ACCOUNTING FOR UNCERTAINTY IN VIEWSHED ANALYSIS OF IED AMBUSH SITES IN AFGHANISTAN

By

Sterling Mitchell Raehtz

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ABSTRACT

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Viewsheds are an important asset in military analysis for geographers in the war in Afghanistan due to the significantly diverse and rugged terrain of the battlefield. At the simplest level, viewsheds answer the question: "What areas can be seen from this location?" But the same is also true if we flip the question to, "What areas can see this location?" It is then logical to extend this question to improvised explosive devices (IEDs), the number one killer of soldiers and civilians in Afghanistan, as it is well documented that insurgents routinely observe the attack as controllers, witnesses, or videographers. The purpose of this study is to account for uncertainty in viewshed analysis in Afghanistan.

Viewsheds are a derivative of digital elevation models (DEMs), an imperfect representation of physical relief. Currently, the highest resolution open-source DEM available for Afghanistan is the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM). This research demonstrates a methodology to extrapolate known error models between ASTER and National Elevation Dataset DEMs to locations in Afghanistan where ASTER is the highest resolution DEM available and error is unknown. This extrapolation then makes it possible to develop more informative probable viewsheds for IED explosion sites via Monte-Carlo simulated elevation models through the visualization of uncertainty in the viewshed. Lastly, this research contributes to the discussion of the dynamic nature of viewsheds and their spatial dependence.

This thesis is dedicated to the United States Department of the Army and Michigan State University.

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LIST OF ABBREVIATIONS

ANA: Afghan National Army

ASTER GDEM: Advanced Spaceborne Thermal and Emission Radiometer Global Digital Elevation Model

CGIAR-CSI: Consultative Group on International Agricultural Research Consortium for Spatial Information

ERSDAC: Earth Remote Sensing Data Analysis Center (Japan)

ISAF: International Security Assistance Force

IED: Improvised Explosive Device

JIEDDO: Joint Improvised Explosive Device Defeat Organization

METI: Ministry of Economy, Trade and Industry (Japan)

MRAP: Mine Resistant Ambush Protected (Vehicle)

NASA: National Aeronautics and Space Administration (United States)

NATO: North Atlantic Treaty Organization

NED: National Elevation Dataset

RMSE: Root Mean Square Error

SPVA: Simulated Percent Viewshed Area

SRTM: Shuttle Radar Topography Mission

TPVA: Target Percent Viewshed Area

USGS: United States Geological Survey

WITS: Worldwide Incident Tracking System

1 Introduction

It is apparent to all soldiers that physical geography is a vital, timeless combat force multiplier. This truth is nowhere more apparent to the U.S. military than in the diverse terrain of Afghanistan. Situated along the Hindu Kush mountain range, the majority of the country lies in extremely rugged terrain where the soldier on the ground is consistently exposed to high ridges and narrow passageways between steep slopes. Consequently, the Afghan insurgency has taken advantage of natural choke points that allow a few men to contain or delay the numerically and technologically superior American force. This tactic has been historically used all over the world. In 480 BC, a contingency of approximately 1,000 Greek warriors defended the Pass of Thermopylae against a Persian force with hundreds of thousands of men gaining time for the rest of the City-States to amass an appropriate fighting force. In 1415, the English successfully defeated a numerically superior French army during the Battle of Agincourt in the Hundred Years' War thanks to a choke point created by a stand of trees and a terribly muddy battlefield. Even in World War II the Allies faced formidable terrain during the invasion of Normandy with German pillboxes positioned high atop bluffs and cliffs, which were insurmountable without special mountaineering equipment. It is difficult to argue that the terrain along the northern French coast during Operation Overlord did not factor into many of the 500,000 casualties from 06 June 1944 to 25 August 1944. The current U.S. involvement in Iraq and Afghanistan is no exception to the inherent advantage of terrain. U.S. troops have grown accustomed to fighting in the urban landscape of cities such as Baghdad or Tikrit, which offer insurgents ample locations for hiding personnel and equipment and for initiating devastating ambushes on coalition forces. Now that the attention of the United States has shifted further east to Afghanistan and Pakistan, the U.S. military, part of the International Security Assistance Force (ISAF), is reacclimating operations to the classic role of physical terrain after nearly a decade of urban warfare.

Military conflicts in the Middle East have received scholarly attention for the better part of the twentieth century to include causation, prevention, and analysis of virtually every dimension of warfare imaginable, especially in recent years due to the explosion of academic grants from the U.S. government following 11 September 2001. Yet, the body of literature regarding the American military presence in Afghanistan has seen relatively little contribution from professional and academic geographers, largely in part to the lack of readily accessible data on specific military operations. The majority of recent research has taken a broad approach to the study of Islamist terrorism[1] and is ignorant of the fact that terrorism is an extremely dynamic phenomenon (Black, 2004; Hoffman, 2004; Schmid, 2004). Academia has answered research questions from the perspective of geography solely as a consequence of geopolitical conflict (Flint, 2003). More importantly, the current body of geographic literature has failed to fully utilize classic theories in geography to answer contemporary military research questions in Afghanistan, such as viewsheds.

Modern combat is a dynamic phenomenon that changes with the tides of political agendas and military strategy. It seems that the best approach for applicable military geography research is at the tactical level. Instead of developing broad theories that apply to many different groups of people, tactical research eliminates potential or unknown variables in a study. For example, a researcher may be interested in the changing spatial patterns of the Afghan

[1] It is imperative to note that the definition of terrorism and the controversy surrounding the attempt to define terrorism is important to the spirit of this paper, yet this research does not label the insurgency in Afghanistan as terrorist movement. This is not the purpose of the paper. The term “terrorism” is only used in reference to pieces of scholarly work that have done so and are cited in this paper.

insurgency from 2004-2009. This type of study is becoming quite common due to the release of the Afghan War Diary by WikiLeaks.org as the abundance of unpublished data can create a supposed academic overnight. There are many variables that factor into this study that are virtually impossible to even be hypothesized by the researcher, such as specific demographic information, especially in a country without a valid census.

Viewsheds are an important military algorithm for geographers, and have begun to receive significant interest for research (Sandia National Laboratories, 2010). The exact location of an enemy is often unknown due to the rugged and expansive Afghan landscape. At the most simple level viewsheds can identify potential observation locations for a particular point. This is why it is important to calculate the viewshed, which enables inference of possible enemy locations. Research extending their utility to analyzing IEDs in Afghanistan is a necessity in counter-IED operations (Vanden Brook, 2010).

This study assesses the performance of ASTER GDEM over the more coarse resolution SRTM elevation model and makes a contemporary extension to viewsheds as a product of variable uncertainty. The three foundational hypotheses of this research are 1) ASTER is a better elevation model than SRTM for use in Afghanistan; 2) Error propagation can be used to help analysts understand the magnitude and impact of uncertainty in ASTER and, consequently, viewshed analyses; and 3) Monte Carlo simulation can be used to create informative probable viewsheds surrounding IED incidents in Afghanistan.

This first chapter will review past literature in three parts. First, a general review of military geography research will be conducted with specialized focus on the tumultuous last thirty years of military activity in Afghanistan. An explanation of viewsheds and their applicability to military geography research will follow thereafter. Lastly, a discussion of general principles in error propagation and their use in viewsheds will establish the theoretical foundation for this study. After this framework has been established, the study will then begin with an examination of the study areas and initial elevation models located in Colorado and Afghanistan. These models will be juxtaposed to determine suitability then viewshed simulations will be run on each study area. The thesis will close with an overview of the results, the limitations of the research, and future research interests this study has exposed.

1.1 Literature Review

1.1.1 Military Geography Research in Afghanistan

Afghanistan has received quite a bit of attention in the last decade due to the “War on Terror.” Not only has the United States had a vested interest in the removal of the Taliban government in 2001, but there has been a long-standing concern about the security implications arising from such a war-torn nation wrought with fraud and corruption, largely in Kabul, at the hands of insurgent organizations. With the number of U.S. troops in Afghanistan now exceeding those in Iraq, geographers have begun to play an important role in understanding security conflicts in Afghanistan. The annual publication from the United Nations Development Programme includes a number political and social challenges in Afghanistan that largely use human ecology and scale as a framework for study (2004).

From a historical perspective, the Soviet conflict in Afghanistan from 1979 to 1988 produced some military conflict literature during its occupation (Reisman, 1987; Donaldson, 1989). The U.S. is fighting on the same terrain, using somewhat similar tactics, and faces the same enemy. The U.S. must also contend with the same nation of disunited tribes where ethnic and familial trust run deeper than ties to a broken nation ever could. This ethnocentrism has been greatly supported thanks in large part to the defeat of the British in the late 19th century and the

Soviets in the 20th Century. Since then, Afghanistan has served as a hot bed for terrorist recruitment, training, and financing through the Taliban regime as well as a safe haven for Al Qaeda and its supporters. Further, the relatively open borders with Pakistan, Uzbekistan, and Iran have improved the fluidity of movement of insurgents, transnational terrorist networking, and drug transportation (Baev, 2007).

Although the social and political issues in Afghanistan are certainly a key factor in the intensity and severity of security incidents, the U.S. and other nations with a military presence in country are just as concerned with the tactical geography of Afghanistan. Recently, the U.S. military and open-source journalists alike have been paying particular attention to the geographic advantages and disadvantages of military campaigns in Afghanistan. The militaristic importance of the Afghan landscape was made clear to the public only ten days after the attacks of 11 September 2001. In an eerily prophetic explanation, the New York Times ran an article detailing the combat challenges in Afghanistan, particularly IEDs and guerilla warfare, due to its expansive and rugged terrain that is dotted with decentralized tribes and clans (Rhode, 2001). This article would be proven more and more accurate with every subsequent IED and ambush; well over 15,000 incidents have killed over 2,000 ISAF soldiers as of March 2010 (Whitlock, 2010).

Academics have acknowledged the tactical importance of the Afghan landscape through the power of geographic information systems (GIS) in the study of asymmetric warfare in Afghanistan. Both Beck (2003) and Schroeder (2005) have published articles detailing the advantages of using geology, GIS, and remote sensing as counter-terrorism tools. These authors have used open-source propaganda from terrorist organizations[2] to analyze potential locations for such terrorists as Osama Bin Laden and Ayman al-Zawahiri as well as training camps based on key terrain and geologic features spotted in videos. The confidence in using this technology has become so great that a group of academics have gone so far as to say that they knew the exact whereabouts of Bin Laden and publicly stated this in the USA Today (Vergano, 2009). Vergano's approach exemplifies emerging methods used by geographers to turn terrorist propaganda into damning evidence of the locations of safe havens nestled deep in the Afghan mountains, albeit certainly imperfect.

Currently, the most applicable type of research regarding the insurgency in Afghanistan is the analysis of improvised explosive devices (IED) attacks. Although the majority of these research efforts are within the United States Intelligence Community and for official use only due to security reasons (Tomasi, 2009), some academics have published research on tools that military and intelligence analysts can use. For example, Parunak (2009) utilizes multi-layer simulation to predict IED hotspots combining leadership, process, and environmental models. The simulation model called DEFUSE (Detecting Enemy Forces United to Strike with IEDs) predicts IED planning, manufacture, emplacement and detonation using geospatial constraints imposed by environmental variables such as vehicular and foot traffic and demographic variables like localized ethnicity, population density, and political motivation. Similarly, Curtin (2009) uses a method known as linear referencing to predict IED placement based on road network density and localized demographic and environmental variables.

One critical limitation of current academic efforts in military geography research is to quantitatively analyze the military and strategic threat of the insurgency based on open-source

[2] As designated by the U.S. State Department

data. Only one geographic study has been done at the tactical level in Afghanistan. O'Loughlin (2010) only begins to scratch the surface of the potential of this data through a series of cluster analyses and general summary statistics based upon geospatial locations of security incidents contained within the Afghan War Diary. Although O'Loughlin's study is extremely informative, it oversimplifies the intricate variables necessary to accurately understand the nuances of IED activity. Most importantly, the study identifies reports of violence as events in which there is at least one casualty, either enemy or friendly. This distinction is clearly problematic considering the numerous cases of direct and indirect enemy fire for which no casualties were reported. Does firing an assault rifle into a patrol of American soldiers constitute a violent act if the shooter has terrible aim? Only 22.49 percent of events classified as direct fire resulted in one or more casualties leaving a significant number of "non-violent" events out of the analysis.

O'Loughlin's study is also the only one to utilize the Afghan War Diary to empirically explore the highly debated question of whether relative proximity to the Afghan-Pakistan border significantly influences the amount of violence in an area. "Nearness" to the border is quantified as a 100 kilometer buffer from the border and differentiates events within the buffer as being "near" to the border and those outside the buffer as "far" from the border. According to O'Loughlin, the 100 kilometer buffer represents approximately one-quarter of the country and if events were to be randomly distributed throughout Afghanistan, far fewer events would have been expected in the "near" category. In fact, throughout much of the war in Afghanistan, nearly half (46.8 percent) of all violent conflicts were located near border areas. This total did not drop until late 2009 when most conflicts moved away from border areas, "illustrating the nationalization of the insurgency away from traditional Taliban strongholds" (486).

O’Loughlin’s study was also the first open empirical analysis of the effect of terrain “ruggedness” on violent conflicts in Afghanistan. In asymmetric warfare, one would assume that more conflicts will occur in highly variable terrain, allowing the insurgency to fortify and defend fighting positions inaccessible to most modern military ground vehicles. In fact, the data proves very different. O’Loughlin once again creates a simple dichotomy to categorize the differences in terrain. Utilizing slope data calculated from the Shuttle Radar Topography Mission (USGS, 2004), O’Loughlin labels flat terrain as those pixels adjacent to a violent event whose mean slope is less than 4 degrees, all others are labeled as hilly/steep. From 2004-2009, the data shows exponentially more violent conflicts to take place on “flat” terrain, especially in later years when more than three-quarters of all conflicts initiated by either ISAF/ANA or insurgents took place on flat terrain.

Although the Afghan War Diary has proven to be an extremely interesting dataset for researchers and muckrakers alike, there are certain legal and ethical issues associated with its use. On one hand, it is a valuable dataset that has significant potential for very attractive research that may be valuable to the war in Afghanistan. On the other hand, the United States government and its allies have made it very clear that the release of this data was unauthorized. It is important to realize that although the data has been released to the public, it is still classified and the willful handling of this data on an unclassified computer is a significant security violation that may have professional consequences in the future. Due to these ramifications, it is not surprising that O’Loughlin is the only academic to have published his findings.

It may be more appropriate, then, to conduct a study that uses open-source information and can still quantitatively assess the battlefield from a tactical standpoint. Global digital elevation models have become widely available at almost astonishing resolutions in the last few years. Most recently, the ASTER GDEM product now offers digital elevation models for nearly the entire world at approximately 30 meter resolution; a far cry from the 1 kilometer resolution of GTOPO30 produced by the United States Geological Survey's Center for Earth Resources Observation and Science in 1996. Due to this significant increase in spatial resolution, the viewshed tool can now be used for military tactical research.

1.1.2 Viewsheds

The viewshed is the total area in the environment that is visible from a fixed vantage point. There are two related questions associated with viewsheds: 1) Is Point A visible from Point B? and 2) What areas are visible from Point A? In relation to the military, these questions can be posed as "Can I see the enemy from here?" and "From where can the enemy see this location?" The viewshed algorithm is a simple, yet fascinating algorithm developed by a number of different geographers as early as the late 1960s (Araki, 1979). The algorithm is essentially a culmination of repetitive line-of-sight functions repeated from the observing cell to every other cell in the scene. If a line-of-sight between the observing cell and the target cell remains unbroken due to higher elevations in between the two cells, the target cell is included in the viewshed. Figures 1-3 utilize a simple elevation grid (one row of ten cells) to illustrate the basics of the line-of-sight function. The viewshed algorithm can be run on grids independent of size although the amount of processing time to complete the process increases exponentially with more rows and columns as the process must evaluate each cell.

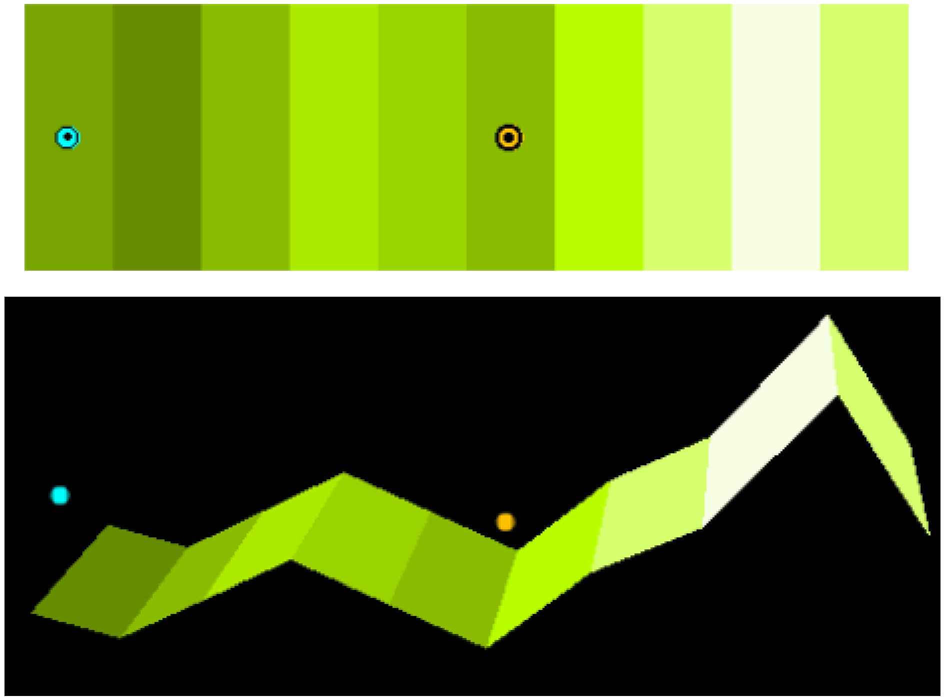

Figure 1: Point A (left) and Point B (right) (Shortridge, 2010). For interpretation of the references to color in this and all other figures the reader is referred to the electronic version of this thesis.

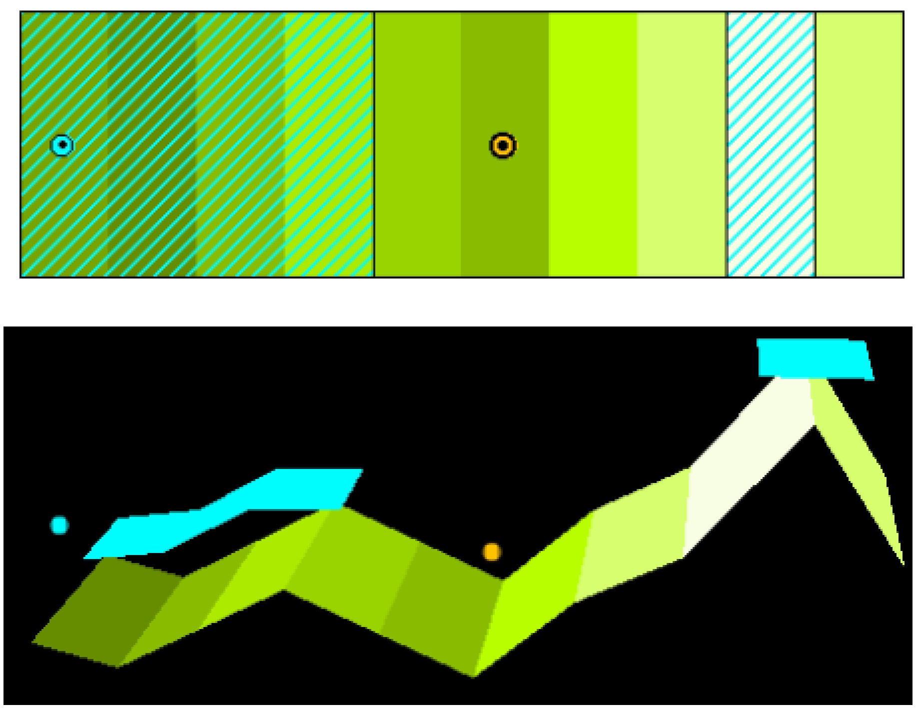

Figure 2: Point B is masked from Point A (Shortridge, 2010).

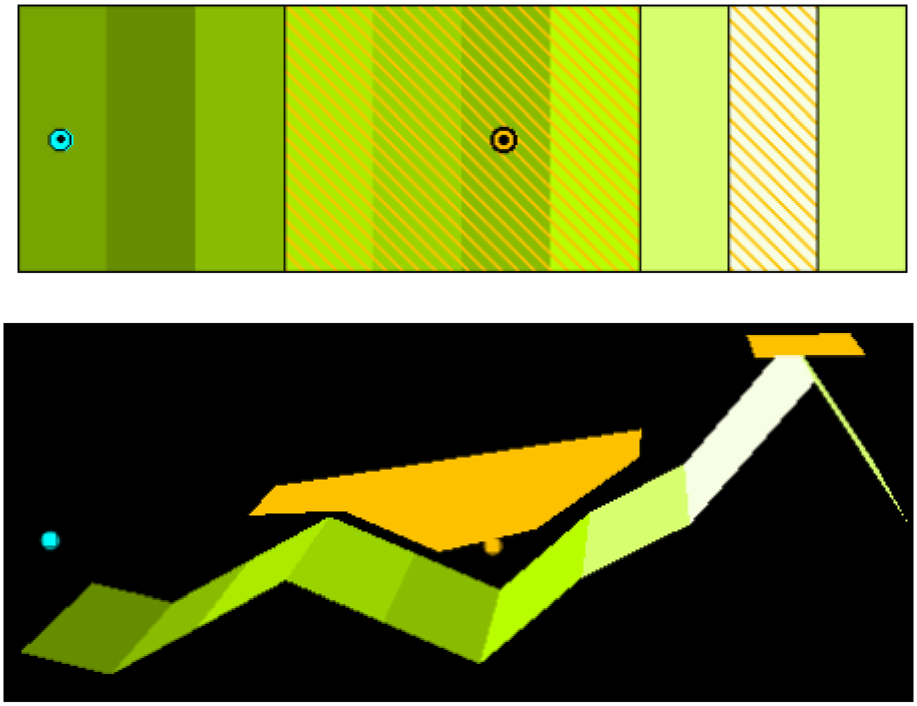

Figure 3: Point A is masked from Point B (Shortridge, 2010).

Viewsheds are intrinsically valuable to military strategists based on the importance of terrain and visibility. For years, academics and military strategists have pondered the implications of positioning military bases in certain terrain based on their visibility to the enemy, planning convoy routes based on the likelihood of being spotted by the enemy, and directing troops in flanking movements to mask their positions until the moment before attack (Caldwell, 2003). The beginnings of this application were simplistic and traditional, not to mention entirely different due to the military climate of the world in the mid-1990s. The purpose of Dunham (1998), for example, was to illustrate the use of GIS and 3D modeling in military construction management, almost five years prior to the war on terrorism and combat operations in the Middle East. Dunham was a private contractor for the US Navy tasked with improving GPS and CAD mapping capabilities for the Public Works Center of Yokosuka US Naval Base in Japan. This article is important to the discussion of where GIS has been used in the military in the early years of the technology as opposed to how it is being used now. Among other responsibilities, the team was tasked to create maps of the most ideal building locations for GPS-satellite connectivity as well as buildings with degraded radio communications due to line-of-sight issues. It is apparent to the reader the military has valued the viewshed algorithm and has continually extrapolated the concept to emerging technology.

Contemporary applications of viewsheds to the military are far more complex and intended to support the battle picture for commanders. Funded by the Finnish Defense Forces, Janlov (2005) and his team set out to explore the specific application of visualization algorithms and topographic information to the “situation picture,” the understanding of the battlefield. Janlov utilizes the so-called observe, orient, decide, act (OODA) -loop as the theoretical framework for the study. The crux of the research relies on the model to verify the spatial integrity of collected information (through a variety of reconnaissance methods), conduct visualization analyses on the data, and finally offer a clear situation picture (e.g, a. map) of the intelligence with which a commander can make an informed decision.

Janlov (2005) extends his model of the situation picture to predictive analyses. One such analysis is predicting enemy movement based on terrain factors. There are two main datasets necessary for this prediction. The first is the observation dataset which is obtained from the situation picture analysis (e.g., type of vehicle, speed/direction of travel) and combined with a topographic dataset. This dataset not only contains elevation models, but more complex variables such as cross country movement layers, military data such as minefields, and current weather conditions. The model can then predict based on all of the above factors what the most likely course of action will be for the enemy. This is an example of the capabilities of contemporary terrain-based decision making.

The last section of this article discusses the development of visualization for the situation picture. It is very important for an analyst to create a map that is easily interpretable for all levels of command. Military commanders often have little time to make decisions that impact the lives of thousands of soldiers. It is the responsibility of the cartographer to develop a visualization technique that distills the complex information synthesized by the analyst. Janlov attempts to incorporate the information in the previous chapters into simple maps that can be easily understood at a glance (206):

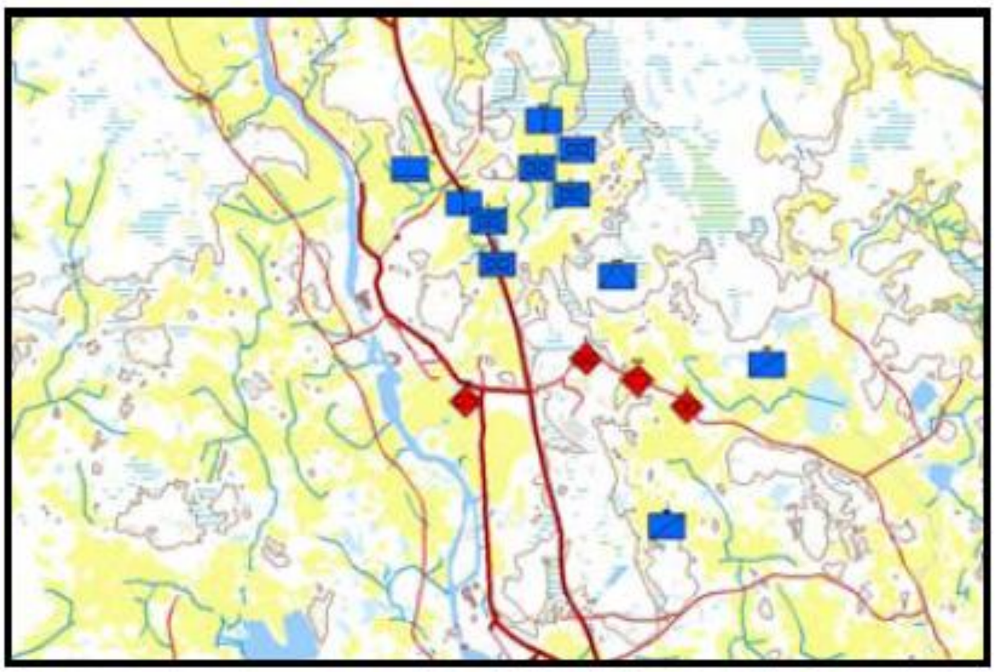

Figure 4: Generalized vector map (by RaveGeo application) in the situations background (Janlov, 2005).

This map depicts a generalized version of the situation picture in the background with friendly (blue) and enemy (red) troop movements overlain. It is extremely difficult to display temporal information in static maps. Janlov takes on this common cartographic problem in the military context (207):

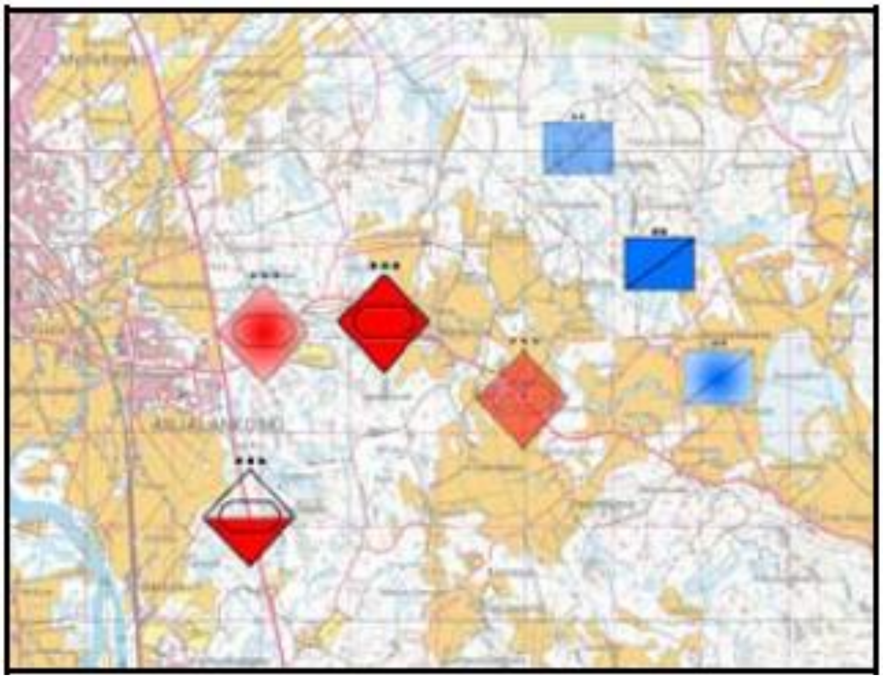

Figure 5: The movements of the troops by the changed tactical signs. This map also includes one tactical symbol (filled only have way) that presents an uncertain observation (Janlov, 2005).

The applications of viewsheds outlined in this section are just a few examples of how the tool has made a significant contribution to militaries around the world. Gaining the line of sight advantage on the enemy has been a determining factor in many conflicts since the beginning of human combat (Wheatley, 1995; Lake et al., 1997). The ever-changing face of modern warfare is accompanied by advances in technology, most recently with the assistance of computer-aided decision making. This type of decision making, as quick and efficient as it may be, ultimately relies on algorithms that process substantial amounts of data with limited regard for uncertainty (Burrough, 1991). Viewsheds are no exception. Digital elevation models, and consequently viewsheds, are famously prone to error. In fact, viewshed are one of the most interesting applications one can study if interested in error issues. Thus, a robust body of literature has developed over the last few decades that support accounting for uncertainty in elevation models and the viewshed algorithm.

1.1.3 Error Propagation

The viewshed tool is an extremely useful tool for the cat-and-mouse nature of combat. Terrain, visibility, and intervisibility can mean life or death for the ground soldier, winning or losing for the commander, and even shift the tides of war for a nation. The Battle of Gettysburg provides a perfect example of the impact of terrain on the soldier, commander, and nation. Thousands of Confederate soldiers died due to the Union's significant terrain advantage atop Cemetery Hill and Cemetery Ridge, Pickett's Charge turned out to be a devastating tactical blunder, and the Union victory proved to be the turning point of the entire war. Even prior to the Battle of Gettysburg, a lack of visibility prevented Major General U.S. Grant's left flank from cutting off Lieutenant General J.C. Pemberton's supply lines at the Battle of Champion Hill and lead to the siege of Vicksburg (USPS, 2011).

With such heavy consequences weighing on the viewshed tool, is it feasible to rely so many important resources on the accuracy of an unaltered DEM? Although the quality and resolution of elevation data has significantly improved in only the last ten years—open-source data has improved from approximately 1 kilometer resolution to 30 meter resolution for the majority of the world—the fact remains that digital elevation models are prone to error at any resolution (Oksanen and Jaakkola, 2000). Error (*e*) at position (X_0) is essentially the difference between the true value $z'(X_0)$ and the prediction $z(X_0)$ such that

$$e(X_0) = z'(X_0) - z(X_0)$$

Figure 6: Error calculated at position X_0.

and, in terms of elevation, is an addition or subtraction to the original value (Atkinson, 2002). This error is the result of potentially hundreds of predictable and unpredictable factors ranging from fixed misalignments within a collection sensor to atmospheric anomalies to the fundamental raster-based storage structure of DEMs illustrated in Figure 6.

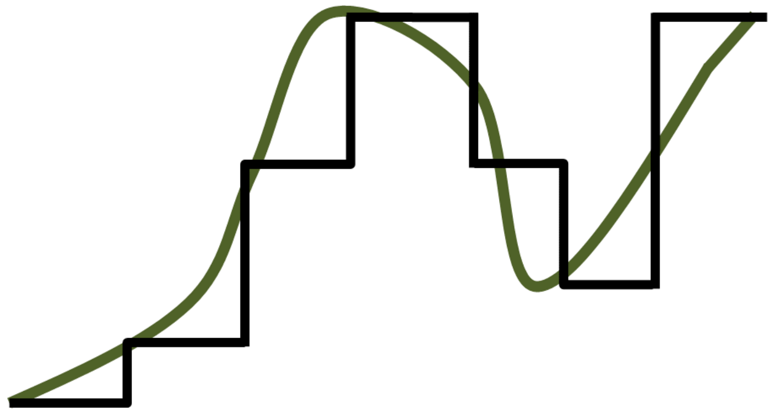

Figure 7: Error is inherent in raster-based digital elevation models. Real landscapes (green) are converted to grid cells with numerical elevation values. Increased cell resolution translates to less error.

There are three important questions when considering error in a dataset: "'What error is present?' (definition), 'How can it be visualized?' (communication) and 'How can the results be used in practice?' (application)" (Hunter and Goodchild, 1993).

There are two approaches to accounting for error in DEMs: random error models and spatially autocorrelated error models. Random error models have been known to be the more conservative of the two as it is considered to be the "worst case scenario"—although Oksanen (2000) argues this is not necessarily true. The model used to represent error in the DEM randomly distributes positive and negative error throughout the landscape. This model is constrained by a Gaussian distribution that is parameterized with a mean error (often zero) and a standard deviation. Spatially autocorrelated error models, on the other hand, assume Tobler's First Law of Geography—near things are more related than distant. The consequence of this assumption is that the error models "clump" together similar degrees of error. A spatially autocorrelated error model for a DEM of Mount Rainier, for example, would assume that error in elevations at its peak are more closely related than errors at the base. This is a logical assumption considering the terrain near the top of the mountain is more rugged than at its base. Geographers from many different sub-disciplines have utilized spatial autocorrelation error models to correct for imperfect DEMs since the early 1990s, e.g., feature extraction (Lee et al., 1992), flow path direction (Veregin, 1997), automatic drainage basin delineation (Miller and Morrice, 1996), route optimization (Ehlschaleger, 1998), and a variety of other surface derivatives (Holmes et al., 2000). In the last twenty years spatially autocorrelated error models have been frequently combined with the Monte Carlo simulation technique (Fisher, 1992; 1995; 1996; Heuvelink, 1989; 1998; Hunter and Goodchild, 1997), a widely used class of methods first developed in the 1940s involving statistics derived from large sets of repeated pseudo-random sampling (Metropolis and Ulam, 1949).

Although a somewhat smaller body of literature than Monte Carlo simulated error models of geomorphologic applications, error propagation has been incorporated into the viewshed operation largely due to its intrinsic risk of significant error. Peter Fisher is a pioneer in the attempt to address scale and error in the viewshed algorithm although the military has been concerned with line-of-sight calculations since the late 1950s (Ford et al., 1959). In contemporary terms, Fisher's articles (1992; 1996) address the problem with viewsheds in the most fundamental form: Boolean classification. He argued that utilizing error propagation in viewshed calculation for both the elevation of a cell and that cell's likelihood of being included in the viewshed gives a more accurate and realistic assumption of the viewshed. Furthermore, Fisher stated that since digital elevation models are created using imperfect collection methods and even assessed based on imperfect products (contour maps) via a measure of the root-mean squared error, a Boolean viewshed analysis is significantly prone to error. Fisher discusses previous attempts to characterize this "fuzzy" viewshed concept, which is actually a measure of certainty that a certain cell is actually within the viewshed. The most important algorithm discussed by Fisher (1992) is one that generates noise in the DEM using the RMSE of varying degrees of spatial autocorrelation and then runs the viewshed process on the error models of the DEM. The binary result of each iteration is added to an empty raster and the resulting viewshed is a surface with each cell containing a value from zero to the number of iterations run. Fisher then used the following equation to quantify the likelihood that a cell is within the viewshed:

$$X'_{ij} = X_{ij}/n$$

Xij: the sum value at row i, column j
n: number of simulations
X'ij: 0-1, degree to which cell is likely to be in view

Figure 8: Equation to create probability within each raster cell.

Fisher ran the viewshed algorithm a number of different times using different degrees of autocorrelated error in the DEM and discovered that there is no significance in using anything except random error. Autocorrelation, Fisher argued, causes less predictable viewsheds and is not necessary to include in the absence of empirical evidence arguing otherwise. However, terrain error is absolutely spatially autocorrelated whether due to the actual landscape (e.g., ruggedness) or from artifacts produced by the collection platform pre or post-processing.

Fisher realized that the "fuzzy" viewshed concept in his first article was concerned more with the inaccuracies of the DEM rather than the viewshed. In 1995 he published another article that was suited solely for the viewshed algorithm (Fisher, 1995). This new approach utilized distance decay theory to assign lower values to the viewshed cells as they increased in distance from the observation point. This formula can be used to reclassify binary values and to produce a surface describing varying levels of viewshed certainty (Ogburn, 2006).

From there, academics have expanded the discussion of error to scale. Franklin (2004) discusses the effect of DEM resolution on intervisibility and if the tradeoff between advantage and computational cost is economical. There are two very important conclusions derived from this study. First, reducing vertical resolution of a DEM, even significantly (0.1 meters to 10 meters) does not worsen the quality of multiple observer siting. Conversely, improving the horizontal resolution even by a factor of two significantly decreases intervisibility. This finding is very important considering the amount of time and money devoted to improving the collection of elevation data, in terms of both horizontal and vertical resolution, is always increasing. This finding suggests that the focus of technological research in remote sensing platforms should be more concerned with increasing horizontal resolution as at least one product derived from the collected data is only benefited in this direction.

Of course, not all uncertainty within a DEM is solely constrained to the model. Ashton (2010) showcases the importance of incorporating land cover data into a digital surface model in terms of viewshed analyses. Ashton's comparison of the bare surface model and the surface model overlaid by vegetation shows significant difference between the resultant viewshed areas. As one might assume, a viewshed uninhibited by vegetation, both natural and agricultural, is disproportionately larger than realistic landscapes. This difference is apparent regardless of terrain ruggedness as one study area was located in the Texan Rio Grande Valley and the other was located in the rolling hills of Maine. Despite similar findings, it was also apparent that the usefulness of incorporating land cover data was greater as terrain variation increased. Although Ashton does not address this issue, the type of land cover located in these different landscapes is important to consider since vegetation in the Rio Grande Valley consists of crops and pasture with sparse hardwoods. Conversely, the vegetation of the Maine landscape consists of significantly more hardwoods and scrubland with fewer areas of crops and pasture. Lastly, Ashton addresses the issue of DEM resolution as he compares 30 meter NED, 3 meter LIDAR, and 1 meter LIDAR, concluding that the 1 meter resolution outperforms all other DEMs, justifying the increased storage requirements.

Viewshed error and its corresponding representation has only recently become an issue within military geography research. One important tool possessed by cartographers for military visualization techniques is the ability to graphically represent phenomena without necessitating precise data. In the example below, Janlov symbolizes viewshed uncertainty with a simple gray border on the viewshed boundary.

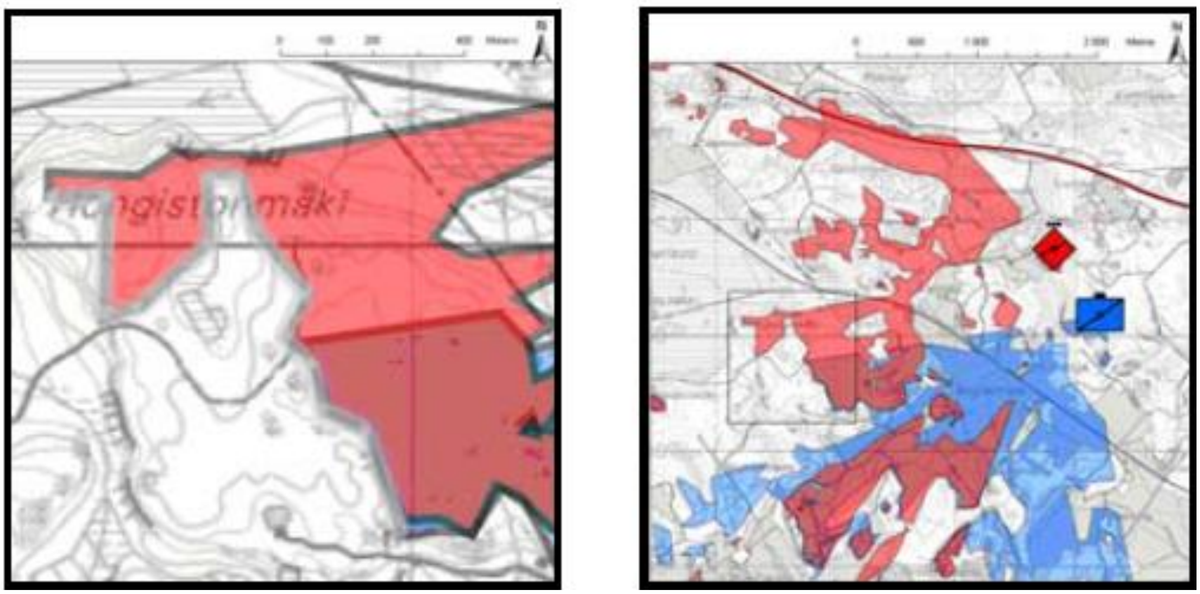

Figure 9: Uncertainty of the viewshed boundary line can be represented with a wider, light grey fuzzy line (Janlov, 2005).

Janlov argues that it is crucial for a commander to know which data on the map is more reliable than others in the situation picture (207). This differentiation is possible by delineating the layers of certainty with different types of symbology. It is clear that despite the vast amount of information produced by GIS databases, representing that data for tactical commanders, the ultimate consumers of the information, is an ever-present issue.

Many different approaches to error propagation in digital elevation models and viewsheds have been discussed in this section. The next chapter utilizes the theoretical framework of previous attempts at modeling spatially autocorrelated error in a DEM to develop error models for rugged landscapes in Colorado and Afghanistan. It will then employ Fisher's original binary summation methodology to develop probable viewsheds to assess the effectiveness of extrapolating the error model and to shed insight on the value of probable viewsheds to counter-IED operations.

2 Data and Methods

It is first necessary to diagram the conceptual framework under which this research is conducted in order to both properly convey the overall purpose of this study and to put into context the following chapters of this thesis. Figure 8 shows the steps in which this research is conducted. First, three digital elevation models are collected from their relevant sources; SRTM from an online portal (http://srtm.csi.cgiar.org/) managed by the Consultative Group on International Agricultural Research Consortium for Spatial Information (CGIAR-CSI), ASTER GDEM from an online portal (http://asterweb.jpl.nasa.gov) managed by the U.S. National Aeronautics and Space Administration (NASA), Japan's Ministry of Economy, Trade, and Industry (METI), and Japan's Earth Remote Sensing Data Analysis Center (ERSDAC), and NED from the Seamless Data Warehouse (http://seamless.usgs.gov) managed by the United States Geological Survey (USGS). A comparative analysis is conducted between SRTM and ASTER DEMs using NED as the ground truth data. A variogram is then developed based on the difference between ASTER (the better performing data source) and NED. This error model is then applied to the ASTER elevation surface at five IED sites in Afghanistan selected from the U.S. National Counter Terrorism Center's (NCTC) World Wide Incident Tracking System (WITS). 100 simulations of the elevation surface are created using Monte Carlo simulation and a viewshed is run on each simulated surface. These 100 viewsheds are aggregated to create a probable viewshed for each site. This probable viewshed is compared to the original ASTER viewshed at the IED location and then the expected performance of the probable viewshed based on the findings of the site in Colorado.

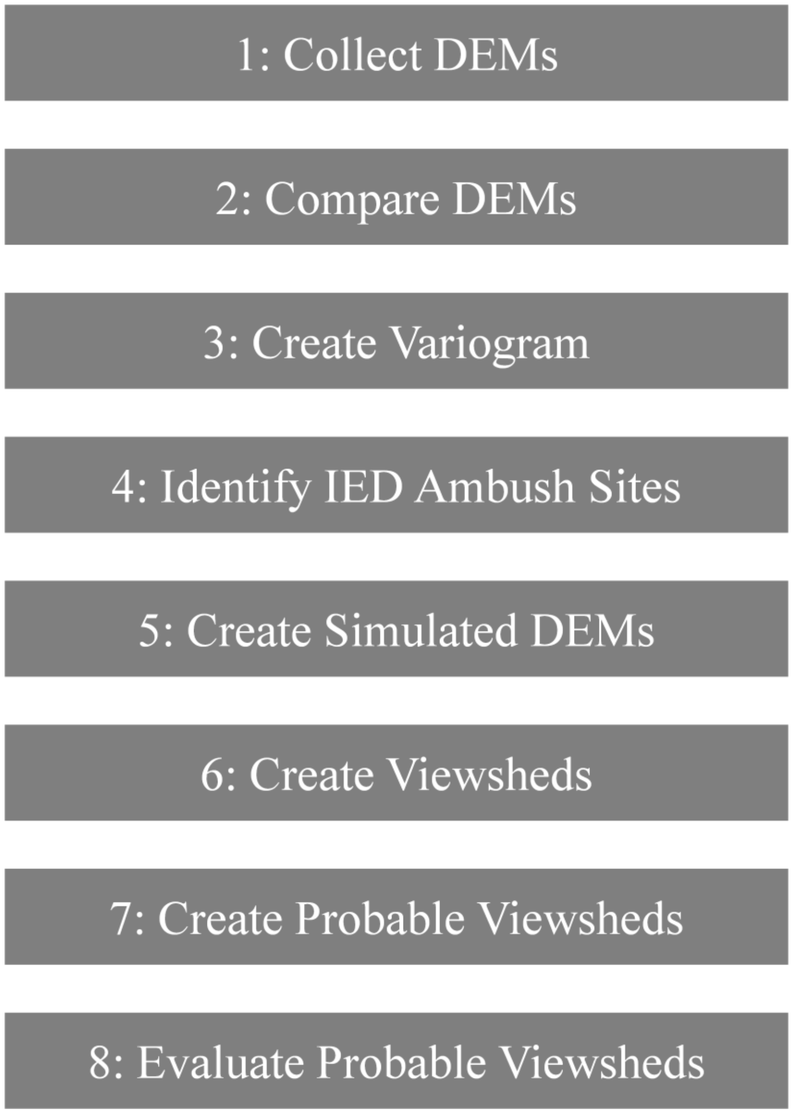

Figure 10: Theoretical framework for this study

2.1 Data

This research is the first viewshed study to utilize publicly available improvised explosive device (IED) attack data from the Worldwide Incident Tracking System (WITS), a comprehensive database of terrorist[3] incidents produced and maintained by the National Counterterrorism Center (NCTC) that tracks global security incidents from 01 January 2004 through 31 March 2010[4] and is maintained by the National Counterterrorism Center. The WITS uses a parameter-based search structure that allows the user to find incidents based on a number of variables (e.g., date, geographic location, event type, weapon used).

The ever-present problem with conducting this research was to determine the importance of each variable and if it was an important factor for the analysis due to the abundance of data in the WITS. For example, is the number of friendly or insurgent casualties a necessary variable to include in an analysis concerning the emplacement of IEDs? It exists with the WITS data and even more so with the Afghan War Diary.[5] In recent years, Google has made it very simple for one to create a "mash up" utilizing Google's map base data along with data provided by the user, presenting an almost immediate visual spatial analysis. However, basic hotspot detection and cluster analyses of open-source military data only scratch the surface in terms of the potential these databases have to reveal the story behind the conflicts. There are still many, many tools available to the geographer to analyze these IED explosions.

The WITS provides a historically unprecedented view into U.S. military actions in any theater of war; it is not possible to capture every nuance of combat through simplistic open-

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[3] It should be mentioned that the definition of terrorism is highly disputed and is deferred to the database owner in this research. According to the NCTC, "terrorism occurs when groups or individuals acting on political motivation deliberately or recklessly attack civilians/non-combatants or their property and the attack does not fall into another special category of political violence, such as crime, rioting, or tribal violence" (WITS, 2010).

[4] Failed, foiled, or hoax incidents are not included in the database as well as hate crimes and acts of genocide as determined by a panel of academics at the 2008 Brain Trust on Terrorism Metrics.

[5] WITS Mash Up: https://wits.nctc.gov/FederalDiscoverWITS/index.do?t=Map&N=0
Afghan War Diary Mash Up:
http://www.guardian.co.uk/world/datablog/interactive/2010/jul/25/afghanistan-war-logs-events

source reports. In addition to the commonly accepted idea of the “fog of war,” the very nature of improvised explosive device emplacement and insurgent operations is constantly changing in a mortal cat-and-mouse game. Each IED event, whether successfully detonated or misfired, is laden with dynamic variables such as operator, trigger type, explosive type, and intended target.

This chapter will serve two important purposes for this research. First, it will identify and describe the locations in Colorado and Afghanistan to be used for this study using a variety of maps and spatial statistics as well as the methodology by which they were selected. Second, it will discuss the different sources from which the data was gathered. This study is intended to be easily replicated as all of the data used are open-source and can be found at a variety of public websites and in the appendix of this thesis. The first part of the chapter will discuss the purpose of the research and the necessity of selecting study sites in two different countries. The latter half of the chapter will focus on the specifics of the data and the importance of the elevation and incident data sets selected for this study.

2.1.1 DEM Study Areas

The selected location for the Colorado dataset is approximately 405 square kilometers in size. This size was considered to be appropriate after contemplating the coarse resolution of SRTM data, the ideal number of sample points to be taken, and the intent of expanding the findings to further research in Afghanistan. Lastly, this location was determined to be an appropriate balance between feasible sample sizes without necessitating increased processing power.

Characteristic	SRTM	ASTER	NED
Production Year	2000	2008	Continuous Updates
Coverage	56°S to 60°N	83°S to 83°N	United States
Spatial Resolution	~90 meters	~30 meters	~30 meters to 1meter
Vertical Accuracy	±16 meter 90% vertical error	±20 meter 95% vertical error	±2.44 meter 90% vertical error

Table 1: Digital elevation model sources

The data were gathered from three different websites. First, the SRTM data was downloaded in one degree chunks from the Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) at http://srtm.csi.cgiar.org/. Next, the ASTER GDEM data was downloaded in one degree grid chunks from the NASA mirror server (https://wist.echo.nasa.gov/wist-bin/api/ims.cgi?mode=MAINSRCH&JS=1). Lastly, the NED data was downloaded from the Seamless Viewer maintained by the USGS (http://seamless.usgs.gov). NED consists of a compilation of many different production sources, methods, and dates. The NED data for this location in Colorado were originally obtained in 1983 and inspected in 1998 by a private contractor using LT4X software.

Since the ultimate purpose of the project is to extend the findings to IED research in Afghanistan, the best comparable location in the United States in terms of ruggedness is within a 550 km^2 section of the Rocky Mountains. More specifically, just west of Denver lies a triangular corridor bounded by I-70, US-24, and CO-91 is a suitable area with elevations ranging from approximately 2500 meters to 4200 meters above sea level that are perfect for this study. Figures 11 and 12 provide a map of the study area.

Figure 11: The suitable area is located approximately 50 miles west of Denver (© ESRI, 2011a)

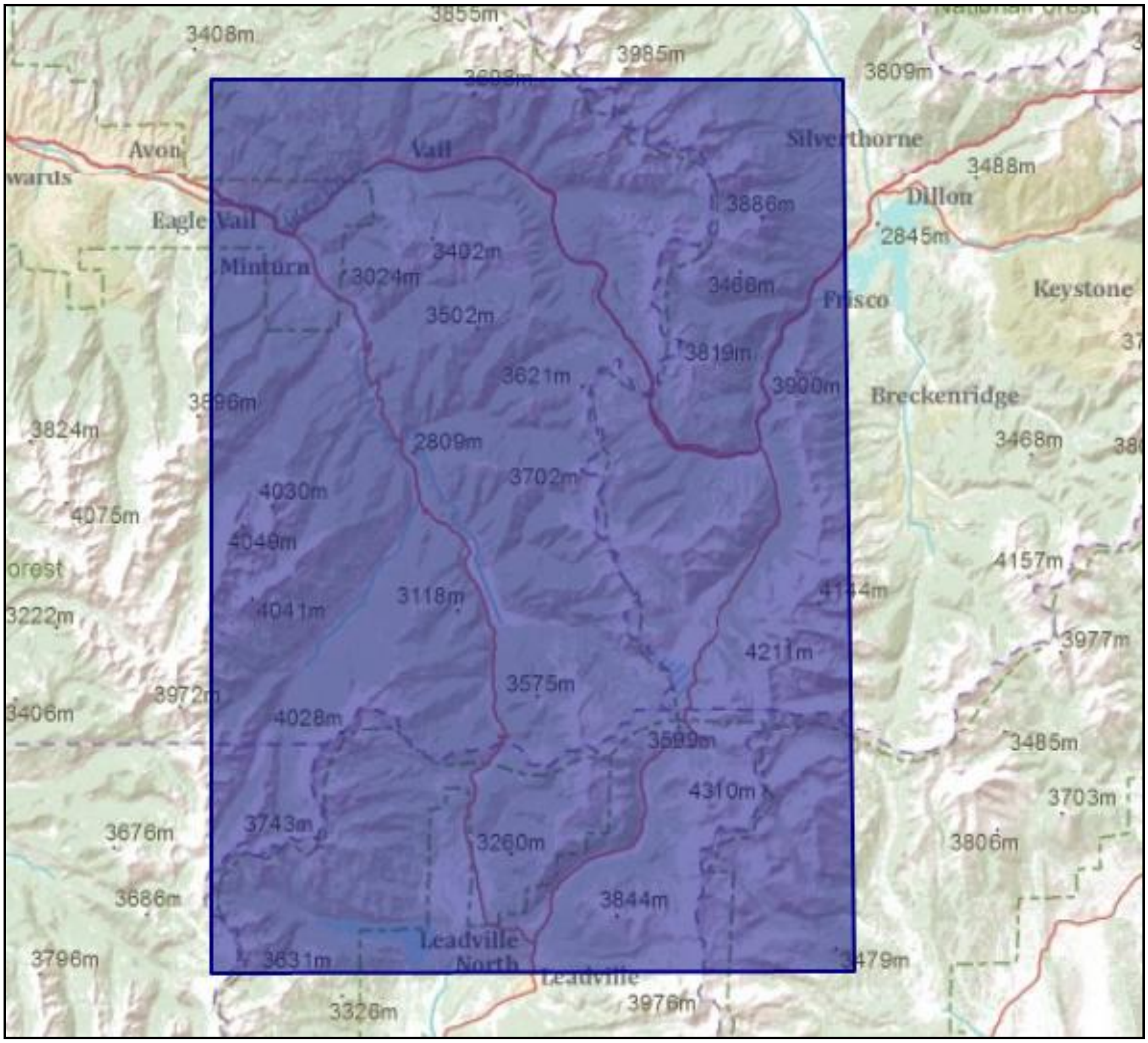

Figure 12: The suitable area is bounded by I-70, US-24, and C-91 (© ESRI, 2011a).

Perhaps a closer view of a site in this study area for each DEM provides an illustration of the differences between these rasters (Figures 13, 14, & 15). It is evident that the NED DEM (10m) is more visually pleasing compared to the SRTM DEM (90m) and ASTER (30m). It should be logical then to assume that increased resolution, at least on the outset, appears to indicate more accurate elevation values due to the presence of more cells in a particular area; NED is as close to ground truth as possible.

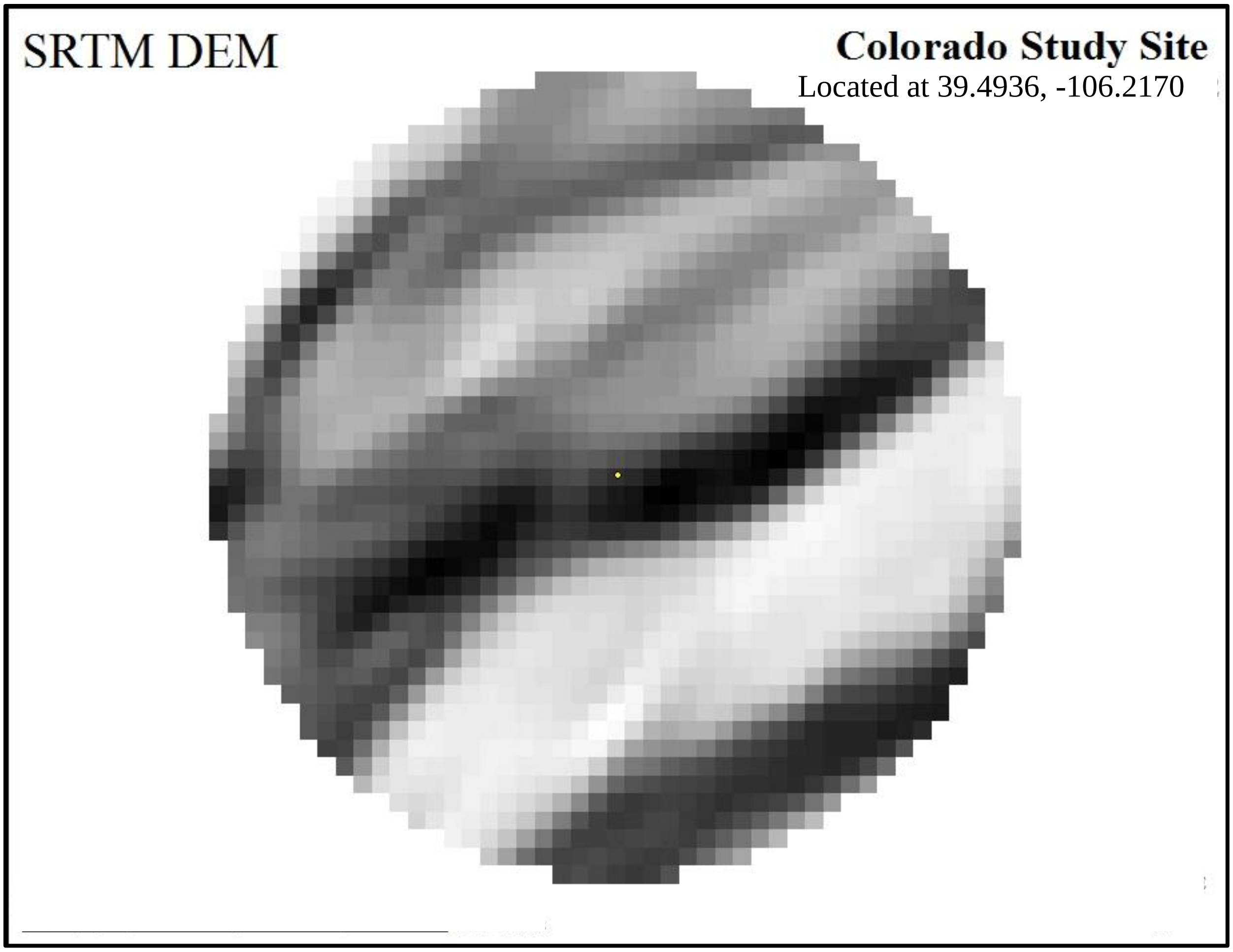

Figure 13: SRTM DEM for Colorado Study Site

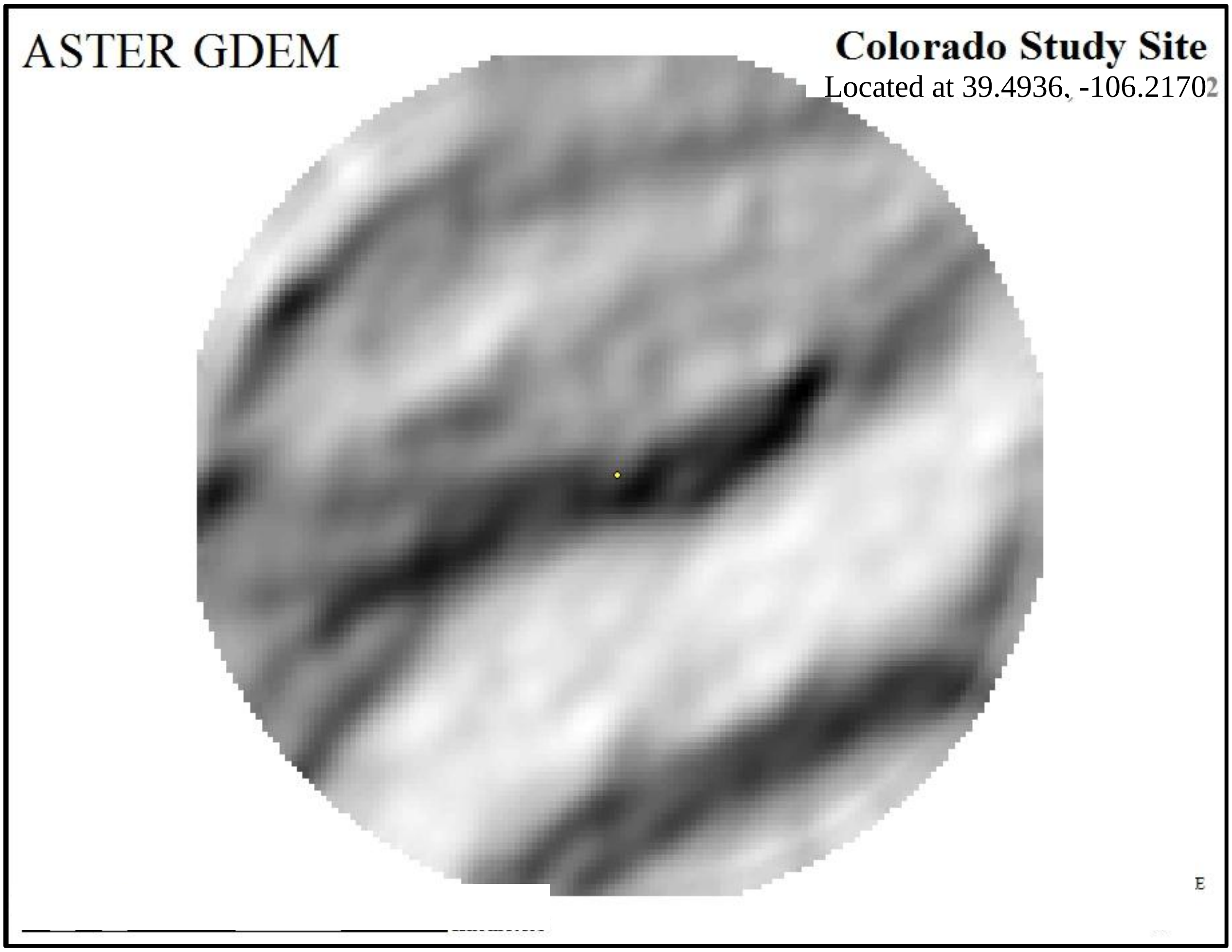

Figure 14: ASTER GDEM for Colorado Study Site

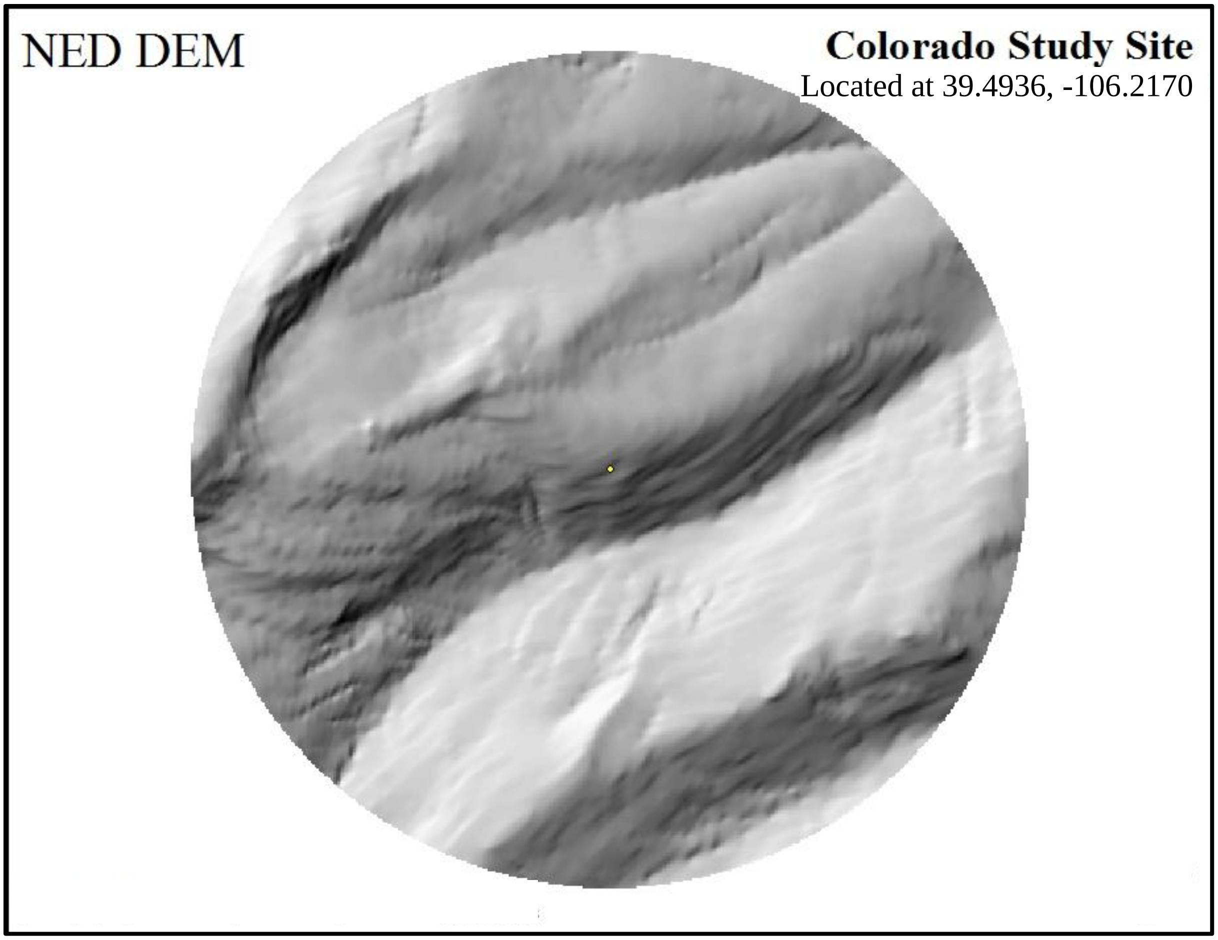

Figure 15: NED DEM for Colorado Study Site

2.1.2 IED Study Areas

Five locations were selected from the WITS to illustrate the use of probable viewsheds centered on IEDs in Afghanistan. These locations were selected from the dataset based on five criteria:

1. The weapon type must have been an improvised explosive device. Since the purpose of this study is to analyze viewsheds in relation to IEDs, there is no purpose for examining an attack in which an IED was not used.

2. The incident was not a suicide. The basis of this study is the theory that IED attacks are supervised, videotaped, and/or initiated by a triggering position that is within the viewshed of the IED. A suicide attack, whether person-borne or vehicle-borne, does not correspond to this theory.

3. The location of the incident must have been in a location without proximity to structures. This criterion is extremely important to the study as it relates to the limitation of the viewshed tool and available data. No data regarding building heights is possible to gather

for an IED explosion occurring within an “urban” setting. Any manmade structure within the search radius of the viewshed tool has a profound effect on the resulting viewshed. Due to this limitation, all incidents must not be within tactical distance of a village.

4. The target must have been National or ISAF military forces. IED attacks are not always targeted towards military forces. Afghanistan is also wrought with intranational conflict, whether between tribes or religious groups. The purpose of this study is to analyze IED attacks against military forces.

Based on these criteria, 5 IED explosions were found in five separate Afghan provinces occurring between 02 July 2005 and 22 January 2010.

Incident Date	Province	City	Latitude	Longitude	Death	Wounded	Total
22 Sep 2009	Farah	Gulistan	32.349998	63.37333	5	7	12
01 Aug 2008	Konar	Sawkai	34.950001	71.13333	5	3	8
06 Jan 2010	Nangarhar	Rudat	34.299999	70.48333	5	42	47
02 Jul 2005	Paktika	N/A	32.416668	68.75000	4	4	8
22 Jan 2010	Vardak	Chak	34.183334	68.51667	5	0	5

Table 2: IED sites used in this research.

For brevity, each site will be referred to by the province in which it is located (e.g., ICN 200808209 will be referred to as “Konar”). It should be noted that all five sites were cross-referenced with the Global Terrorism Database, an open-source database including information on terrorist events around the world from 1970 through 2008 that is maintained by the National Consortium for the Study of Terrorism and Responses to Terrorism (START). Incidents are added to this database. The only incident that positively matched between the WITS and GTD is the Paktika IED site. An accompanying news article from the Washington Post elicits new information that the IED was remotely controlled. It is not alarming, however, that only one of the five sites matched since the WITS and GTD utilize different collection methodologies. The WITS, on one hand, accesses unclassified U.S. government sources whereas the GTD only gathers open-source information, most often from news articles and press releases. Further searching on Google confirms the other four incidents (USA Today, 2009; Toosi, 2008; AFP, 2010; Laredo Sun, 2010).

The ASTER GDEM product was obtained for a 2,000 meter buffer around each IED site[6]. Since the sites were dispersed about the entire country, the DEMs were transformed to a customized projection ideal for the nation of Afghanistan in order to properly perform the viewsheds. This was a Lambert Conic Conformal projection with a central meridian at 67.5 degrees east, standard parallels at 32 degrees north and 36 degrees north, the latitude of origin at 28 degrees north, a false Easting of 700,000 meters, and a false Northing of -130,000 meters. Lastly, the DEMs, including the Colorado site, were smoothed using a 3x3 focal mean as a means to reduce extraordinary elevation values due to known error that is intrinsic to the ASTER GDEM product (Nikolakopoulos, Kamaratakis, and Chrysoulakis, 2006).

While the terrain upon which the IED explosions occurred is relatively similar across all five explosions, there are slight nuances about each site that play significant roles. The Farah site exists inside of a valley in which it is flanked by steep slopes on all sides. The Konar site is the “smoothest” landscape of all five, relatively speaking. The IED site is not located in a valley nor is it located on a ridge. Elevations in this scene slowly decrease from northeast to southwest. While the Nangarhar site has the smallest range of elevations, the landscape is influenced by a river running north to south located 500 meters to the west of the IED site, which sites just below a ridge. The landscape surrounding the Paktika site exhibits pronounced terracing as it is located on the side of a steep slope. It is likely that this IED explosion occurred on or near an agricultural field. Lastly, the landscape of the Vardak site is dominated by a north to south

[6] 2,000 meters was chosen as an ideal buffer for reasons pertaining to the viewshed that are covered in the methods section.

running valley. The site is located on the side of one of many draws running laterally into the valley from higher elevations.

The following images depict the IED sites at the five locations in Afghanistan overlaid upon a two kilometer buffer of the ASTER DEM. Note the location of the IED site in relation to the surrounding terrain. For example, the IED site in Nangarhar is surrounded by higher elevation on all sides as compared to the IED site in Vardak which is located on top of a hill in close proximity to a valley of much lower elevations. The consequences of spatial location will become apparent in later chapters of this thesis.

Figure 16: The five sites are located in five different Afghan provinces (©ESRI, 2011a).

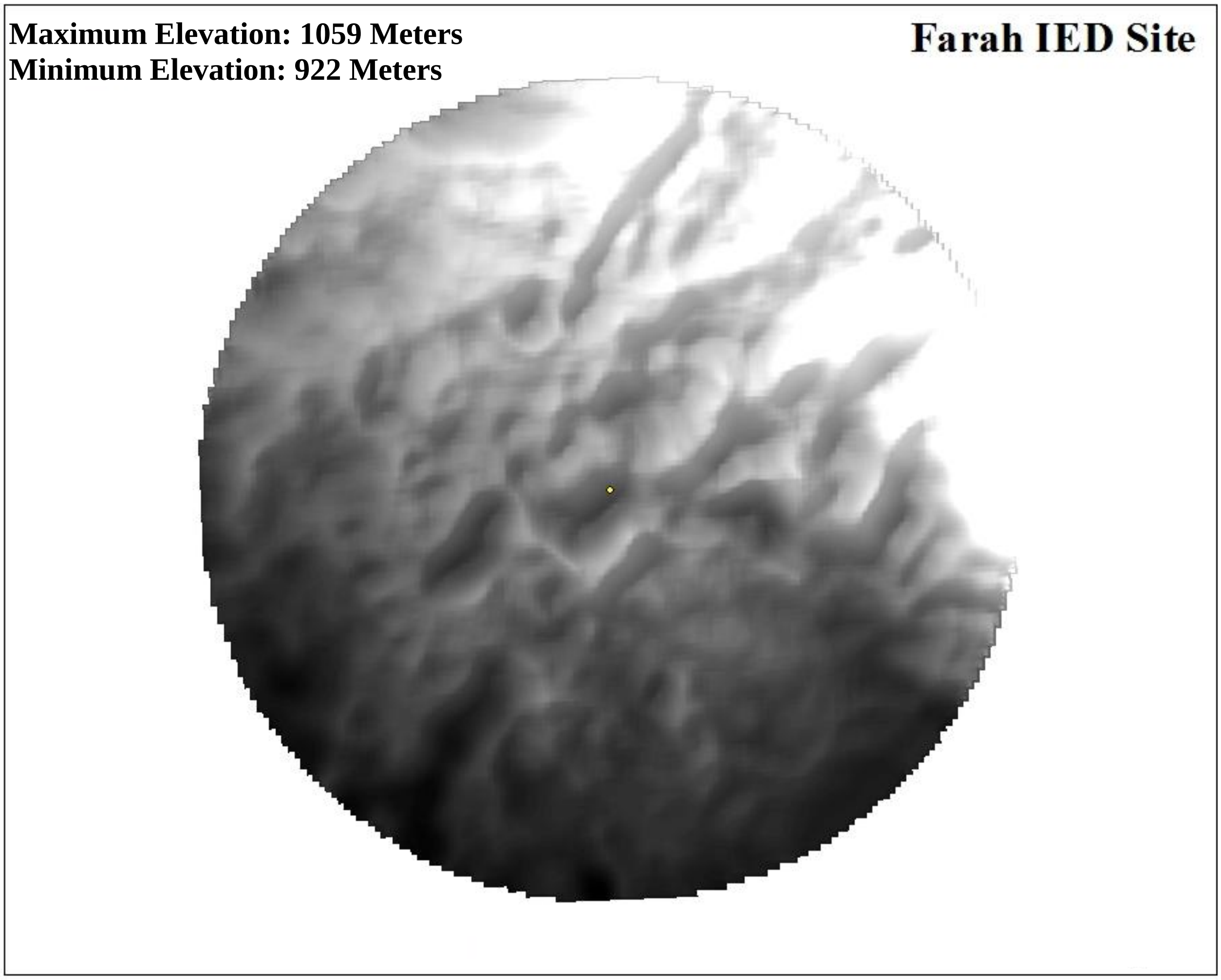

Figure 17: 2 kilometer buffer surrounding the Farah IED site.

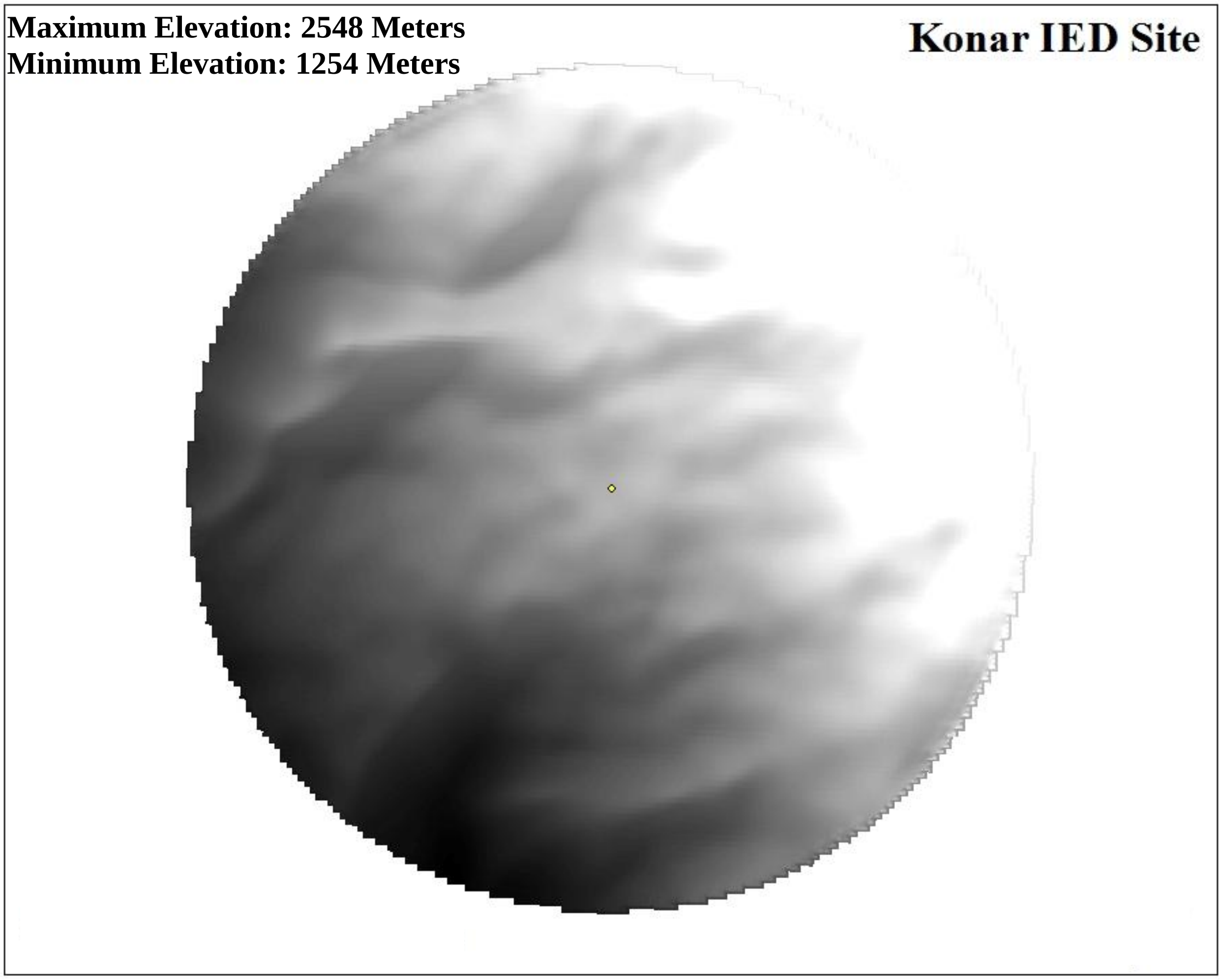

Figure 18: 2 kilometer buffer surrounding the Konar IED site.

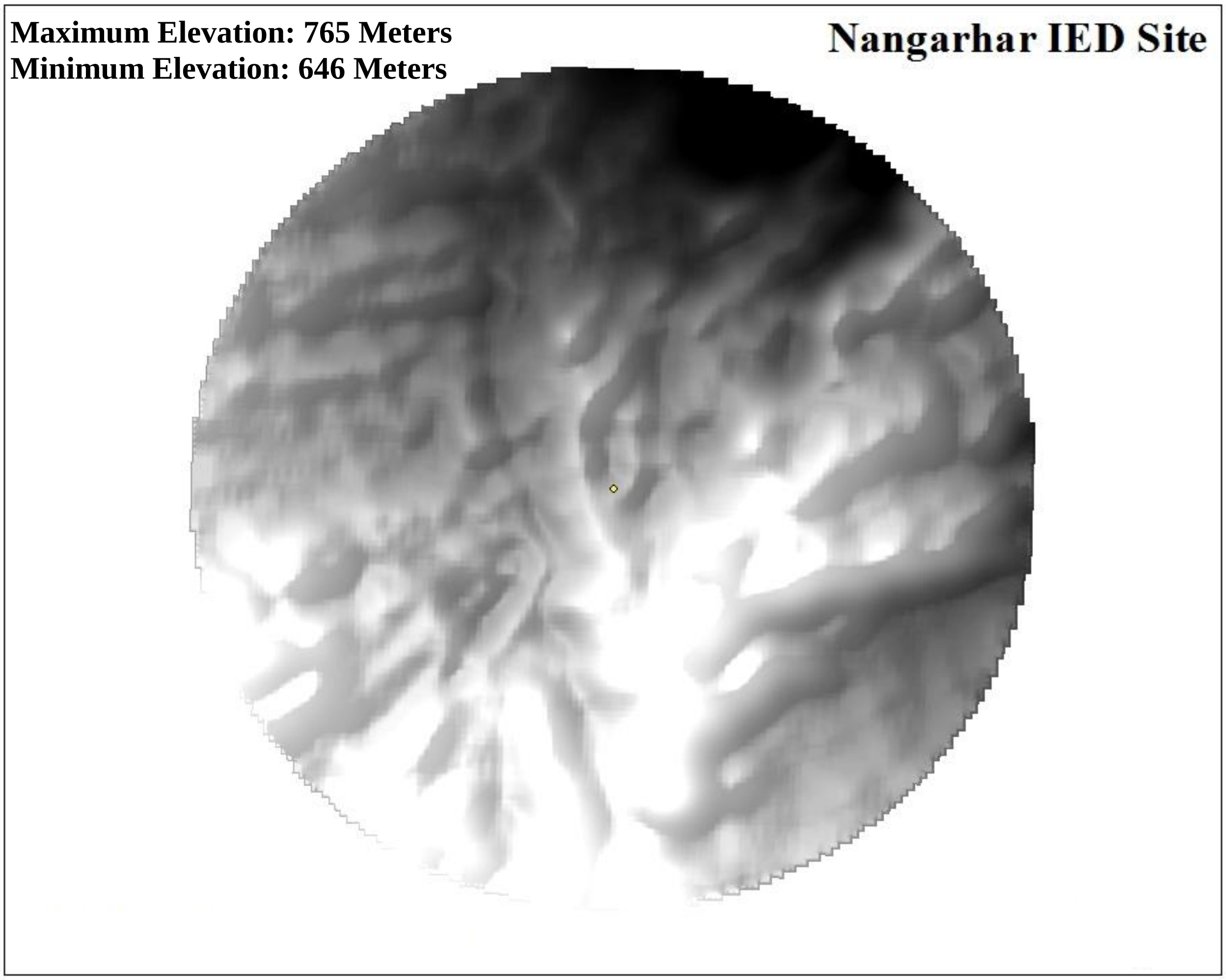

Figure 19: 2 kilometer buffer surrounding the Nangarhar IED site.

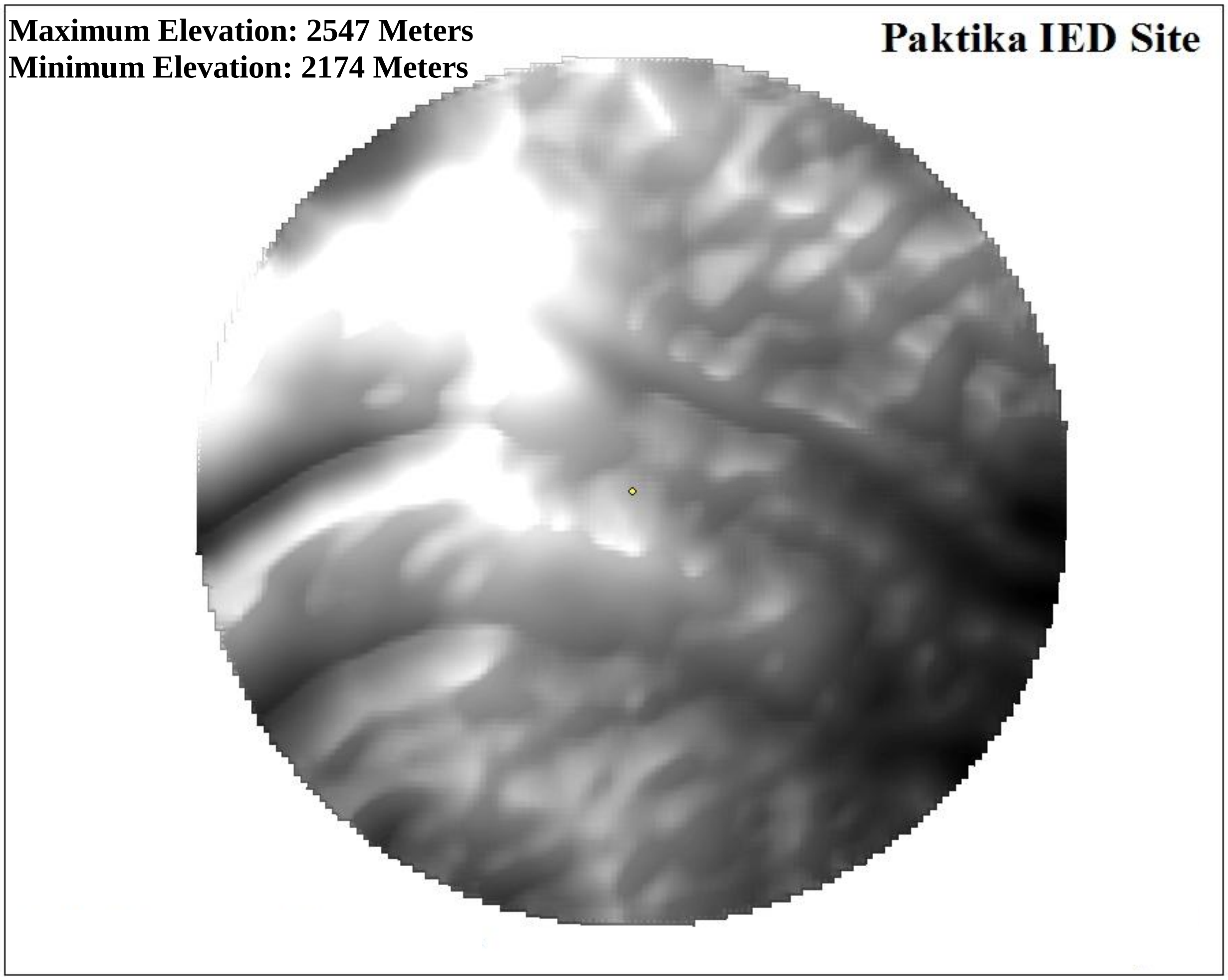

Figure 20: 2 kilometer buffer surrounding the Paktika IED site.

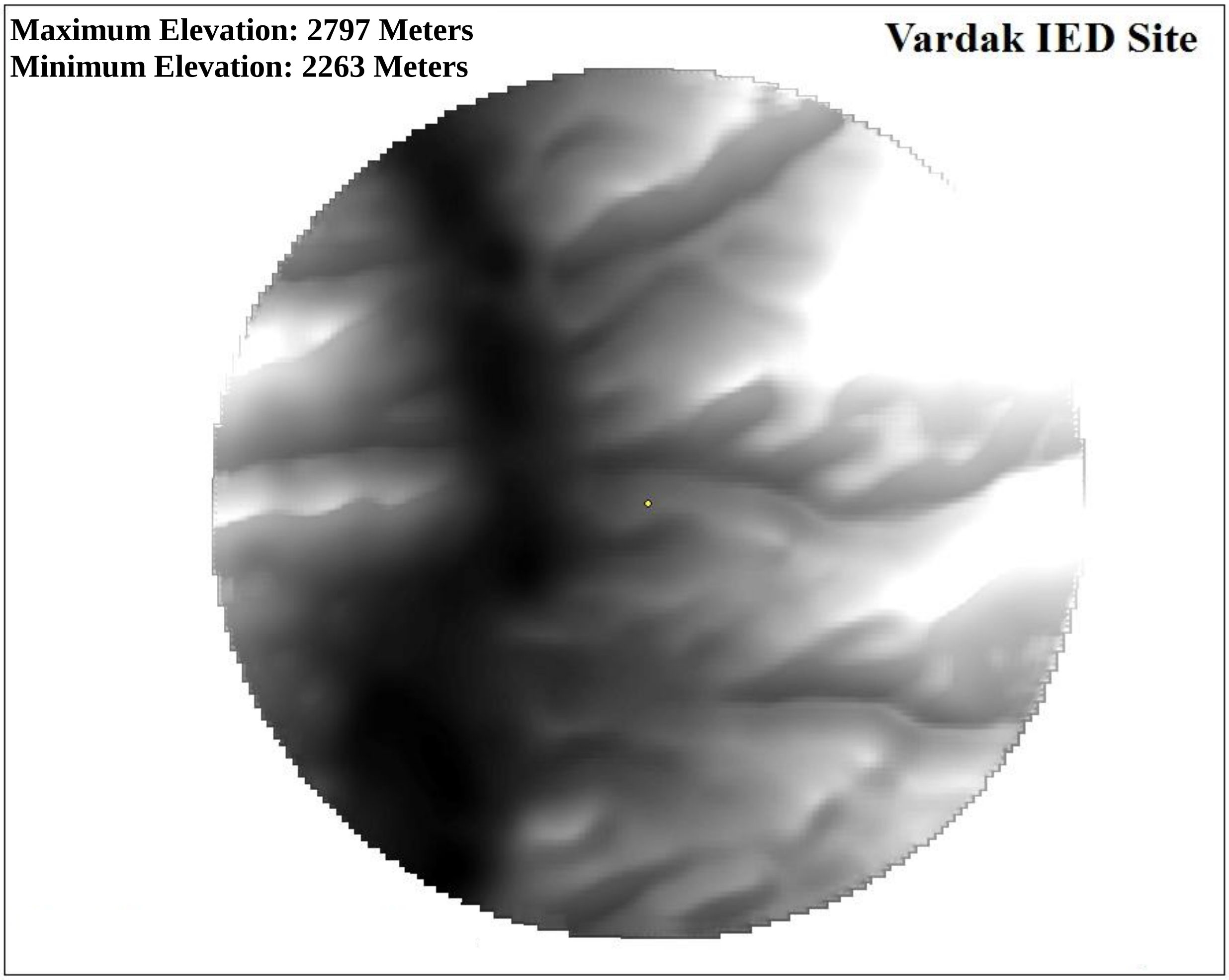

Figure 21: 2 kilometer buffer surrounding the Vardak IED site.

2.2 Methods

2.2.1 DEM Accuracy Assessment

The purpose of this comparison is to assess the accuracy of different resolution digital elevation models in Colorado and to apply those findings to develop simulated terrain models in Afghanistan that are ultimately used to create probable viewsheds. The general consensus is that higher resolutions mean better spatial models, but is it not possible for high resolution models in rugged landscapes to produce more “noise?” A comparison is conducted of DEMs derived from the Shuttle Radar Topography Mission (SRTM; 3", ~90 meter resolution), the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER-GDEM; ~30 meter resolution), and the National Elevation Dataset (NED 1/3"; ~10 meter resolution) in central Colorado to answer one question: Does increasing the resolution of a digital elevation model in rugged terrain increase accuracy or simply introduce noise into the model?

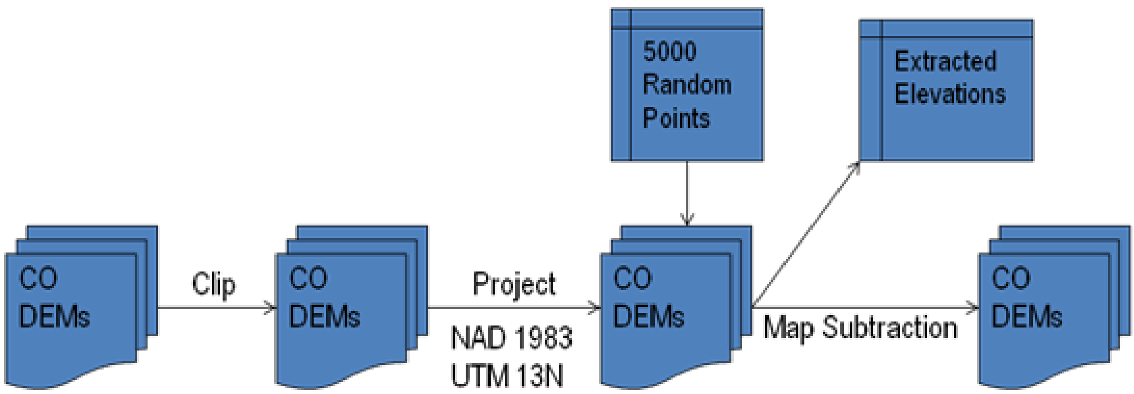

Figure 22: Workflow to develop sample errors between SRTM, ASTER, and NED DEMs.

First, the digital elevation models were compiled from their respective websites discussed in the data section above. Next, they were mosaicked and projected in ArcGIS. The Colorado DEMs were projected to NAD 1983, UTM Zone 13N and clipped to their respective study areas. 5,000 points were distributed over the study area in a stratified random clusters and the elevation value of each raster was extracted and appended to the shapefile as seen in Figure 16. ArcGIS Geostatistical Analyst and Microsoft Excel were utilized for the semivariogram creation and mathematical analysis. This type of sampling techniques was necessary due to the need to capture short-short range variation for the semivariogram as well as limited processing power. Lastly, simple raster subtraction was utilized to create the difference maps (see Figures 17 and 18). These difference values were also extracted and appended to the point shapefile. The comparison is made using a simple visual analysis, summary statistics, root mean square error, a measure of correlation, and semivariograms.

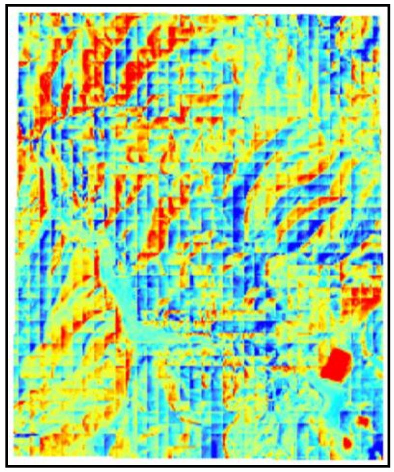

Figure 23: 90m-10m difference map. Red indicates elevations of SRTM are higher and blue indicates lower.

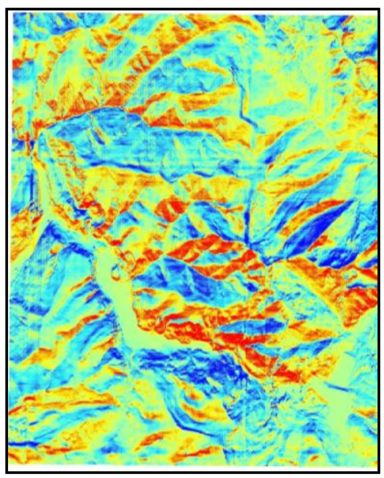

Figure 24: 30m-10m difference map. Red indicates elevations of ASTER are higher and blue indicates lower.

Upon first look at the difference maps it becomes painfully clear that any analysis utilizing SRTM data is severely influenced by artifacts from the sensing platform. There is a clear gridded pattern of error throughout the scene that must be attributed to the coarse resolution of SRTM data. The 90m-10m map shows a significant bias towards higher SRTM elevations within draws and other areas of significant slope, but not along ridgelines. This is likely due to the sensor's inability to account for abrupt changes in slope as well as the fact that SRTM most often measures canopy height as opposed to bare surface elevations (Shortridge, 2006). Furthermore, there is a large area in the southeast corner of the scene that SRTM designates as significantly higher than the rest of the platforms. This location straddles the Continental Divide at Fremont Pass and was an expansive molybdenum mine operated by Climax Molybdenum Company from 1924 to 1995 (Voynick, 1996). The SRTM elevation is higher at this location than NED indicates, which confirms two things. First, it confirms the effort of Freeport-McMoran Copper & Gold Inc. to clean up old tailings of the mine in the early 2000s in preparation to reopen the mine in 2010. More importantly, the mass movement of earth indicates NED data in this location is more recent than SRTM.

The ASTER DEM is not without its own issues. There is a clearly defined gridded nature to the difference map with the NED DEM, albeit less pronounced. This indicates that it is an issue with SRTM/ASTER and not with NED. Additionally, error is clearly more significant in areas of steep slope. According to the map, elevations are recorded much lower than the NED DEM on the south side of the valley running through the scene while overestimates of elevation are present along the majority of mountain slopes.

Summary Statistics

Difference	**Minimum**	**Maximum**	**Mean**	**St. Deviation**	**RMSE**
90m-10m	-109.08m	90.84m	7.19m	15.19m	14.63m
30m-10m	-43.40m	37.71m	-0.07m	4.63m	4.36m

Table 3: Summary statistics for differences between SRTM and NED, ASTER GDEM and NED.

The summary statistics of the difference maps show an important distinction in the performance of SRTM and ASTER GDEM. When compared to the "ground truth" NED digital elevation model, SRTM has a much wider range of elevations (~200m) compared to ASTER

(~80m), a significant positive bias in mean difference, and a RMSE value more than three times that of ASTER. Interestingly, the difference map for SRTM and ASTER has roughly the same characteristics as the difference map for SRTM and NED pointing towards the assumption that ASTER and NED datasets are similar.

Correlation

When using R^2 as a measure of correlation in the elevation values, it is clear that using 5,000 points is problematic at the very least. The 90-10 plot shows a strong correlation between the entire dataset (~0.998816). However, there appear to be a few important points that lie outside of the perfect 1-1 trend, particularly at elevations greater than 3500 meters. Compared to the 30-10 plot (~0.999842), the 90-10 dataset seems to contain less correlation even if the R^2 value is astronomically high for both. It is important to realize that this method of comparison is strictly for visual purposes since the large number of points in the dataset can “drown out” global measures.

Semivariograms

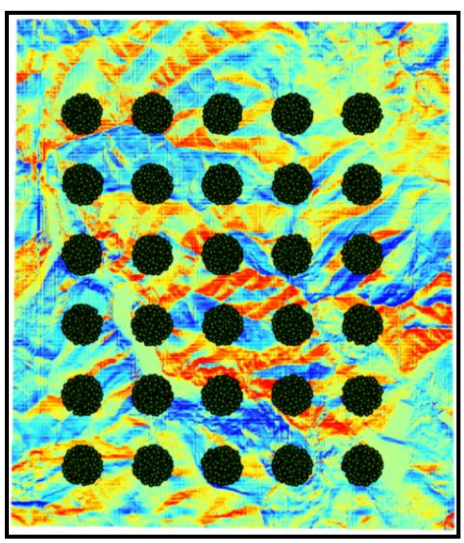

Figure 25: Stratified random cluster sampling of error values.

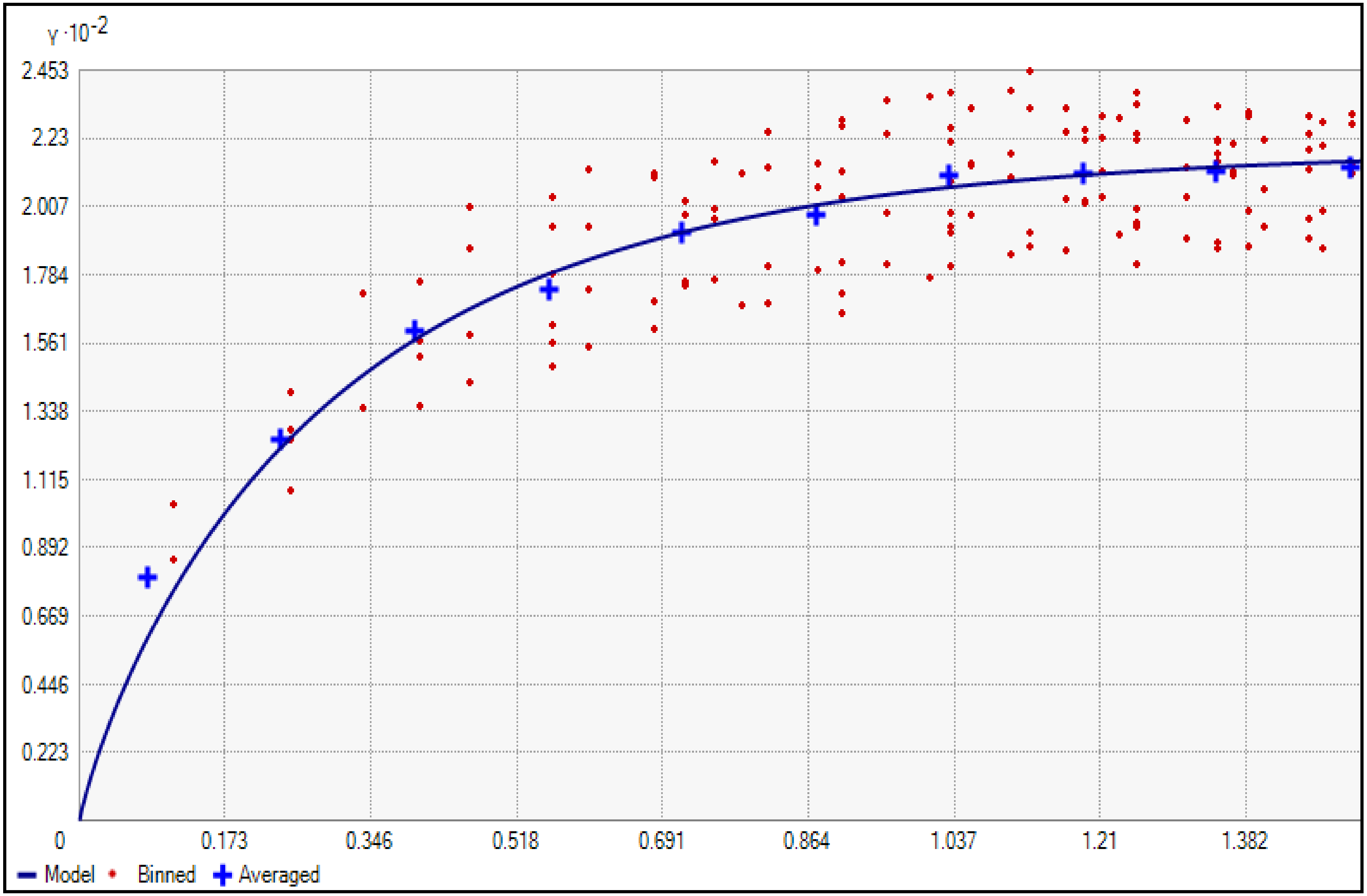

Figure 26: Semivariogram for 90m-10m difference.

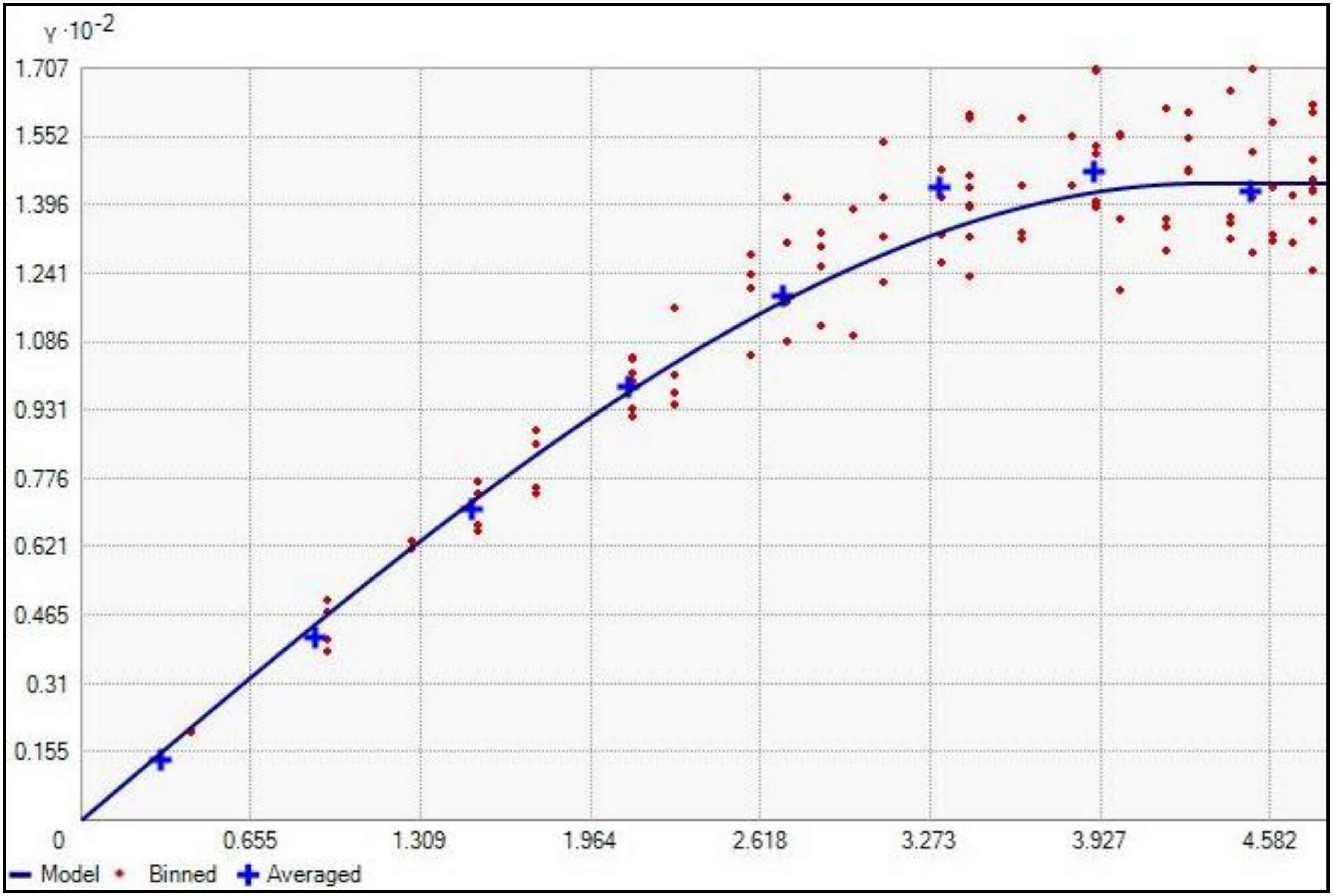

Figure 27: Semivariogram for 30m-10m difference.

The semivariograms for the difference models certainly show that there are differences in spatial autocorrelation between the SRTM and ASTER elevation surfaces. The parameters for the 90-10 semivariogram are: A spherical model with a lag distance of 180 meters yielded the following parameters: nugget = 0 meters; partial sill = 219.55 meters; range = 1087.24 meters. The parameters for the 30-10 semivariogram are: A spherical model with a lag distance of 60 meters yielded the following parameters: nugget = 0 meters; partial sill =144.32 meters; range = 433.32 meters. It is clear that point pairs at short distances have less variability than point pairs at longer distances and that aspatial variance occurs at the sill with some distance *h*. The 30-10 semivariogram had a significantly smaller nugget:sill ratio indicating more spatial autocorrelation in the data. In other words, the 30-10 difference dataset had less random spatial variation than the 90-10 dataset. The importance of this finding is that it can be inferred that error from the 30-10 data is dependent on space, likely the result of ruggedness, and a better spatial model can be developed to represent the data.

It is also important to note that there is a significant problem in the 90-10 semivariogram. The semivariogram map does not have the “bullseye” pattern expected of isotropic variance. The specific direction of the variance in the 90-10 model is assumed to be due to the flight path of the SRTM sensor since the direction of the variance (from approximately 220° to 40°) is similar to the recorded flight path of the shuttle over Colorado.

The majority of research assessing the performance of SRTM and ASTER has concluded that unpredictable anomalies in ASTER make SRTM a more consistent and reliable digital elevation model (Bolch, Kamp, and Olsenholler, 2005; Nikolakopoulos, Kamaratakis, and Chrysoulakis, 2006). However, the semivariograms support more recent findings that ASTER outperforms SRTM in certain types of rugged terrain, specifically mixed forest/barren landscapes such as those found in the Colorado and Afghanistan sites, when compared to NED (Tighe and Chamberlain, 2009).

2.2.2 Simulation

Given the significant spatial autocorrelation present in the ASTER DEM, it is unnecessary to model the variance across the entire scene. In order to utilize the variogram for Monte Carlo error propagation, it is better to model the variance at shorter lag distances through

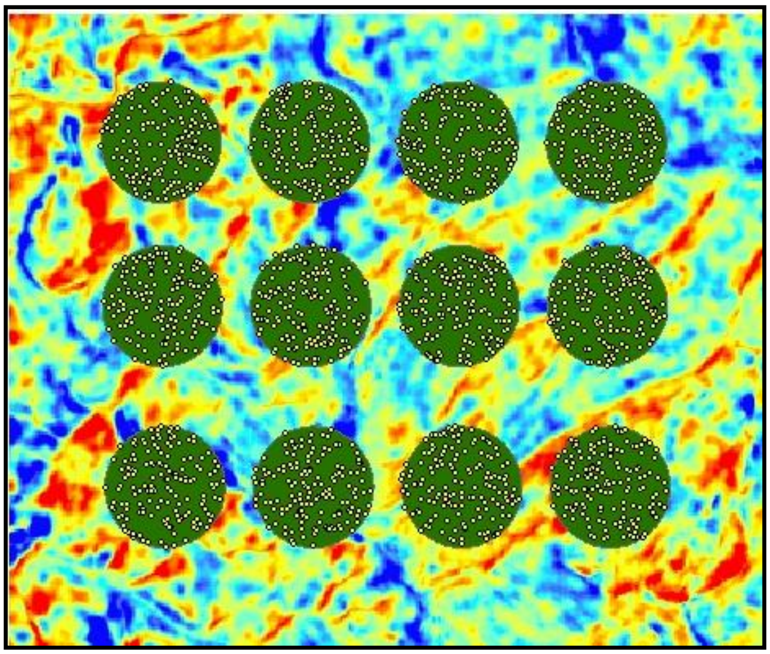

Figure 28: Sample pattern for ASTER and SRTM differences.

a stratified random cluster approach to variography. First, a set of 12 stratified points were created using Hawth's "Generate Regular Points" tool that were 1500 meters apart. These points were then buffered with a radius of 810 meters for a total of approximately 2200 ASTER cells in each buffer. Finally, Hawth's "Generate Random Points" tool was used to randomly place approximately 150 points within each buffer (a total of 1800 points) that were at least 30 meters apart. Lastly, the values of the ASTER-NED difference raster were extracted to the points in order to perform variography (see Figure 23). Positive differences on this map indicate higher elevations recorded by ASTER and negative values indicate lower elevations recorded by ASTER.

The variogram, performed in ArcGIS 10 Geostatistical Wizard, on this set of points captures spatial autocorrelation much better than the semivariogram of the entire scene. A spherical model with a lag distance of 60 meters yielded the following parameters: nugget = 0 meters; partial sill =144.3151 meters; range = 433.3151 meters. The variogram showed significant spatial autocorrelation at short distances, which is expected since almost all DEMs are prone to error in areas of high variability. It is imperative to characterize this short lag variability in the Colorado model so that the simulated surfaces of the rugged Afghanistan mountains are accounting for error along steep slopes.

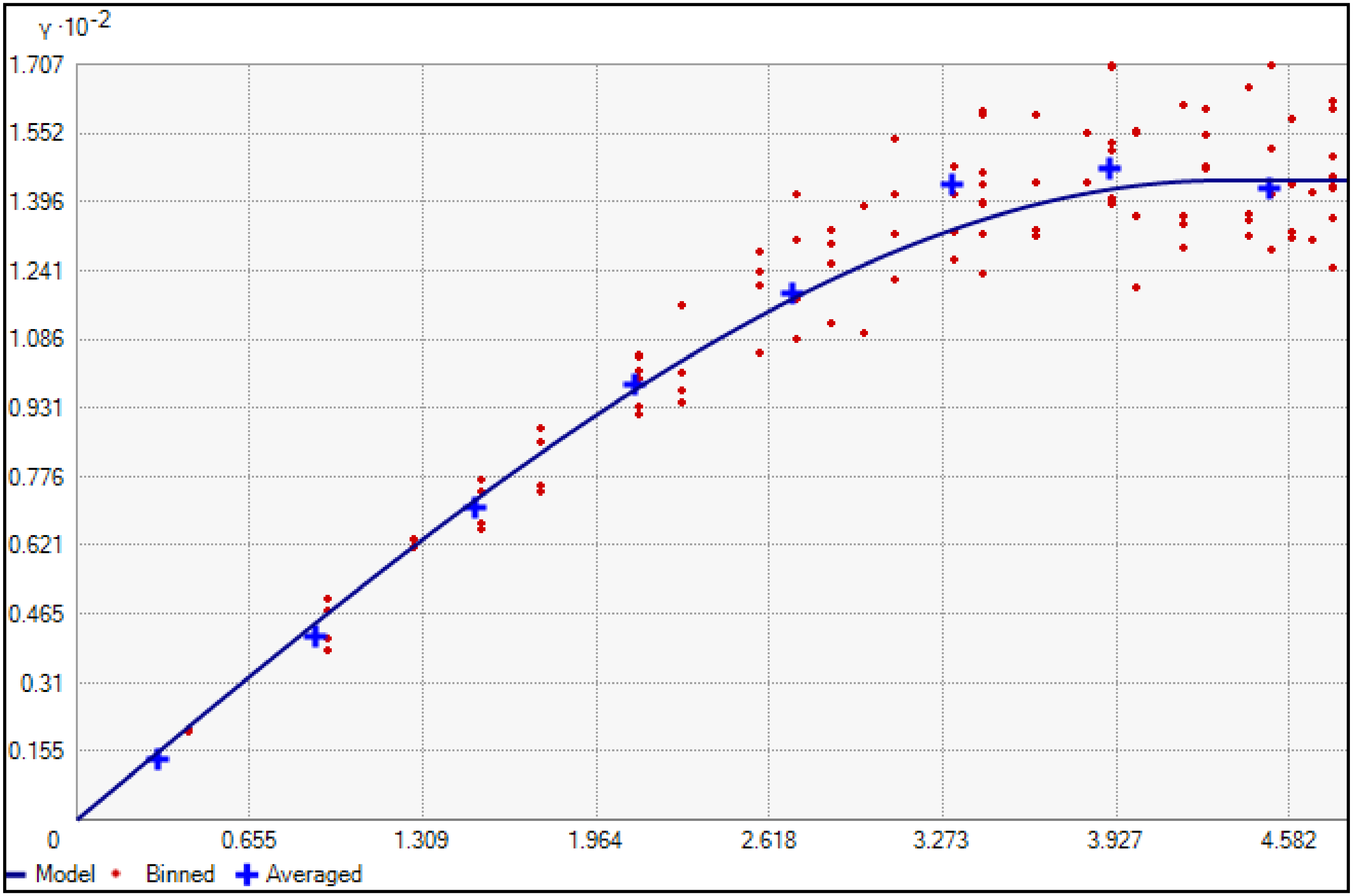

Figure 29: Variogram for ASTER and NED differences.

How, then, can known error between different resolution DEMs in Colorado be used by academics to investigate IED explosions in Afghanistan? Since DEM error is spatially autocorrelated in rugged terrain, this thesis assumes the variogram produced by the 30m-10m variability in Colorado can be used to model similarly rugged terrains in Afghanistan with only 30 meter DEM availability in order to give a better estimate of the true elevations. Based on the foundations of Monte Carlo simulation, the degree of error in each cell is drawn from a normal distribution parameterized by the Colorado variogram, repeated for the entire gridded surface, and iterated 100 times to produce 100 separate error surfaces. These surfaces contain spatially autocorrelated elevation error ranging between approximately -40 meters to 40 meters between the ASTER and NED products with a mean of approximately -4 meters. To illustrate the structure of these error realizations, Figures 25-29 show the 30th simulated surface for each location:

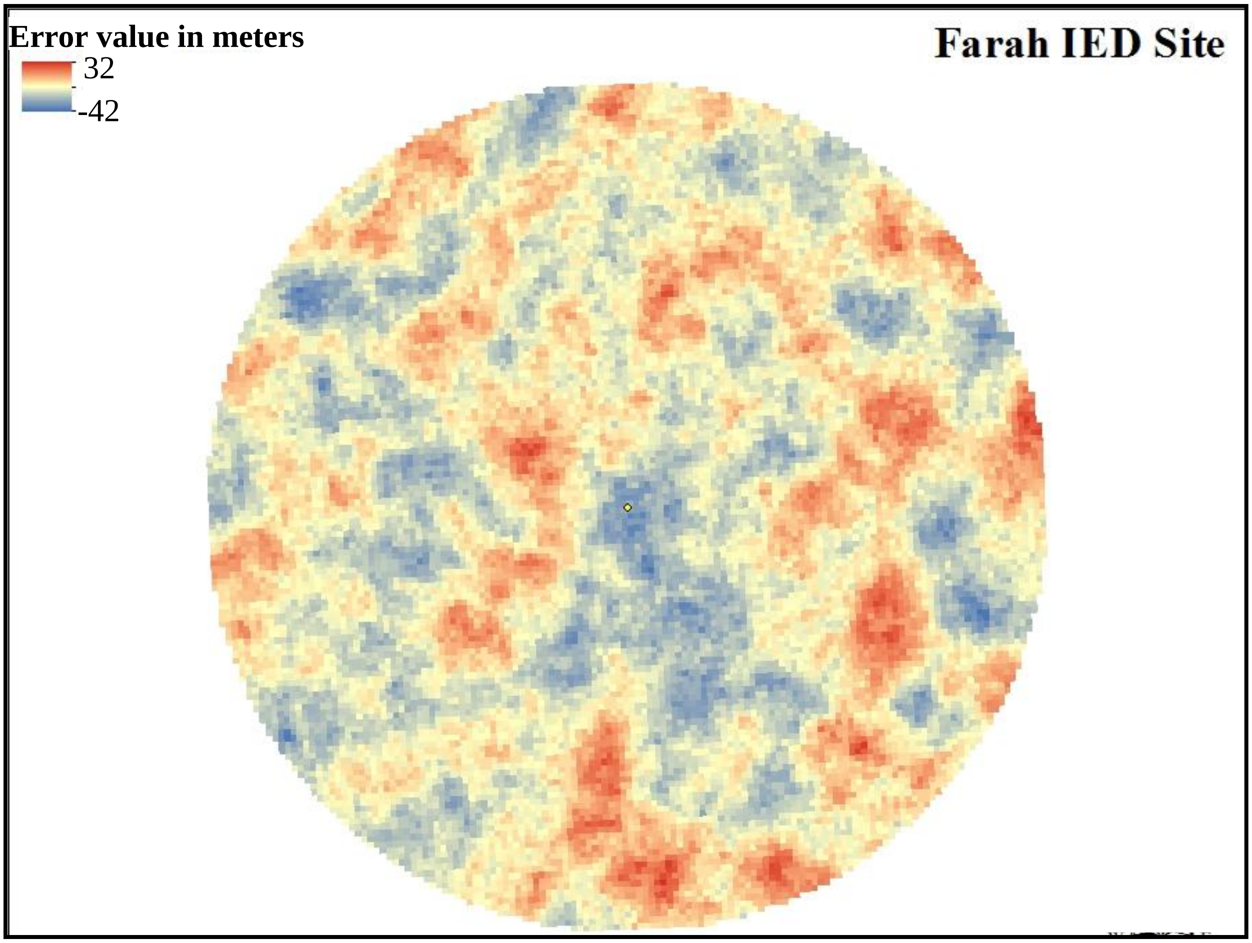

Figure 30: 30th simulated error surface for Farah developed from the Colorado variogram.

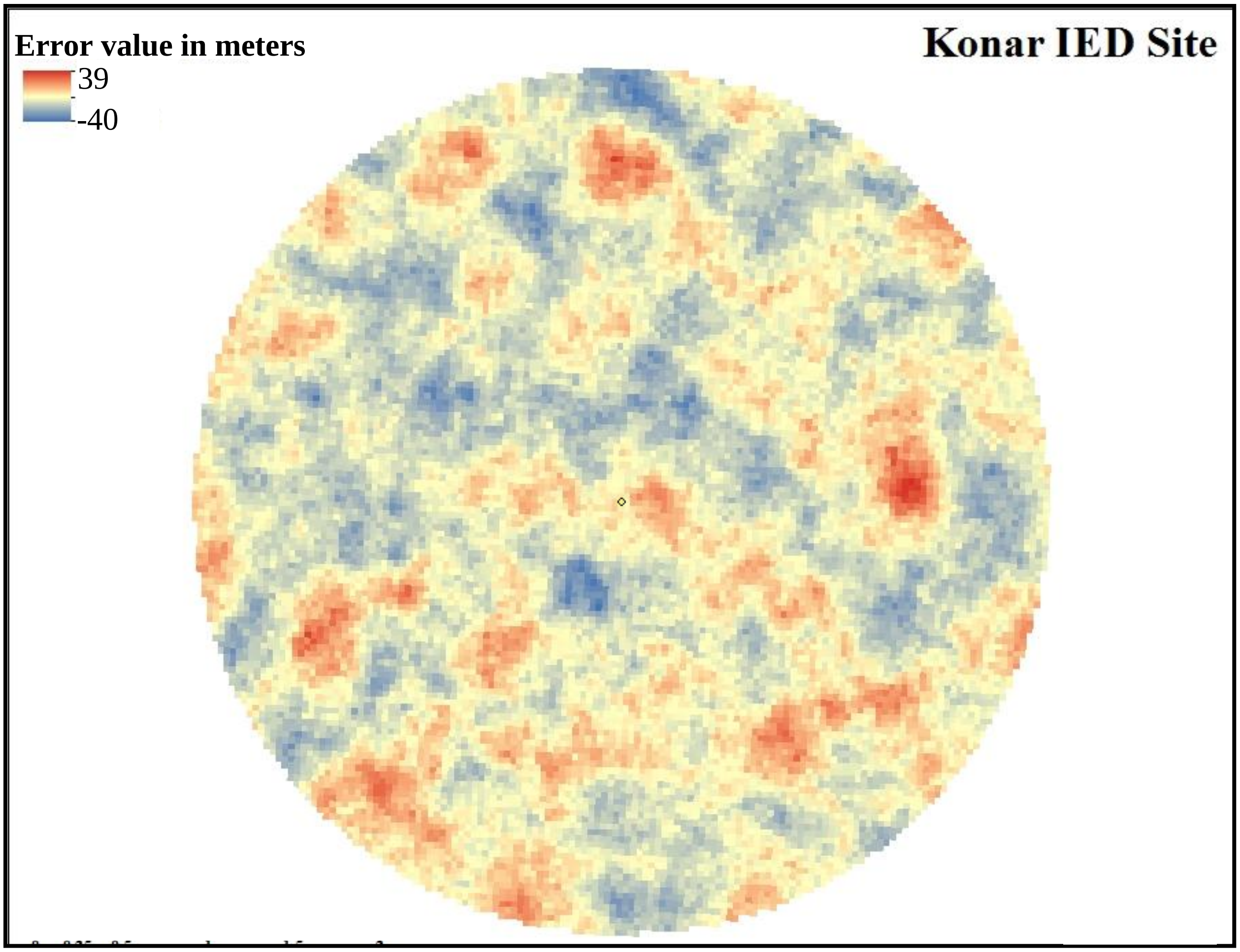

Figure 31: 30th simulated error surface for Konar developed from the Colorado variogram.

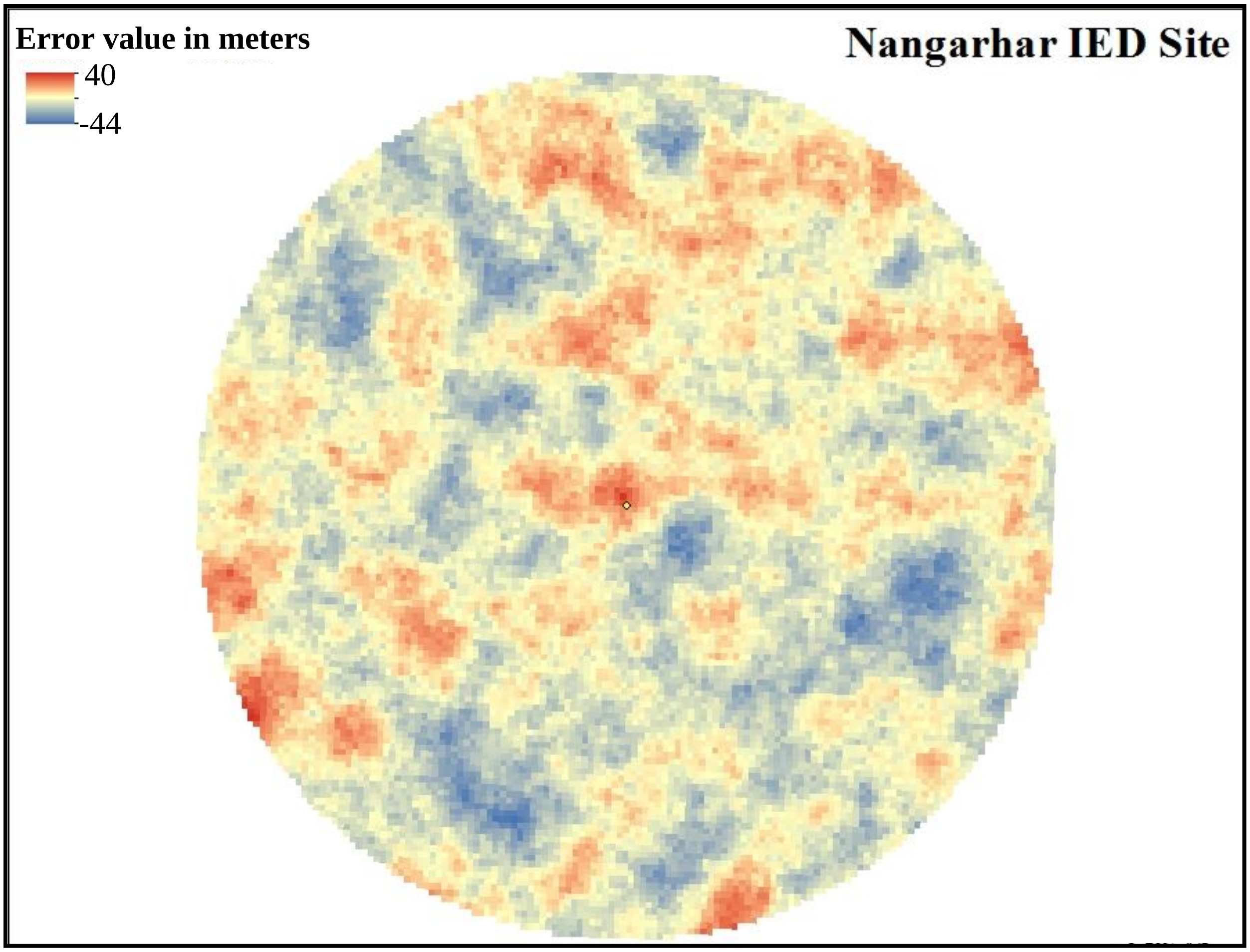

Figure 32: 30th simulated error surface for Nangarhar developed from the Colorado variogram.

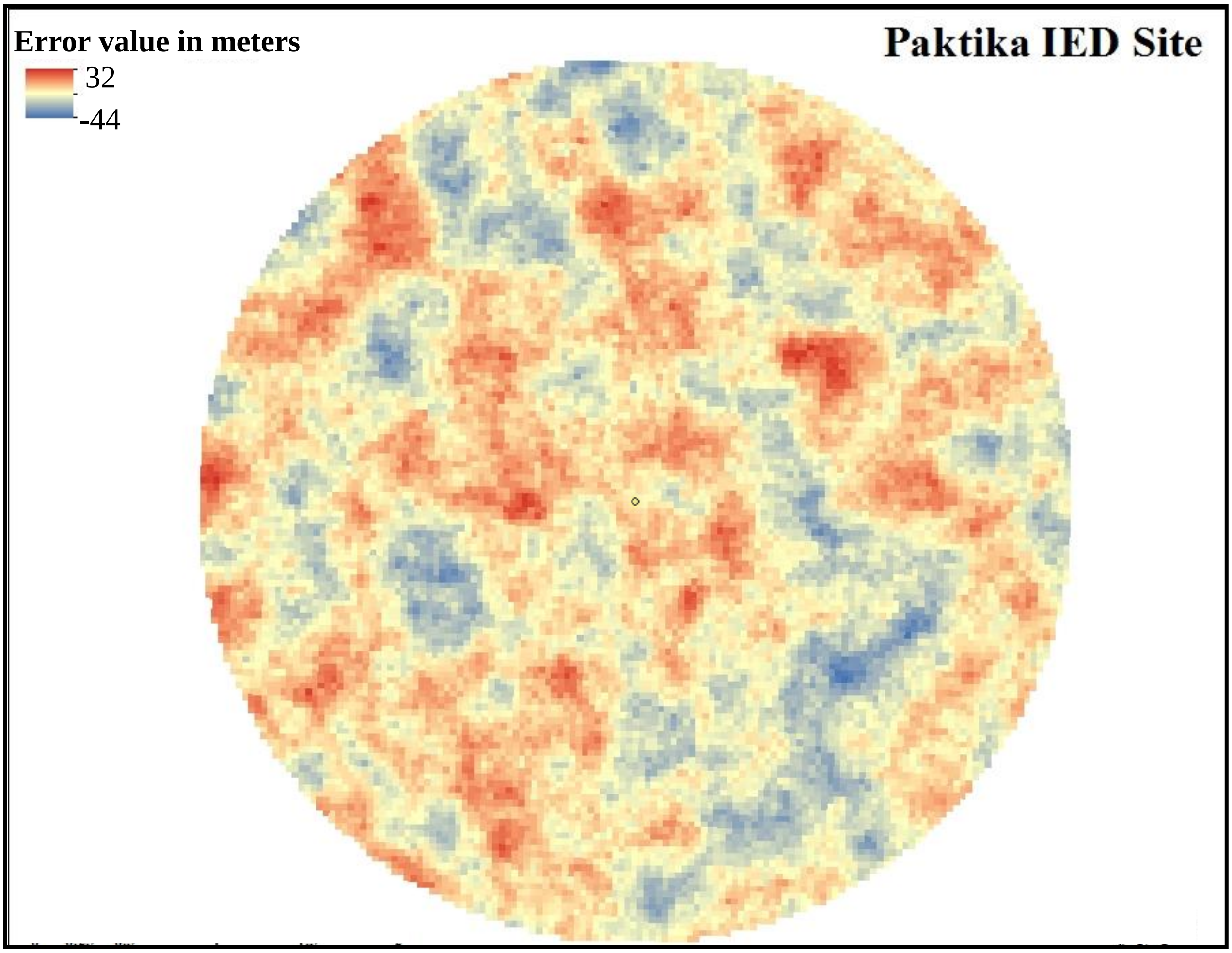

Figure 33: 30th simulated error surface for Paktika developed from the Colorado variogram.

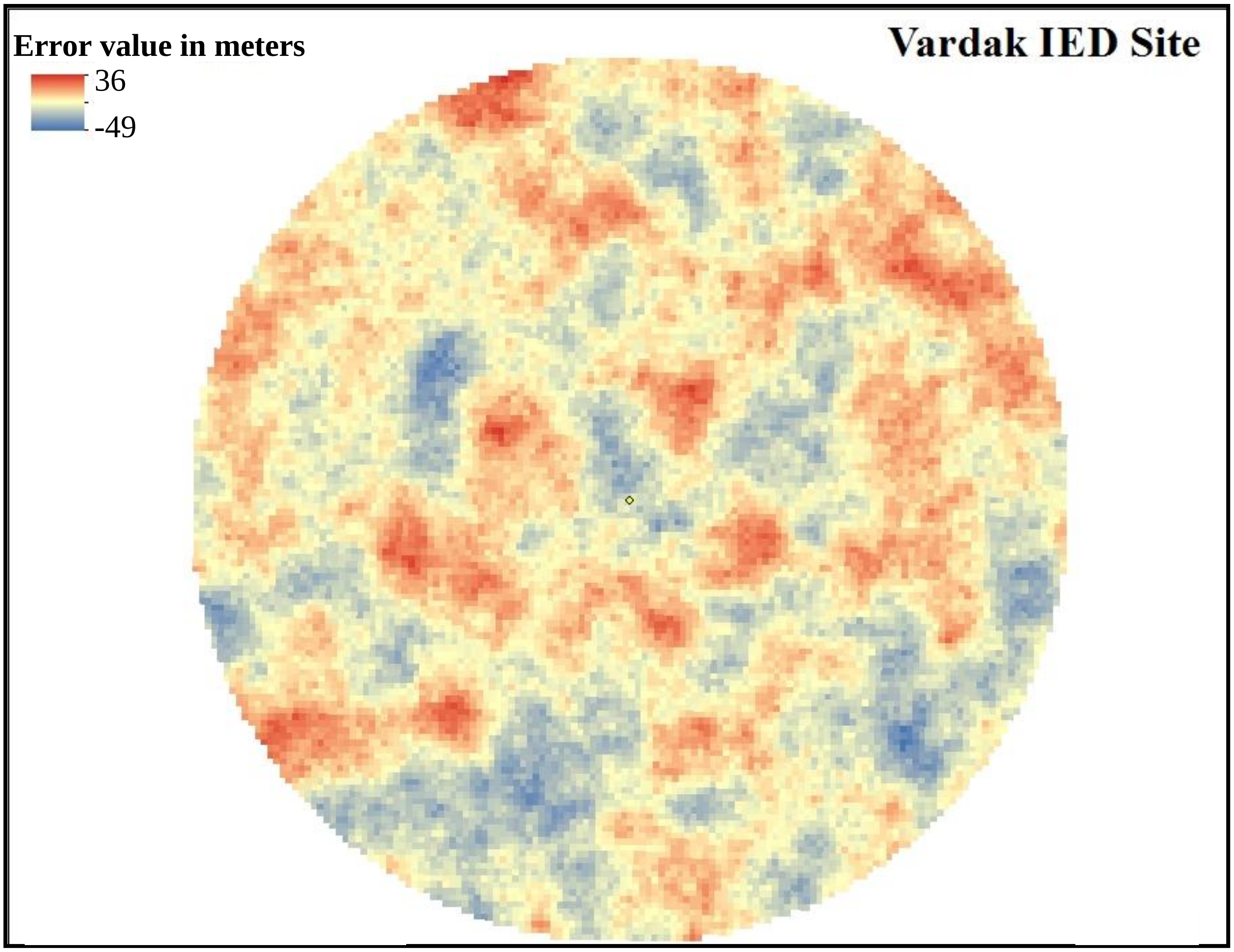

Figure 34: 30th simulated error surface for Vardak developed from the Colorado variogram.

It is clear that while the magnitude of error varies between the scenes and, in fact, between the simulations, they are still spatially autocorrelated to the same extent as the Colorado location. Again, although the extreme values seem to range between -50 meters and 40 meters, the mean value is approximately -4 meters with a standard deviation of about 12 meters. This is a positive indication that the parameters derived from the ASTER-NED difference map in Colorado hold true through the simulation script. These error simulations are the driving force for the creation of probable viewsheds. Each of the 100 simulated error surfaces for the five IED locations were then added to the extracted and smoothed ASTER product. These newly created elevation surfaces make it possible to create a probable viewshed surface, a measure of confidence for each cell in the scene that it is actually within the viewshed of the IED, via Monte Carlo simulation based on the variogram developed in the Colorado scene.

2.2.3 IED Viewshed Analysis

After simulating the surfaces, the viewshed tool found in ESRI ArcGIS 10 Spatial Analyst was utilized. The algorithm is controlled by a number of parameters to customize the type of line-of-sight calculation needed for analysis: There are many important characteristics[7] of the viewshed tool, but two present significant issues with this research that must be considered: offset heights and search radius. First, the offset heights for both the origin and the observer locations were created to simulate a convoy operation. This research utilized an offset value of three meters for the incident location (OF1) to simulate the height of a Mine Resistant Ambush Protected (MRAP) vehicle; the most commonly used vehicle by the U.S. Army and Marine Corps in Afghanistan. The offset value for the viewable locations (OF2) is two meters to account for the average height of a person. This is a fairly liberal estimate considering a combatant would likely be crouching or in the prone position to avoid detection.

Second, the appropriate search distance had to be determined for both the inner and outer radii. The inner search radius was obviously zero since the insurgent could be extremely close to the IED site, yet the outer search radius was more difficult to determine. Meteorological factors can significantly affect visibility due to cloud cover and atmospheric refraction. An analysis of over 30 years worth of meteorological data from Afghanistan at 97 different weather stations yielded a mean visibility distance of 14.3 kilometers with a standard deviation of 3.14 kilometers and some locations with upwards of 30 to 40 kilometers. It was determined that visibility at the

[7] The viewshed searches in all directions for all altitudes, which means the default values for VERT1, VERT2, AZIMUTH1, and AZIMUTH2 were used.

tactical scale of an IED ambush would not be restricted by meteorological factors due to the large potential visibility distances. A much more vital question is what are the limits of perception for the human eye and how far from an IED explosion is a small arms ambush likely to be set. The following is a table of information extracted from a recent New York Times article (Chivers, 2010) detailing the types of weapons confiscated from Taliban insurgents:

Weapon	**Maximum Effective Range to Area Target**
RPG-7 Launcher	~200 meters
AK-47 Assault Rifle	400 meters
PK Machine Gun	1,500 meters
1915 Lee-Enfield Bolt Action Rifle	500 meters
Mosin-Nagant Rifle 7.62x54mm	500 meters
M-16 Assault Rifle	800 meters
RKG-3 Hand Grenade	30 meters
PP 87 82mm Mortar	5,000 meters

Table 4: Ranges of weapons found in Afghan insurgent caches.

A conservative estimate would indicate that 5,000 meters is the potential maximum distance to be used for a well-organized and premeditated ambush. However, the type of IED triggering mechanism can substantially vary the distance: a command-wire trigger may necessitate a distance of within a couple hundred meters, while a cellular phone-based triggering mechanism may enable a virtually unlimited functional distance from the IED. A final consideration for the functional distance from the IED is the fact that many jihadist websites and community message boards distribute propaganda from IED attacks. Most often, these propaganda videos depict attacks in which American vehicles are destroyed and soldiers killed. It is clear, then, that the parties responsible for emplacing and/or triggering these IEDs are close enough to the attack location to record the operation on camera (Wilson, 2006). It was determined that although the triggering device of the IED could not plausibly be inferred, ancillary data (small arms ranges, potential IED triggers, meteorological factors, and an assumption of maximum perception distance of the naked eye) suggests a reasonable maximum viewshed distance is 2,000 meters. Lastly, since the horizon is approximately 5 kilometers there was no need to correct for the curvature of the Earth in the analysis.

Figures 31-35 depict the viewshed of the 30th simulated elevation surface includes error derived from the 30th simulated error model (see simulation discussion). The purpose of these maps is to give the reader an understanding of the general shape of the viewshed at each site and to serve as a comparison with the total probable viewshed map to see how one simulation may fall within or outside of the general bounds of the viewshed. In other words, the following examples are just 1 of the 100 viewsheds created from the simulated error surfaces for each site and may or may not directly correspond the actual bounds of the consensus (e.g., Figure 33 is an outlier compared to Figure 38).

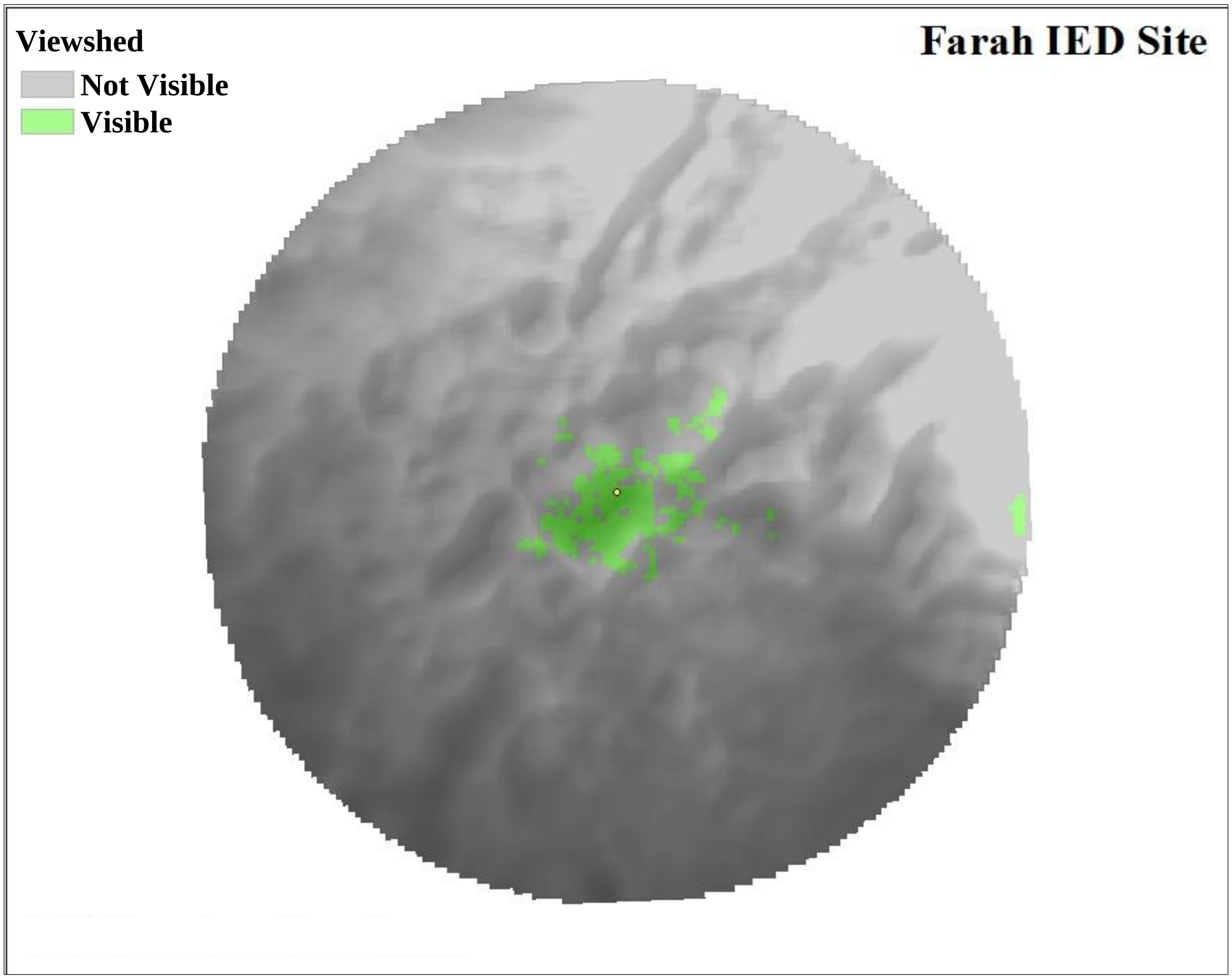

Figure 35: Viewshed for 30th simulated elevation surface for Farah based on 30th simulated error surface.

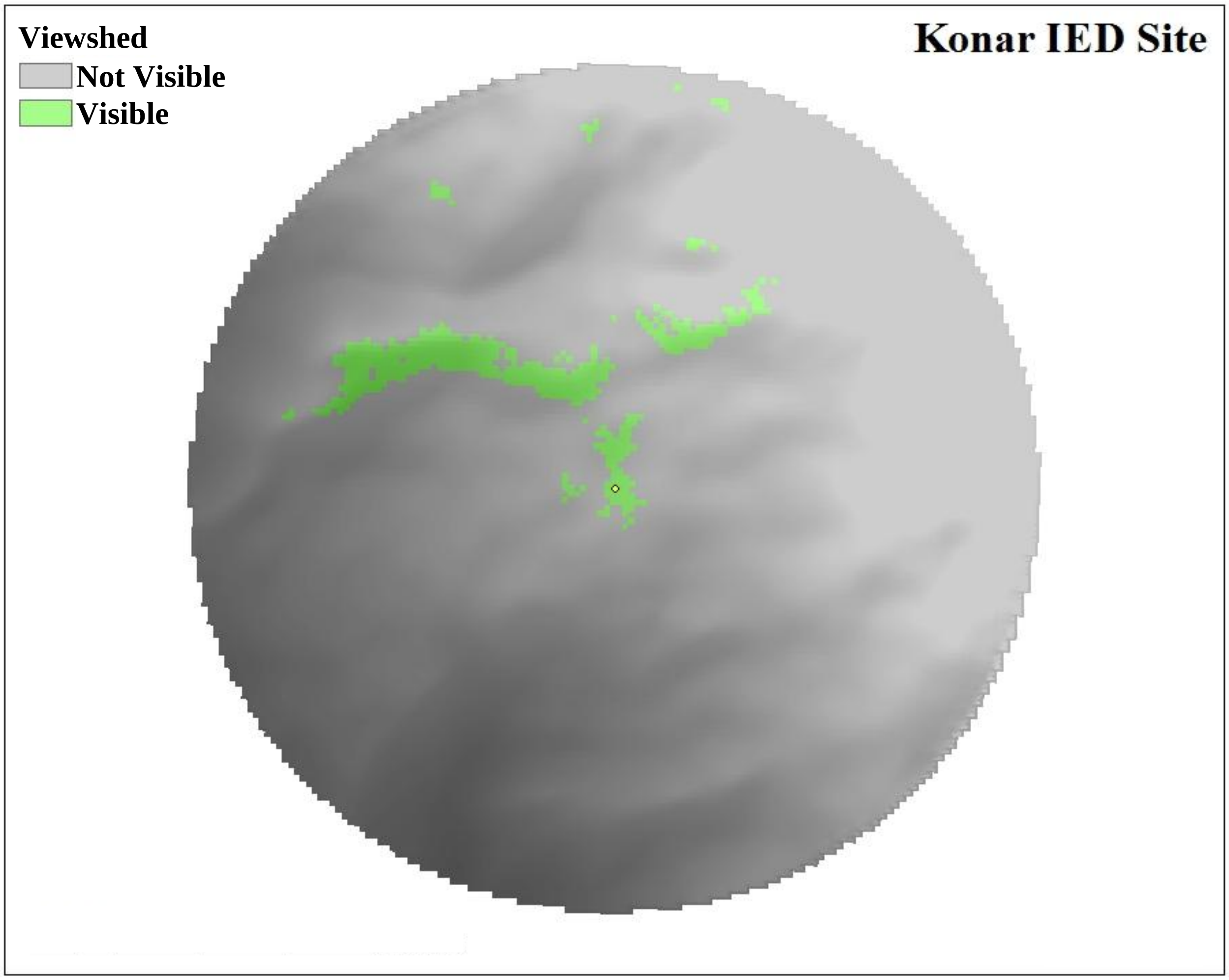

Figure 36: Viewshed for 30th simulated elevation surface for Konar based on 30th simulated error surface.

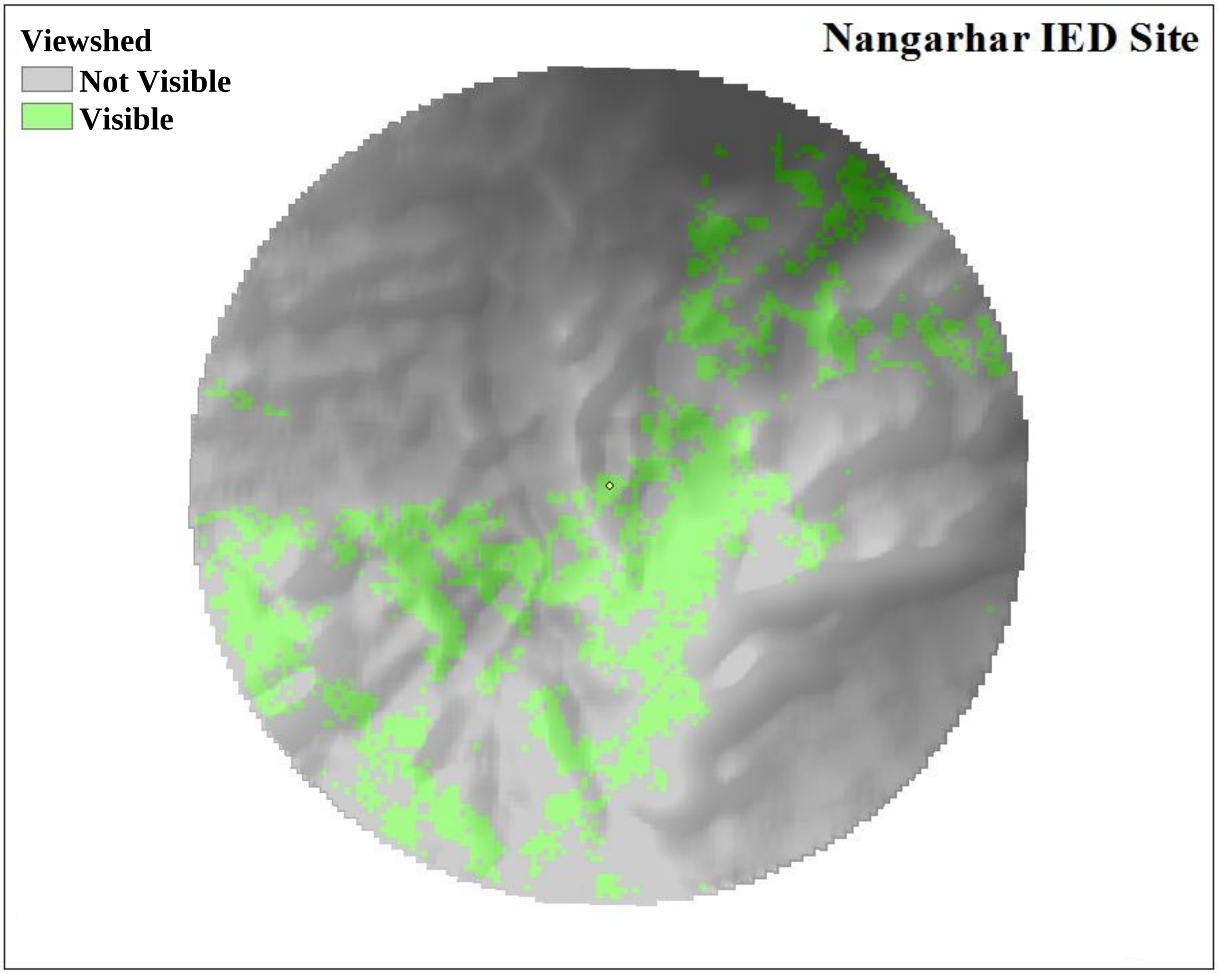

Figure 37: Viewshed for 30th simulated elevation surface for Nangarhar based on 30th simulated error surface.

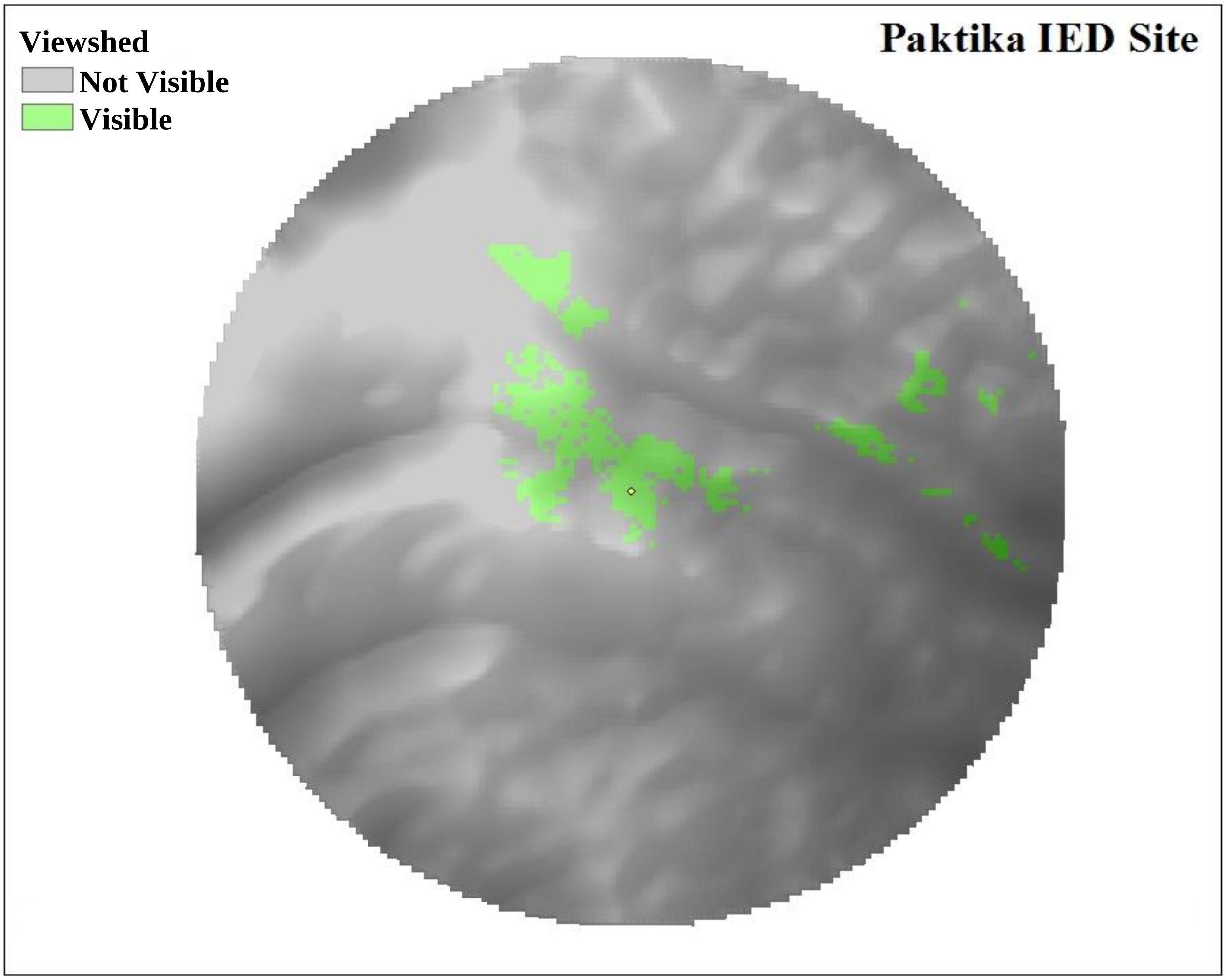

Figure 38: Viewshed for 30th simulated elevation surface for Paktika based on 30th simulated error surface.

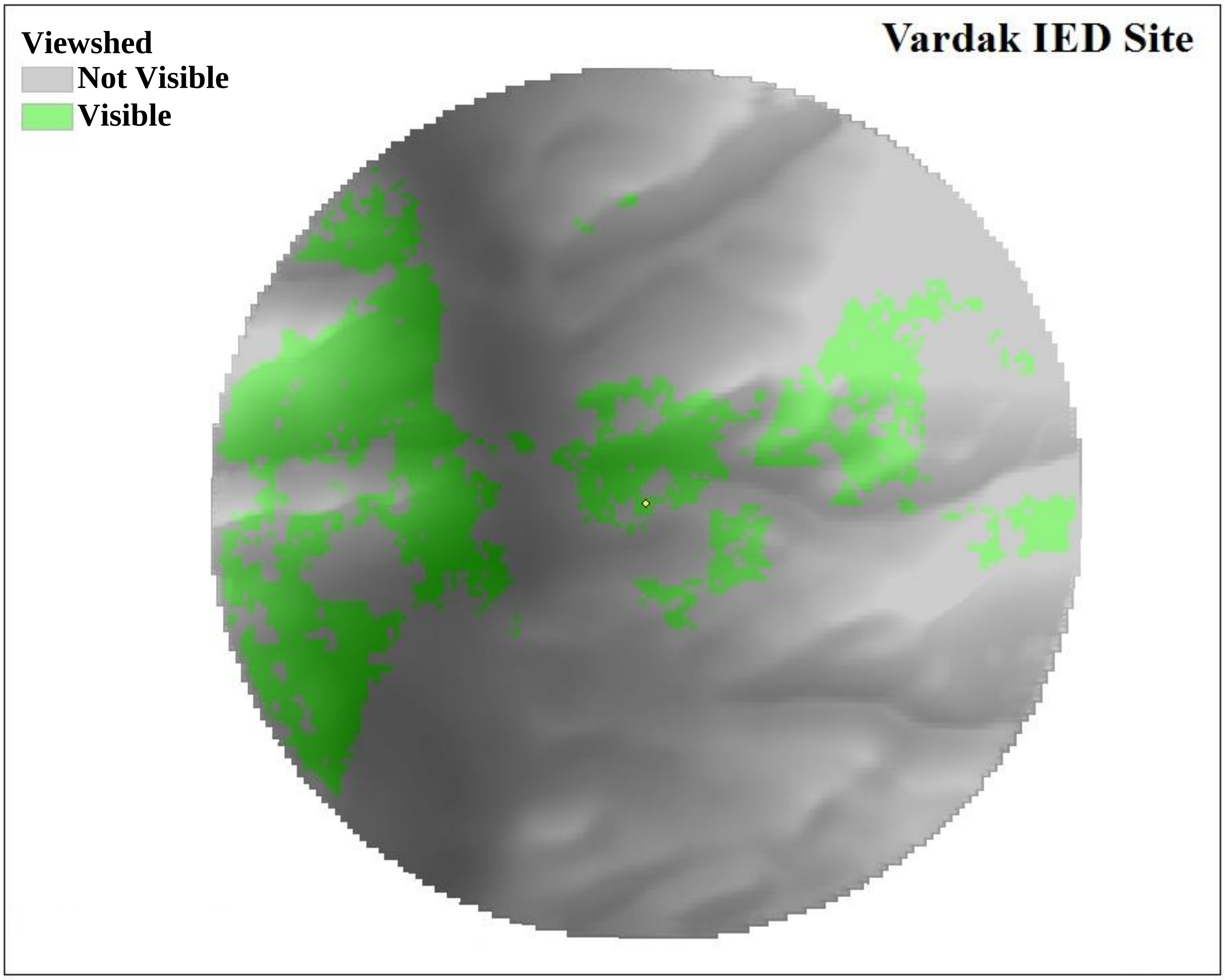

Figure 39: Viewshed for 30th simulated elevation surface for Vardak based on 30th simulated error surface.

3 Results

Figures 36-40 depict all of the possible values of the probable viewshed for each IED site. This measure was created by adding the binary result of all 100 simulations together to create a surface of cells with values ranging from 0 to 100. The final value of each cell represents the probability that the cell is within the actual viewshed as represented by the summation of the number of times it was included over the 100 simulations. As expected, the probable viewshed maps for all five sites show an inverse relationship between the number of times a cell was included in the simulated viewsheds and its distance from the IED site.

These viewshed maps are a good indication of the probability that a cell exists within the actual viewshed of each site. The distribution of this probability is a direct result of the positioning of the site on the terrain. The Farah site (Figure 41), for example, has higher probabilities constrained within a small radius of about 150 meters around the site. This is a good indication that the site is surrounded by higher elevations as the elevation variation induced by the simulation process had little effect in expanding many viewshed iterations. Conversely, the Vardak IED site (Figure 45) shows higher confidence for much more of the landscape. This is a good indication that more area in the scene is probably within the actual viewshed. The site must be located on the landscape in a position that cannot be heavily influenced by elevation variation such as in a valley or on a ridge. The rest of the sites are somewhere in between these two cases. It is important to notice that all sites exhibit a concentric pattern of probability with high elevations in the viewshed having the highest probability and that probability decreasing with elevation. The pronounced ridgeline in the Konar site (Figure 42), for example, shows that the top of the ridge has the highest probability of existing in the viewshed and that probability quickly decreases as locations move into the small valley in between the site and the ridge. This is due to not only the relative positions of the cell and the site on the landscape, but because random elevation variations between those two locations more easily break the line of sight as the angle over which the line is drawn becomes more accute.

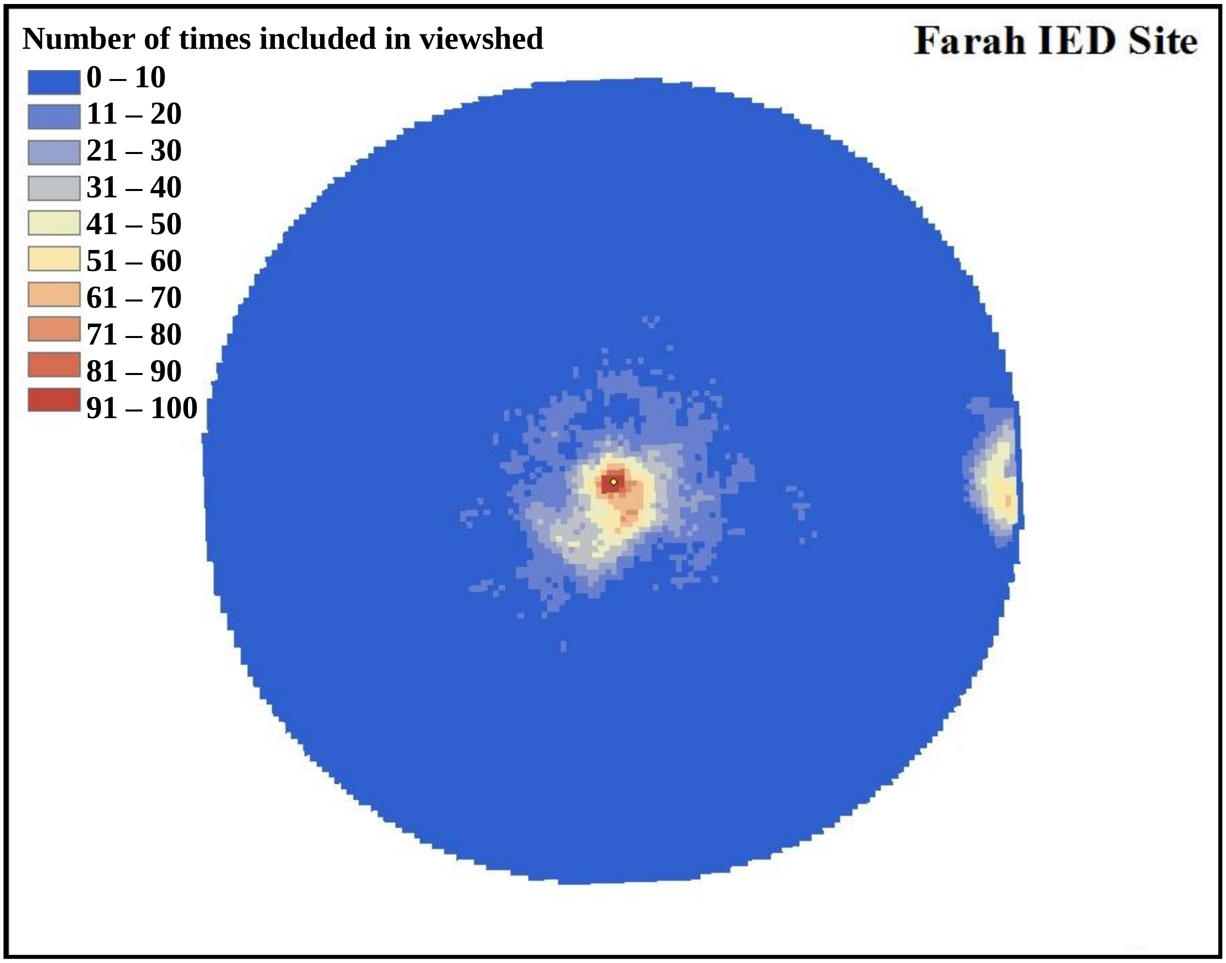

Figure 40: Probable viewshed for Farah created by adding all 100 binary viewshed simulations.

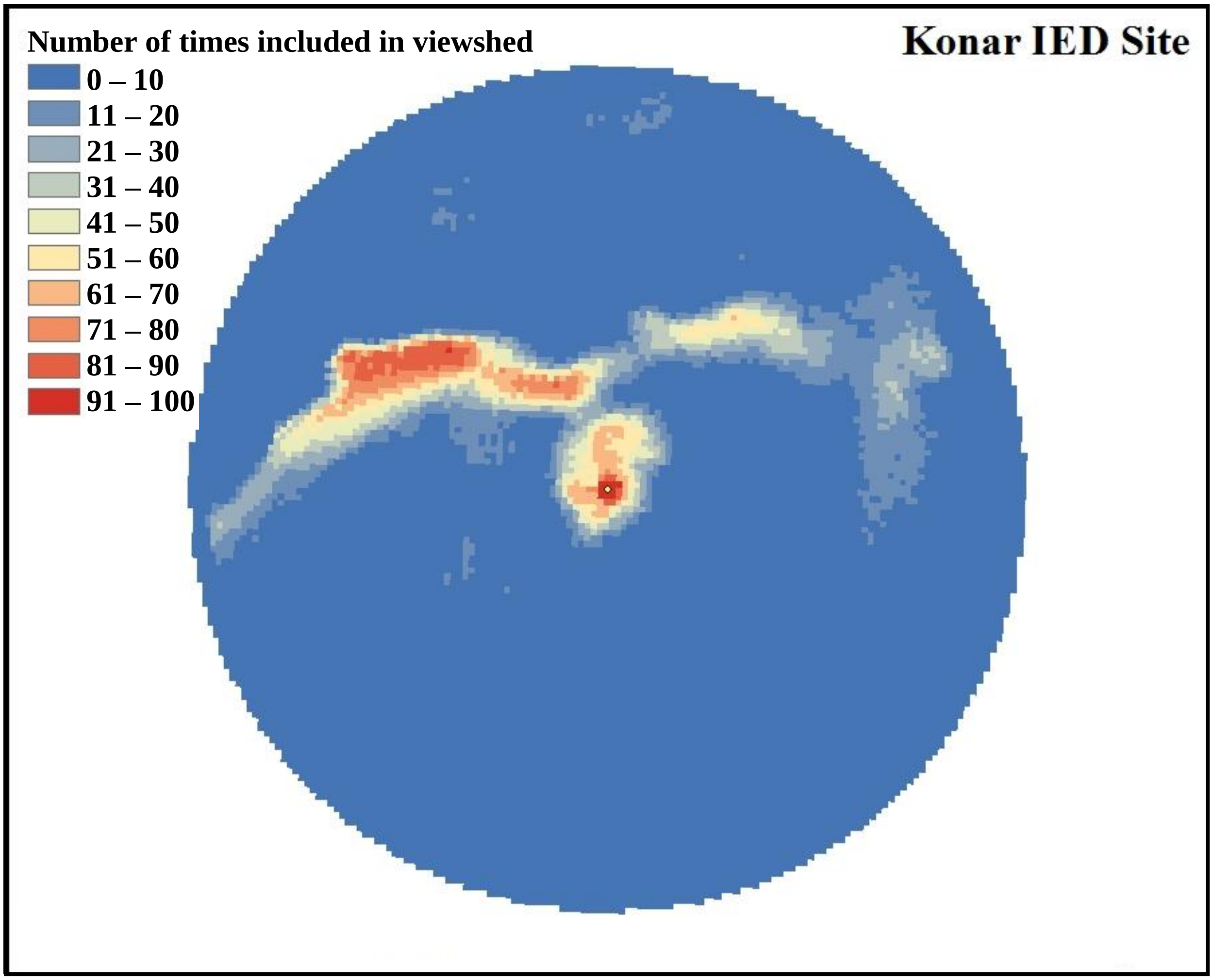

Figure 41: Probable viewshed for Konar created by adding all 100 binary viewshed simulations.

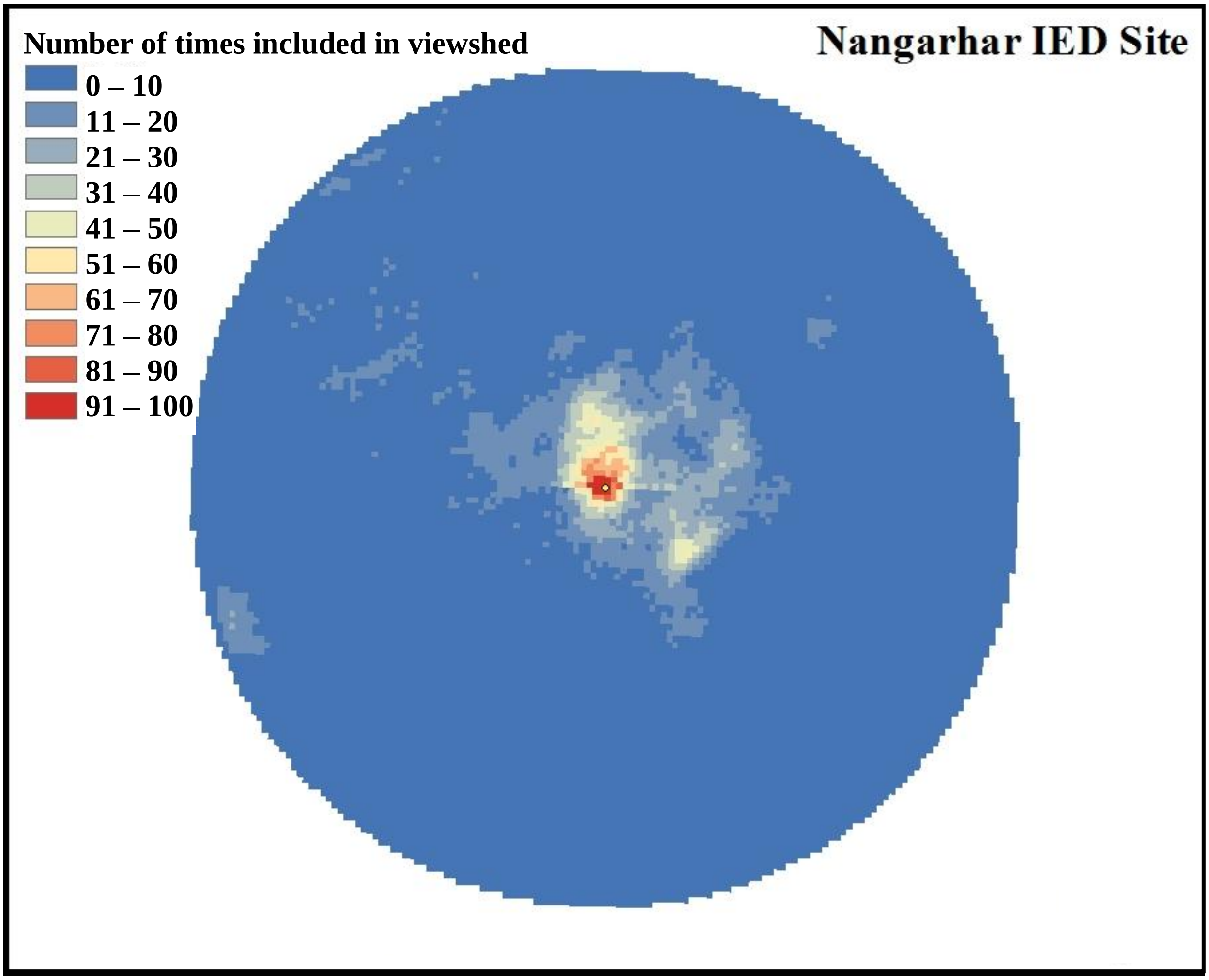

Figure 42: Probable viewshed for Nangarhar created by adding all 100 binary viewshed simulations.

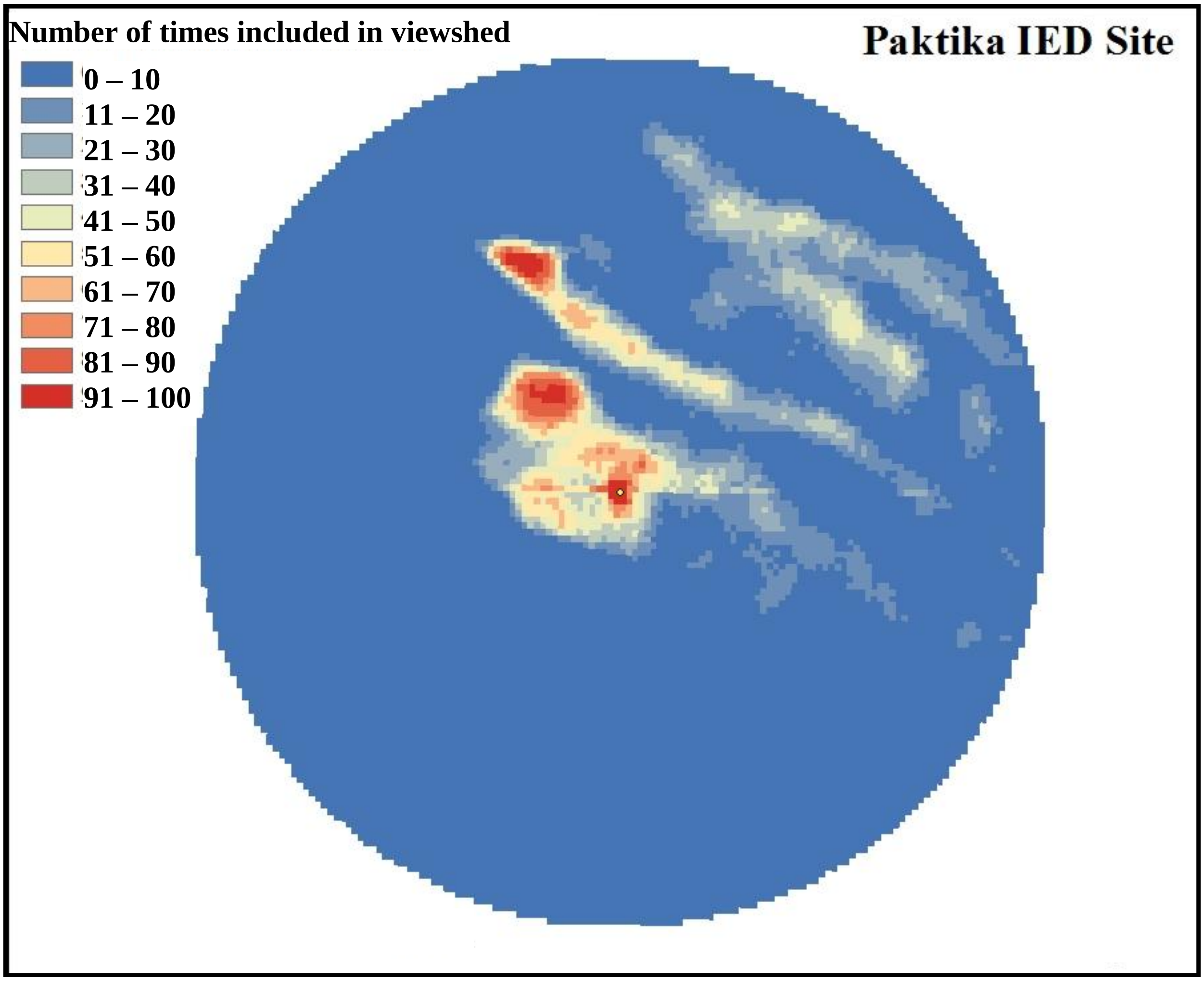

Figure 43: Probable viewshed for Paktika created by adding all 100 binary viewshed simulations.

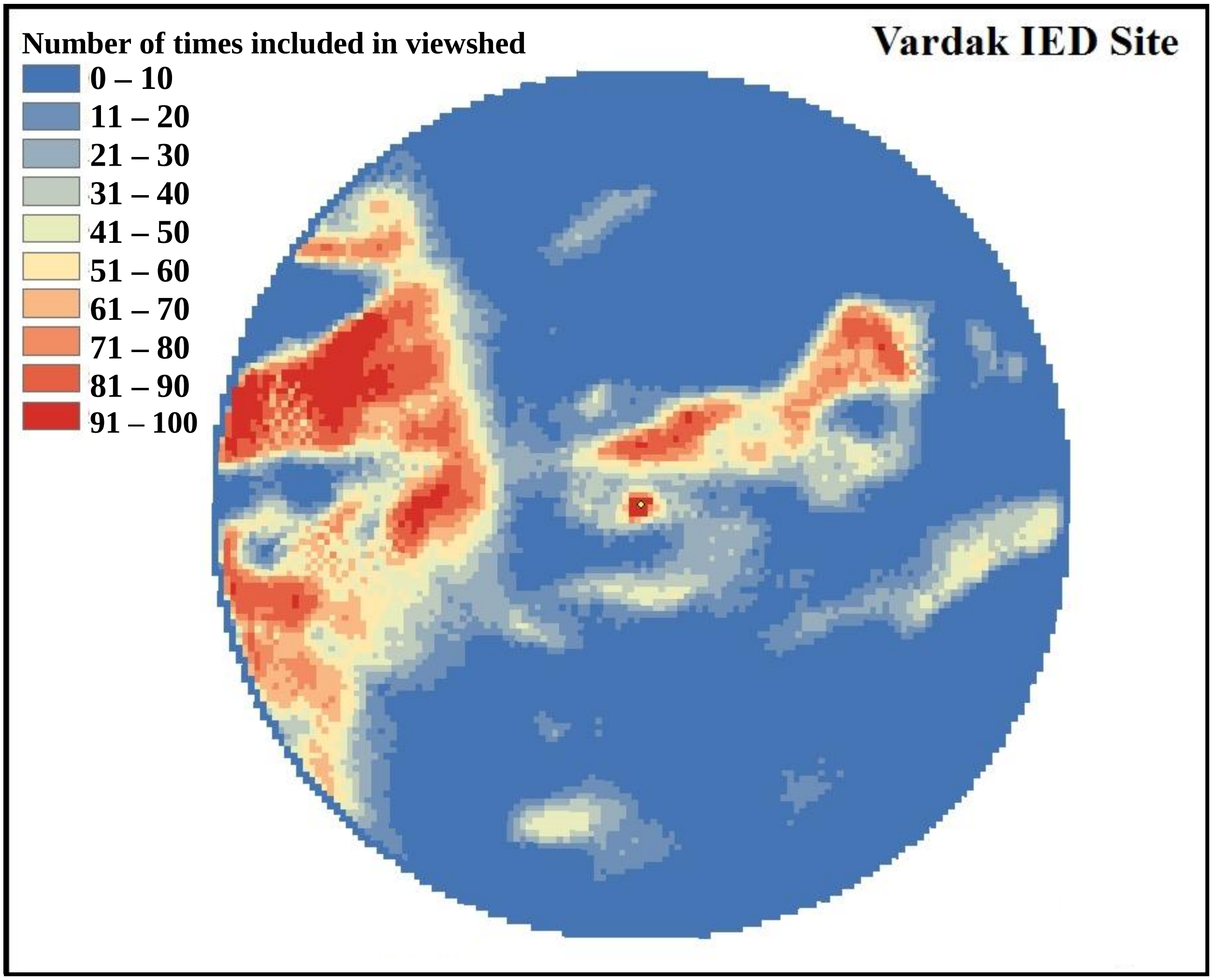

Figure 44: Probable viewshed for Vardak created by adding all 100 binary viewshed simulations.

Figures 46-50 depict the difference in viewsheds between the ASTER GDEM surface and the viewshed for which 33 simulations agreed. Again, this measure was based on the mean value derived from the NED viewshed (assumed to be ground truth) in the Colorado scene. The simulated viewshed area was significantly less than was anticipated. The NED viewshed in Colorado was approximately 96% of the area of the ASTER viewshed, which was assumed to be due to a better measurement of the obstructing micro-relief. While the viewshed was indeed smaller in the simulated viewsheds in Afghanistan, they were considerably smaller. As discussed earlier, the mean value of the probable viewshed surface that intersected with the NED viewshed was 33. This value is assumed to be the realistic extent to which the viewshed boundary exists in the Afghanistan study sites based on the ASTER-NED difference in Colorado.

The following values are the simulated percent viewshed area (SPVA) of each site in relation to the viewshed created from ASTER GDEM. The target percent viewshed area (TPVA), according to the NED viewshed area compared to ASTER GDEM in Colorado, is 96.63%. Presumably, the closer the SPVA is to the TPVA, the better the extrapolation has performed.

Province	**ASTER VIEWSHED AREA (km^2)**	**33 SIMULATED VIEWSHED AREA (km^2)**	**PERCENT AREA OF SIMULATED VIEWSHED**
Farah	0.958	0.261	27.216
Konar	1.153	0.737	63.941
Nangarhar	1.932	0.190	9.850
Paktika	1.855	0.790	42.560
Vardak	4.651	3.044	65.444

Table 5: Total viewshed areas. The 33 Simulated Viewshed Area represents the number of simulations needed in the Colorado area for the ASTER viewshed to equal the NED viewshed. The Percent Area should be close to 96%.

As can be seen from Table 4, the simulations for Vardak (65.24%), Konar (62.30%), Paktika (42.47%), Farah (27.22%) and Nangarhar (9.85%) performed rather unexpectedly since the percent area of the simulated viewshed should have been close to 96% since that is the percent of the ASTER viewshed that NED made up. Clearly this outcome was not ideal for this portion of the methodology since the extrapolation would have resulted in all percentages being close to 96%. The results, however, should not be immediately written off. Figures 46-50 illustrate the difference between the ASTER viewshed and the SPVA at each IED site. It is clear to see the better performance at the Vardak and Konar sites compared to the Nangarhar site. Once again, comparing the relative positions of the IED locations on the landscape reveals important findings in regards to the dynamic nature of error, digital elevation models, and viewsheds.

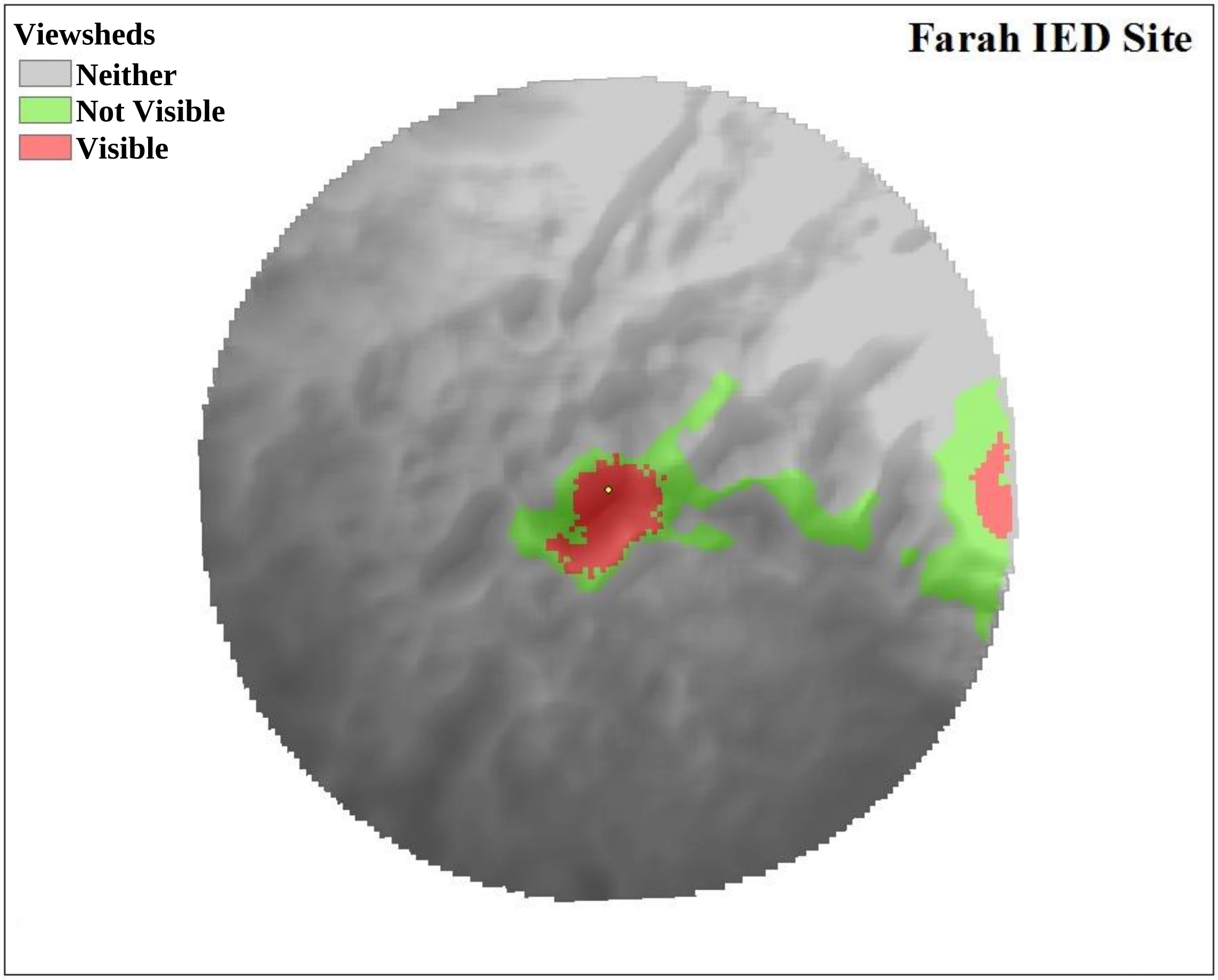

Figure 45: Comparison of ASTER viewshed and boundary at which 33 simulated viewsheds agree for Farah IED site.

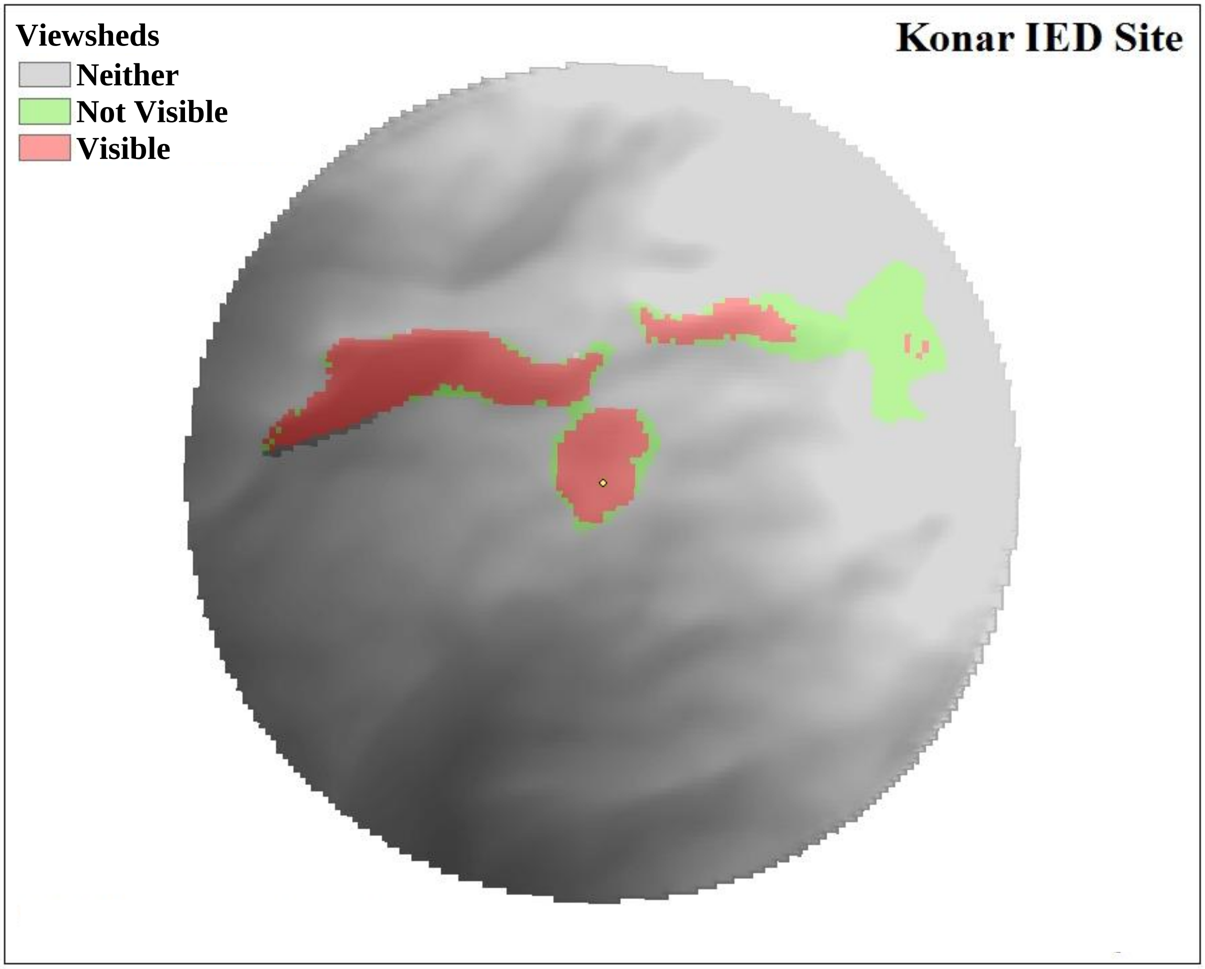

Figure 46: Comparison of ASTER viewshed and boundary at which 33 simulated viewsheds agree for Konar IED site.

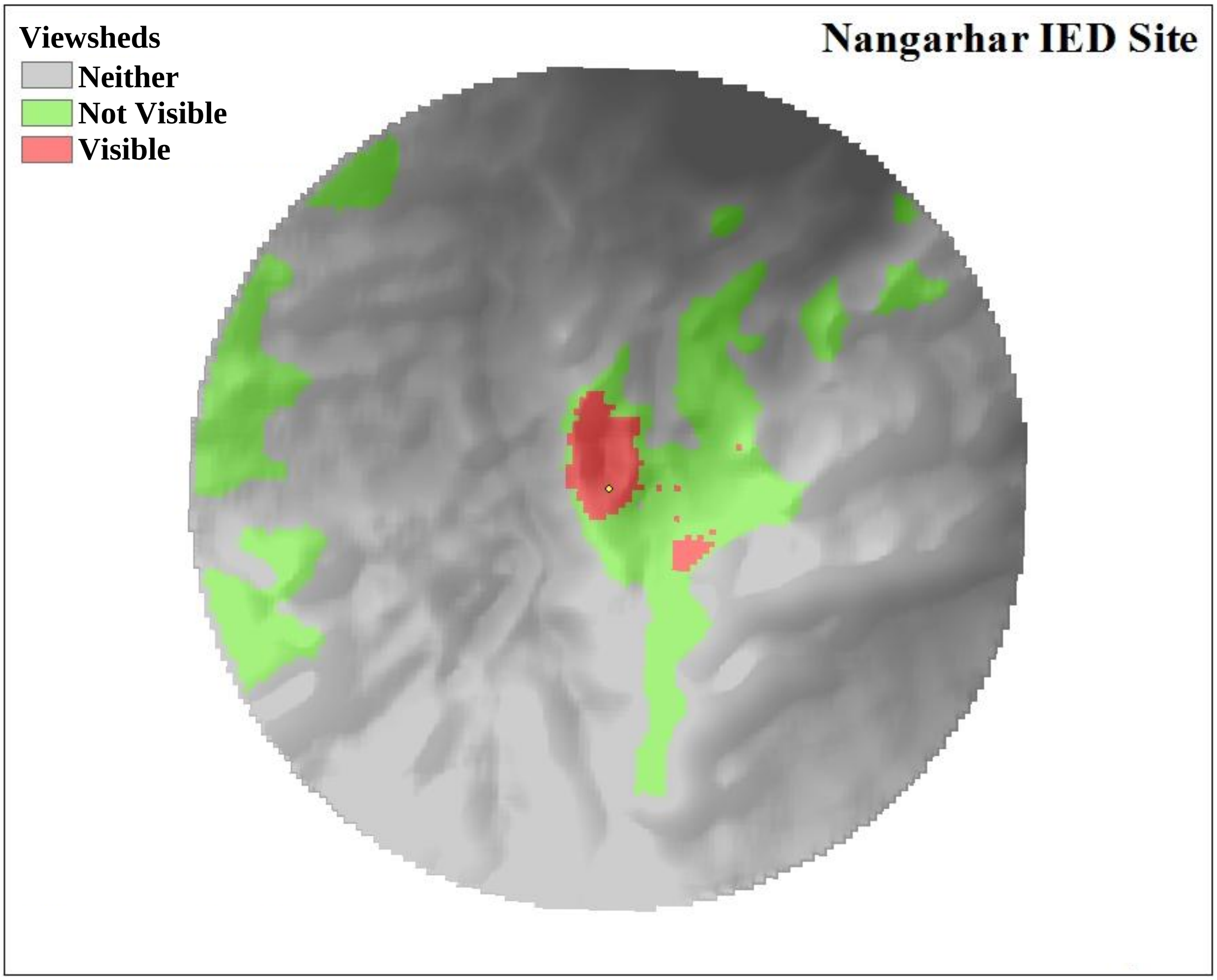

Figure 47: Comparison of ASTER viewshed and boundary at which 33 simulated viewsheds agree for Nangarhar IED site.

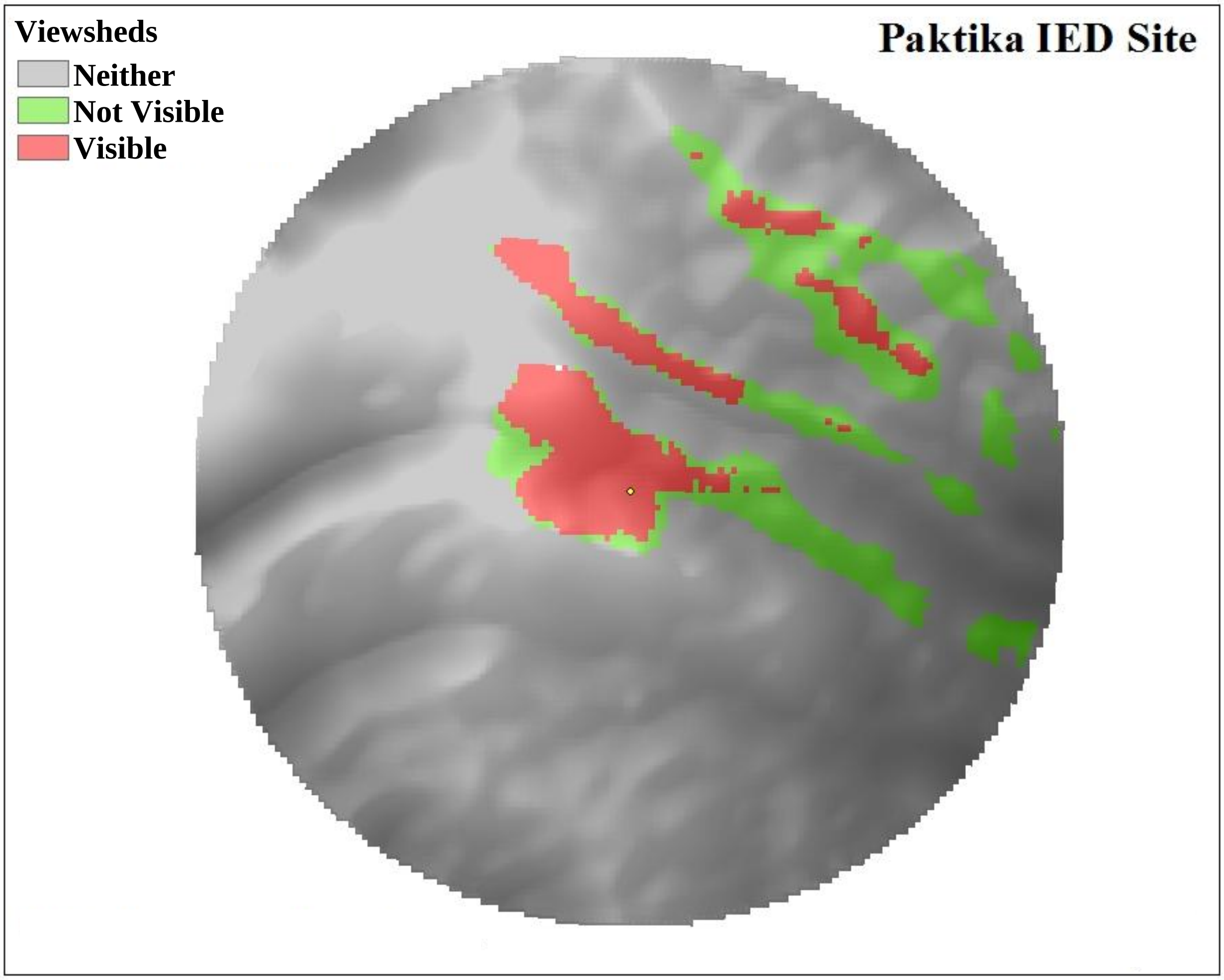

Figure 48: Comparison of ASTER viewshed and boundary at which 33 simulated viewsheds agree for Paktika IED site.

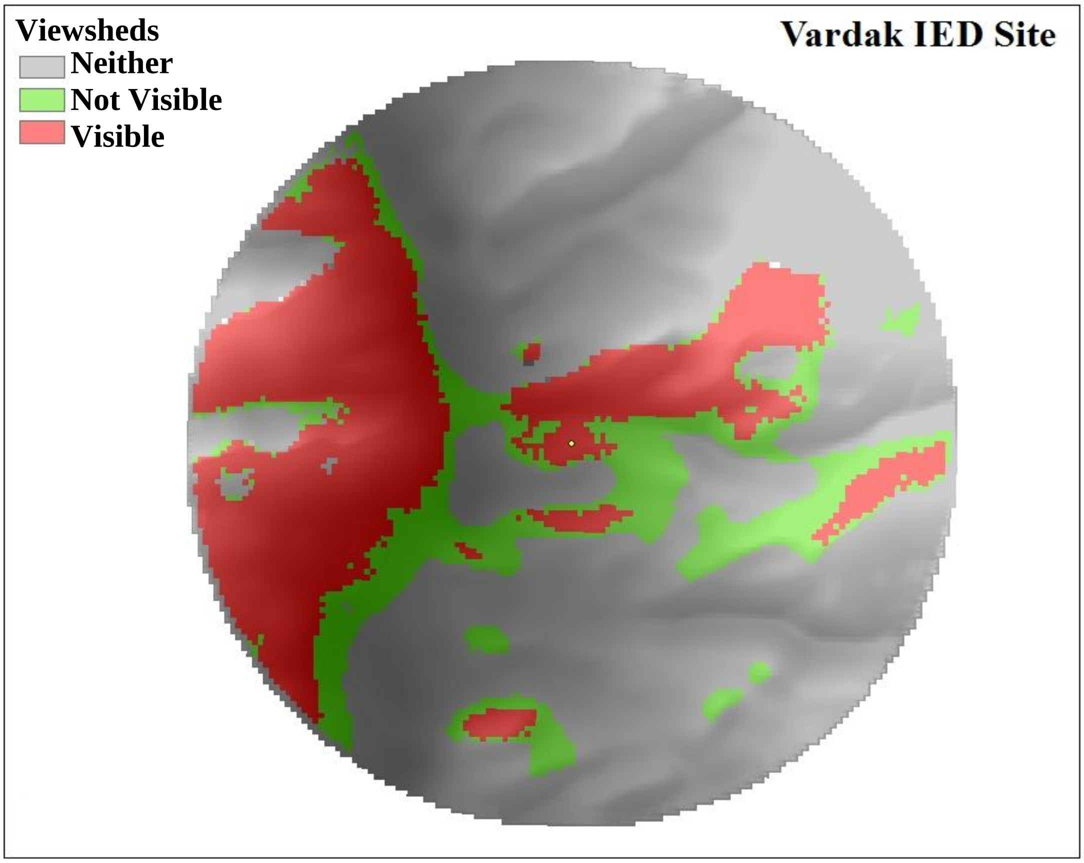

Figure 49: Comparison of ASTER viewshed and boundary at which 33 simulated viewsheds agree for Vardak IED site.

When comparing the initial viewshed using the ASTER GDEM product and the viewshed in which 33% of the simulated viewshed surfaces agreed, it is clear that using the Colorado error model does not yield the exact same results for the Afghanistan study areas due to the decreased simulated viewshed area proportion compared to what was expected. The simulated viewshed areas range from approximately 9% of the original ASTER viewshed area to just over 65%. The simulated viewshed areas were expected to be closer to 96%. The range of SPVA results demonstrates the principle that visibility analyses are extremely sensitive to error in elevations near a site and are amplified in proportion to distance (Floriani, 2009). In Figures 51-55, it is apparent that more simulations were needed to approach the TPVA (~96% of the area of the ASTER GDEM viewshed). In fact, the ideal TPVA occurs around an agreement of approximately 15 simulations for most sites. The shape of the viewshed simulation cumulative area curve is also something to note. As expected, total area significantly increases as fewer viewsheds agree—the more this curve is positively skewed, the less reliable the probable viewshed. The skewness indicated that more area exists in which only a few viewsheds agree. The Farah graph, for example, is far more negatively skewed than Paktika graph. The comparison of these graphs is another confirmation of the differing performances between the probable viewsheds.

The results of the viewshed analysis reveal that spatial summary statistics may be less important than the shape of the landscape:

Site	Elev Min	Elev Max	Elev Mean	Elev StDev	Slope Min	Slope Max	Slope Mean	Slope StDev
Colorado	3129	3707	3375.61	112.27	0.40	34.41	13.07	5.98
Farah	922	1062	942.63	13.41	0.00	29.77	1.95	2.30
Konar	1254	2548	1895.27	327.93	0.49	56.15	20.79	6.58
Nangarhar	646	765	693.98	18.41	0.00	16.27	3.03	2.33
Paktika	2174	2551	2297.04	61.02	0.00	47.79	10.33	7.08
Vardak	2262	2797	2406.16	98.87	0.00	37.30	12.54	7.05

Table 6: Elevation and slope summary statistics for all sites.

At first glance the results from the simulations at these sites were disappointing, but upon further inspection the varied results support the methodology rather than challenge it. The sites were originally selected based on the variables of the attack and few eligible incidents met the criteria. The limited number of eligible incidents in the WITS restricted the study since less emphasis was given to the geographic variables of the location, such as average elevation and elevation range. Fortunately enough, the elevation ranges of the Colorado and Afghanistan sites were close enough to continue with the analysis. However, the simple spatial summary statistics of each location are not adequate measures of the shape of the landscape. A more deterministic characteristic of the landscape is needed to determine the validity of this methodology.

Viewsheds are incredibly dynamic and slight movements, even less than 30 meters, have profound impacts on the shape and area of the viewshed. The total viewshed area of Point A at the edge of a cliff next to the Grand Canyon will have a significantly larger viewshed than Point B ten horizontal meters from Point A, yet 500 vertical meters lower. A similar effect appears to be happening in comparison of the Farah and Nangarhar viewsheds. If the Nangarhar site was moved just meters onto the top of the hill instead of on the side, the viewshed would increase significantly and the simulated viewshed would have been much larger. The following maps compare Nangarhar (the worst performing simulation) and Vardak (the best performing simulation) as a demonstration of the importance of point placement and the shape of the landscape.

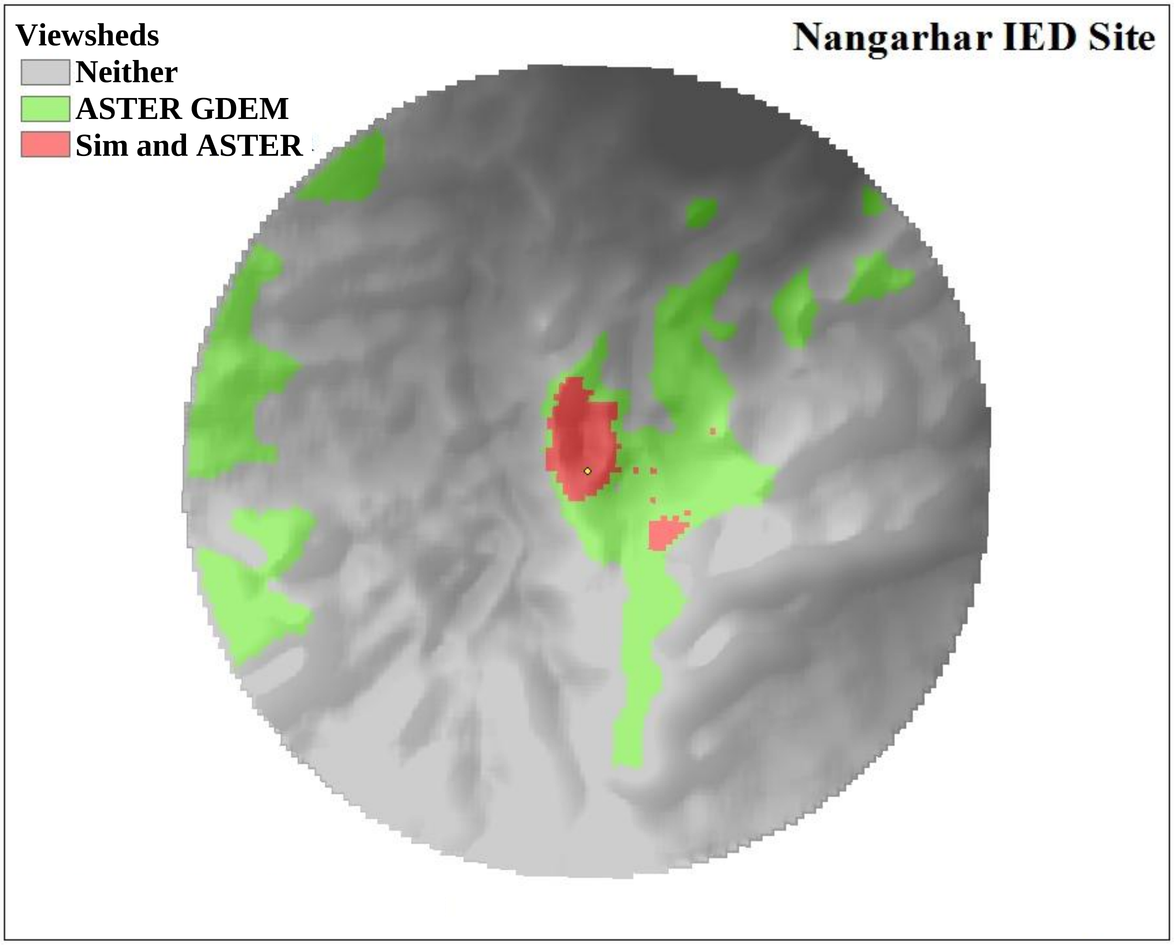

Figure 50: Comparison of ASTER and simulated viewshed boundaries on hillshaded DEM at Nangarhar IED site.

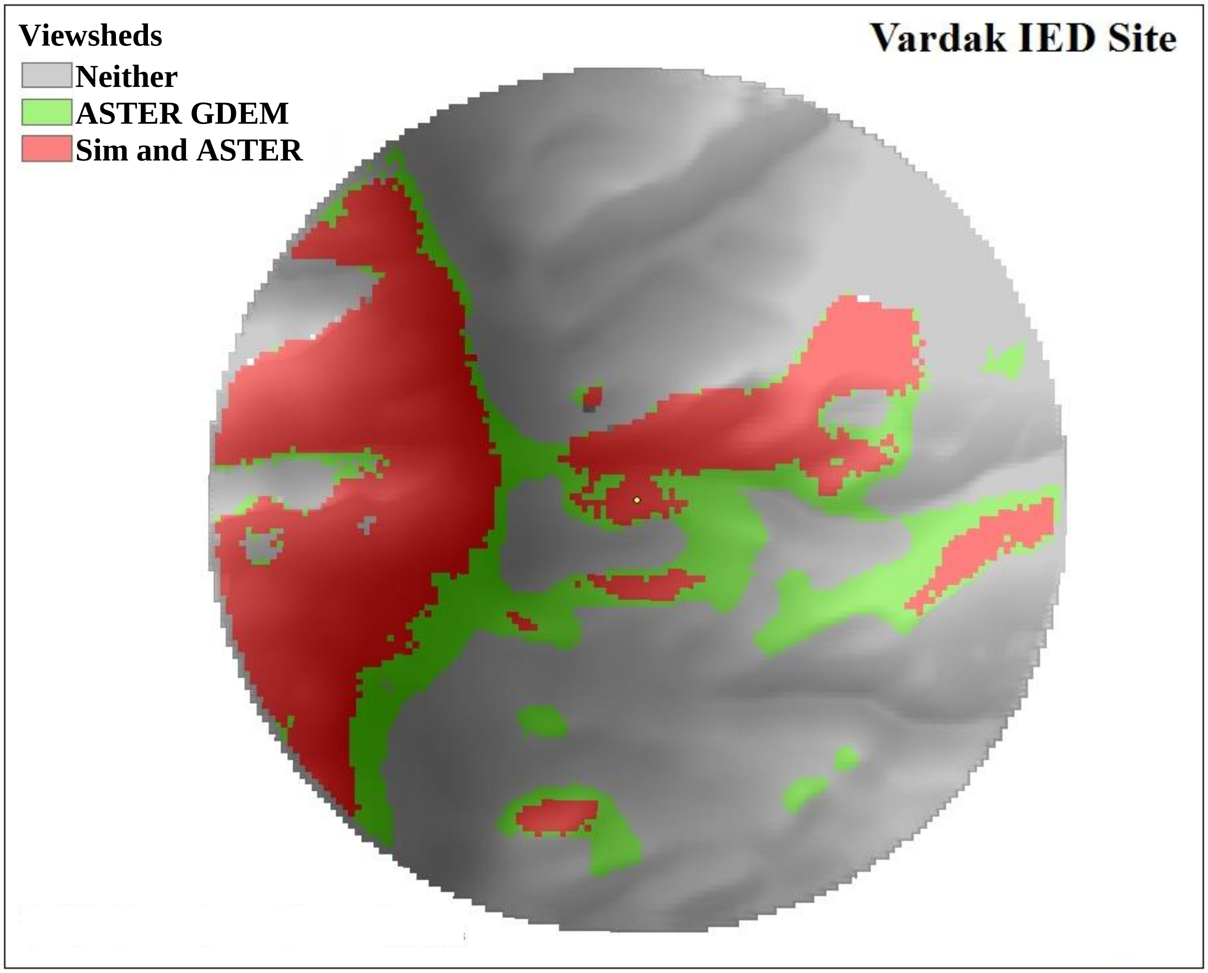

Figure 51: Comparison of ASTER and simulated viewshed boundaries on hillshaded DEM at Vardak IED site.

After hillshading the surface, it is easy to see that two IED sites are placed at different elevation points. The Nangarhar is perched on the side of an incline. This position severely limits ability of an observer to see the immediate landscape to the southeast and further disruptions of the surface due to the error simulations will further restrict the viewshed. In essence, the point is located on the inside of a depression and only areas that are significantly higher in elevation are visible. Conversely, the Vardak site is located in a slight valley and is flanked by ridges directly to the east and west. Elevation disruptions from the simulated error surface have a far less significant effect on this scene as the majority of the visible area is located on the side of ridges that all face the point. In fact, the only non-visible area from the IED site is at similar elevations near the base of the ridges. The error models obstruct these locations because any positive elevation changes between two points at similar elevations, no matter how slight, will cause the line of sight to be broken.

4 Conclusion

4.1 Overview

This research yields three strong findings to address the research hypotheses in the beginning of the paper. First, ASTER GDEM outperformed the SRTM DEM in the Colorado study site. Under the assumption that NED is as close to ground truth as possible, ASTER performed better in summary statistics (50% smaller ranger and a mean of nearly zero), variography (significantly less variation over shorter distances), and measures of correlation (a nearly perfect 1-1 relationship). Second, the dynamic nature of viewsheds is explained by the varied performance of the simulations. The Nangarhar and Vardak cases provide an informative example of the effect of the landscape and site placement on the size and shape of the viewshed. A site placed on the side of an incline, more specifically just below the ridge, will have a viewshed that is more affected by variations of elevations in close proximity during simulation. In other words, the original DEM may indicate the point to be on top of a ridge and have an expansive viewshed in any direction. Conversely, any number of the 100 simulated DEMs may raise or lower the site and surrounding elevations to essentially take it off the ridge, thus, restricting the size of the simulated viewshed as demonstrated in the research. The viewshed area for which 33 simulations agreed at the Nangarhar IED site was a mere 10% of the original

ASTER viewshed. The demonstration of Monte Carlo simulation in this research confirms the third hypothesis.

Although studies have been conducted in the past to models known error in DEMs (Ehlschlaeger, Shortridge, and Goodchild, 1997), this research is one of the first to extrapolate an error model of ASTER GDEM in one location to another location nearly 7,500 miles away. Furthermore, no academic study has utilized probable viewsheds for IED attacks in Afghanistan. Very few papers utilize existing terrain-based algorithms and apply those geographic principles to IED emplacement. Consequently, this research adds to the body of literature supporting IED preventative policies and can act as a tool to understand contemporary insurgent tactics.

Despite the findings in this research, geographic intelligence (GEOINT) is only one piece of the greater military intelligence puzzle. A laundry list of different types of intelligence exist within the intelligence community to include human (HUMINT), signal (SIGINT), financial (FININT), and open-source (OSINT) to name just a few. The fog of battle begins to roll away when analysts combine many different intelligence types to gain a better picture of the situation. Of course it is very beneficial for a transportation unit to know the historical danger zones of IED activity along a route, but utilizing HUMINT may provide clues as to future IED emplacements, thus saving equipment and, more importantly, soldiers' lives.

4.2 Limitations

Both SRTM and ASTER are known to have significant issues when it comes to vegetation and ruggedness. Digital elevation models created from SRTM data are acknowledged to have widespread systematic error since the sensing platform measures elevation from the top of the vegetation canopy instead of ground level. In other words, a block of cells may appear to have increased elevation compared to the surrounding cells not because some sort of plateau exists, but because a stand of trees may be interfering with the sensor. ASTER, on the other hand, is becoming notorious for dealing poorly with areas of steep slope and rugged terrain.

As discussed earlier, the semivariograms for the 90-10 and 30-10 Colorado datasets show artifacts in SRTM in the direction of the flight path. This is evidence of directional bias inherent within SRTM data and, if so, is a serious flaw that must be accounted for in any application of the data. The semivariograms not only revealed potential flaws with the SRTM data, but showed significant evidence that ASTER GDEM performed better. It is fair to say that in the case study of this area in Colorado, an extremely rugged terrain where ASTER is said to have serious flaws, GDEM outperformed SRTM as demonstrated in Figures 8 and 9.

The single most limiting factor of this research is the absence of land cover in the analysis, which is explained by the limited availability of such data in this war torn and remote terrain. As any ground soldier knows, almost just as important as finding cover behind terrain is the ability to conceal a position using vegetation and modern forms of camouflage. As mentioned earlier, viewsheds answer the question: "What can see here?" But it is difficult for the viewshed tool, a computational algorithm, to account for phenomena that limit human perception or cognition that is only present at the level of the individual soldier. For example, something as simple as a soldier's uniform is intended to blend into the landscape. This makes it possible, in theory, for him to remain hidden when in plain view of the enemy—something for which the algorithm cannot account. Land cover and vegetation across a four kilometer scene, on the other hand, can be accounted for in the presence of an accurate, timely, and high resolution dataset.

It is possible that the parameters used in this research are not the optimum values for the specific IED explosions due to a lack of tactical information available to the author. However, the values for the variogram, offset heights, and search radii can be readily altered in the course of the methodology using the R code provided and altering the attribute information of the point location in ArcGIS. Examples of additional information that would benefit this study include exact locations of insurgents during the IED explosion and subsequent firefight, higher resolution and more accurate elevation data, and the number and type of friendly vehicles hit by the IED.

Lastly, no model will ever perfectly reflect the real world. The intrinsic limitations of the data storage structure (raster) quantify the real world into artificial cells and error is introduced from the outset. This type of application research attempts to address macro-level error in DEMs, yet is limited by micro-level relief that would also dictate the methodology. If known, it may be possible for an insurgent to hide behind a half meter mound that is virtually undetectable using satellite-based models. Since the micro relief of the landscape cannot be known this type of error is absorbed by researcher as a limitation (Hunter and Goodchild, 1993).

4.3 Future Research

One important extension to this research is the implication of a location-based sensitivity analysis (Cova & Goodchild, 2002), which could evaluate the significance of error modeling across different types of landscapes. The IED sites presented in this research fell along valleys, hillsides, and terraces and the resulting viewsheds from both the GDEM and the simulated DEMs were dictated by those different types of terrain. It would be extremely useful to analyze the impact of error propagation of sites along ridges to determine if the location of the input point for a viewshed has a significant influence on the total variation of the final simulated viewshed. For example, a set of simulated surfaces with a centroid straddling a ridge line may significantly vary according to the elevation errors immediately surrounding the point. That is, if the immediate cells surrounding a point along a ridgeline in one simulation are determined to be, in fact, higher in elevation than that point, the viewshed will be extremely restricted as opposed to another simulation that allows the viewshed to continue unrestrained across the landscape as if the point on the ridge line were indeed the highest in the scene.

In Fisher's early work with probable viewsheds (1992), he eventually concludes that an error model with spatial autocorrelation performed unpredictably. In fact, the models without spatial autocorrelation (completely random) performed the best in Monte Carlo simulation. This type of error model is unrealistic because spatial autocorrelated error is an intrinsic property of error in DEMs (Fisher, 1998). Based on the results of this methodology, future research should still be concerned with developing realistic and accurate error models before any product of the DEM is derived.

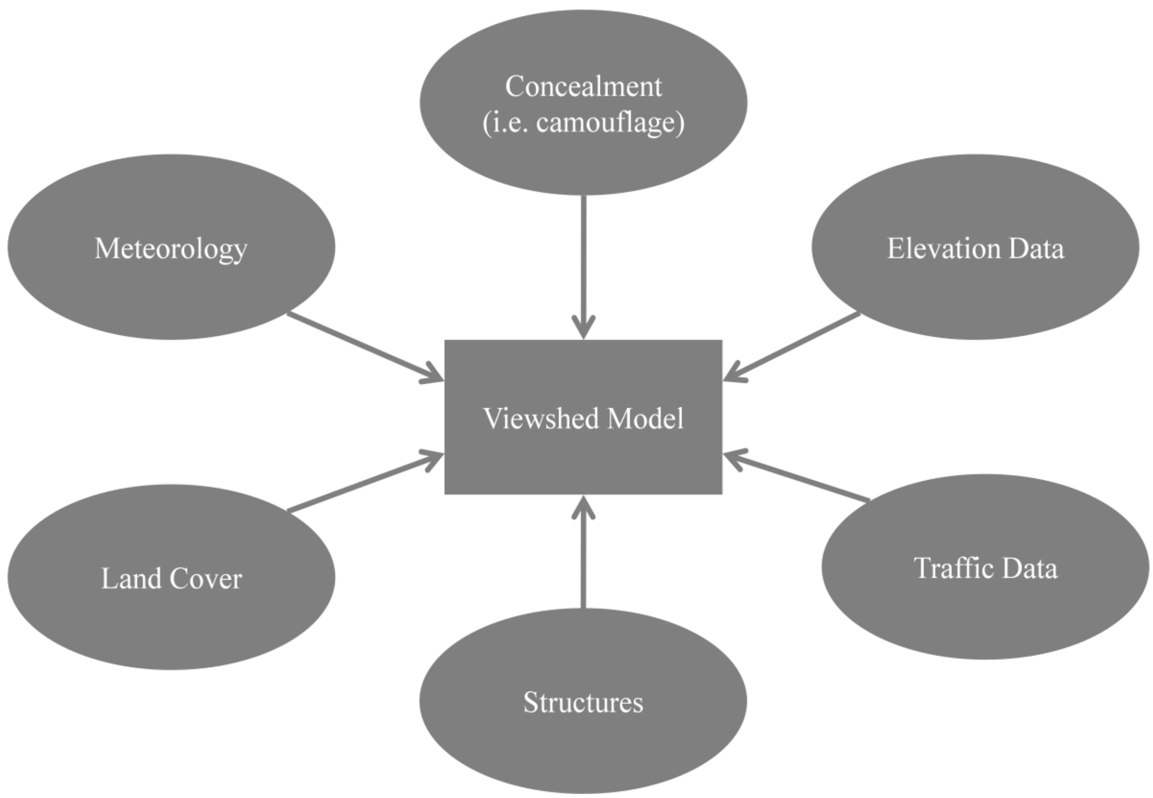

Figure 52: Ideal viewshed model

Lastly, the viewshed is an extremely complex tool that is heavily influenced by the quantity and quality of data input by the researcher. There are many sources of error that impact line-of-sight analyses of which this research only addresses one: elevation uncertainty. As shown in Figure 58, accounting for meteorological elements such as cloud cover can impact line-74 of-sight as well as addressing buildings in urban areas and especially land cover in rural areas. It is certainly possible that more advanced viewshed models can incorporate dynamic information such as real-time traffic data and other remote sensing techniques that can possibly account for camouflaged targets that are computationally within the viewshed, but cannot actually be seen by the observer.

The results of this research should be used as one piece of the puzzle that will contribute to creating more informed soldiers on the front lines in Iraq and Afghanistan. With every additional year of American involvement in Iraq and Afghanistan, revisions are made to military field manuals to cope with the ever changing tactics of modern combat. It is the responsibility of the U.S. military and academics alike to provide soldiers with contemporary counterinsurgency tools, dexterity to adapt to change, and a fundamental understanding of current insurgent operations and motivation. As stated by the Greek historian Thucydides, “A nation that makes a great distinction between its scholars and its warriors will have its laws made by cowards and its wars fought by fools."

APPENDIX A
R SCRIPT FOR MONTE CARLO SIMULATION

Appendix A
R Script for Monte Carlo Simulation

```
# farah_errsim.R
#
# This script is heavily borrowed from Shortridge (2010)

## Load the Afghanistan GDEM
library(gstat)
GDEM <- read.asciigrid("farah_smooth.txt", as.image = FALSE, plot.image = FALSE)

## 100 simulations of IED site based on variogram model from Colorado elevation data
g.dummy <- gstat(formula = z~1, locations = ~x+y, dummy = TRUE, beta = -4.522306,
        model = vgm(nugget=0,"Sph",psill=144.3151, range=433.3151), nmax=100)
z.sim <- predict(g.dummy, newdata = GDEM, nsim = 100) # takes a little bit of time.

## show first sim
sim.cols <- colorRampPalette(rev(c('sienna', 'bisque3', 'white', 'skyblue3', 'slateblue')))
spplot(z.sim['sim1'], col.regions=sim.cols,main='Farah Variogram Parameters: Sph, nug=0,
psill=144.3151, range=433.3151, beta=-4.522306')
dev.print(png, "sim1.png", height=1100, width=1100)

# Ensure cells are square
slot(slot(z.sim, "grid"), "cellsize") <-
  rep(mean(slot(slot(z.sim, "grid"), "cellsize")), 2)

# Write to text files

write.asciigrid(z.sim['sim1'], "farahsim1.txt", na.value=-9999)
write.asciigrid(z.sim['sim2'], "farahsim2.txt", na.value=-9999)
write.asciigrid(z.sim['sim3'], "farahsim3.txt", na.value=-9999)
…
write.asciigrid(z.sim['sim98'], "farahsim98.txt", na.value=-9999)
write.asciigrid(z.sim['sim99'], "farahsim99.txt", na.value=-9999)
write.asciigrid(z.sim['sim100'], "farahsim100.txt", na.value=-9999)

## End script
```

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