Analysis and Visualization of Visibility Surfaces

D.R. Caldwell[1], M.J. Mineter[2], S. Dowers[2], and B.M. Gittings[2]

[1] U.S. Army Engineer Research and Development Center,
Topographic Engineering Center
7701 Telegraph Road, Alexandria, VA, 22315-3864, USA
Tel +1 703-428-6802 X2236
Fax +1 703-428-6425
Email: Douglas.R.Caldwell@erdc.usace.army.mil

[2] Geography, School of GeoSciences
University of Edinburgh,
Drummond Street, Edinburgh EH8 9XP, Scotland
Tel +44 131 650 2662
Fax +44 131 650 2524
Email {mjm, sd, bruce}@geo.ed.ac.uk

Abstract

Visibility analysis has traditionally been restricted to point-to-point line-of-sight profiling or point-to-area viewshed analysis. This constrained view of visibility necessarily limits our ability to understand the visibility surface characteristics of the terrain. Recent research by the University of Edinburgh has resulted in the development of a Complete Intervisibility Database (CID), where viewsheds are stored for every point in a Digital Elevation Model (DEM). This paper builds on the CID concept and presents an exploratory examination of visibility surfaces. Two types of products are described: Descriptive Metrics and Tactical Decision Aids (TDAs). Descriptive Metrics characterize the visibility surface and include measures of cumulative visibility, slope of cumulative visibility, fragmentation, core area visibility, and ratio of cumulative visibility to core area visibility. These basic metrics can be combined and analysed to form TDAs, which represent higher level processing to support decision-making. TDAs include percent target visible and least/most visible route. This research represents a first step toward the longer-term goal of understanding the relationship between elevation and visibility.

1. Introduction

Visibility analysis is a basic terrain analysis capability used in a wide variety of applications, from resource management and urban planning to crime mapping and military operations analysis. Current visibility products, including line-of-sight profiles and masked area plots, are limited in their ability to represent the overall visibility surface characteristics of the terrain. Line-of-sight profiles model point-to-point visibility, while viewsheds, model point-to-area visibility. Neither line-of-sight profiles nor viewsheds provide information on the overall visibility characteristics of the terrain surface.

Visibility surfaces were introduced in the mid-1990s by Ray and Richbourg (Ray, 1994a; Ray, 1994b; Richbourg et. al., 1995a). The focus of their innovative research was on the generation and exploitation of visibility surfaces, but the individual viewsheds used to calculate the surfaces were not maintained. Researchers at the University of Edinburgh have built upon Ray and Richbourg's research with a suite of visibility analysis capabilities developed from a Complete Intervisibility Database (CID). The CID maintains viewshed information for every point in a Digital Elevation Model (DEM), resulting in a sampling of information that characterizes visibility over the entire terrain surface. Details of the CID computing architecture, construction process, format, and links between the GIS software and JAVA programs are described in other publications (Mineter et. al., 2003; Mineter et.al., 2002a; and Mineter et.al. 2002b)

By pre-computing and storing the viewshed information, the CID simplifies the retrieval and analysis of visibility information. The tradeoff is the time necessary to compute the CID once versus the time to generate viewsheds at the time of analysis in response to specific user queries. Most of the metrics and Tactical Decision Aids (TDAs) described in this paper require that the entire data set be analyzed. Only one TDA, the percent target visible, can be calculated without accessing the entire data set. The choice of whether or not to use a CID depends on the type and frequency of user queries. We believe that CID generation will increase in the future in order to reduce repetitive viewshed generation for analysis.

2. Analyzing and Visualizing Visibility Surfaces

The CID aids researchers in developing a deeper understanding of the visibility characteristics of the terrain, as well as the relationship between elevation and visibility. The CID provides the source data for a suite of visibility surface analysis products. Descriptive metric products, such as cumulative visibility, cumulative visibility slope, fragmentation, core area visibility, and ratio of cumulative visibility to core area visibility provide basic information about the visibility characteristics of the terrain. TDAs, such as percent target visible and least/most visible route build upon basic measures to provide synthesized products for decision makers.

2.1 Complete Intervisibility Database (CID)

Researchers at the University of Edinburgh created the prototype CID from a U.S. Geological Survey DEM of the Southwest Harbor, Maine, USA quadrangle (Figure 1). It represents a northeastern United States coastal area dominated by north-south ridges, with the Atlantic Ocean in the southeast corner and a bay extending from the southeast through the central part of the DEM. Data production artefacts, in the form of east-west striping, are visible in the data.

The source DEM contained 466 rows and 336 columns of elevation data, resulting in an 84 Mb CID containing 156,576 viewsheds. This CID was generated using a multi-computing architecture that involved 13 processors and took 43 hours and 26 minutes to complete.

It is important to remember that the viewsheds of the CID have edge effects, similar to edge effects in any viewsheds based on a DEM. The viewsheds represent visibility accurately within the DEM, but do not necessarily reflect real world visibility. For example, two peaks may have similar-sized viewsheds in the real world, but their viewsheds in a given DEM may not be equal. It may be the case that all visible points from one peak are contained within the DEM, while the second peak may be near the edge of the DEM, and many of the points visible from the second peak lie outside the extents of the DEM. This would cause them to have viewsheds of differing sizes, with respect to the DEM. This does not invalidate the results of analyses made on the viewsheds individually or within a CID, but merely restricts their applicability to the limits of the area covered by the DEM. This distinction is important when analysing the metrics and TDAs generated from the CID.

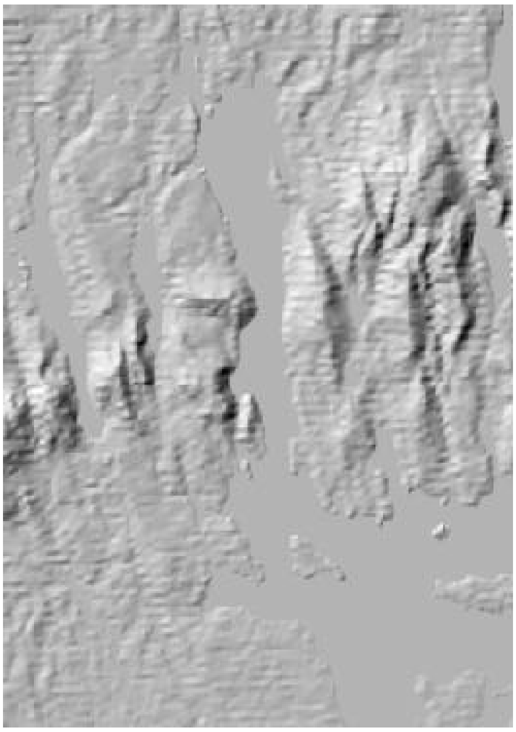

Figure 1. Shaded relief image of the Southwest Harbor, Maine, USA Digital Elevation Model

2.2 Descriptive Metrics

Descriptive metric products provide basic information on the characteristics of the terrain surface and fall into two categories, primary descriptive metrics and secondary descriptive metrics. Primary descriptive metrics, such as cumulative visibility, fragmentation, and core area visibility are derived directly from an analysis of the CID. Secondary descriptive metrics, such as cumulative visibility slope and ratio of cumulative visibility to core area visibility are derived from primary descriptive metrics.

2.2.1 Cumulative Visibility

Cumulative visibility (Figure 2) records, for each point in the DEM, the total number of visible pixels in the viewshed, the visible area, or the percent visible area of the DEM associated with an observer location at that point. When counting the number of pixels in viewsheds, the value can range from 1 to the total number of points in the DEM, with higher values indicating locations with greater visibility. Cumulative visibility is useful for rapidly identifying areas of low and high visibility in a DEM and can be used as a cost surface for selecting most and least visible routes.

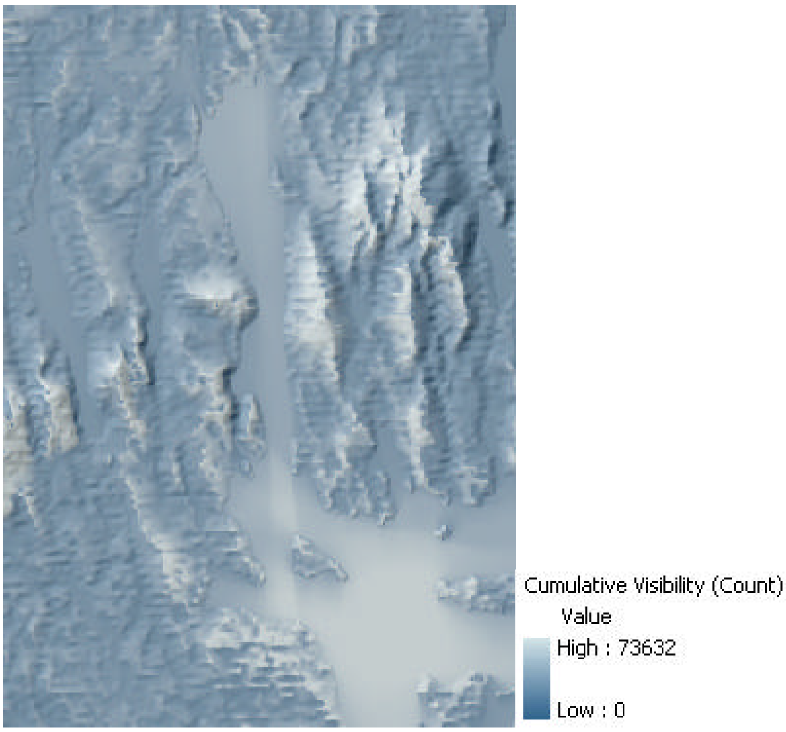

Figure 2. Cumulative visibility (Count of Visible Pixels)

For the Southwest Harbor. Maine, USA DEM, high visibility locations are found along the north-south ridges and in the large flat, ocean area located in the southeast corner of the DEM. As noted earlier, cumulative visibility is artificially restricted by the boundaries of the data set and do not necessarily reflect 'real world' cumulative visibility. This restriction is reflected in the hillside values, which appear lower on the western slopes of the ridges in the western part of the image, as well as lower on the eastern slopes of the ridges in the eastern part of the image.

2.2.2. Slope of Cumulative Visibility

Cumulative visibility slope (Figure 3) measures, for each point in the DEM, the slope of the cumulative visibility values associated with an observer location at that point. The value can range from 0 to 90 if the slope is calculated in degrees, or 0 to infinity if the slope is measured as a percent. Higher values equate to steeper slopes.

Cumulative visibility slope can be used to identify locations with sharp changes in visibility characteristics. Slope can be used as a guide for changes in visibility characteristics, but it does not have the conventional meaning of slope. When slope is calculated from a DEM, the X,Y, and Z units should all be the same. When slope is calculated from a cumulative visibility map, the X and Y dimensions represent measures on the earth, i.e., degrees, meters, feet, etc., while the Z values represent viewshed pixel counts, viewshed areas, or viewshed areas as a percent of the total area.

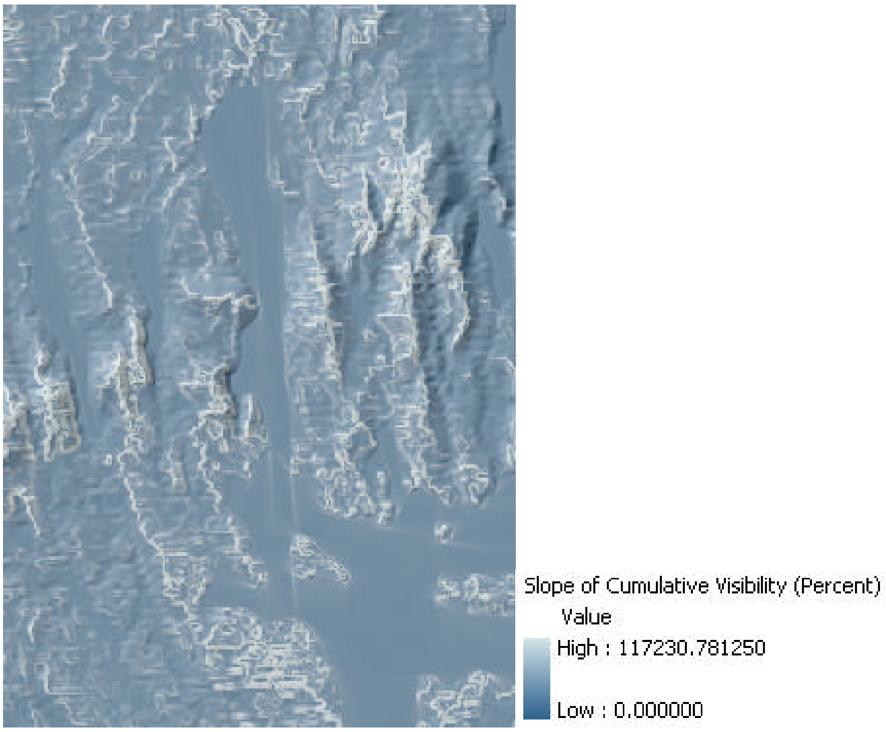

Figure 3. Slope of cumulative visibility (Percent)

The slope of cumulative visibility (percent) for the Southwest Harbor DEM shows high values along the ridges. This is because the tops of ridges tend to have the highest cumulative visibility, which drops off lower down on the hillslopes.

2.2.3. Fragmentation

Fragmentation (Figure 4) records, for each point in the DEM the total number of connected regions contained within the viewshed for each observer location at that point. Regions can be defined using 4-connected or 8-connected criteria. The lower value of this measure can equal one, with higher values indicating locations with greater masked area plot fragmentation. The range of values for 4-connected fragmentation is lower than the range of values for 8-connected fragmentation. Fragmentation is largely controlled by the nature of the intervening features. One long intervening ridge will reduce fragmentation, but a series of small ridges and gaps covering the same length as the long intervening ridge will increase the fragmentation. Fragmentation provides an indication of the degree of connectedness of the viewsheds.

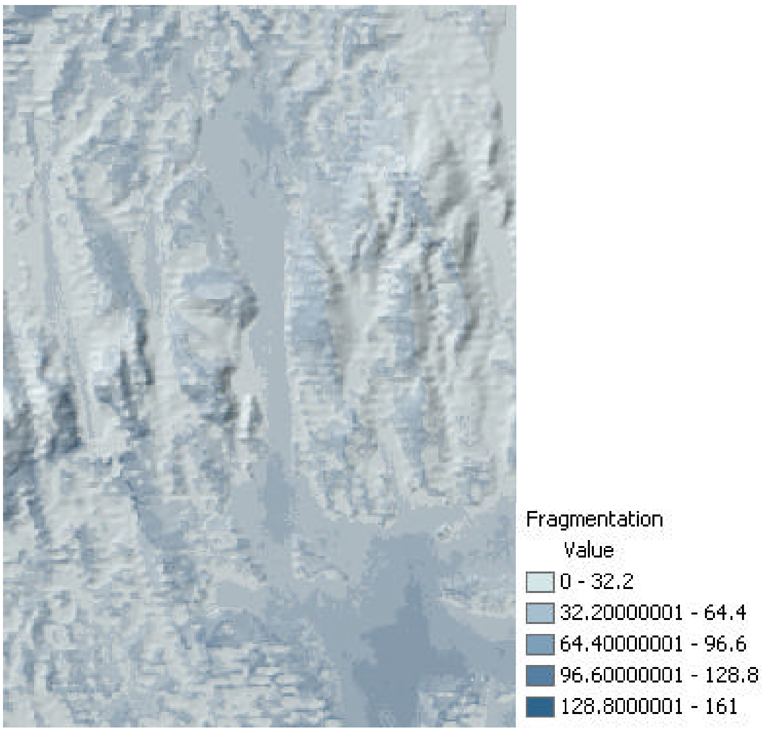

Figure 4. Fragmentation (8-connected)

The fragmentation (8-connected) map for the Southwest Harbor DEM is very similar to the cumulative visibility map. Higher values of fragmentation are found on the north-south running ridges and in the large flat, ocean area located in the southeast corner of the DEM.

2.2.4. Core Area Visibility

Core area visibility (Figure 5) records, for each point in the DEM, the total number of visible locations, the visible area, or the percent visible area of the DEM contiguous with the observer. This core region can be defined using 4-connected or 8-connected criteria. When counting the number of pixels in viewsheds, the value can range from 1 to the total number of points in the DEM, with higher values indicating larger core areas. Core area visibility is used to measure the visible area extent adjacent to a location. Analysis of the result can identify locations where large areas can be observed directly adjacent to the observer location, as well as areas with limited visibility from the observer location. This information can be combined with viewshed information to determine locations that can view a target, but which have minimal visibility immediately surrounding the observer.

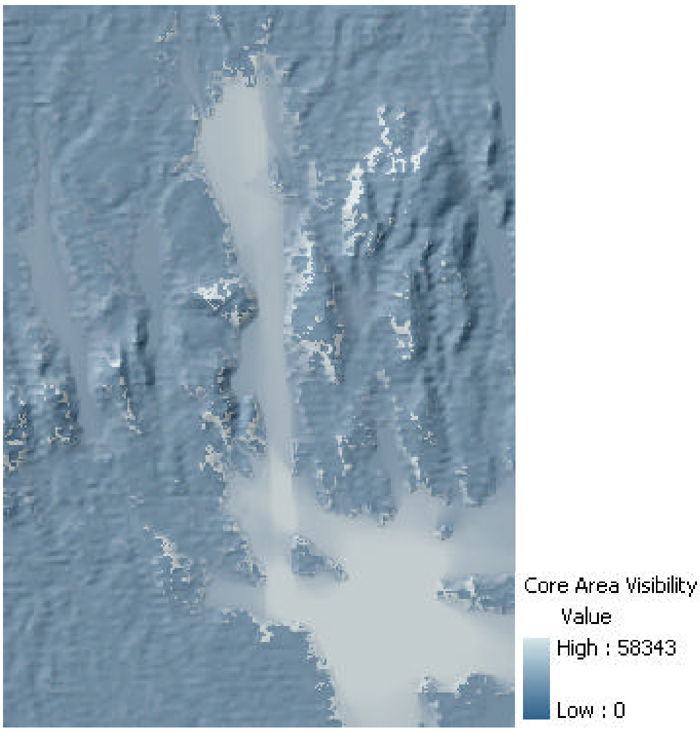

Figure 5. Core area visibility (8-connected)

The core area visibility (8-connected) for the Southwest Harbor DEM presents an interesting pattern. The values are higher in large flat areas, such as the ocean depicted in the southeast corner of the map and the bay in the center of the map. High values are also found along the lower hillslopes adjacent to the larger flat areas.

2.2.5 Ratio of Cumulative Visibility to Core Area Visibility

The ratio of cumulative visibility to core area visibility (Figure 6) is calculated by dividing the cumulative visibility by the core area visibility. Both should be measured in the same units, either the total number of visible pixels in the viewshed, the visible area, or the percent visible area of the DEM. This measure gives an indication of relationship between the areas of the viewshed and core visible area for each observer location and has a lower limit of 1, where the core area is the same size as the entire viewshed. The upper limit is dependent on the size of the DEM.

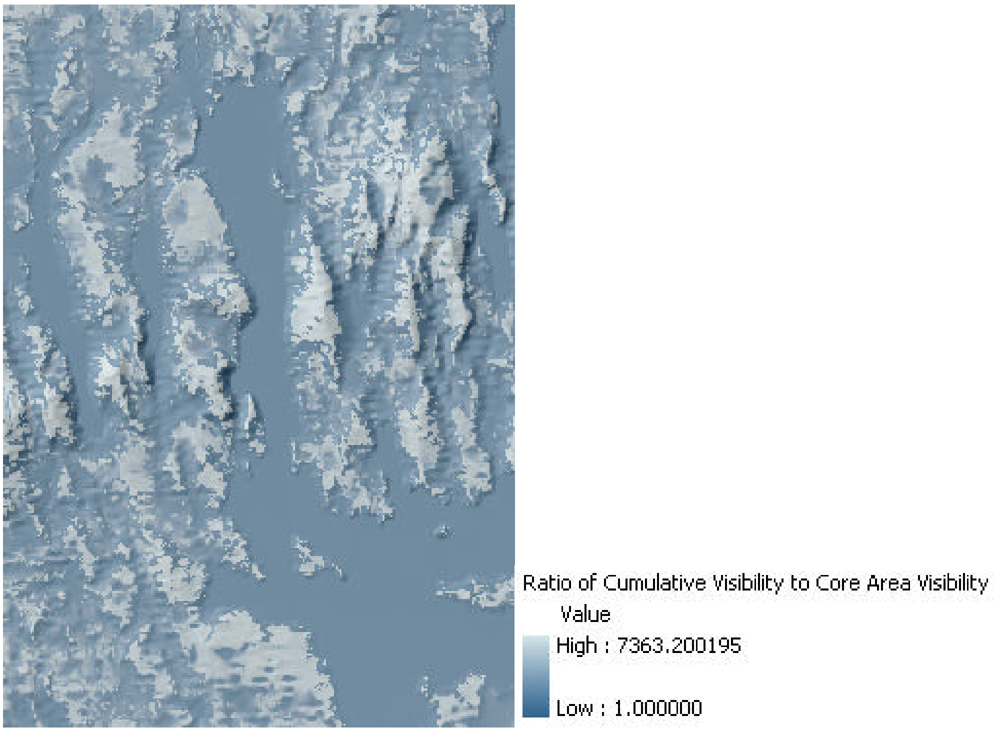

Figure 6. Ratio of total area visibility to core area visibility (8-connected)

The ratio of total area visibility to core area visibility (8-connected) for the Southwest Harbor DEM has low values in the large flat areas, such as the ocean depicted in the southeast corner of the map and the bay in the center of the map, but also in the valley bottom areas. The north-south trending ridge tops have higher values, indicating increased fragmentation and smaller core area visibility.

2.3 Tactical Decision Aids (TDAs)

TDAs provide processed information that can be directly used by a decision maker. Production of a TDA may involve analysis of the CID and/or use of a primary or secondary descriptive measure product.

2.3.1 Percent Target Visible

The percent target visible TDA (Figure 7) displays the percentage of a target feature that is visible from each point in the DEM. Point, line, or area target features can be modelled using a raster grid. The masked area plot for each point in the DEM is intersected with the target feature and the percentage of the target feature covered by the masked area plot is calculated. The values can range from 0 to 100, where 0 indicates that none of the target feature is visible, and 100 indicates that the entire target feature is visible. The percent target visible tactical decision aid is valuable for identifying the number and location of optimal observer sites for viewing a target feature.

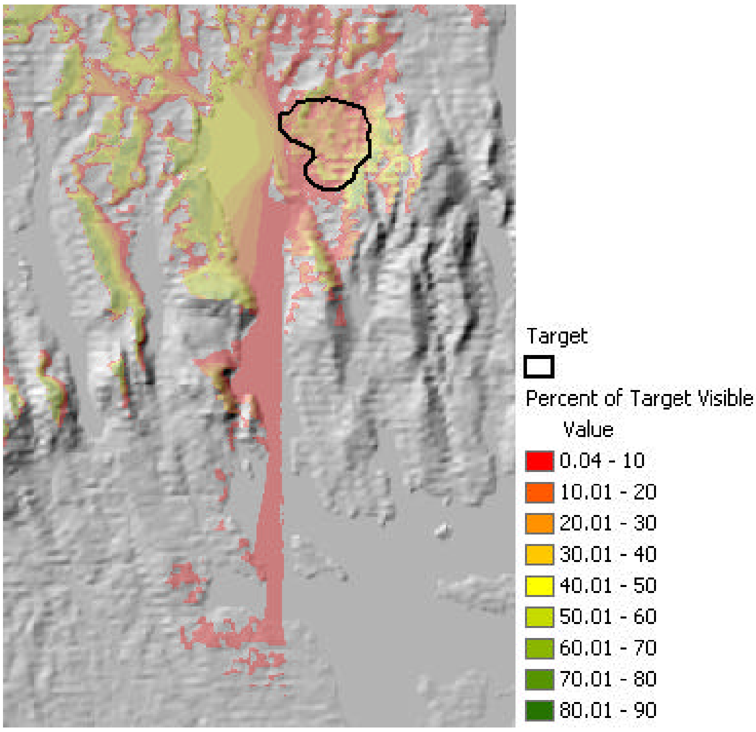

Figure 7. Percent Target Visible

The percent target visible TDA (Figure 7) indicates that no single location can view the entire target feature. Higher locations on selected ridges have the highest visibility, while small portions of the target feature are visible from a great distance along the corridor formed by the bay in the center of the DEM. The point with greatest visibility of the target feature lies outside the target feature.

2.3.2 Least/Most Visible Route

The least/most visible route TDA (Figure 8) uses the cumulative visibility map as a cost surface when calculating routes between a source and destination. The cumulative visibility map is used directly as the cost surface for the least visible route, since higher visibility represents the increased cost associated with higher detection probability. For the most visible route, the order of the cumulative visibility values are reversed, using a technique, such as subtracting all values from zero or subtracting all values from the largest value in the data set. This process makes the more visible locations have a lower value, decreasing the cost for transit.

While the least/most visible route maps shown in Figure 8 were generated using visibility as the sole input to the cost surface, visibility could be integrated with other inputs, such as slope, vegetation, etc. to create a composite cost surface.

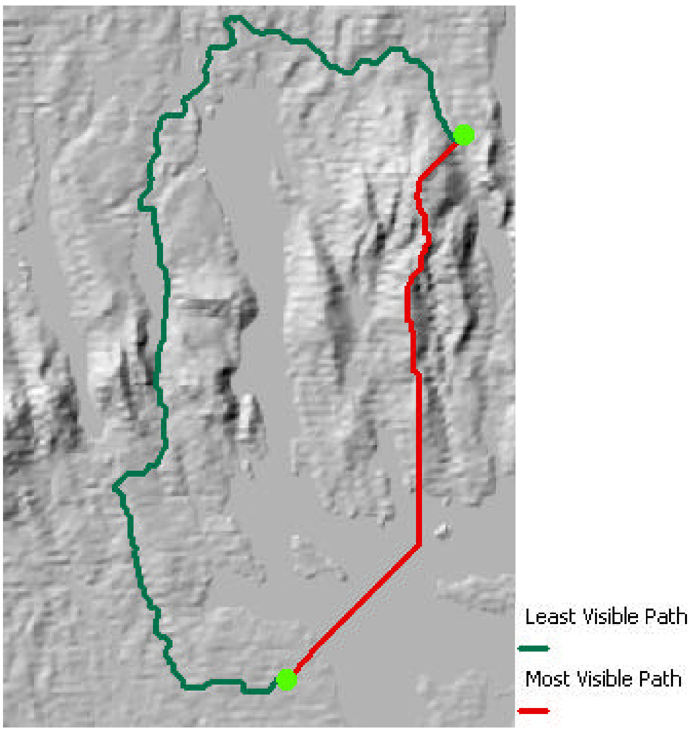

Figure 8. Least/Most Visible Routes

The least and most visible routes shown in Figure 8 present a sharp contrast. The most visible route is shorter and crosses the highly visible ocean in the southeast corner of the DEM and the ridge tops. The least visible route takes a longer, more circuitous path, following the lower lying valleys.

3. Summary

The CID extends the traditional visibility analysis models, line-of-sight profiles (point-to-point) and masked area plots (point-to-area), by storing viewsheds for every point in a DEM. This opens a new line of research related to visibility surface characteristics, properties, and the relationship between terrain and visibility.

This paper focuses on preliminary descriptive metrics and TDAs that exploit the CID. The descriptive metrics provide basic measures of the visibility surface such as cumulative visibility, cumulative visibility slope, fragmentation, core area visibility, and ratio of cumulative visibility to core area visibility. More sophisticated TDAs, such as the percent target visible and least/most visible route, can be developed from the CID and descriptive metrics. These products represent the beginning of a new generation of research on visibility surfaces that will include the development of additional descriptive measures and TDAs, as well as basic research into the relationship between terrain and visibility.

4. Acknowledgements

This research was sponsored by the U.S. Army Engineer Research and Development Center, Topographic Engineering Center, Alexandria, VA, and the U.S. Army European Research Office (ERO), London, England. The authors also wish to acknowledge the significant contributions of the following pioneering visibility analysis researchers: Clark Ray, Bob Richbourg, Peter Guth, and Danny Champion.

5. References

CALDWELL, D., MINETER, M., DOWERS, S., and GITTINGS, B., 2002, Explorations in Visibility Analysis: Applying ArcInfo in a Distributed Computing Environment. Poster, 22nd Annual ESRI User Conference.

MINETER, M., DOWERS, S., GITTINGS, B., and CALDWELL, D., 2003, High-Throughput Computing to Enhance Intervisibility Analysis. Submitted to GeoComputation 2003.

MINETER, M., DOWERS, S., GITTINGS, B., and CALDWELL, D., 2002a, A Multicomputing Software Environment for ArcInfo Intervisibility Analysis. In *Proceedings of the 22nd Annual ESRI User Conference*. (Redlands, ESRI)

MINETER, M., DOWERS, S., GITTINGS, B., 2002b, Software Infrastructure to Enable Parallel Spatial Data Handling: Final Technical Report. R&D 8707-EN-01 Contract N68171 00 M 5807 (London: U.S. Army Research Office)

RAY, C. ,1994a, Representing visibility for sighting problems. PhD Dissertation, Rensselaer Polytechnic Institute

RAY, C. ,1994b, A New Way to See Terrain. *Military Review*, 2, 81-89

RICHBOURG, R.F., RAY, C.K., and CAMPBELL, L.W., 1995, Terrain Analysis from Visibility Metrics. Proceedings of the SPIE Conference, April 1995, 2486, 208-219