army doctrine, this factor is determined through manual measurement using paper maps and approximations; topographic lines over a given area are counted and compared to standard measurements. As previously described, SIF approximates rather than replicates curvature, the negative concave or positive convex degree to which a line deviates from straightness. Substituting SIF directly with curvature results in higher fidelity information.

Previous digital CCM calculations replicated the manual SIF method by utilizing the 3D Pythagorean theorem with aspect and the sine and cosine of slope to quantify changes to the terrain in a 3 × 3 pixel neighborhood. The digitized curvature method utilized here fits a plane to a 3 × 3 pixel neighborhood, essentially creating contours based on the elevation value of each cell. Using this calculation instead, room for error is reduced and a

more precise measurement derived. As with each other factor, the values for curvature were also normalized, such that F2 was set to represent areas of high curvature in either the positive or negative direction as less favorable for traversing. One key difference between curvature normalization and that for the other factors is that 1 indicates no curvature while 0 is less desirable or extreme curvature.

Additionally, surface roughness was eliminated from consideration as F5 given the inclusion of curvature for F2. As also found by SAGE and supported by similar documentation (Wright 2006), the granularity afforded by digital data effectively makes measurement over larger areas redundant. Obtaining reliably consistent surface roughness data is also difficult if not altogether impossible to estimate.

The remaining factors—Slope/Speed for F1, Vegetation for F3, and Soil for F4—were unchanged and calculated according to the method described in the source document (Defense Mapping School 1993). The finalized equation is expressed identically to SAGE.

2.2 TIN attribution and structure

2.2.1 TIN creation

TINs are a vector data product derived from raster elevation datasets used to generalize terrain, effectively depicting three-dimensional landscapes in a two-dimensional medium. They are generated by selecting points, triangulating between them, and connecting each point with edges or lines to form a network (Figure 1) (Esri 2021). Point selection may be random or determined by algorithms that place vertices based on significance, meaning points are more frequently placed over more highly varied or flatter terrain depending on the type of algorithm utilized. The performance of various algorithms is compared in earlier works (Lee 1991; van Kreveld 1997).

Figure 1. A DEM with TINs generated utilizing the DEM2GPKG tool and each of the three algorithms, with the ratio of pixels to use as points set 0.0025.
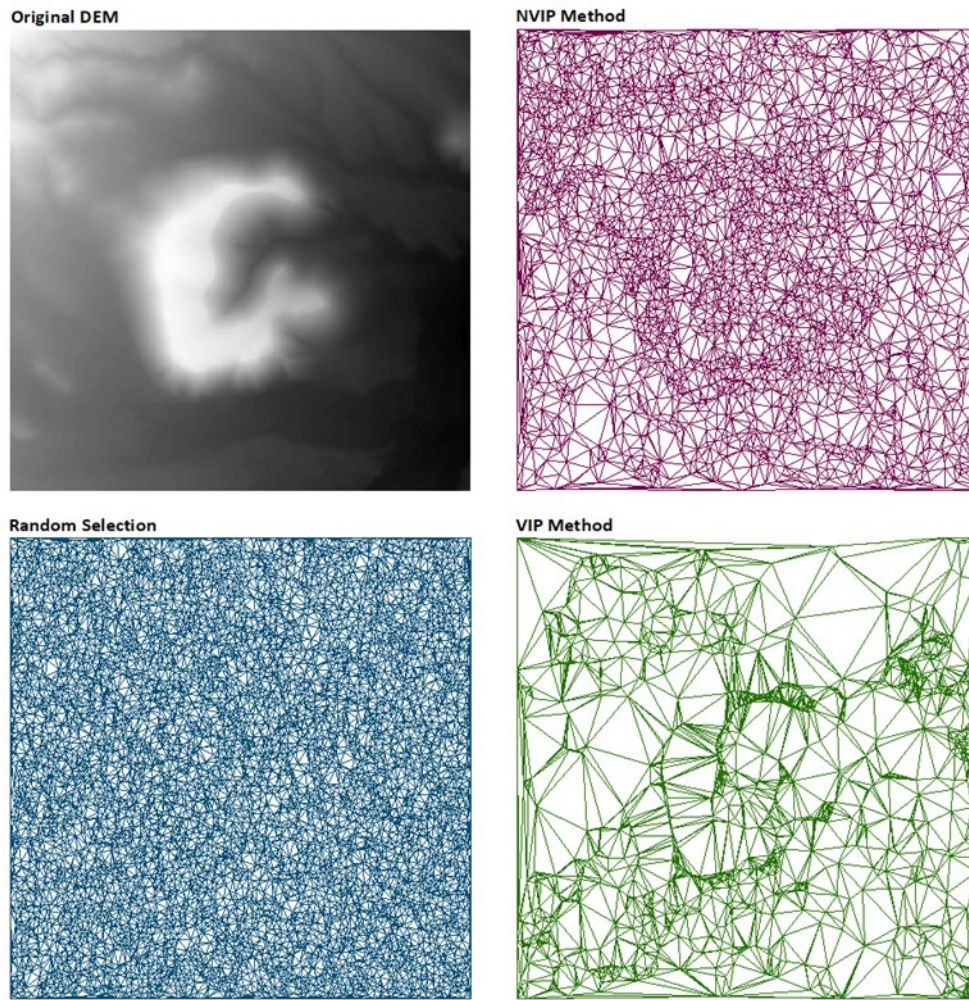
Resolution can also vary within a dataset depending on placement of triangles over differing terrain types, with clusters of smaller triangles representing areas with higher relief and greater changes in elevation (Esri 2021). Overall TIN quality and accuracy of triangle placement are determined by the level of error that occurs during generation. Higher error levels are most often seen along the boundary of a regularly shaped AOI where triangles may become stretched to fill the space; this is dependent on the selection of points as significant or insignificant.

Several proprietary and open source software solutions—in addition to standalone algorithms—exist for TIN creation. As described above, a custom interface integrating three of these algorithms was built, known internally as the DEM2GPKG tool. These algorithms for selecting vertices

select random points, Very Important Points (VIP), or Not Very Important Points (NVIP) from an input DEM (Figure 1). The random method is the simplest and generates a TIN from randomly selected points. The VIP method chooses significant points for the TIN by comparing pixels to their immediate neighbors within a 3 × 3 pixel window. A significance value calculated for each pixel, and those points significantly above or below a user-defined point, are kept to generate the TIN. The NVIP method is essentially an inverse of the VIP method; points are selected based on the lowest calculated significance values rather than highest (Chen 1987). The user chooses the algorithm, as well as the input DEM, input land cover and soil rasters, and the ratio of pixels to use as nodes, and a GeoPackage vector dataset containing a TIN attributed with slope and LULC information for each triangle is produced. Centroids, or the middle point of a given triangle, are created at the same time.

2.2.2 TIN attribution

As described previously, each triangle in a TIN can store information necessary for various types of geospatial analysis including CCM. The DEM2GPKG tool as well as many other solutions either extracts or derives this information from input raster files. For variable data, such as within a DEM, pixel values are averaged and the resulting number added to the TIN's underlying attribute table for each triangle as a new attribute; for thematic data, such as within LULC and soil rasters, the modal pixel value, or most commonly occurring class, is added instead (Figure 2).

Figure 2. Attributed TIN layered over a slope raster with accompanying attribute table. Each row shows the averaged slope value as well as modal values for soil and LULC for a given triangle.

Slope_Pct	Soil_type	LC_type	OBJECTID *
2.96981	120	7	13
38.188446	120	7	14
21.094981	13	7	15
13.411065	13	7	16
16.336426	13	7	17
18.839976	13	7	18
17.97069	13	7	19
21.690602	13	7	20
18.613095	13	5	21
11.641281	13	5	22
23.213293	13	5	23
25.668373	13	5	24
28.309675	13	5	25
35.348006	13	5	26
35.196126	13	5	27
36.758367	13	5	28
38.448462	13	5	29
35.05493	20	5	30
28.980408	20	5	31
28.12999	20	5	32
25.715544	20	5	33
22.921159	20	5	34
4.503754	20	5	35
12.787145	20	5	36
123.013117	120	7	37

For this project, slope, LULC, and soil were retained as created by the DEM2GPKG tool. These three pieces of information best reflect the landscape and are constant regardless of what vehicle is used to calculate CCM. With this data populated on the network, additional calculations can then be performed at routing runtime against measurements specific to a user-chosen vehicle and the resulting information stored in new fields added to the existing TIN attribute table. This foundation data then allow the TIN to be classified and symbolized to show the final allowable CCM areas and shared for use with other applications (e.g., Open Routing Interface (ORI)).

2.2.3 Edge vs. centroid routing

TINs afford a unique situation wherein triangle edges or centroids may be used to create the routing network. Initially it was planned to use the TIN edges as they are a natural counterpart to lines in a standard routing network. Within the TIN, however, the triangles are used to represent areas of similar characteristics. This is in keeping with Tobler's first law of geography that "near things are more related than distant things," with the edges of these triangles serving as the border between delineated areas (Tobler 1970). While two neighboring triangles are likely similar, this is

not inherently true, and thus their shared edge cannot represent the data from both. It is possible then for a route to form between two extremely dissimilar terrain types.

The centroid network approach provides a more faithful representation of the landscape by utilizing the center points of each triangle to form an underlying network (Figure 3). Origin and destination triangles are selected, and like neighbors are chosen between them in proportion to the amount of the line that exists within each triangle. Routing corridors may be identified representing more accurate paths for traversal since it is possible to show areas with good average values between triangles and sections that may be better than others for movement. For these reasons, the centroid networking method was utilized here.

Figure 3. TIN generated from the random selection method with adjacent triangles (black) and overlapping centroid network (purple).
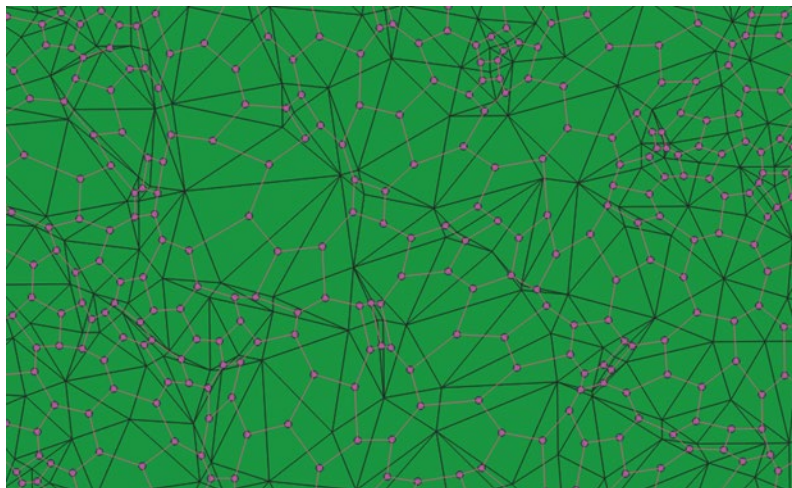
2.3   CCM test conditions

2.3.1 Test areas and calculation

For testing and illustration, four 2 km × 2 km AOIs were selected based on common terrain patterns and are named after primary terrain behaviors or prominent features within each: Extreme Mountains, Mixed Relief, Mostly Flat, and Flat Small Ridge (Figure 4). One meter resolution Buckeye DEMs (Figure 5) for each were obtained along with 30 m VISNAV LULC and SoilScape rasters (Figure 6) from the Common Map Background (CMB) online portal at the Army Geospatial Center. The initial TINs were then generated using the DEM2GPKG tool with the ratio

of pixels as nodes set to a percent on parity with what the SAGE tool produces in raster format.

Figure 4. Natural color imagery of the four AOIs. Each tested area is contained within a white bounding box.
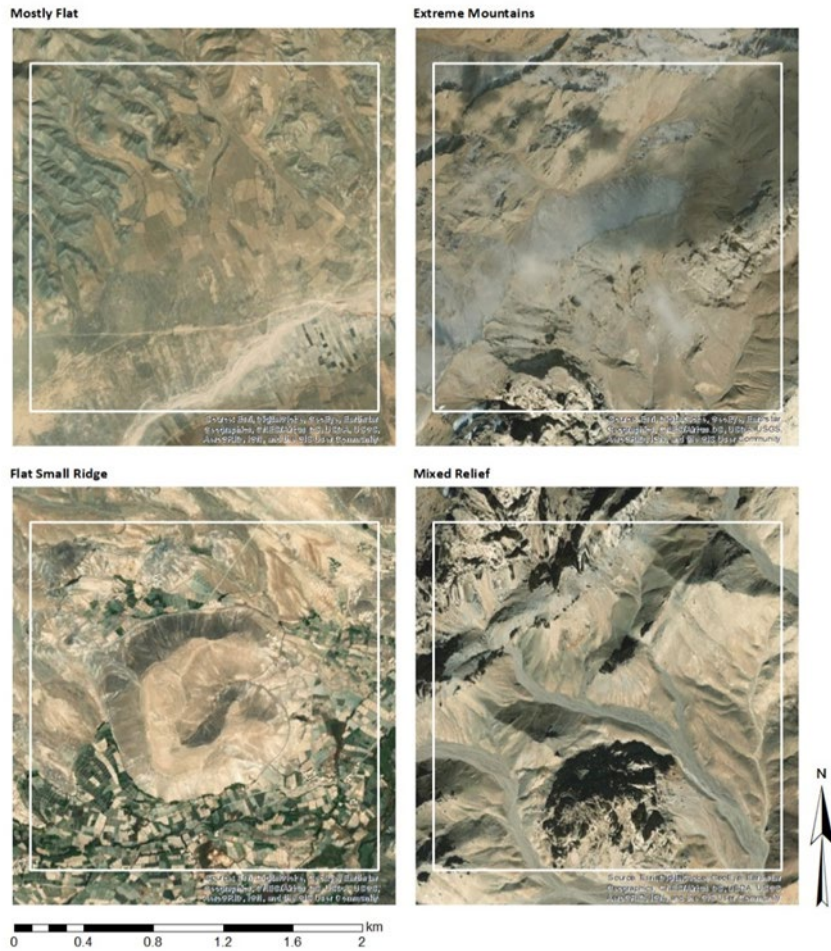
Figure 5. One meter Buckeye DEMs for the four AOIs.
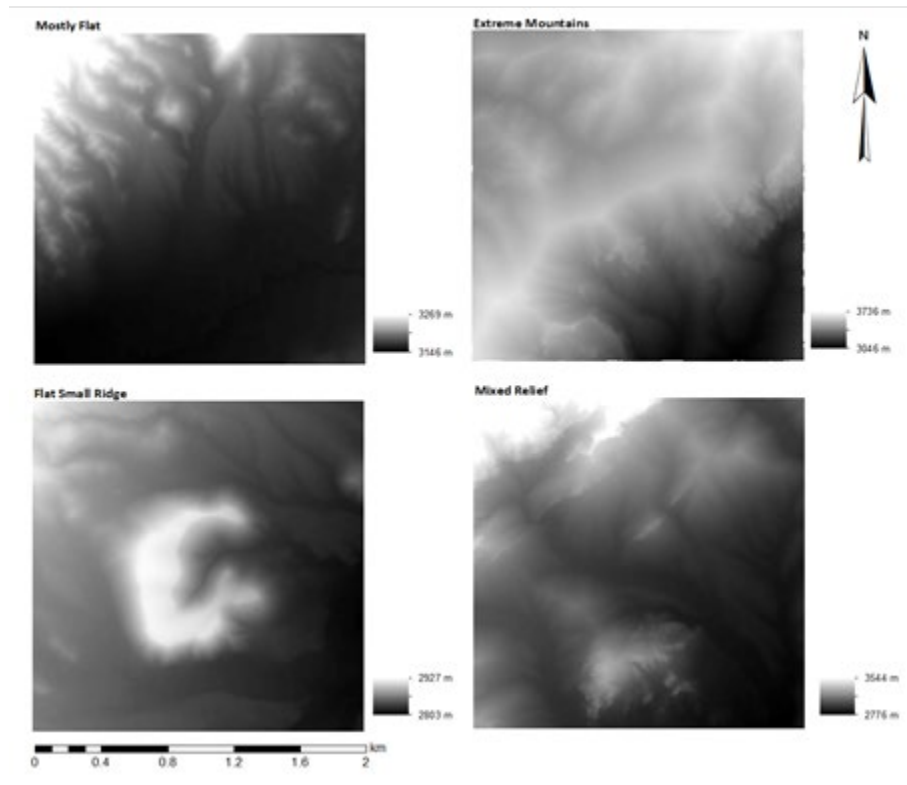
CCM was calculated utilizing the custom Java tool and default Army manual values for an M917 Utility Vehicle in dry soil conditions to maintain uniformity of the results. Each of the CCM factors were calculated along with the final speed, all of which were attributed directly to the TIN triangles. The process was also completed in SAGE using the same input data and settings to provide a comparison between TIN vs. raster output information. To note, in a routing application it would not be necessary to calculate for all triangles, only the most advantageous ones along the path as selected by the chosen routing algorithm.

Figure 6. Thirty meter VISNAV LULC and SoilScape rasters for the four AOIs.
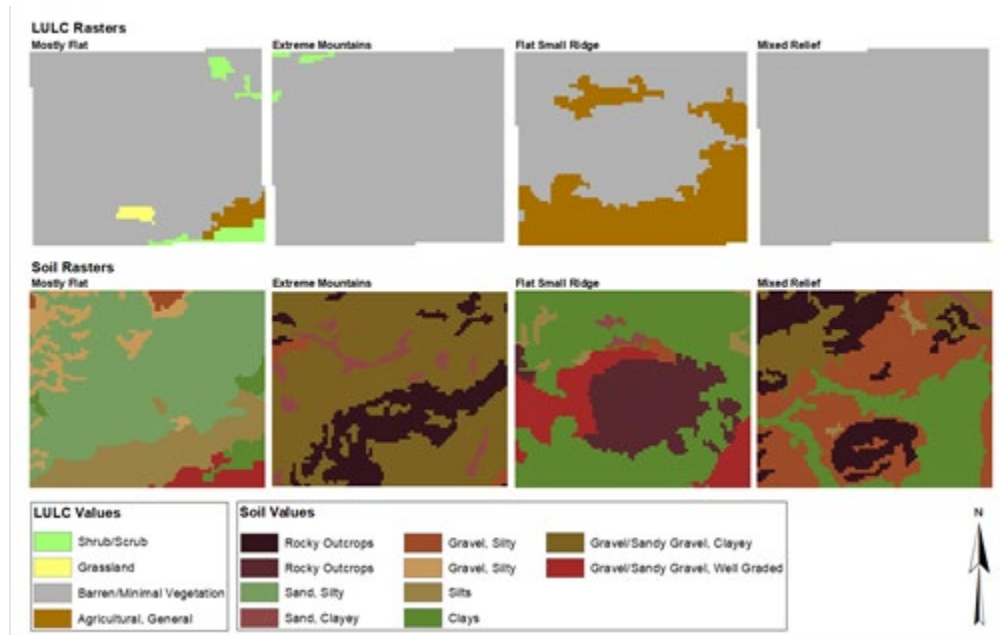
A standard red-to-green color scale—red or orange representing no or restricted progress, yellow representing slow progress, and green representing fastest progress—was applied to illustrate the relative ease of mobility over the selected test areas (Figure 7).

Figure 7. TIN CCM overlays, with red being impassable and green allowing for maximum vehicle speed.
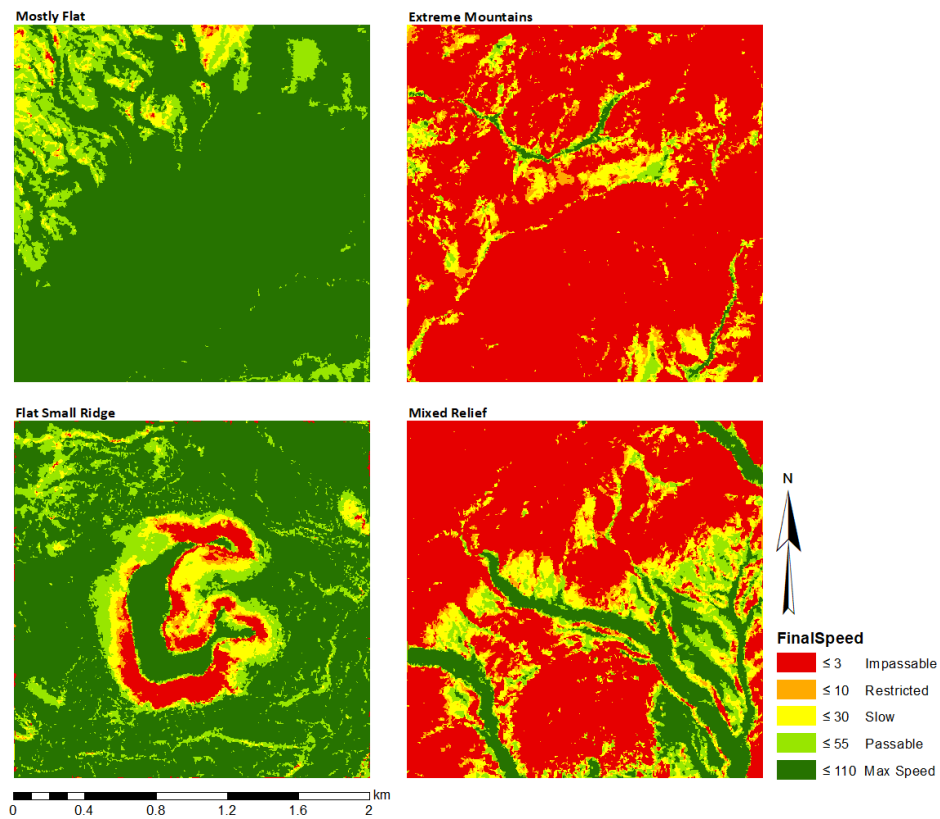
The speed in kilometers per hour (kph) was categorized as follows:

- ≤3: Impassable
- ≤10: Restricted
- ≤30: Slow
- ≤55: Passable
- ≤110: Max Speed

Speed was divided into more bins than are included in FM 5-33 and the Defense Mapping School student guide due to the increased resolution this method provides compared to the manual method.

2.3.2 Results and comparison to SAGE

The TIN and SAGE methods of generating CCM overlays yielded similar results with interesting differences. The same general subareas were highlighted within each AOI with like mobility levels, and both methods selected areas with low slope and minimal land cover as passable terrain,

while areas with high slope gradient or high curvature were selected as impassable (Figures 7 and 8). Non-ideal but still potentially acceptable conditions were displayed somewhere in between.

Figure 8. Raster CCM overlays produced by SAGE, with a scale of red being impassable and green allowing for maximum vehicle speed.
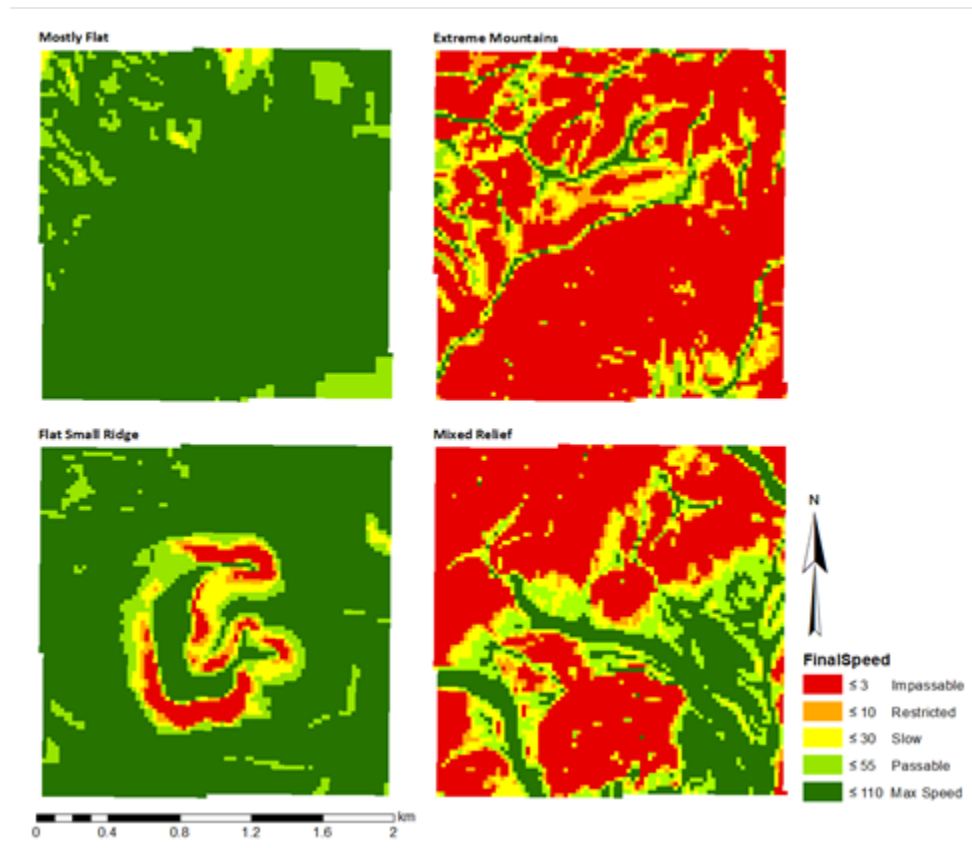
The greatest differences, however, lie in overall visualization and the total area categorized between bins. The SAGE raster overlays are rougher with distinct pixilation of the terrain, while the TIN overlays are more detailed and better capture smaller individual features. This difference in resolution is due to the ability to choose more or fewer points for inclusion in a TIN, as well as clustering over more variable terrain. Smaller and more distinct areas can be captured that are lost to averaging in the raster method or down-sampling in the case of SAGE. While the SAGE method minimizes file size, it can have unexpected impact on mobility and understanding of the operational environment.

The TIN method overall also allows for clearer CCM classification. By examining the total area represented by each category, it was revealed for all of the AOIs that more area was impassible and less area could be traversed

at maximum speed (Table 2). This is even more distinct when subareas over individual features represented as solid blocks of color in the SAGE overlays were compared to their TIN counterpart. In Figure 9 (right) and Table 3, a 0.25 km × 0.25 km sample area of the Mostly Flat AOI containing the small ridge of a nearby hill shows mostly passable terrain with some slow areas as calculated by SAGE using only raster data. The TIN algorithm (Figure 9, left), however, reveals several areas as impassable or restricted and a higher total area wherein the test vehicle would need to move slowly.

Table 2. Total area in square kilometers (km²) for each classification within each AOI.

Classification	≤ 3 km²	≤ 10 km²	≤ 30 km²	≤ 55 km²	≤ 110 km²
Extreme Mountains (TIN)	3,314,225.00	221,935.50	314,098.00	104,669.00	40,394.00
Extreme Mountains (SAGE)	2,717,768.77	277,634.48	449,350.61	229,489.78	148,446.18
Flat Small Ridge (TIN)	235,784.50	71,242.50	240,308.00	568,835.00	2,879,152.00
Flat Small Ridge (SAGE)	174,925.77	77,031.53	190,974.01	345,839.49	3,028,302.14
Mostly Flat (TIN)	7,105.00	12,525.00	136,226.00	485,364.50	3,354,101.50
Mostly Flat (SAGE)	802.41	802.41	36,108.53	301,706.84	3,478,455.16
Mixed Relief (TIN)	2,394,214.00	204,413.00	464,872.50	351,555.00	580,267.50
Mixed Relief (SAGE)	1,953,070.32	170,111.30	431,697.55	476,632.61	790,375.62

Figure 9. TIN (left) vs. SAGE (right) raster comparison of an individual feature subarea within the Mostly Flat AOI.
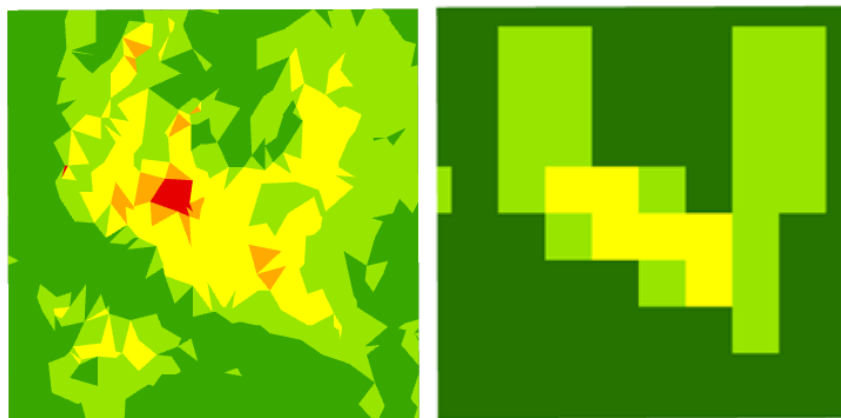

Table 3. Total area in square kilometers (km²) for the subareas represented in Figure 5.

Classification	≤ 3 km²	≤ 10 km²	≤ 30 km²	≤ 55 km²	≤ 110 km²
Mostly Flat (TIN)	391.00	1,228.00	11,691.00	22,088.66	27,101.30
Mostly Flat (SAGE)	None	None	4,814.47	17,096.60	40,588.89

3   Summary

Utilizing TINs to store and represent CCM information achieves comparable results to raster cost analysis with the additional benefits of an integrated network useful for visualization and routing and a reduction in overall file storage needs. TINs specifically store terrain characteristic information as attributes within individual triangles, an advantage over creating, analyzing, and storing multiple raster datasets. When symbolized, the triangles within a TIN can also more accurately show the contours of the landscape and reveal feature details or impediments that may be lost within a raster, thus improving the quality of CCM overlays.

References

Chen, Z.-T., and J. Armando Guevera. 1987. "Systematic Selection of Very Important Points (VIP) from Digital Terrain Model for Constructing Triangular Irregular Networks." In *AutoCarto* 8: 50–56.

Defense Mapping School. 1993. *Procedural Guide for Preparation of DMA Cross-Country Movement (CCM) Overlays*. Student handout. Fort Belvoir, VA: Defense Mapping Agency.

Esri. 2021. *What Is a TIN surface?* Accessed 2021. https://desktop.arcgis.com/en/arcmap/latest/manage-data/tin/fundamentals-of-tin-surfaces.htm.

Hart, P. E., N. J. Nilsson, and B. Raphael. 1968. "A Formal Basis for the Heuristic Determination of Minimum Cost Paths." *IEEE Transactions on Systems Science and Cybernetic* 4 (2): 100–107.

Khona, D. S. 2016. *SAGE User Manual Version 1.1.0*. Alexandria, VA: Geospatial Research Laboratory.

Lee, J. 1991. "Comparison of Existing Methods for Building Triangular Irregular Network Models of Terrain from Grid Digital Elevation Models." *International Journal of Geographical Information System* 5 (3): 267–85.

Tobler, W. R. 1970. "A Computer Movie Simulating Urban Growth in the Detroit Region." International Geographical Union. Worcester, MA: Clark University, 234–40.

US Army. 1990. *FM 5-33 Terrain Analysis*. Washington, DC: Headquarters, Department of the Army.

US Army. 2017. *ATP 3-34.80 Geospatial Engineering*. Washington, DC: Headquarters, Department of the Army.

van Kreveld, M. 1997. "Algorithms for Triangulated Terrains." *SOFSEM '97: Proceedings of the 24th Seminar on Current Trends in Theory and Practice of Informatics: Theory and Practice of Informatics*, 19–36.

Wright, N. C. 2006. *Raster Based Cross-Country Movement Model*. Model summary. Alexandria, VA: Army Geospatial Center.

Appendix A: Vegetation Lookup Table

Table A-1. Vegetation lookup table.

Name	LULC Value	Roughness Value
No Data	0	0
Forest, Deciduous	1	1
Forest, Evergreen	2	1
Shrub/Scrub	3	0.6
Grassland	4	0.9
Barren/Minimal Vegetation	5	0.95
Urban/Built Up	6	1
Agriculture, General	7	0.8
Agriculture, Rice Paddy	8	1
Wetland, Permanent/Herbaceous	9	1
Wetland, Mangrove	10	1
Water	11	0
Permanent or Nearly Permanent Ice/Snow	12	1
Cloud/Cloud Shadow	13	0
Open Pit Mines	14	1
Sand Dune	15	1
Salt Evaporators	16	1
Salt Pans	17	1
Sabkha	18	1
Filtration/Aeration Beds	19	1
Fish Ponds	20	0
Foreshore Flats	21	1
Reefs	22	1
Large Piers	23	1
Dams	24	1
Large Bridges	25	1
Utility Corridors	26	1
Golf Courses	27	0.9
Cemeteries	28	1
Vineyards	29	1
Orchards	30	1

Appendix B: Soil Lookup Table

Table B-1. Soil lookup table.

Code	Soil Type	Soil Values	Cone Index Dry	Cone Index Moist	Cone Index Dry
GW	Gravel or Sandy Gravel, Well Graded	20–25	163	123	83
GP	Gravel or Sandy Gravel, Poorly Graded	30–35	160	120	81
GM	Gravel, Silty	40–45	120	76	32
GC	Gravel or Sandy Gravel, Clayey	50–55	130	91	52
SW	Sand, Well Graded	60–65	155	116	78
SP	Sand, Poorly Graded	70–75	145	109	73
SM	Sand, Silty	80–85	119	72	25
SC	Sand, Clayey	90–95	126	86	46
ML	Silts	100–105	118	69	20
CL	Clays	120–125	123	81	40
CLML	Clay-Silt Mixture	N/A	116	65	14
OL	Organic Silts	140–145	111	57	3
MH	Inorganic Elastic Silts	110–115	114	61	8
CH	Fat Clays	130–135	136	99	62
OH	Fat Organic Clays	151–155	107	54	1
PT	Highly Organic Soils or Peat	160	106	52	0
RK	Rocky Outcrops	12, 13	165	165	165
W	Open Water	1	0	0	0
NA	No Data	N/A	0	0	0

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
11-2022	Final Technical Report	FY2022

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Cross Country Mobility (CCM) Modeling Using Triangulated Irregular Networks (TIN)	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT
	PE 633463
6. AUTHOR(S)	5d. PROJECT NUMBER
Sarah Rehrer, Andrew Griffin, Matthew Renner	AU1
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
US Army Engineer Research and Development Center (ERDC) Geospatial Research Laboratory (GRL) 7701 Telegraph Road Alexandria, VA 22315-3864	ERDC/GRL TR-22-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Headquarters, US Army Corps of Engineers Washington, DC 20314-1000	USACE
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Cross country mobility (CCM) models terrain that has insufficient or unavailable infrastructure for crossing. This has historically been done with either hand-drawn and estimated maps or with raster-based terrain analysis, both of which have their own strengths and weaknesses. In this report the authors explore the possibility of using triangulated irregular networks (TINs) as a means of representing terrain characteristics used in CCM and discuss the possibilities of using such networks for routing capabilities in lieu of a traditional road-based network. The factors used to calculate CCM are modified from previous methods to capture a more accurate measurement of terrain characteristics. Using a TIN to store and represent CCM information achieves comparable results to raster cost analysis with the additional benefits of an integrated network useful for visualization and routing and a reduction in the number of related files. Additionally, TINs can in some cases more accurately show the contours of the landscape and reveal feature details or impediments that may be lost within a raster, thus improving the quality of CCM overlays.

15. SUBJECT TERMS

Military topography; Military geography; Trafficability; Vehicles, Military; Off-road vehicles--performance; Geospatial data

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	none	30	19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified			