

Line of Sight Analyst: ArcGIS Python Toolbox for visibility analyses

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Abstract: *Visibility analyses are essential analyses in both landscape and urban planning. Currently, available tools do not provide means to answer many complex questions related to the visibility. These complex questions are solved by so-called extended viewsheds or visibility indices. This article describes the Line of Sight Analyst toolbox for ArcGIS (version 10.x), which is focused on the creation and analyses of line-of-sight. The toolbox provides tools for a user to construct and analyse lines-of-sight, through calculation of extended viewsheds, and extract locations of horizons from line-of-sight. Most of the visibility indices that are calculated by this toolbox cannot be calculated in any currently available geographical information system.*

Keywords: *visibility, extended viewshed, toolbox, ArcGIS*

Introduction

One of the classic utilizations of visibility analysis, which is also commonly referred to as viewshed (Rød and Meer 2009), is in visual impact analysis of planned structure (Turnbull and Gourlay 1987). The topic is especially important when high-rise buildings, with potential to be visible from large areas, within cities are considered (Rød and Meer 2009, Czyńska and Rubinowicz 2017). However, the use of so-called binary viewshed in these analyses might be problematic as described by Fisher (1996a). In most situations, some ancillary property, derived from Line-of-Sight (LoS), would provide a better answer on a question related to visibility (Fisher 1996a).

Standard viewshed tool implemented in commonly available GIS can only answer the question "What areas are visible from point X?" and possibly "From which areas is the point X visible?", but that only applies if the parameters of analysis are set correctly (Caha 2017). For complex assessment of visibility other questions, such as "How significant is the target above a horizon?" or "How high part of the target is visible above a horizon?" are important. Such questions cannot be answered by classic viewshed analysis (Fisher 1996a), a more comprehensive visibility assessment can be performed by extended viewsheds (Fisher 1996a) also called visibility indices (Caha and Rášová 2015). Some of these extended viewsheds are implemented in Advanced viewshed analysis plugin for QGIS (Cuckovic 2016).

In this paper, the extension (toolbox) for ArcGIS focused on determination of extended viewsheds is described. The toolbox works on point to point bases, unlike viewshed algorithm which works on point to area bases. The main aim of the Line of Sight Analyst toolbox is to provide simple tools for determination of extended viewsheds, for the most commonly used GIS, even though that the toolbox works functionally different from viewshed tool.

Theoretical background

Line-of-Sight is a ray originating at observation point ongoing through target point and further beyond the target. To assess visibility of target point only the part of LoS between the observation point and the target point is necessary, however, for complex assessment of visibility and distinctiveness of the target point even the part of LoS located beyond target point

is essential. For the purpose of this article, we will distinguish between LoS which is between the observation and target points and global LoS which continues beyond target point and is usually limited by the extent of the surface on which the visibility is determined.

Visibility analysis is always performed on point to point bases (observer to target). In case of tools like viewshed (Esri 2017, Haverkort et al. 2009) the nature of the analysis is slightly shifted by analysing more than one pair of points at the time. Viewshed generally works in such way that there is one observing points and many target points (cells of the raster).

LoS consists of observation point V , target point P_t and other points P_i . Observation point V has elevation Ve that consists of surface elevation at V and vertical offset of the observer from the surface. Points on LoS $P_i, i \in 1, \dots, n$ have elevation $P_i e$ that is obtained from surface at the location of P_i and distance from V denoted as $P_i d$. P_t is a particular type of P_i which has target offset added to the surface elevation at the given location. For LoS P_t is equal to P_n with elevation plus the offset. In case of global LoS the P_t is one of P_i again with vertical offset added to the surface's elevation. Example of LoS is in Fig. 1.

For visibility earth's curvature and atmospheric refraction are essential factors especially if the LoS is longer than 3 km. In such cases we replace $P_i e$ value with:

$$P_i e_k = P_i e - \frac{P_i d^2}{d} + r \frac{P_i d^2}{d},$$

where $P_i e_k$ is corrected elevation of the point P_i , d is the diameter of the Earth and r is the refractivity coefficient (Esri 2017). According to Esri (2017) the value of d is 12 740 000 meters and the default value for r is 0.13 for visibility analysis implemented in ArcGIS.

For the determination of visibility it is crucial to know viewing angle of each point on LoS:

$$P_i \alpha = \frac{180}{\pi} \arctan\left(\frac{P_i e - Ve}{P_i d}\right).$$

The target point P_t is visible if $P_t \alpha > P_i \alpha$ for all points which have $P_i d < P_t d$. In other words, the target point is visible only if its viewing angle is greater than viewing angle of any other point on LoS which lies between observation and target point. As mentioned previously the classic visibility is a qualitative variable which outputs Boolean result – visible or invisible.

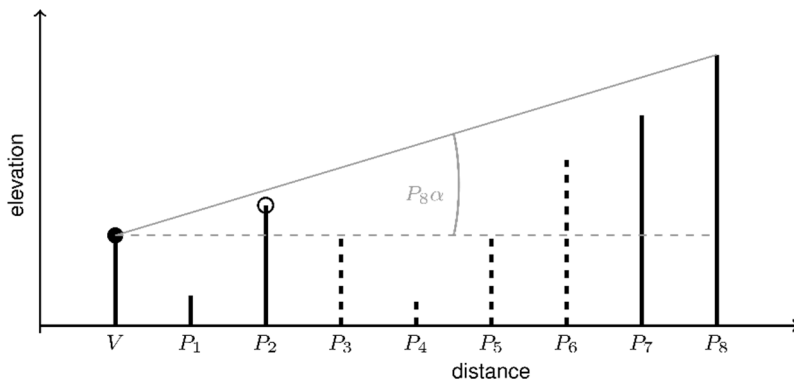


Fig. 1. LoS with 8 points. Points marked with full line are visible, points marked with dashed line are invisible to the observer. Viewing angle of point P_8 is shown. P_2 is a local horizon of this LoS.

Characteristics of the visibility

As mentioned previously LoS contain much more information than the Boolean visibility. This supplementary information about visibility is often referred as extended visibility (Fisher 1996b, De Florian and Magillo 2003) or visibility indices (Caha and Rášová 2015).

Foundation for a significant amount of visibility indices is determined with respect to horizons. Horizon is a visible point P_i on LoS immediately followed by point P_{i+1} that is not visible to the observer. Horizons are denoted as H_j as usually there is more than one on LoS. Horizons have the same properties as other points located on LoS. Two horizons are of particular importance for visibility indices. The first is horizon with maximal viewing angle $H_j\alpha$ located between observer and target. Such horizon will be referred as the maximal local horizon and denoted as $maxH$. The second important horizon can be only found on global LoS and is named global horizon GH , global horizon is the maximal horizon on global. Several visibility indices require the assumption that the P_t cannot be a GH , otherwise the indices would not make sense. The reason why GH can only be obtained from global LoS is that LoS between observing point and target point does not necessarily contain global horizon. Of course, the situation can happen that the dataset as a whole does not contain GH . For example, if visibility analysis is performed within a city, the true GH s for certain lines-of-sight can be in the mountains far behind the city which are not included in the dataset on which visibility is calculated. However, this situation can only be handled by the user and his preparation for the analyses.

It is practically impossible to list all the visibility indices that can be calculated from LoS. Most of them is based on concepts introduced by (Felleman 1979) that were later further developed by various authors. Following is a list of visibility indices implemented in *Line of Sight Analyst* with the remark of their first definition in the literature. The values of indices are either degrees (angular indices), the same units as input data (elevation indices) or other units that are specific to the given index.

Viewing angle (Felleman 1979) equals $P_t\alpha$. Determines how far from the observer's plane of sight the target point is and if it lies below the plane of sight (negative values) or above it (positive values).

Elevation difference (Felleman 1979) is defined as $Ve - P_te$ and provides information whether observation point is higher than target point (positive values) or if it is located lower (negative values).

Angle difference to the horizon (Fisher 1996a, 1996b) has value $P_t\alpha - maxH\alpha$ and describes how far from the highest horizon on LoS the target point is. If the value is negative, then the target is not visible, and the value specifies how many degrees below the horizon the target point is. Positive value describes how high above the horizon the target point raises.

Angle difference to the global horizon (Fisher 1996a, 1996b) has the definition $P_t\alpha - GH\alpha$. The value specifies if the target point raises above the global horizon (positive values) which means that it is visible against the clear sky or if it is located below the global horizon (negative values) in which case it might either be invisible or it has some background (specific part of surface). The negative value of this index does not specify in any way whether the target point is visible or not, as it is not important if the horizon is located closer or further to the observer than target point for this visibility index. The positive value of this index indeed suggests that P_t is the GH of this line of sight, but as mentioned previously to provide relevant measure of this index the P_t cannot be the GH .

Elevation difference to the horizon (Fisher 1996a, 1996b) describes how big part of the target point from its top is visible. The value is defined as:

$$\Delta e = P_te - Ve - \tan\left(\frac{\pi}{180}maxH\alpha\right)P_td.$$

If the value is positive then the specified part of the target is visible, the negative value specifies how much higher the target had to be, to be visible.

Elevation difference to the global horizon (Fisher 1996a, 1996b) has value:

$$\Delta e = \begin{cases} P_t e - V e - \tan\left(\frac{\pi}{180} GH \alpha\right) P_t d & \text{if } GHd < P_t d \\ GHe - V e - \tan\left(\frac{\pi}{180} P_t \alpha\right) P_t d & \text{if } GHd \geq P_t d \end{cases}.$$

The positive value specifies how big part of the target point (from the top) is higher than global horizon and thus visible against the clear sky. Negative value shows how much higher the building had to be, to pierce the global horizon. The same notes as for angle difference to global horizon regarding

The difference of viewing angle and slope of LoS (Caha and Rášová 2015) indicates how well the target part of LoS is visible. Ideal value is 90 at which the viewing angle and slope of LoS intersect at the upright angle. Deviations on either side from this value cause deteriorated visibility of the target. The index is defined as:

$$\Delta angle = \frac{180}{\pi} \arctan\left(\frac{P_t e - P_{n-1} e}{P_t d - P_{n-1} d}\right).$$

Horizon Count (Fisher 1996a) specifies the number of horizons located between observer and target. The index indicates the complexity of LoS.

Horizon Count behind Target Point (Fisher 1996a) is the same as the previous index but for global LoS. Specifies how many horizons is behind target point and thus indicating how complex the LoS behind the target point is.

Horizon Distance (Felleman 1979) equals $maxHd$. Shows the distance at which the highest horizon between observing point and the target point is located from the observing point.

Global Horizon Distance (Felleman 1979) is defined as $GHd - P_t d$. Negative values indicate that the GH is located on LoS before target point. The positive value shows that GH is located behind T_p .

Fuzzy Visibility was first described by (Fisher 1994) and later improved by (Ogburn 2006). The index describes visibility of an imaginary object of specified size h for an observer who has recognition acuity of visibility β and clearly sees the object at distance b_1 . Then the fuzzy visibility is:

$$b_2 = \frac{h}{2 \tan \frac{\beta}{2}}$$

$$fv = \begin{cases} 1 & \text{if } P_t d < b_1 \\ \frac{1}{1 + 2 \left(\frac{P_t d - b_1}{b_2}\right)^2} & \text{otherwise} \end{cases}.$$

The closer the resulting value is to 1 the better the distinctiveness of the target object for the user. If the value is zero, then the user would not be able to distinguish the object at all.

The toolbox

Line of Sight Analyst is Python toolbox for ArcGIS version 10.3 and higher. The toolbox should work for older versions such as 10.2, 10.1 and 10.0 but it was not tested for these versions. Some of the tools require extensions 3D Analyst and Spatial Analyst to be presented and turned on in ArcGIS. The toolbox itself is released under GNU General Public License Version 3 and is available from <https://jancaha.github.io/Line-of-Sight-Analyst/>.

Line of Sight Analyst was developed to simplify creation and analyses of lines-of-sight. The LoS created between observation and target point is regularly sampled to obtain elevation from the surface through bilinear interpolation. The algorithm is close to Fisher's triangulation of the grid algorithm (Fisher 1993). Fisher (1993) also compared different variants of algorithms for obtaining LoS from surface model.

The toolbox provides eight tools:

- Optimize Point Location,
- Create Lines of Sight,
- Create Global Lines of Sight,
- Analyse Lines of Sight,
- Analyse Global Lines of Sight,
- Extract Local Horizons,
- Extract Global Horizon,
- Export Line of Sight into CSV.

The typical workflow for utilisation of *Line of Sight Analyst* is shown in Fig. 2.

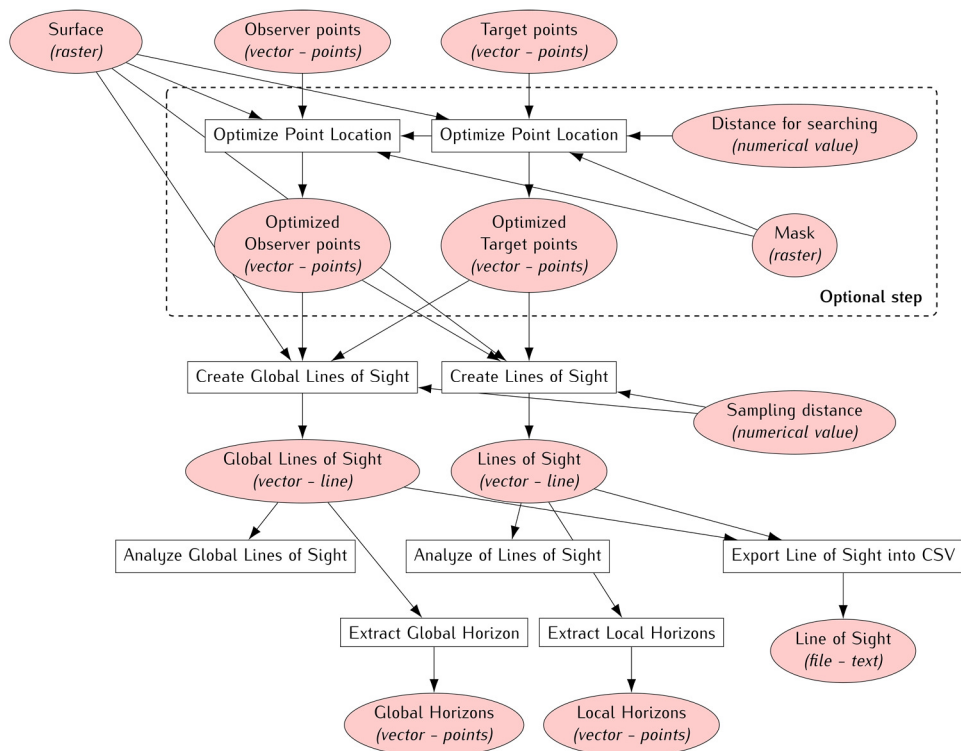


Fig. 2. Typical workflow for *Line of Sight Analyst*.

Optimize Point Location is a tool that optimizes the location of points (observation or target) based on raster values in a specific neighbourhood. The highest raster value specifies the new location of the point. Optionally the user can also specify a mask that can exclude some parts of the raster as unsuitable for point location. The raster for optimization can be elevation raster or some characteristic of a surface such as local dominance or positive openness (Kokalj et al. 2016, Kokalj, Zakšek and Oštir 2011). This type of optimisation has potential to positively affect visibility, although, because of the complex nature of visibility it cannot be guaranteed that the optimised position will have better visibility characteristic. However, in certain situations, it might be helpful for selecting highest point, to improve the visibility.

Create Lines of Sight and **Create Global Lines of Sight** are tools to create LoS and global LoS based on observer points, target points and surface. Optionally the user can define sampling distance to specify with what spacing the points are placed on LoS. Default value of sampling distance is the cell size of the surface raster. The LoS created by these tools do not compensate for Earth's curvature or refraction, this step needs to be done when analysing or exporting the LoS. The main reason for this is the extraction of horizons. If the LoS would include effects of Earth's curvature and refraction on visibility, then it would not be possible to extract horizons with their true elevation.

Tools for analyses of LoS and global LoS are **Analyse of Lines of Sight** and **Analyse Global Lines of Sight**. There are three types of parameters for these tools. The first type are parameters of the LoS – offset of observer and target (X and Y coordinate of the target for global LoS). The second type of parameters is focused on whether Earth's curvature and refraction coefficient should be used. The third type of parameters is specific to local LoS and sets up details for determination of fuzzy visibility. These tools append new fields to the feature classes with values of visibility indices. For LoS the following characteristics are calculated: visibility of the target point, viewing angle of the target point, elevation difference between observing and target point, angle and elevation difference to the horizon, the difference of viewing angle and slope of LoS, horizon count, horizon distance and fuzzy visibility. For global LoS the characteristics are: visibility of the target point, angle and elevation difference to the global horizon, global horizon distance and horizon count behind target point.

It is possible to extract horizons and global horizons from either LoS or global LoS with tools **Extract Local Horizons** and **Extract Global Horizon**. Both types of horizons are extracted as points with several essential characteristics stored as layers attributes.

The tool **Export Line of Sight into CSV** is used to extract LoS or global LoS from the form of spatial data into a numerical representation that can be used for further processing (e.g., plotting) outside of GIS.

All the details regarding the individual tools and their parameters and outputs are summarized in the toolbox manual (Caha 2018). The tools from toolbox act in ways as complements to tools “Construct Sight Lines” and “Line of Sight” which belong to “Visibility toolset” of extension “3D Analyst” of ArcGIS (Esri 2017). These tools provided by Esri served as an inspiration for the creation of the *Line of Sight Analyst toolbox*. While “Construct Sight Lines” is quite is in many ways quite alike **Create Lines of Sight** there are several important differences. The output of **Create Lines of Sight** is a 3D line that consists of start and endpoint as well as all points along the line where the elevation was sampled. “Construct Sight Lines” on the other hand stores only start point and endpoint. This difference allows LoS, which includes all the necessary information to determine visibility indices, created by the toolbox to be exported for processing outside of ArcGIS. “Line of Sight” tool is used to determine if target point is visible from observing point in the output of “Construct Sight Lines”. The result only stores information if the target point is visible (Boolean visibility) and the line is divided into visible and invisible segments for the observer (Esri 2017). While such outcome can be undoubtedly interesting for assessing visibility, unfortunately, it does not allow determination of visibility indices. The *Line of Sight Analyst toolbox* can be seen as an extension or a supplement to the existing tools that are implemented in ArcGIS Desktop.

Case study

In this section, a brief case study that shows the possible utilisation of the toolbox for visibility assessment is described. The study is focused on the description of visibility of main tower of St. Vitus Cathedral which is located within Prague Castle (Czech Republic). The panorama of Prague castle is probably the most famous view in Prague with the cathedral being the dominant. Both the cathedral and the panorama of Prague castle are shown in if Fig. 3.

The proper assessment of visibility requires detailed digital surface model (DSM) that contains not only terrain elevation data but also information about the height of buildings and vegetation. Probably the best DSM are LiDAR-based (Klouček, Lagner, and Šimová 2015). For this study DSM of Prague provided by "© IPR Praha" (www.geoportalpraha.cz), which is provided as open data under licence CC BY-SA 4.0, is used. The dataset and its metadata are available from website of Prague Institute of Planning and Development (IPR 2018). It has spatial resolution of 1 meter which is adequate for DSM of a city (Rød and Meer 2009, Garnero and Fabrizio 2015). For visibility assessment of the target building, a set of viewpoints defined by analytical planning materials for Prague city (Útvar rozvoje hlavního města Prahy 2008) is used. This set contains 323 viewpoints from which 51 that are located within 3 kilometres from the cathedral were selected. These viewpoints will be used as observer locations for visibility assessment. For this type of analysis, we are mainly interested in how well the target is visible, how high part of the tower is visible and where is the maximal local horizon ($maxH$). The Prague castle is located on a terrain ridge and the target building (tower) is rather high (96.5 meters), so it is not sensible to expect the existence of global horizons behind the target. Because of this fact only local LoS and its analyses are performed.

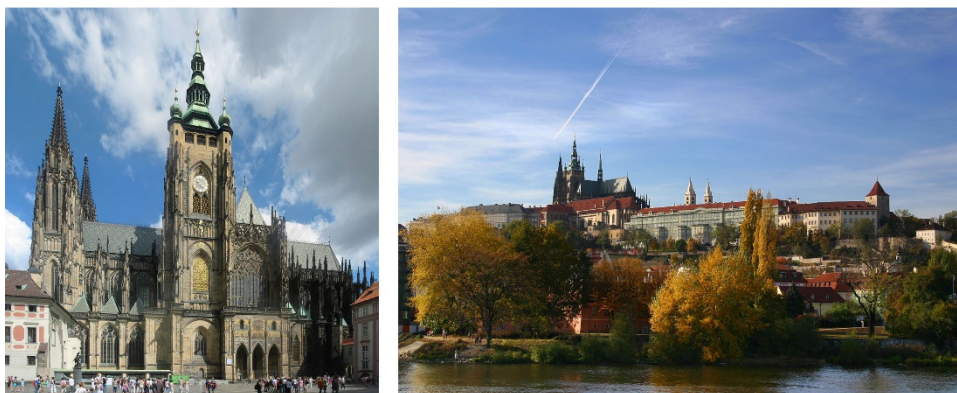


Fig. 3. Left - St. Vitus Cathedral (© Oliver Beckstein / CC-BY-2.0), right - panorama of Prague Castle (© Stefan Bauer / CC-BY-SA-2.5).

The first step in the analysis is the selection of target point that will represent the main tower of the cathedral. It is not necessary to place the point precisely within the highest cell of the cathedral in the DSM raster. Approximate location is sufficient since the exact placement is later optimised using Optimize Point Location tool. After that, as a second step, 51 lines-of-sight are constructed amongst the observer points and target point using the tool Create Lines of Sight. The observer's offset is set to 1.5 meters which is slightly less than eye level of average human. The offset of the target is set to zero. The sampling distance is the same as raster resolution (1 meter). The constructed lines-of-sight can be then analysed using the tool Analyse Lines of Sight. The analysis takes into account the Earth's curvature and atmospheric refraction. The visibility indices specified in section 3 are added to attribute table. The horizons are extracted from the LoS using the Extract Local Horizons tool.

Visualization of angle difference to horizon for all 51 LoS is shown in Fig. 4. This visibility index provides information about the distinctiveness of the target above the maximal local horizon. From the Fig. 4 we can observe that if the target is not visible, then the horizon is usually located near the observer. The LoS are divided into four categories. Values $-75.51^\circ - -2^\circ$ indicate that the building is significantly hidden by horizon. Second category ($-1.99^\circ - 0^\circ$) shows observation points for which the target is just below horizon. Two remaining categories show LoS where the target is visible. For category with values $0.01^\circ - 1^\circ$ the building is just above horizon while for the category $1.01^\circ - 4.19^\circ$ it can be considered as well above the horizon. Similar evaluation can be found in Caha (2017).

Fig. 5 shows how high part of the target will be visible above the local horizon. The results are visualized only for points from which the target is visible. The category limits used in legend of Fig. 5 are selected to represent specific elevation breakpoints of the cathedral. The category 0 - 4 meters represents top of the tower where golden Czech lion with a cross is located. Even though that the observer should see this part of cathedral, it is quite unlikely that it will distinguishable as the horizontal size is not distinctive. Category where 4.1 to 40 meters of the building is visible represents the roof of the tower along with the gallery (which is located at height 56 m). Just 6 meters below that starts the roof of main part of the cathedral. The category 40.1 - 46 m indicates that the tower but not the main roof is visible. The last category (46.1 - 63.6 m) represents locations from which the roof of cathedral is visible. If there would be values larger than 63.3 meters it would indicate that even the arches of the main structure are visible. Unfortunately, none of the observation points provides such view. Looking at the pattern in Fig. 5 it is obvious that observer can see larger part of the cathedral from viewpoints located south of the cathedral.

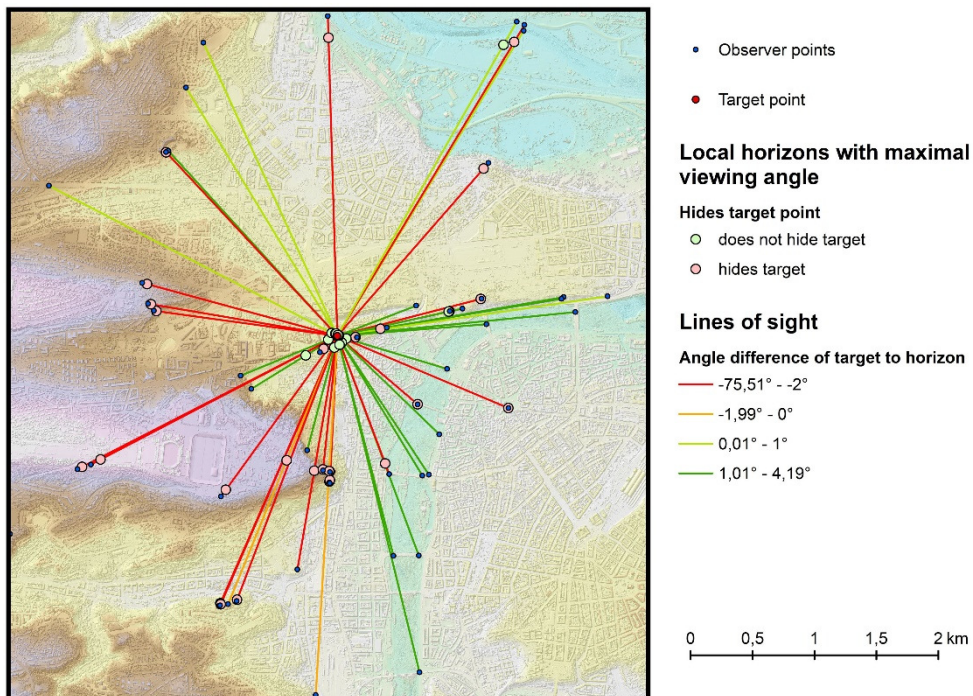


Fig. 4. Visualization of visibility index angle difference to horizon with horizons highlighted.

The case study demonstrates that the toolbox *Line of Sight Analyst* provides valuable information in the form of visibility indices that otherwise cannot be obtained in either commercial or open source GIS.

Conclusions

The need for more suitable tools that would allow more sophisticated assessment of visibility is well documented in the literature (Ervin and Steinitz 2003). The primary focus of this area of research is probably urban planning with two most important topics being visibility of high-rise buildings (Caha 2017, Czyńska and Rubinowicz 2017, Rød and Meer 2009) and protection of important horizons and panoramas (Czyńska and Rubinowicz 2015, Wróżyński, Sojka, and Pyszny 2016).

Unfortunately, the existing tools often do not allow users to perform the visibility analyses they need. The tools are either too simplistic or not focused on information that is necessary to correctly and appropriately assess visibility (Caha 2017). The unavailability of tools leads the user to complicated solutions, e.g. performing repeating analyses with different settings that are utilized as a replacement for more complex analyses. This approach can be seen in articles by Czyńska and Rubinowicz (2017), Rød and Meer (2009) or Rubinowicz and Czyńska (2015). While this approach solves most of the problem, there are more suitable methods for this types of analyses – determination of visibility indices (Fisher 1996a, Caha 2017).

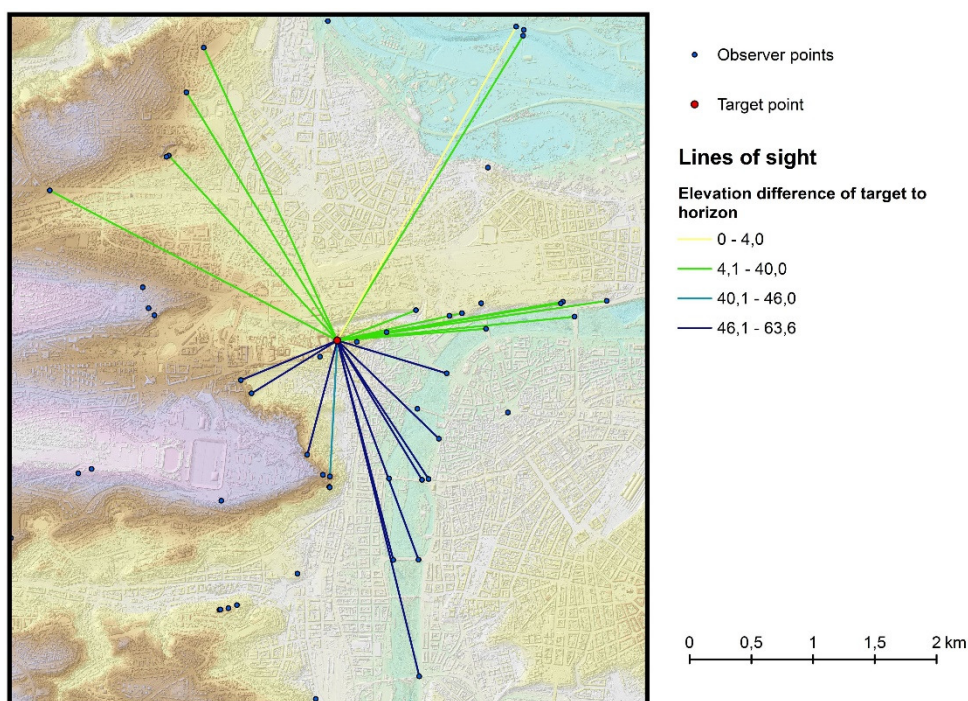


Fig. 5. Visualization of visibility index elevation difference to horizon.

The presented toolbox (Line of Sight Analyst) provides tools for complex visibility analyses on line-of-sight. The tools are designed to work for visibility on point (observer) to point (target) bases. This type of visibility analysis is more straightforward for implementation than viewshed algorithm that works on point (observer) to area (target) bases. Obviously, the viewshed algorithm is more intriguing for users as it provides more extensive results. However, the adjustments of viewshed algorithm is significantly more complex and in commercial GIS not possible at all since the source code of the algorithm is not available. Although, the toolbox is not the best possible solution it still provides rather interesting results and outcomes that users can use to analyse the visibility more appropriately.

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