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Exploring Optimal GPS Signals for Autonomous Vehicles

CHRISTOPHER MILLER

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Abstract

GPS signal quality is crucial to the reliability of Autonomous Vehicles on city streets. One method for determining GPS signal quality on streets is through line-of-sight analysis tools in ArcMap. However, due to these tools limited efficiency for a single user, the capacity to produce high quality results is restricted. This paper explores the importance of GPS signals in Autonomous Vehicles and the restrictions of obtaining accurate line-of-sight results from satellites across the Washington, D.C. area.

Introduction

There are many hurdles associated with the reliability of Autonomous Vehicles (AVs). One primary issue related to their reliability is GPS signals. When lane detection is not a viable option in an AV because of inclement weather, poor road conditions or construction, GPS is used to locate and operate the vehicle according to its surroundings. However, within an urban environment, when this scenario can increasingly occur, GPS may too be unavailable due to large buildings obscuring city street visibility from satellite signals. This paper attempts to determine GPS signal availability across a city in order to find optimal AV driving locations and address areas of concern.

Literature Review

The overwhelming growth and reliance of the automobile has led to increased environmental problems across each city. According to Gossling (2017), “there are now an estimated 1.3 billion vehicles on the road, with expectations that these will increase to total 2 billion in 2030.” With this dramatic growth, there are negative attributes “in line with these developments: accidents, air pollution, congestion, noise and the transport sector’s contribution to climate change” (Gossling, 2017). Correspondingly, AVs are increasingly becoming one of the most talked about technological advances of our time in the hopes of minimizing these costs. However, without first understanding safety concerns and reliability of AVs, alleviations associated with making AVs available to the public will not be introduced.

It may come of little surprise that automation has already been made available to the public across a wide variety of vehicles. The Society of Automotive Engineers (SAE) defines Levels of Driving Automation “ranging from no driving automation (level 0) to full driving automation (level 5)” (SAE International, 2018a). While certain driver-less features are available to the public (specified in levels 1-3 in Figure 1) the SAE states further that an ADS, or Automated Driving System, is the “hardware and software that are collectively capable of performing the entire DDT […] used specifically to describe a level 3, 4, or 5 driving automotive system” (SAE International, 2018a). As such, for this project, I will only be focused on, and refer to, AVs specified by SAE’s definition of ADS.

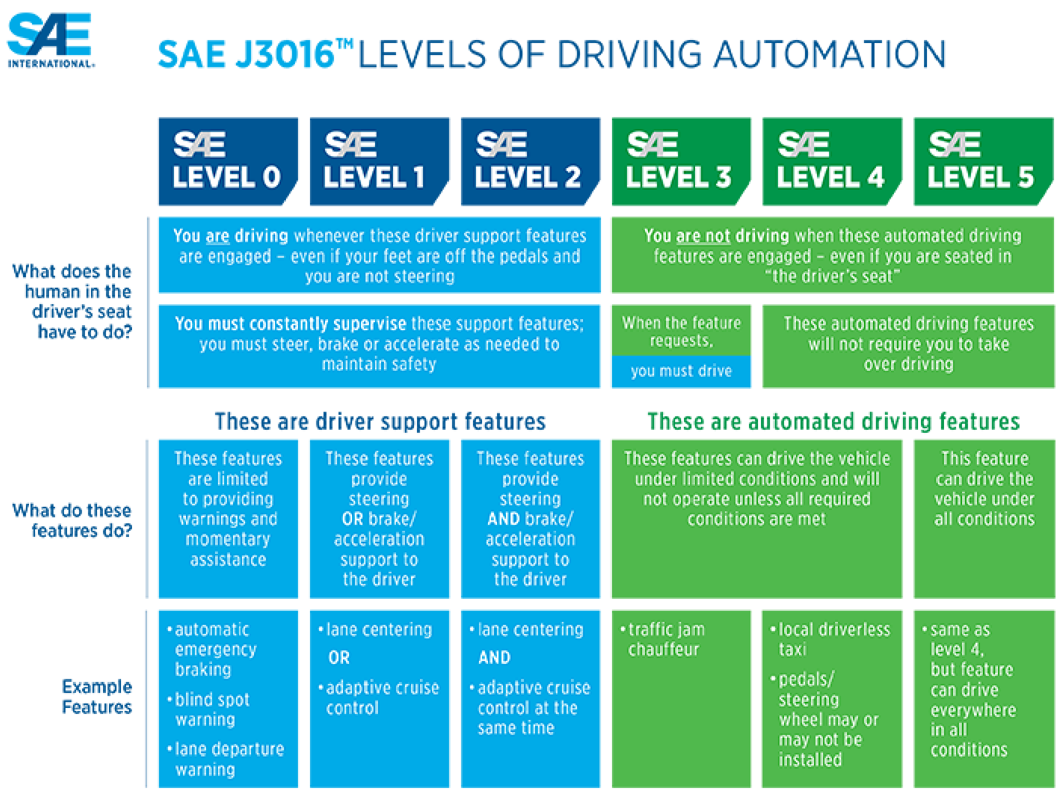

Figure 1. *SAE Levels of Driving Automation (SAE International, 2018b): Levels 0-3 have automation features currently available for the public in various models while levels 4-5 are not available to the public.*

There are many optimal requirements needed in order for AVs to operate safely on the road. However, for purposes related to this project, I will only focus on a few: weather, road and GPS signal conditions. One main component for AV technology is the lidar (light detection and ranging) system. They "provide high resolution and accurate 3D maps around the vehicle that allow obstacle detection and support safe navigation" (Filgueira, 2017). It is widely known within the GIS field that, for lidar, as weather conditions worsen, accuracy is diminished as light pulses are unable to reflect and communicate respective objects. In a similar fashion to AVs, the "detected lidar intensity and the sampled points attenuate [or worsen] with the increasing of rain intensity" (Filgueira, 2017). Therefore, as technology for lidar systems currently stands, AVs rely on optimal weather conditions to safely navigate among their surroundings.

There is emerging technology within AVs, including one use of the lidar system, called lane detection. An AV must rely on accurate data from their systems including, as Adali (2018) mentions, a "clean and reliable state information on the dynamic and static contents of the environment." Adali (2018) goes on to define lane detection as the "identification of lane lines [which] forms the foundation of this accurate representation". As discussed earlier, optimal weather conditions are needed for lidar systems to function properly. In addition to weather, optimal road conditions are also needed in order for AVs to detect and move within lane markings. Challenges then occur when there are "reduced contrast of the lanes (e.g., reflections, low light) or other disruptive factors such as snow or old lane markings" (Adali, 2018).

During inclement weather or substandard road conditions contributing to insufficient lane markings, AVs must then use GPS technology to navigate. As we have come to understand, GPS is only as reliable as the visibility of the sky to retrieve a satellite signal. For this reason, there are many criticisms of this usage within AVs including Adjrad (2019) who states, the "denser the environment, the more direct lines of sight to satellites are blocked by buildings." However, "for conventional GNSS[1] positions, the higher the sky visibility, the more direct LOS signal received and thus the better accuracy" (Adjrad, 2019). Therefore, if there was a way to know locations where direct lines of sight (LOS) could retrieve satellite signals, GPS could be more reliable within AVs.

AVs present many challenges for public safety which make it nearly impossible for their automobile manufacturing to commence: lidar systems fail in inclement weather, construction or undetectable lane markings hinder steering and driving in rural areas or near tall buildings causing AV navigation to fail completely due to lost GPS signals. Consequently, problems related to weather and road conditions for AVs do not have clear solutions. Lane markings are often not present on neighborhood streets and, often times, road maintenance, such as paving or underground utility work, could cause them to be buried or indistinguishable. Rain, snow or other precipitation can certainly be predicted. However, like road maintenance, even if this information is known, not allowing any AVs on the road during these events seems inconsiderate and unrealistic.

[1] GPS is a component of GNSS: "The U.S. Government continues to improve the GPS space and ground segments to increase performance and accuracy. With the development of the new global navigation satellite systems (GNSS) constellations, including U.S.'s GPS, Russia's GLONASS, and the coming European Union's GALILEO system and China's Beidou/COMPASS system" (Jin, 2014).

On the other hand, there are more clearly defined solutions to GPS signal failure. For AVs across rural areas, “it is well known that GPS signals get weak or corrupted in dense forests” (Luettel, 2012). As discussed earlier, within an urban environment, the major hurdles to AV GPS signals are tall buildings obscuring satellite LOS. As a result of the indeterminate difficulties with other AVs requirements, the direction to pursue GPS signal reliability emerges more distinctly. Therefore, the methodology proposed was to explore city streets within an urban city where GPS signals are obscured from tall buildings.

Proposed Methodology

The initial methodology proposed by the author set out to uncover areas within Washington, D.C. that have low to high GPS signal quality. This methodology focused on a line-of-sight (LOS) analysis including use of the Visibility tool within ArcMap and its associated data inputs: a surface raster, observer points and observer altitude. However, as revealed in later sections of this paper, this methodology was modified to accommodate significant barriers to ArcMap tools themselves.

Despite these methodological updates, the District of Columbia was still used as the subject city for GPS signals. It was selected due to its availability of elevation data (in particular a digital surface model produced from their lidar point cloud), the city's skeleton and infrastructure as well as its interest in AVs.

The framework of D.C. has many benefits to study when evaluating a potential introduction of AVs. It is surrounded by high occupancy vehicle (HOV) lanes which offer a well-maintained network of roads with little, to no, obstruction of buildings. HOV lanes are also separated from the majority of traffic conditions making these promising candidates for integrating AVs. Similar to the benefits HOV lanes provide AVs for intracity traffic, D.C. also has height restrictions on their buildings[2]. A height restriction could diminish AVs barrier of entry whereas a "typical" city infrastructure resides with taller buildings resulting in subsequent weak GPS signals. Finally, D.C. is taking steps forward to make this barrier of entry even more seamless. They recently "became a member of the Bloomberg Aspen Initiative on Cities and Autonomous Vehicles […] that have produced a set of principles and tools to plan for driverless technologies" (DMPED, 2019).

Unfortunately, even with these advantages across D.C., LOS for GPS signals could still be disrupted. One tool that was taken under consideration to analyze LOS for GPS satellites is the Satellite Viewsheds Tool. The Satellite Viewsheds tool, according to Germroth (2005) "predicts GPS satellite visibility while considering surface features in the receiver's environment that may influence its performance". It could be "used to predict performance for a receiver at any location on the earth's surface and for any time" (Germroth, 2005). However, after further research, it was determined that this project no longer exists. Therefore, the hope was to instead analyze objects LOS to their surroundings using the Visibility tool in ArcMap.

[2] In 1910, Congress amended a prior height restriction Act referred to as The Height Act. "The Height Act remains in effect today and includes the following restrictions: Mixed use or commercial areas: buildings may be as high as the width of the street plus 20 feet, but may not exceed 130 feet. Residential areas: heights are limited to 90 feet." (NCPC, 1998)

Proposed Methodology: Data Inputs

The Visibility tool in ArcMap requires that a user obtain three main components: a surface raster, observer features and observer height[3]. In order to accommodate the first input, a digital surface model, or DSM, was retrieved from Washington D.C.'s GIS portal, OpenData.gov.

The D.C. DSM retrieved for this analysis is a high quality, 1-meter resolution specification shown in Figure 2 below. This "accurate terrain elevation information is important in many applications of land surface modeling" including an urban setting with a sizeable map scale (Kim, 2019). Therefore, even though other resolutions of the DSM were not fully taken into account for this initial proposal, when analyzing LOS, using accurate elevation information was deemed a necessary component.

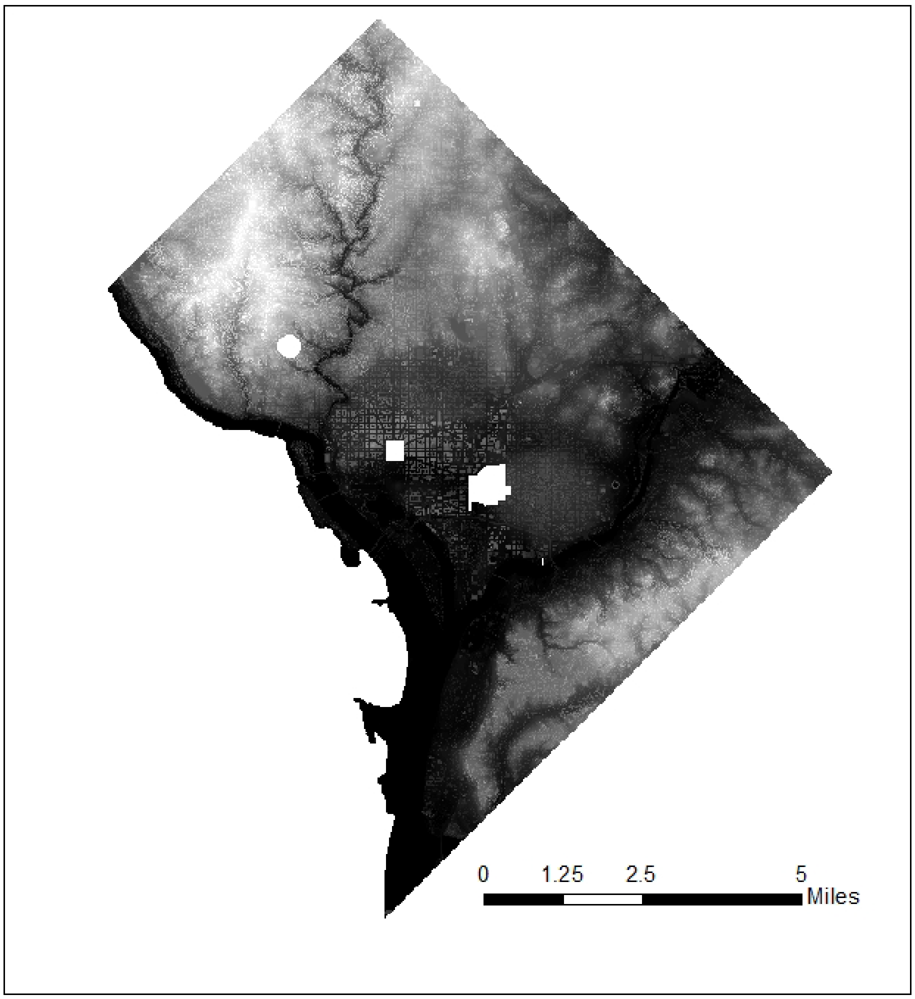

***Figure 2. Washington D.C. Digital Surface Model**: Retrieved from D.C.'s GIS data portal OpenData.gov, high elevations can be seen downtown (white) with the Potomac River running from the south to northwest.*

[3] Usually optional but, for the proposed analysis, it was a requirement.

The second input, observer features of satellite locations, required more acute investigation. This included the gathering and calculating of particular locations through orbital element data called ephemerides. Ephemerides data “perform the calculation of GPS satellite position in ECEF [or Earth-Centered, Earth-Fixed] coordinate system” (Monaghan, 2006). Therefore, given the identification of this “position on the Earth's surface by an Earth-Centered, Earth-Fixed XYZ coordinate […] we can identify the same point with a geodetic latitude, and longitude, and height” (Sickle, 2019).

Research revealed that “three sets of data are available to determine position and velocity vectors of the satellites in a terrestrial reference frame at any instant” including the Almanac as well as broadcast and precise ephemerides (El-naggar, 2012). Each of these data are described in more detail:

> *Almanac* – This data includes satellite properties from all operational satellites. It is easily accessible as .txt files on the U.S. Department of Homeland Security’s Navigation Center from 1997 until 2019[4]. There are clearly defined years, days and record text files of all 31 GPS satellites[5]. However, this data is more isolated and inaccurate than its counterparts as satellites are only recorded approximately every six days (El-naggar, 2012).
>
> *Broadcast and precise ephemerides* **–** In opposition to Almanac data, as the latter name suggests, this is more precise orbital parameter data to use given the addition of positional accuracy and reoccurrence. However, this data is more difficult to obtain and translate which impacts usability. For instance, all ephemerides data is available across dense folders as less apparent listings of .sp3.Z format files, a UNIX compressed ASCII[6].

Ultimately, the option to use one of these data was dependent on the ability to view and manipulate in a practical time frame as well as which is better suited to calculate the three parameters specified above (latitude, longitude and height). Fortunately, precise ephemerides data were obtained and extracted from each file which contains geocentric coordinates for each satellite[7]. There were also three versions of precise ephemerides to consider: IGS, IGU and IGR. While all were considered, IGR was chosen due to its accuracy as “calculated results show that the two ephemerides, igs and igr, are equivalent to each other in orbit determination accuracy (about 9.5 cm), while igu is slightly less accurate, at about 10.5 cm” (Peng, D.J., 2009).

With the type and version known, the author chose to query 32 satellite locations[8] across three times and three days (or 288 prospective coordinates). While days were chosen at random, the following times were chosen to accommodate both rush hour periods and lunch: 9am, 12pm and 5pm. The

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[4] Almanacs are available in SEM and YUCA formats. YUCA is more user friendly while SEM is to be used more for software purposes (Navigation Center, 2019).
[5] “As of January 9, 2021, there were a total of 31 operational satellites in the GPS constellation, not including the decommissioned, on-orbit spares.” (GPS.gov, 2021).
[6] GPS Satellite Ephemerides (Orbits) data are available through the International GNSS Service through their ftp: ftp://cddis.gsfc.nasa.gov/gnss/products/ (IGS, 2019).
[7] In accordance with SP3 format file from the National Geodetic Survey (National Geodetic Survey, 2000).
[8] For many of the dates, 32 available GPS satellite coordinates were retrieved even though only 31 are operational (as specified early in the paper).

collected ephemerides data was then converted to latitude, longitude and altitude using the NGS Coordinate Conversion and Transformation Tool, or NCAT[9].

The goal for the final component of the Visibility tool, observer height, was to use the average altitude across all satellites for the specific date and time. As a result, because 9 options were selected for 32 satellite locations, output from the Visibility tool would supply 9 raster datasets across 285 observer points[10]. However, before this occurred, the expectation was to perform a feasibility test on one coordinate closest to the DSM. The observer height would then be set to 20,200,200 meters as "GPS satellites fly in medium Earth orbit (MEO) at an altitude of approximately 20,200 km" (GPS.gov, 2021). Unfortunately, after testing this single GPS satellite observer point (a single date/time with a height of 20,200,200 meters) on D.C.'s DSM, the Visibility tool failed to work properly.

[9] NOAA's National Geodetic Survey has a conversion tool for XYZ geocentric coordinates into latitude and longitude: https://www.ngs.noaa.gov/NCAT/ (NGS, 2019a).

[10] 288 points were anticipated but some satellites were unavailable. This could be as a result of only 31 of the 32 satellites being operational. In addition, satellite coordinates could have been outside the bounds of the NCAT tool as it "does not support transformation which are outside the boundaries of the supported areas (generally, CONUS, Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands, American Samoa, and Guam and Northern Mariana Islands)" (NGS, 2019b).

Proposed Methodology: Obstacles with Visibility Tool

When attempting to run line-of-sight analysis (LOS) on satellite coordinates to the Washington, D.C. DSM using the Visibility tool, there were a few problems: no visible areas found, errors causing ArcMap to shut down as well as a continuous run with no output. This paper describes the problems in more detail below with attempts to resolve.

Before completing iterations of the Visibility tool, a feasibility test was first run on the closest GPS satellite point (across 285 coordinates for 9 date and time intervals) to the D.C. DSM. At approximately 259 miles away, this observer point (as seen in Figure 3) was set to 20,200,000 meters above the surface. However, after running the tool using these parameters, an error occurred and produced a raster output which showed no visible areas across the D.C. DSM. This process was completed several times with additional problems including ArcMap failing and closing the application or ran continuously where the user had to stop after continuous hours of processing time.

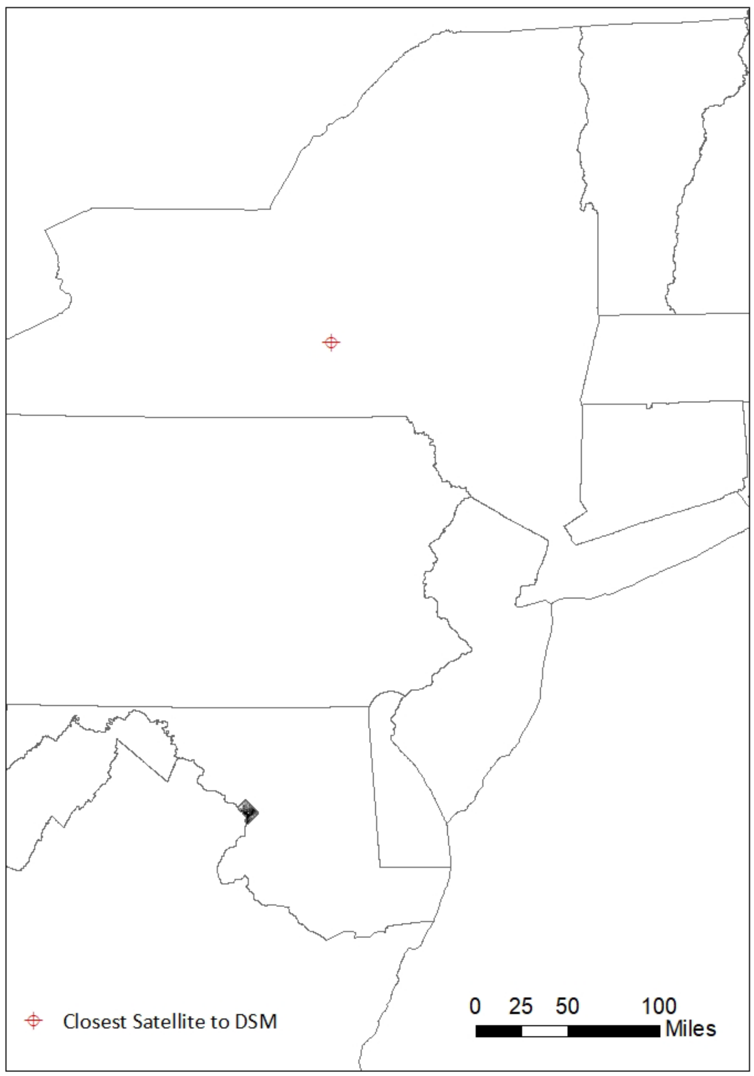


Figure 3. Satellite Coordinate: *The closest satellite across the 258 possible coordinates is approximately 259 miles away from D.C. located in central New York.*

The initial belief was that the Visibility tool could not be performed from the observer point to the DSM because there were large distances of no height values. In order to mitigate this issue, a dummy raster of small elevation heights (.01 meters) was created from this GPS coordinate to the D.C. DSM. A mosaic was then created by merging the DSM and the dummy raster of very small elevation heights for a GPS coordinate (shown in Figure 4). Unfortunately, when running the Visibility tool using the mosaic DSM and the input and GPS coordinates as observer points, it was having similar long processing times before it required termination.

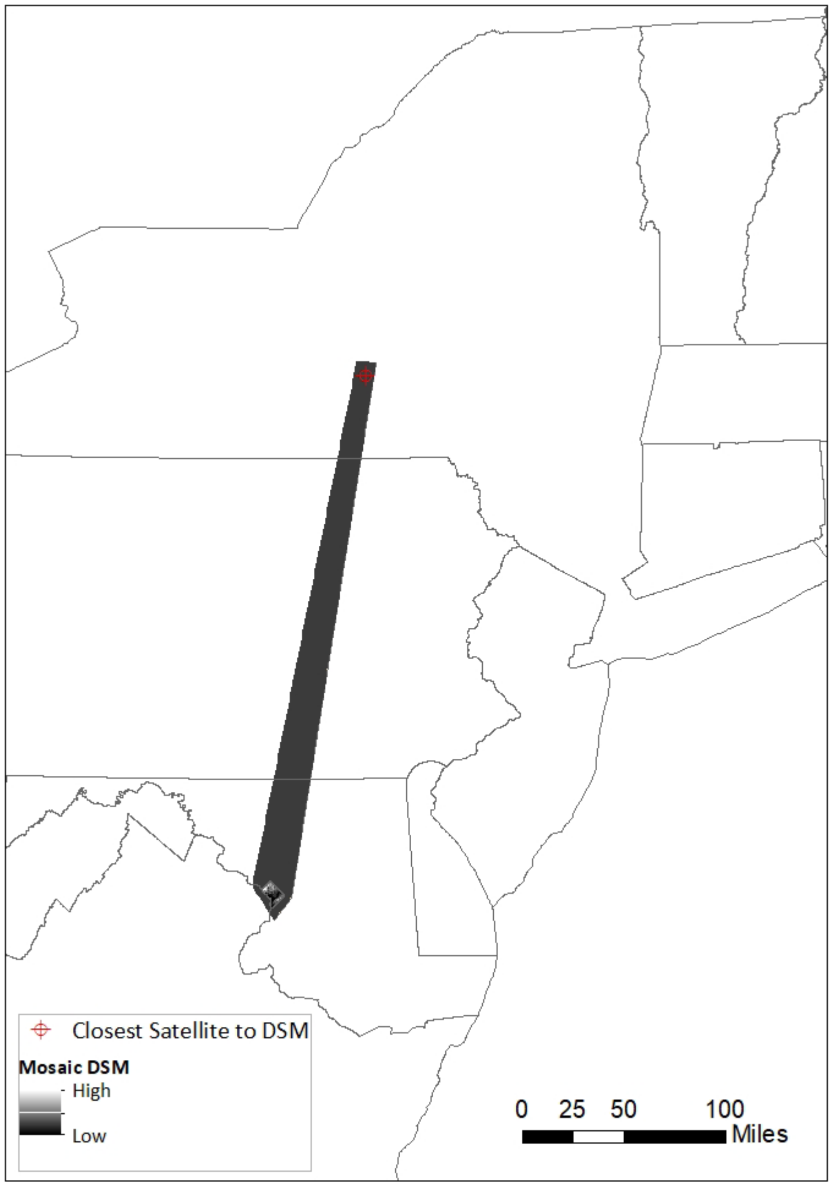


Figure 4. Mosaic DSM: *While troubleshooting the Visibility tool in ArcMap, a mosaic of the DSM and a polygon feature class was created to seemingly display a line-of-sight with small dummy elevation values.*

The long processing time for the tool was, at least to be determined at the time, caused by large cell sizes of the mosaic. Therefore, one solution to reduce this time was to reduce the default raster cell size of 1 to larger cell sizes of 50, 100 and 200. Converting the low cell size of the raster seemingly appeared to have a similar unsuccessful result: all areas not visible across the D.C. DSM. However, even if there was a successful output, the extent by which to produce 285 times (a mosaic for each satellite coordinate across the world) would have been particularly cumbersome to replicate.

One interpretation of the Visibility tool at this point of the analysis was that the observer height parameter could not show granularity beyond a certain distance away from the Earth's surface (or, even still, that any point feature class would produce an output using this DSM). In order to verify this hypothesis, a point within the DSM was created and set to increasingly higher observer heights.

After approximately 100,000 meters, as seen in Figure 5, nearly all areas in D.C. became visible. Therefore, it was inconclusive to determine if observer height at 20,200,000 meters would be able to show any line-of-sight across the DSM. As a final test, the Visibility tool was rerun in ArcPro for multiple iterations with a similar result at the beginning of the analytical work: large run times where the user had to terminate the application.

The goal of this paper was to produce all satellite coordinates across at least three dates and three times (displayed in Figure 6). Given the extent of processing time to calculate LOS on even a single GPS coordinate, it proved unattainable to complete any useful results using the Visibility tool in ArcMap within a reasonable timeline.

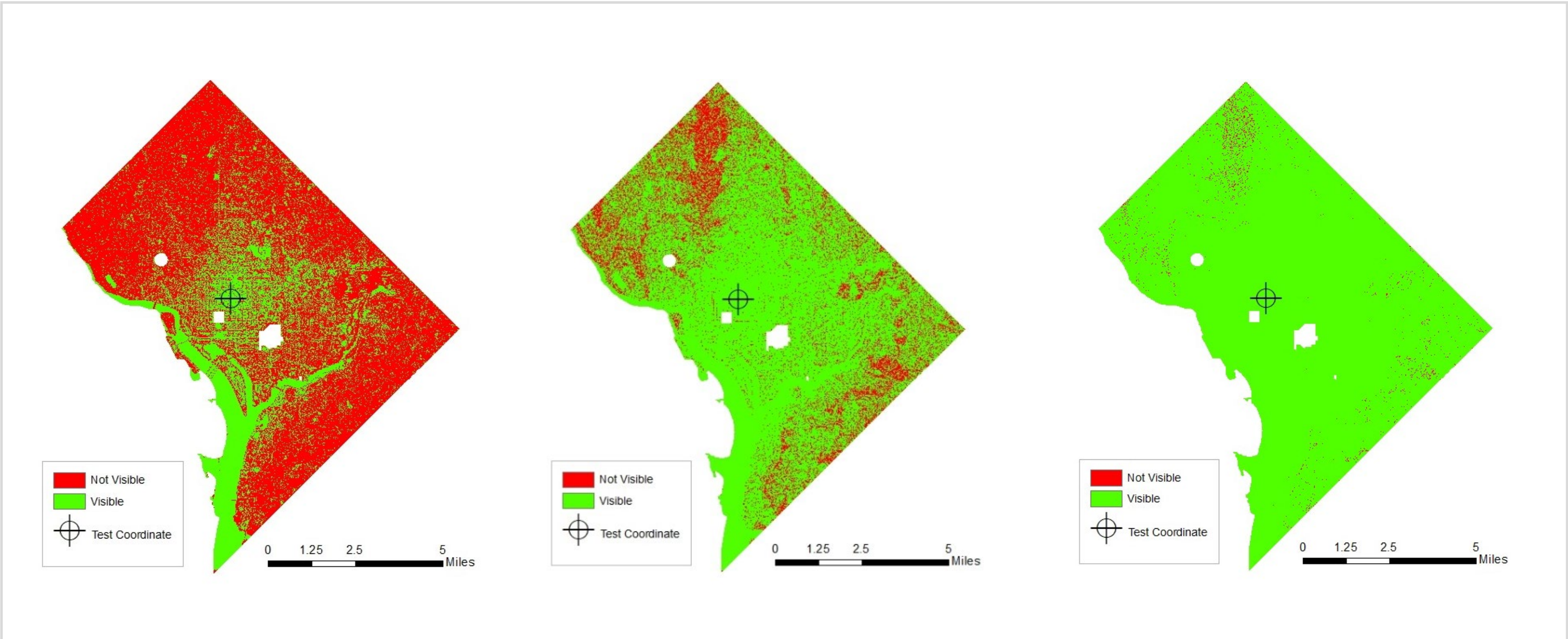
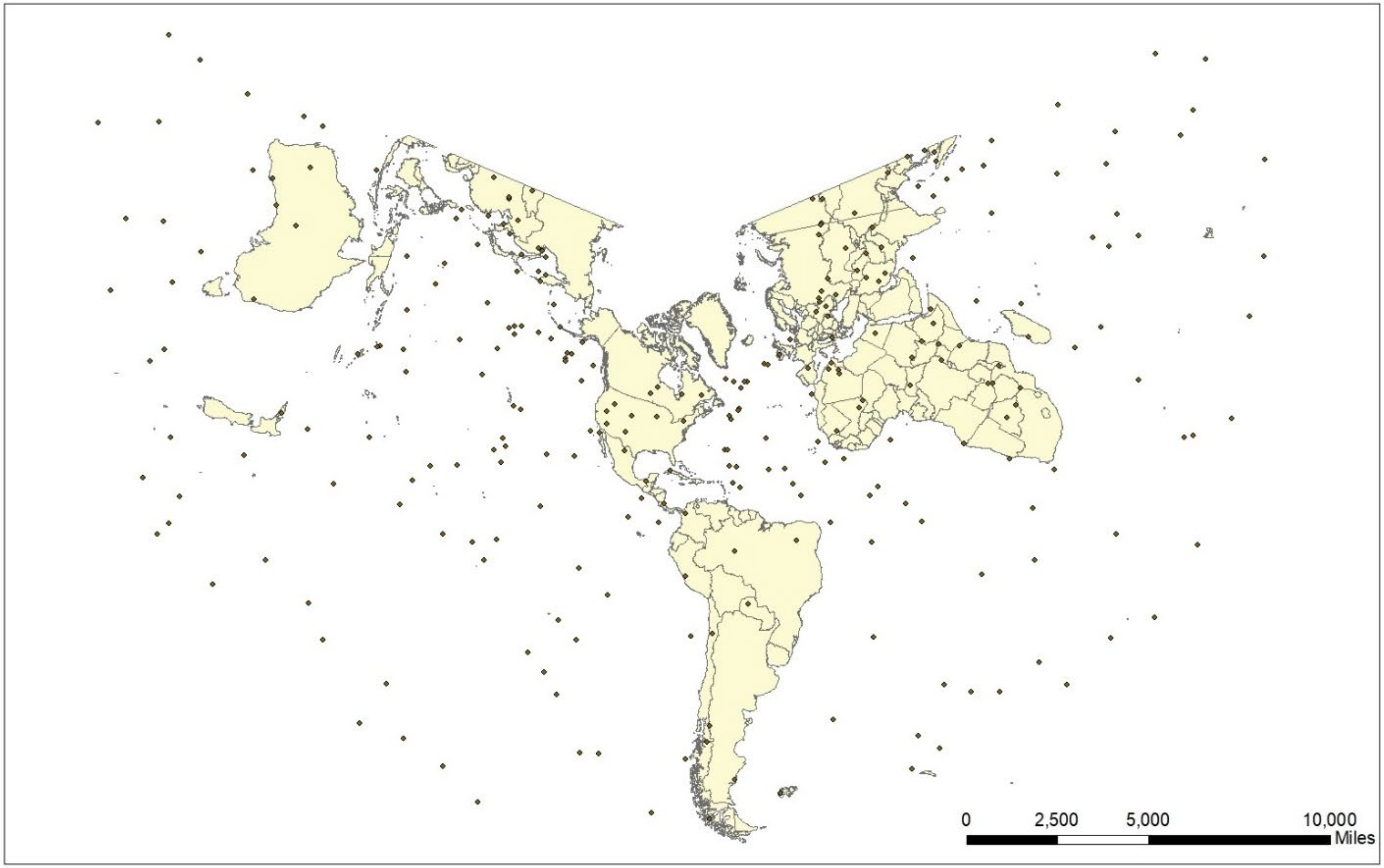


Figure 5. Visibility Test: *An observer point was given an increasingly larger value. From left to right, at 1,000 meters above the earth's surface, the first image shows the majority of D.C. (primarily away from city center of the test observer point) was not visible. The second image (in the middle), at 10,000 meters above the earth's surface, shows most of the DSM is visible. The third image (far right), at 100,000 meters above the earth's surface shows almost the entire DSM as visible. Even at a 1-meter DSM, the line-of-sight analysis may be limited once a height has reached at least 100,000 meters. The median height needed for the analysis of a satellite is 20,200,000 meters.*


0
2,500
5,000
10,000
Miles

Results: New Methodology

The proposal for this paper did not reach a conclusion. GPS coordinates were unable to be used as inputs to the Visibility tool for a line-of-sight analysis across a DSM. However, the remainder of this paper highlights one alternative considered to investigate viable GPS quality across city streets: solar radiation analysis.

One alternative to produce line-of-sight analysis across D.C.'s DSM is the Area Solar Radiation analysis tool in ArcMap. While not exactly simulating GPS satellite behavior, the Area Solar Radiation analysis tool enables a user "to map and analyze the effects of the sun over a geographic area for specific time periods" (ESRI, 2016a). The tool uses three primary input parameters: raster elevation dataset, sky size and a time configuration. Whereby the raster elevation data could be the D.C. DSM, time configuration sets the time/date of the sun's positioning and the sky size is "the resolution of the viewshed, sky map, and sun map rasters that are used in the radiation calculations" (ESRI, 2016a).

While replacing solar radiation as a restrained line-of-sight analysis, "solar modeling in GIS is a very intensive geoprocessing (computational time) process" which, on a single simulation "can range from a few hours up to multiple days" (Chow, 2014). This intensive process is caused primarily by the resolution of the raster elevation dataset and the sky size. The greater the resolution of these inputs, "the more accurate and visually appealing the results will be" but "will cause simulation time to increase exponentially" (Chow, 2014). Therefore, even though radiation analysis could prove to be an alternative, unless resolution of the DSM would be reduced, it may be just as (if not more) inefficient as the line-of-sight analysis across GPS coordinates where results were unsuccessful.

By this stage of this research, unlike the line-of-sight analysis, reduction in resolution of the 1-meter DSM was not considered. However, given this finding, it was then made apparent that the priority to sacrifice resolution of the sky size and the DSM should occur in order for the analysis to complete on time.

Results: Solar Radiation Analysis

A variety of sky size values and time configuration parameters were tested in order to produce timely results for the solar radiation analysis. These were tested across three levels of resolution for the DSM (1-meter, 10-meter and 30-meter), three sky sizes (200, 2800 and 10,000) and two time configurations (2 days and 3 special days[11]).

As shown in Table 1 below, the 1-meter DSM, similar to prior line-of-sight analysis, was unable to produce results. Or, rather, a minimum of 16 hours of processing time occurred before user termination.

Table 1. Area Solar Radiation Inputs and Results

DSM Resolution	Sky Size (Resolution)	Time configuration	Result	Output Available
1-meter	200	2 days: 1/5/21 until 1/6/21	>48 hours	N
1-meter	2,800	3 days	>24 hours	N
1-meter	10,000	3 days	>16 hours	N
10-meter	2,800	3 days	12.5 hours	Y
30-meter	2,800	3 days	1.5 hours	Y

As a result of these tests under the high resolution, 1-meter DSM, and research indicating that processing time is problematic when using high-resolution elevation data, the decision was made to reduce the resolution of the DSM to 10 and 30[12] meters. The decision was also made to use the 3 special days to reduce processing time while diversifying sun effects as well as keeping sky size as 2,800. Sky size was set to 2800 because ESRI (2016b) recommends for a small number of days being analyzed under the time configuration, the sky size be at least 2,800 or more.

Given the modified inputs under new 10-meter and 30-meter resolution DSMs, the Area Solar Radiation tool was finally able to produce viable outputs (shown in Figures 7 and 8). Therefore, under the limitations of using ArcMap tools under a single Desktop user, in order to analyze viable road options with high quality GPS signals, the recommendation is to use a 10-meter DSM using solar radiation analysis.

[11] Special days refers to an option in the Area Solar Radiation tool specifying the summer solstice, equinox and winter solstice.
[12] This was produced prior to the 10-meter in order to verify that the Area Solar Radiation worked properly.

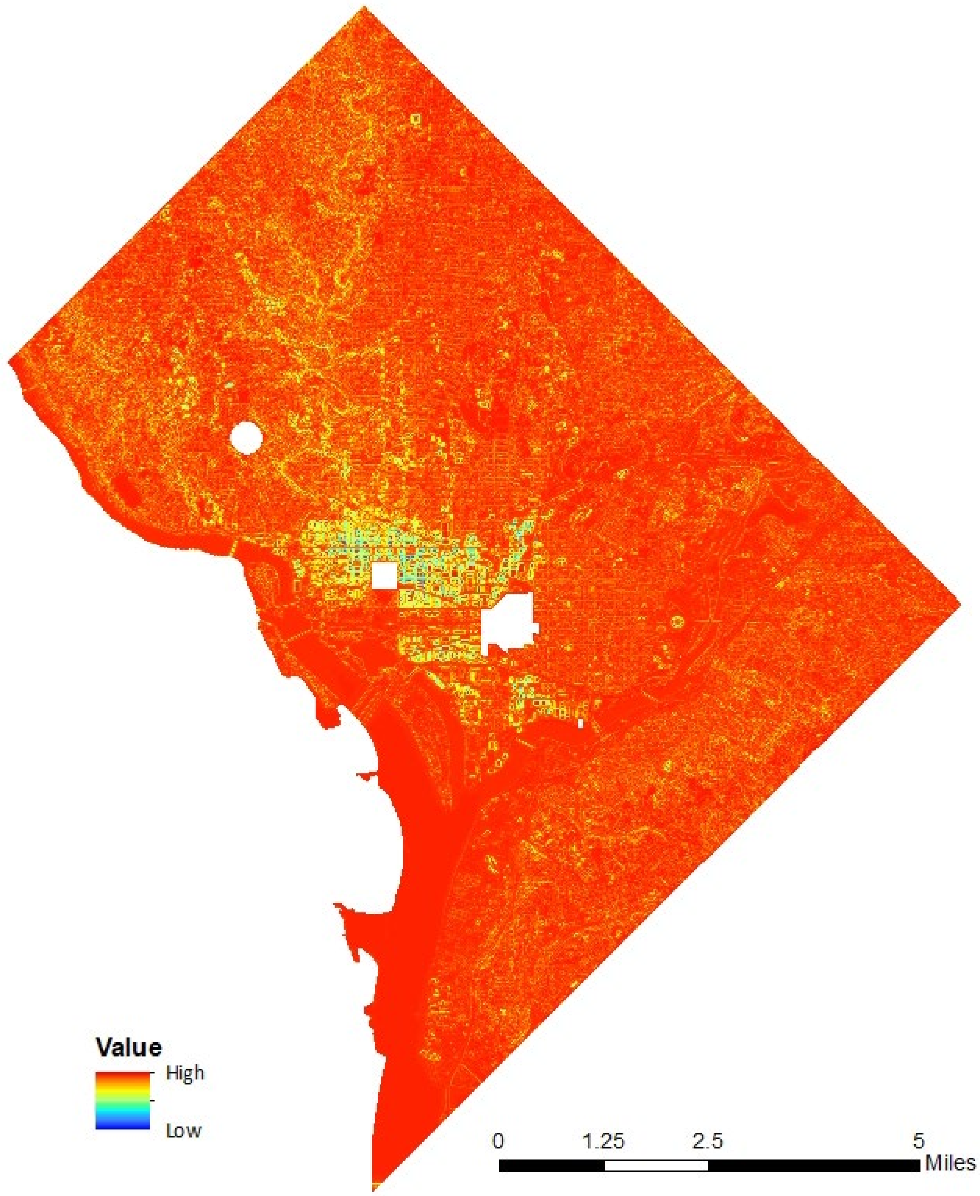


Figure 7. Solar Radiation Analysis – 10 Meter DSM: *Adjusting the resolution from a 1-meter DSM to 10-meter DSM created the only viable option for analyzing line-of-sight in a reasonable time frame. The 10-meters has more definition than the 30-meter as shown by the greater quantity of medium levels of radiation (in yellow) and a more defined, high radiation of the river (shown in dark red in the south).*

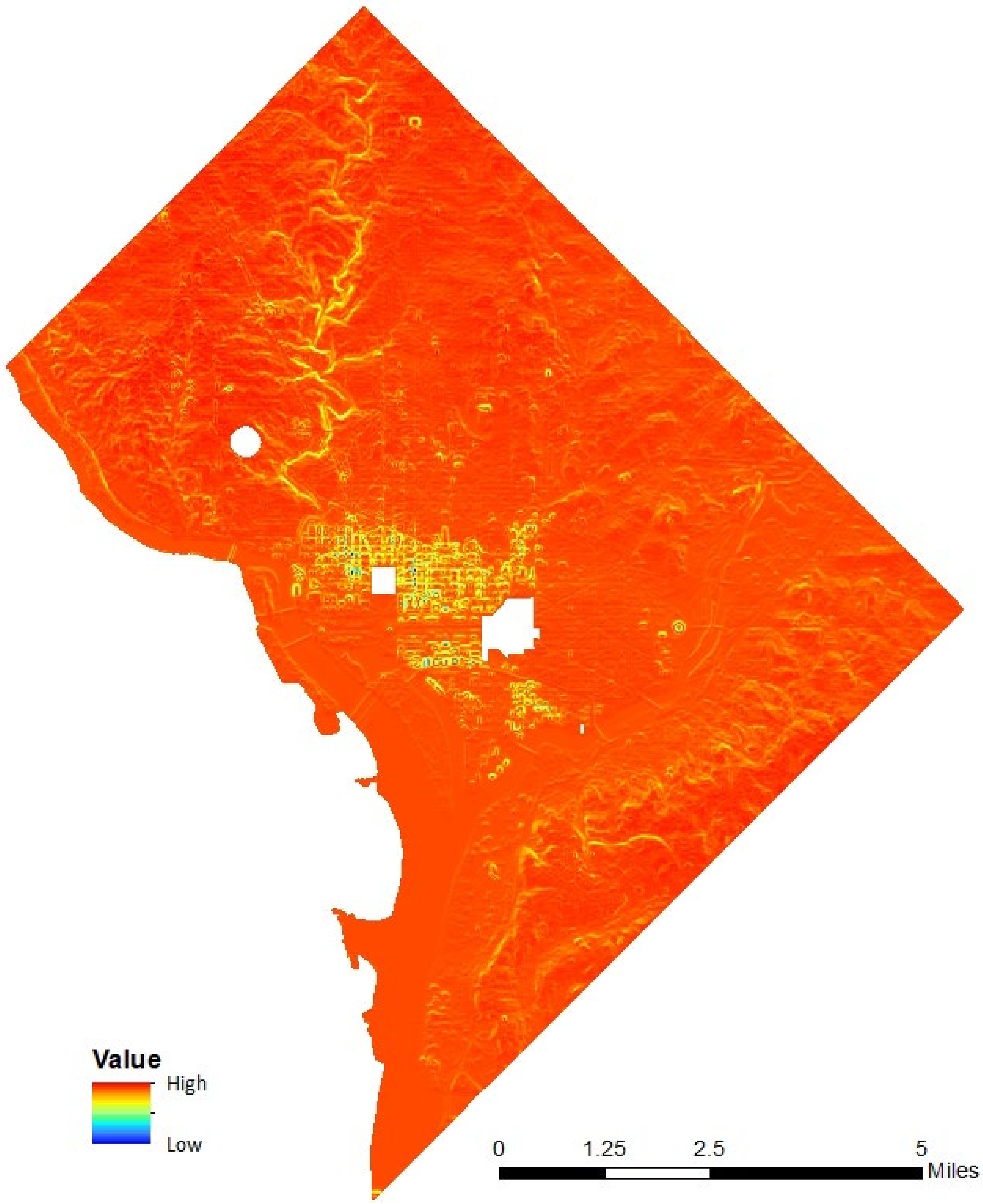


Figure 8. Solar Radiation Analysis – 30-meter DSM: *While still a valuable output, the 30-meter DSM has less detail in radiation across the DSM when compared to the 10-meter. If time is a sensitive resource or a user is reproducing across a larger area (or multiple cities) the 30-meter DSM could be a better option.*

Results: Viable Roads

Given the solitary, feasible option to perform solar analysis on the remaining 10-meter DSM, one could assume this as a suitable alternative for producing viable road options for GPS signal quality. Notwithstanding line-of-sight analysis, the classification of this analysis is translated from high and low solar radiation to high and low visibility across the D.C. DSM (shown in Figure 9).

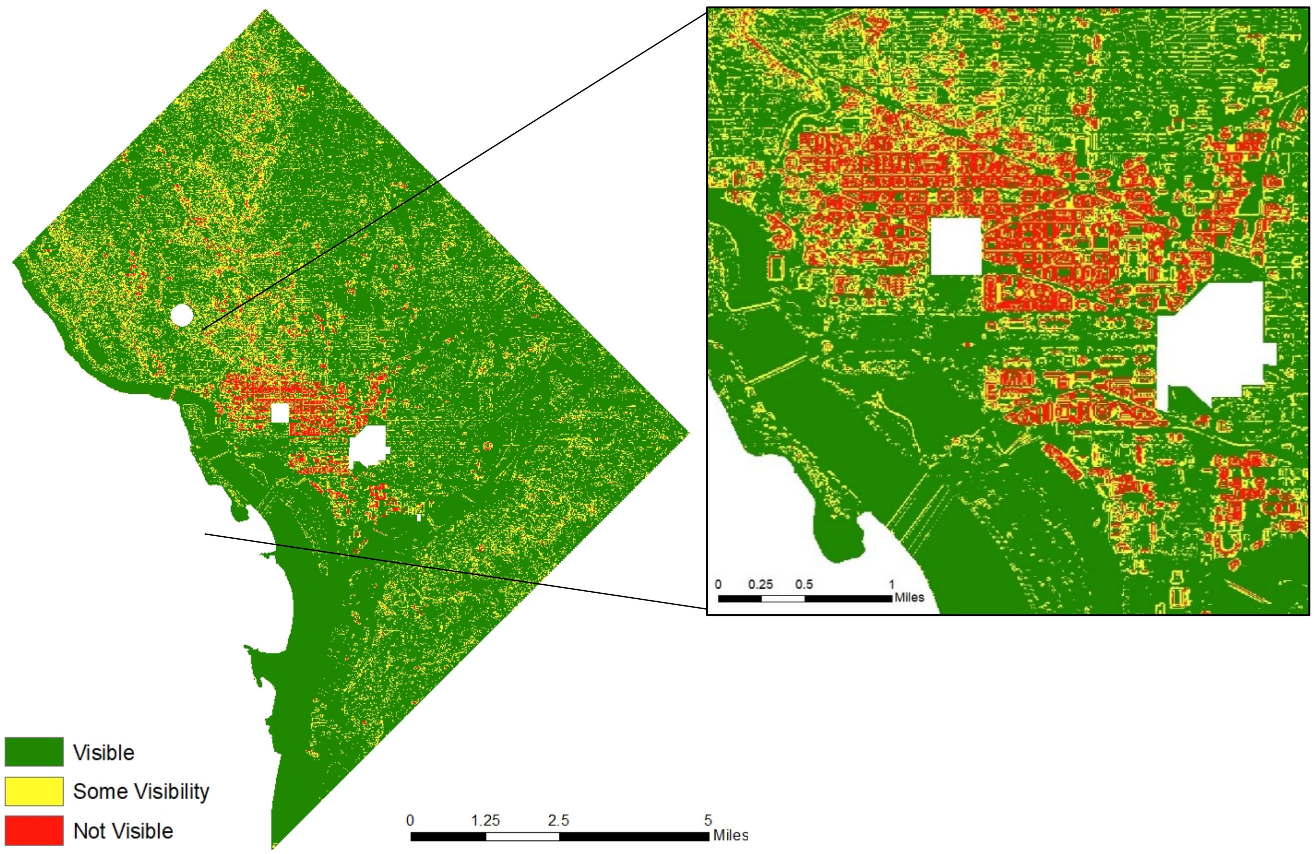


Figure 9. Visible Areas Across D.C*: High concentrations of not visible areas are in the center of the city. However, most of the DSM is visible according to the solar radiation analysis.*

Figure 9 seemingly displays most of viewing area as visible. However, this is not the case in the center of the map where more densely crowded buildings are concentrated in the downtown area and, as one would expect, restricts visibility. When limiting this analysis only to the visible streets of D.C.[13] (shown in figure 10), it appears that, even despite the city center's restricted visibility, most of the streets are viable, high visibility options or, in this case, high GPS quality.

[13] City streets here refers to the minimum lane width of "2.7 meters for local roads" applied across two lanes (Federal Highway Administration, 2007). Therefore, a buffer was created for the outline of all D.C. streets of 5.4 meters to represent this minimum road width.

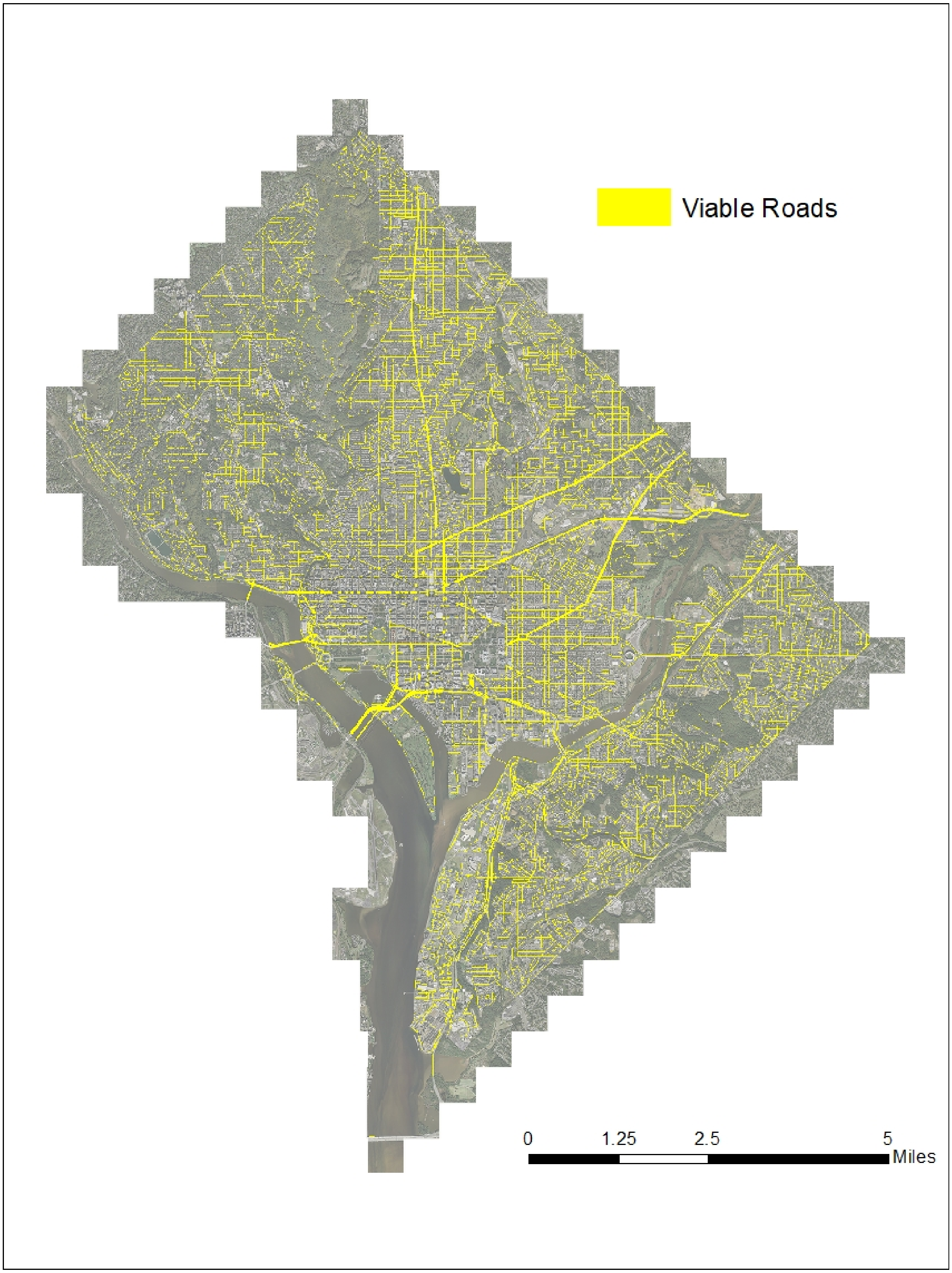


Figure 10. Viable Roads to use with High GPS Quality*: The viable roads (in yellow) are where there is a high solar radiation indicating a decent line-of-sight to a GPS satellite. These roads span most of the DSM.*

This analysis is proved further by observing the number of raster cells across the DSM, all roads and major roads. As Table 2 displays, approximately 79% of the DSM is visible. Even still, the percentage of visibility increases to 81% when observing all roads and 84% for major roads.

Table 2. Visibility Across Raster Cells[14]

	Total DSM	**all roads**	**major roads**
not visible	3%	2%	3%
some visibility	18%	17%	13%
visible	79%	81%	84%

As explained in the literature review, HOV lanes connecting to major roads in D.C. were a motivating factor when choosing the study of interest. According to the solar radiation analysis, the majority of D.C. streets are visible. One hope, as a result of this analysis, was to determine further viability of major roads in D.C. that connect to these HOV lanes. Figure 11 highlights that, while 84% of major roads are visible, there are some connectivity issues of visibility across the roadways. In particular, within the center of the city, major roads could lose GPS signal quality.

[14] Raster cell sizes for the DSM are 10 x 10 meter squares. Road feature classes were converted to a raster surface with this same cell size and totaled by visibility to create these percentages.

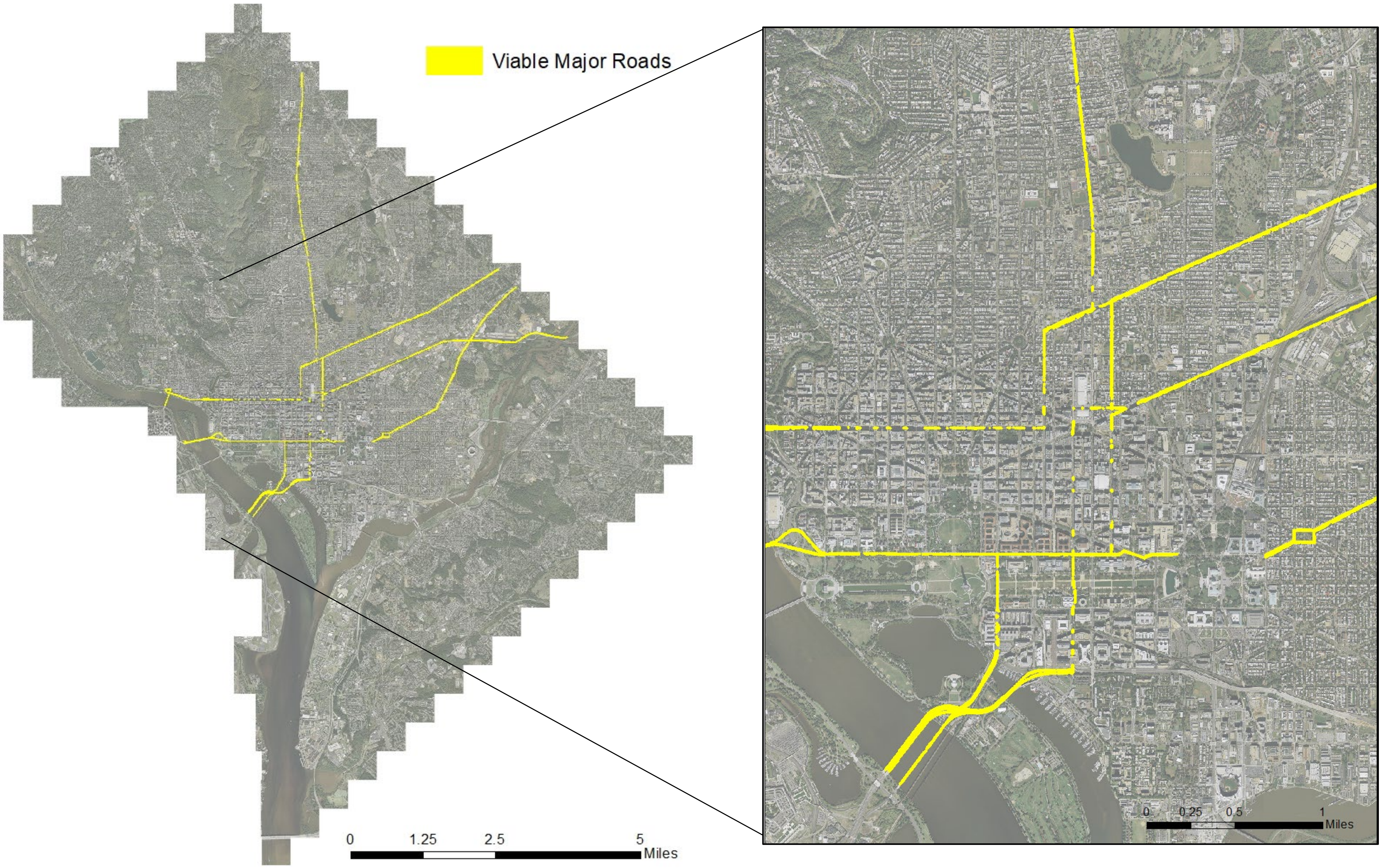


Figure 11. Viable Major Roads to use with High GPS Quality: *Viable major roads (in yellow) are those designated by the Census Bureau as a "U.S." route type and have a high solar radiation (U.S. Census Bureau, 2019). There are gaps major roadway connectivity especially in the city center. These roadways include the intersection of the U.S. Capitol Building and U.S. Highway 1 (alternative route) as well as U.S. Highways 1, 29 and 50.*

Reflections and Conclusion

Visibility across Washington D.C. can be determined using solar radiation analysis. A conclusion from this analysis is that D.C. is a viable city to incorporate Autonomous Vehicles because a large portion of city streets are visible and, moreover, have a high GPS signal quality. However, beyond the obstacles already explained when performing this analysis, one must understand the limitations and opportunities if replicated analysis across other cities.

Seemingly, the height restriction for D.C. was an opportunity for this study as it could increase visibility and GPS signal quality. After performing this analysis, it appears this could have been a contributing factor. Therefore, if this analysis were to be replicated across other cities without height restrictions, this would certainly become a significant limitation.

A limiting factor for the solar radiation analysis alternative to line-of-sight was that it could not applied to objects out of view from urban canopies such as overpasses, tunnels or other street obstructions. GPS signal enhancers were also not taken into account. One could, then, make additional assumptions and conclude that further streets of D.C. are more or less visible. Furthermore, this information could also be used for other cities whereby a GPS signal enhancer is used in lieu of an obstruction to a GPS signal.

Beyond these limitations and opportunities, one outcome from this investigation upholds that GPS signal quality is important to the functionality of Autonomous Vehicles on city streets. Line-of-sight analysis in ArcMap is one way to determine this signal quality. However, due to ArcMap's limited efficiency for a single user, the capacity to produce high quality results is restricted. One alternative to line-of-sight is using solar radiation analysis. Despite further inefficiencies with solar radiation analysis requiring a reduction in input resolutions, it was found to be the primary avenue to analyze viable road options within D.C.

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