

Extending the Applicability of Viewsheds in Landscape Planning

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Abstract

The determination of the visible area or viewshed from a viewing point looking out on a landscape is a widely available function in a GIS. A reconsideration of the queries which may be made of the viewshed, however, reveals that often the function does not address them correctly. This has led to the specification of alternative viewshed functions intended to give flexible outcomes which can be used to respond to the queries directly. The alternatives include the horizons viewshed, the local offset viewshed, the global offset viewshed, and reverse viewing versions of all three. Applications of these alternative viewshed functions to answer queries about the landscape and the view which the binary viewshed is not able to respond to either precisely or flexibly are examined.

Introduction

The determination of the area visible from a location or locations in the landscape is a process which landscape architects have dealt with for many years (Smardon *et al.*, 1986). With the advent of computer processing of spatial information, and the realization that elevation data can effectively be held in digital form, visible area determination was an early subject for algorithm development and implementation (Travis, 1975; Yoeli, 1985). The function has since become one of the standard operations available within commercial geographic information systems (GIS) which are designed for processing land-surface elevation data. There has been continuing research interest in the visible area determination. Topics have included optimization in selecting sites on the basis of visibility (Lee, 1991; DeFloriani *et al.*, 1994a), influence of database error (Felleman and Griffin, 1990; Fisher, 1991; Fisher, 1992), reliability of different algorithms (Sorensen and Lanter, 1993; Fisher, 1993), and implementation on parallel architectures (DeFloriani *et al.*, 1994b).

The visible area is determined by defining one location as the viewing point and then calculating the line-of-sight to every other point within the area of interest (the target points). If the land surface rises above the line-of-sight, then the target is out-of-sight, and otherwise it is in-sight. The result is based on a Boolean concept of visibility and reported as a binary field. Consideration of this binary Boolean image reveals that it does not actually address the types of query which is asked of it in many investigations. This revelation has led to a reconsideration of visible area determination and to the presentation of a set of variant algorithms. That reconsideration has been published elsewhere (Fisher, 1994b; Fisher, 1996), and is summarized below. The purpose of this paper is to show that the application of the variants proposed enables more precise responses to a range of queries.

The next section includes a review of the types of query which are not answered by a standard binary viewshed.

There follows a summary of the proposed variants, and a review of their sensitivity to database error. Finally, a discussion of how these variants may be used to respond to the motivating queries is presented.

Problematic Queries

A binary viewshed answers a basic query, namely, whether a target location can be seen from the viewing point. Viewshed analysis is widely used to assess the visual impact of construction and to plan visible areas for amenity and routing. In these applications, however, it is rarely sufficient to determine the viewshed from one, or a set of, viewing locations. Rather, it is usual that some ancillary property (related to the line-of-sight) is really required, and the binary viewshed simply provides an easily determined surrogate.

In locating a forest-fire observation tower, for example (Travis *et al.*, 1975; Lee, 1991), the viewable area is not limited to the area which is directly within lines-of-sight from the tower, but rather the observer can effectively see a forest fire where the ground surface is beyond the horizon so long as the vertical difference between the ground and the line-of-sight to the horizon is less than enough for the smoke to be dispersed by the wind (Figure 1A; Mees, 1978).

Similarly, when determining the visual impact of a new structure in the landscape, it is necessary to identify whether the structure rises above the skyline or remains below it, not whether either the ground surface at that location or even the top of the structure is in- or out-of-view. The visual impact of an object which is behind the horizon and completely masked by the horizon is very different from one which pierces the skyline, and the impact of a development which is within the visible area is very different depending on the degree to which it too pierces the skyline (Middleton, 1952). It is relatively easy to camouflage an object which has a landscape as a background, as opposed to one which is silhouetted against the sky (Figure 1B), although some objects can be well designed to avoid visual impact even if they are backed by the sky. Also, when designing routes through terrain with concern to visibility, it is essential to know whether a location is on the skyline with respect to an observer or not; such locations should probably be avoided. Similarly, in landscape planning for recreation, locations should be avoided if they entertain a view of an unsightly object on the skyline. Furthermore, in archaeology, the visibility of sites on the skyline is widely held to be of importance for astronomical alignments, as well as territory markers (Ruggles *et al.*, 1993).

The standard viewshed algorithm determines the area

Photogrammetric Engineering & Remote Sensing,
Vol. 62, No. 11, November 1996, pp. 1297-1302.

0099-1112/96/6211-1297\$3.00/0

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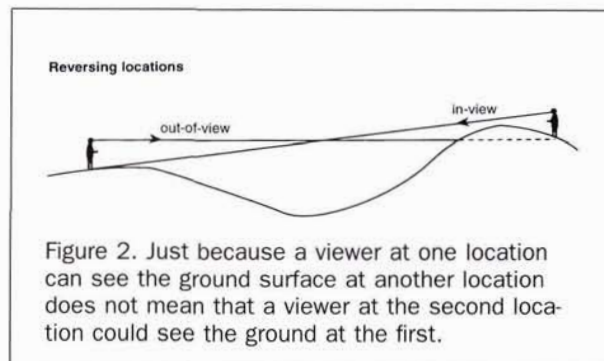
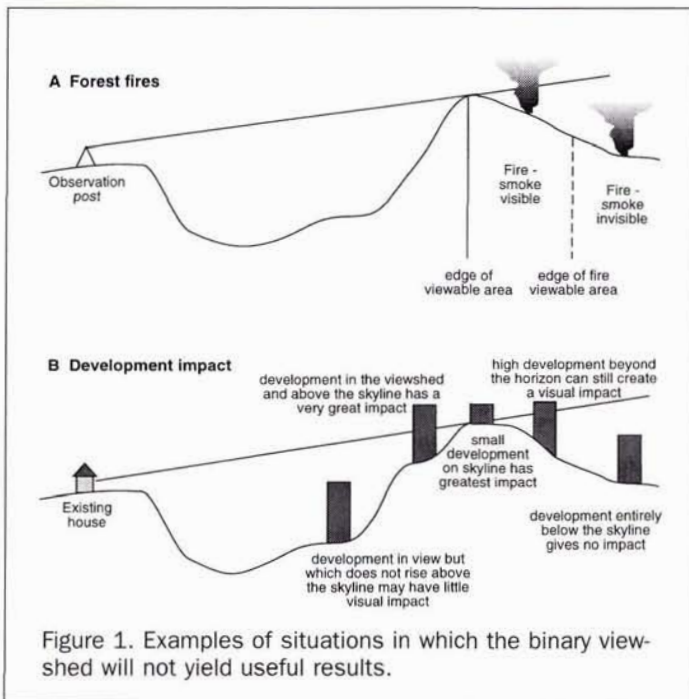


Figure 2. Just because a viewer at one location can see the ground surface at another location does not mean that a viewer at the second location could see the ground at the first.

- 1—indicates a location is simply in-view;
- 2—indicates what is referred to here as a local horizon (an intermediate horizon might be another name), which is, for example, the top of a landscape feature such as a hill which is backed by more land surface;
- 3—is a global horizon (the skyline) where the landscape is seen to meet the sky;
- 0—again is the area which is not visible.

The Local Offset Viewshed

If the target point is in-view, then the vertical offset (the vertical height) between the land surface at the target location and the line-of-sight to the next local or global horizon in the direction of the line-of-sight is reported as a positive number.

If the target is out-of-sight, then the offset is reported as a negative number which is the height between the land surface at the target location and the line-of-sight to the previous horizon in the direction of the line-of-sight.

Any location which is on an horizon will have value 0 (Figure 3C).

The Global Offset Viewshed

If the target point is in-view, then a positive number is returned which is the vertical offset (the vertical height) between the land surface at the target location and the line-of-sight to the global horizon in the direction of the line-of-sight.

If the target is out-of-sight, then the height between the land surface at the target location and the line-of-sight to the global horizon in the direction of the line-of-sight is reported as a negative number.

Any location which is on a Global Horizon will have value 0 (Figure 3D).

Reverse Viewing Variants

All the above four versions of the viewshed have a reverse variant. Rather than reporting on whether many target locations can be seen from a single viewing point, as is the basis of all the above, the visibility of a single target or viewed point from many viewing points is determined. As noted above, the reverse binary viewshed can be determined in some commercial software, but it would appear that none of these other variants are currently available in any commercial software.

Error Modeling

Just as the binary viewshed is very sensitive to the accuracy of the digital recording of the elevations (Fisher, 1991; Fisher, 1992), so these variants are sensitive. Fisher (1996) shows how it is actually possible to determine error-sensitized versions of the above products. Using Monte Carlo simulation, as in the earlier work, it is possible to determine the probability of a location being in-view, out-of-view, or on a

which is visible from a particular *viewing* location. Frequently (as when planning a new structure, or exploring archaeoastronomy) we are actually interested in the area from which that location can be *viewed*, which is not equivalent to the area which can be seen from the location, because the height of the object at the viewing point may well be different from the height of the viewing object (Figure 2). Only if the heights of the viewer and the viewed are equal will the area which is viewable from a location and the area from which the location is visible be the same (Franklin and Ray, 1994). Under any other circumstances the two are very likely to be different, and although we may only be talking of the difference between the eye level of a human being and the ground surface, it may make a significant difference in the area determined. It is both interesting and disturbing to notice that the standard viewshed algorithm is actually regularly used to determine this area in studies of visual impact, for example, to determine the area to determine the area-which-can-see, as opposed to the visible area (the area-which-can-be-seen) is only implemented in some GIS, including, for example, the **Visibility** command in Arc Info (ESRI, 1992), and the **Vista** command in Genacell (Genasys, 1993).

The Alternative Viewsheds

Three alternative viewshed functions have been developed to address the shortcomings recognised above. These are reviewed in this section, but detailed algorithms and implementation details as well as a detailed analysis of the sensitivity to error in the digital elevation model (DEM) are reported by Fisher (1996).

The Binary Viewshed

The standard viewshed as it is implemented in the majority of commercial software is the binary viewshed; a location which is determined to be in-view is recorded as 1, while an area which is out-of-view is 0 (Figure 3A).

The Horizons Viewshed

The horizons variant of the viewshed returns a four-way categorization of the visible area (Figure 3B):

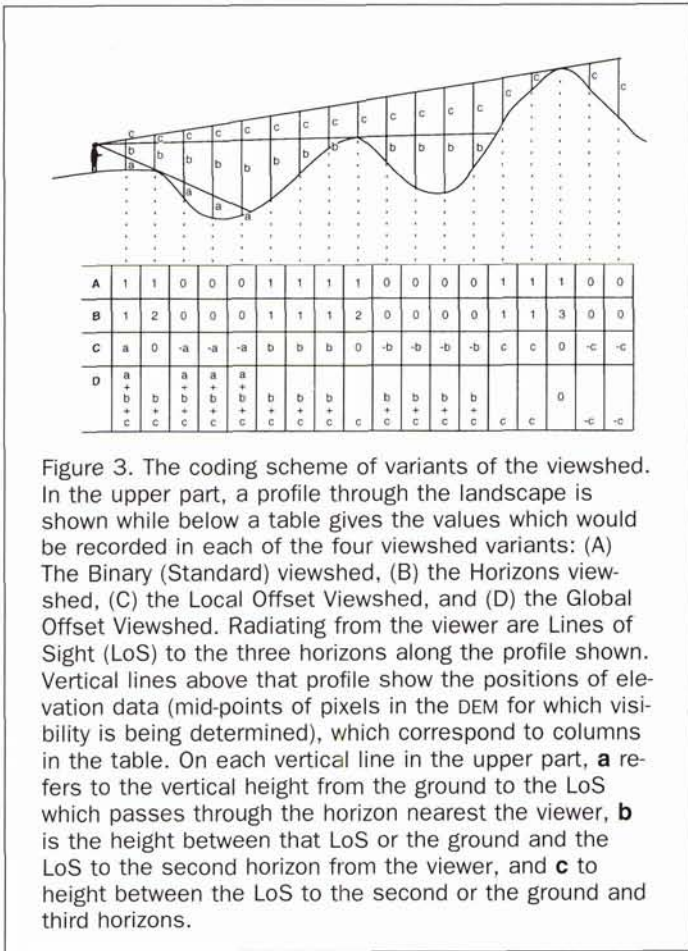


Figure 3. The coding scheme of variants of the viewshed. In the upper part, a profile through the landscape is shown while below a table gives the values which would be recorded in each of the four viewshed variants: (A) The Binary (Standard) viewshed, (B) the Horizons viewshed, (C) the Local Offset Viewshed, and (D) the Global Offset Viewshed. Radiating from the viewer are Lines of Sight (LoS) to the three horizons along the profile shown. Vertical lines above that profile show the positions of elevation data (mid-points of pixels in the DEM for which visibility is being determined), which correspond to columns in the table. On each vertical line in the upper part, **a** refers to the vertical height from the ground to the LoS which passes through the horizon nearest the viewer, **b** is the height between that LoS or the ground and the LoS to the second horizon from the viewer, and **c** to height between the LoS to the second or the ground and third horizons.

local or global horizon. Equally it is possible to generate a mean estimate of the offset and a standard deviation of the multiple estimates caused by the Monte Carlo simulation. A complete error model requires reporting of the mean and standard deviation of positive, negative, and combined estimates.

Details of this Study

To exemplify the applicability of these variants of the viewshed, a small part of the Coweeta Basin, North Carolina was studied. The dataset itself is a 100 by 100 subset of the USGS 30-m resolution DEM derived from 1:24,000-scale quad sheet (Figure 4). A single viewing or viewed location is used in all subsequent discussion and is shown by a cross in Figure 4. The viewshed variants were all coded in Turbo Pascal 7.0 running on a Pentium-based PC compatible computer. As in previous work, error simulation was achieved by drawing random numbers from a normal distribution. The spatial autocorrelation in the error field has been shown to influence several aspects of the viewshed and its appearance (Fisher, 1991; Fisher, 1992; Fisher, 1996). Spatial autocorrelation was achieved, as in the previous work, with the variant of the algorithm proposed by Goodchild (1980), with spatial autocorrelation measured by Moran's I which varies from approximately -1 to 1, where a value of just less than 0 represents a completely disordered distribution and a value tending to 1 indicates that similar values are neighboring (Goodchild, 1986). The IDRISI raster GIS package was used for all post processing and display (Eastman, 1992)

Applications

Forest Fire Observation

As discussed above, and illustrated in Figure 1A, the area from which a forest fire is visible is larger than the binary viewshed. Some amount of vertical offset from the line-of-sight can be accepted because the smoke can be visible even when the flames are not and the existence of smoke is a reliable indicator of fire (Mees, 1978). For a particular geographic location, a negative vertical offset from the line-of-sight needs to be defined and then the actual area over which a forest fire is visible can be determined from the local offset by recoding the values to give a new binary viewshed (Figure 5a). The amount of the negative offset would be based on the usual wind conditions, especially when fires may be expected to start (a seasonal phenomenon), and the amount of offset may be dependent on the bearing from the observation point.

The mean estimates of the offsets determined in multiple error simulations can be used to yield alternative versions of this variant of the viewshed. The means of the estimates of the local offsets are shown in Figure 5b, where the spatial autocorrelation in the error fields is $I = 0$, and Figure 5c shows the resulting area when $I = 0.9$ in the error fields. The resulting viewsheds appear similar, but the former has a much more speckled appearance due to the irregularity in the noise fields used to generate it.

The mean and standard deviations of the estimate of the offset may be used in combination to estimate the probable area which would be visible. Thus, adding and subtracting one standard deviation to the mean of the estimated offsets, and applying the same threshold (-20 m) as above, yields the areas with 15 percent, 50 percent, and 85 percent probability (approximately + and - 1 standard deviation) of being visible (Figure 5d).

Another version of the probabilistic model of the viewshed with specific offset may also be derived by taking the acceptable offset from a horizon, but it would need to be determined by generating and summing multiple versions of the binary viewshed for multiple noisy DEMs. However, this approach would need an investigator to redetermine the viewshed from the DEM. Using the mean and standard deviations of the estimated offsets means that the area visible for

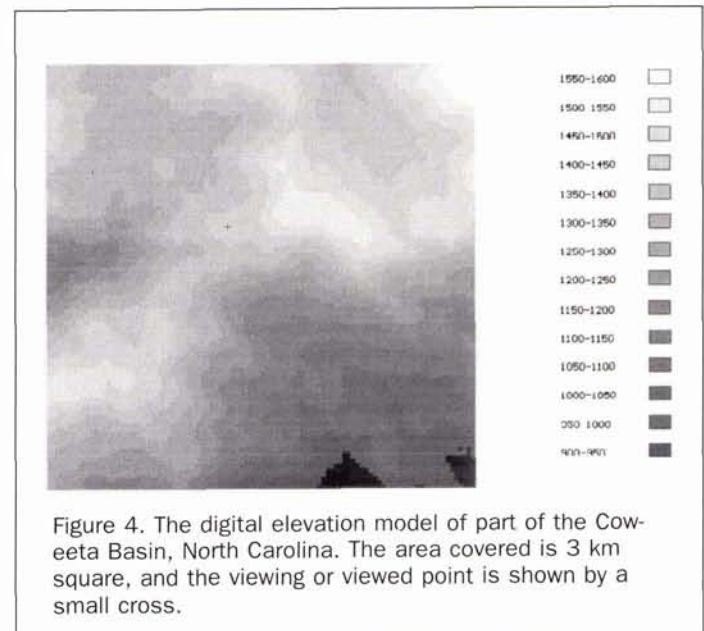
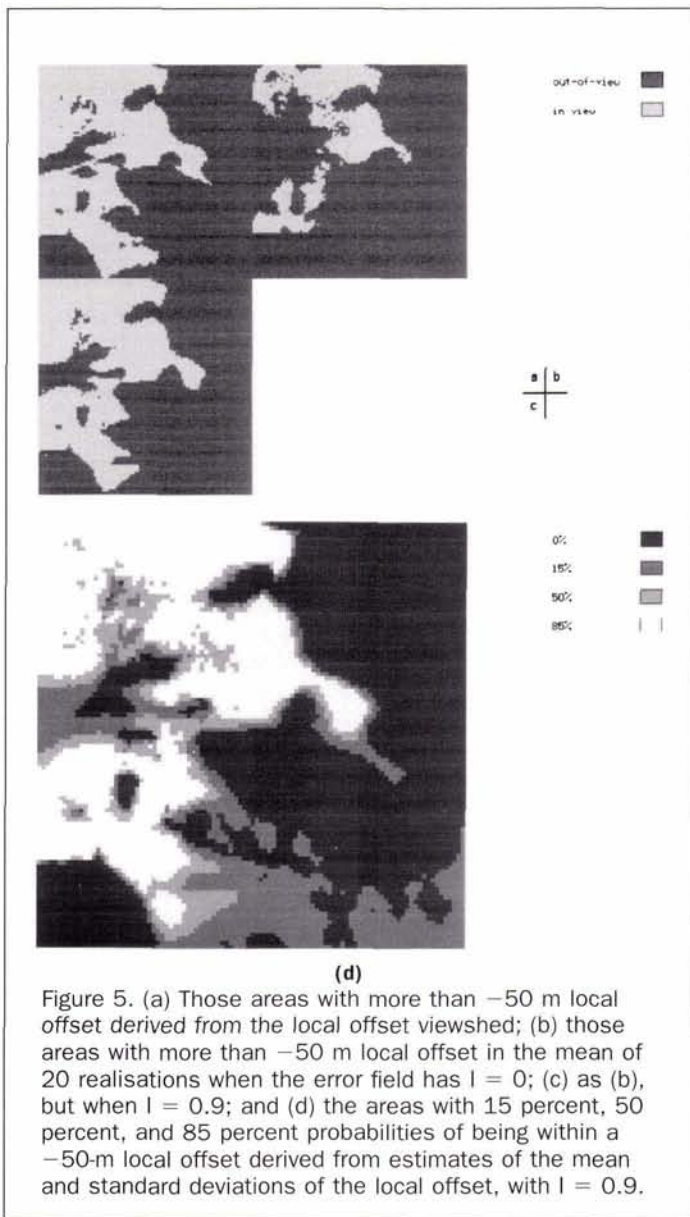


Figure 4. The digital elevation model of part of the Coweeta Basin, North Carolina. The area covered is 3 km square, and the viewing or viewed point is shown by a small cross.



(d)

Figure 5. (a) Those areas with more than -50 m local offset derived from the local offset viewshed; (b) those areas with more than -50 m local offset in the mean of 20 realisations when the error field has $I = 0$; (c) as (b), but when $I = 0.9$; and (d) the areas with 15 percent, 50 percent, and 85 percent probabilities of being within a -50-m local offset derived from estimates of the mean and standard deviations of the local offset, with $I = 0.9$.

any other offset can be rapidly determined without going back to the viewshed determination.

It is not possible to choose among all these different versions of the same viewshed product reliably. The only thing to say for sure is that Figure 5d, with three different levels of probability, contains the most information, and so is probably the best for planning purposes.

Planning Visual Impact

The visual impact of a new construction seems to be one of the most widely quoted applications of visibility analysis. If a new development is proposed at a location, then the viewshed variants reviewed here give a powerful analytical potential beyond the use of either the binary or reverse binary viewsheds. The binary viewshed gives an idea of the area which can be seen from the construction site. If the viewing point is an existing building, or is an important scenic location, then this is an important consideration. The local offset shows the height the new construction can be at any location before it pierces the horizon from the viewing point and so the maximum height of the structure at any location to mini-

mize visual impact. Figure 6a shows the area where construction of a feature over 10 m high might be banned if consideration were being given to the area visible from the test viewing point, because the structures would be higher than the next local horizon, although the structures could be in-view from the viewing location (values of $+ \text{ or } - 10\text{ m}$ in the local offset viewshed are included). With greater consideration to the view, a proposed structure may only be allowed to be visible if it is at a considerable distance from the viewing point. Alternatively, less consideration may be given to the visible area by only banning construction in areas within $+ \text{ or } - 10\text{ m}$ of the global horizon, where it would be backed by the sky (Figure 6b).

If the viewing point is actually the potential construction site (a more common situation), then the reverse viewsheds are more useful in evaluating the visual impact. The locations with values greater than 10 m in the reverse local offset viewshed are shown in Figure 6c, and are the areas from which the construction would impact the horizons.

A set of error analyses similar to those included in the discussion of forest fire observation would be possible for results presented in Figures 6.

The height to which a structure could be built at any location without becoming visible from the viewing point may also be determined from the offset viewsheds, and error estimates may be determined. Therefore, it is possible to make relatively precise statements of the areas which will not be visible, or the amount of the structure which will be visible, and so judge the impact of that part of the structure.

Frost Exposure

The distance to the global horizon (Figure 7) allows calculation of exposure of locations to the sky and to frost hazards, something not achievable from the binary viewshed. If the distance is found from the viewing point to the global horizons in various directions, and the average, maximum, and minimum values can all be extracted, then the exposure may be calculated (Dozier *et al.*, 1981). Again, error statements are possible based on the standard deviation of the offset estimates.

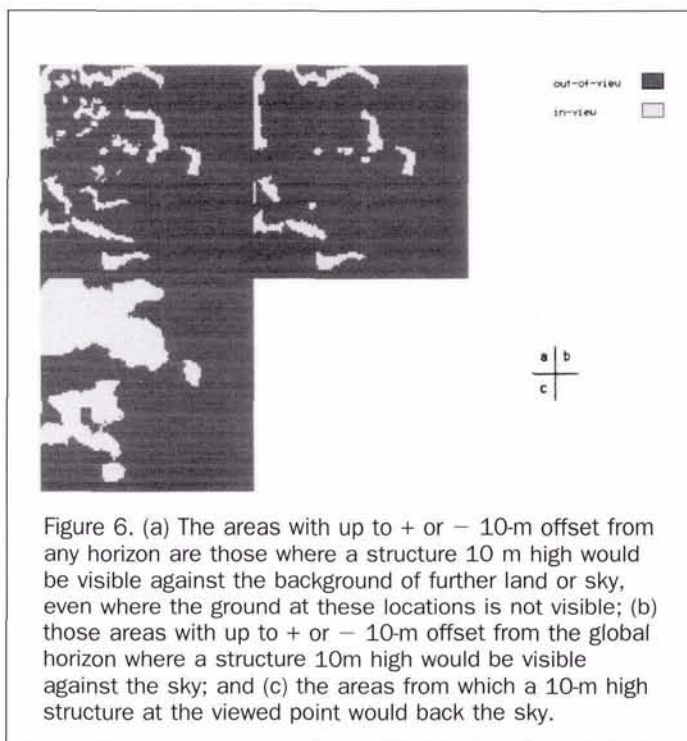


Figure 6. (a) The areas with up to $+ \text{ or } - 10\text{-m}$ offset from any horizon are those where a structure 10 m high would be visible against the background of further land or sky, even where the ground at these locations is not visible; (b) those areas with up to $+ \text{ or } - 10\text{-m}$ offset from the global horizon where a structure 10 m high would be visible against the sky; and (c) the areas from which a 10-m high structure at the viewed point would back the sky.

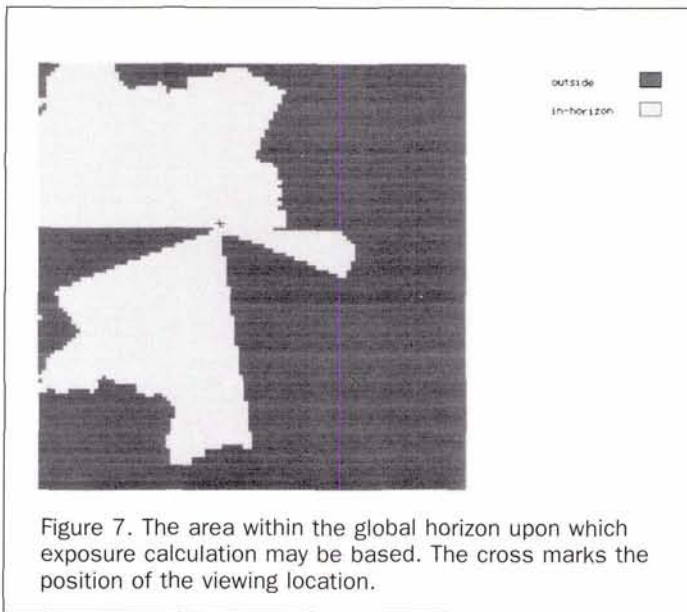


Figure 7. The area within the global horizon upon which exposure calculation may be based. The cross marks the position of the viewing location.

Most Concealed Observer Positions

It is often the case that an observer needs to be placed such that the observer has concealed visibility of a location. In other words, the observer needs to see a target location, but also need not be easily seen from it. Candidate locations for this can be determined by taking the intersection of the area which is in-view in the reverse binary viewshed and out-of-view in the standard binary (Figure 8a). In these locations the standing observer can see the target location, but when lying on the ground a person standing at that location cannot see the first person (Figure 3). These locations can be further prioritized by examining the local offset at those locations, the site with the highest local offset being the optimal viewing location.

It is also possible to derive the probability that the locations are in this category of being able to see when standing but without being seen when lying down. The intersection of the probable versions of the binary and reverse binary viewsheds can be determined by the multiplication rule (assuming for the sake of simplicity independence of the observations): i.e.,

$$p(xA \cap B) = p(xA) \cdot p(xB) \quad (1)$$

where $p(x)$ is the probability of a location belonging to the set of points A which can not be seen from the viewing point, and B which can see it. Figure 8b shows the result of this operation, and it is apparent that even when $I = 0.9$ the pattern is very different from the analysis of binary viewsheds; the locations with high probabilities do not necessarily coincide with locations identified in the binary analysis, and many more candidate locations are present, although many of those have very low probabilities. Furthermore, from this probabilistic version it is possible to derive the path of least probability of being visible in approaching the viewing point.

Conclusion

There is a very real and ever present risk that GIS users will misunderstand the logic of the functions they use, and will use those functions to answer queries for which they are not designed. Such failures with respect to the viewshed have motivated the current research, but they are present with respect to other operations as well. The risks of this may not

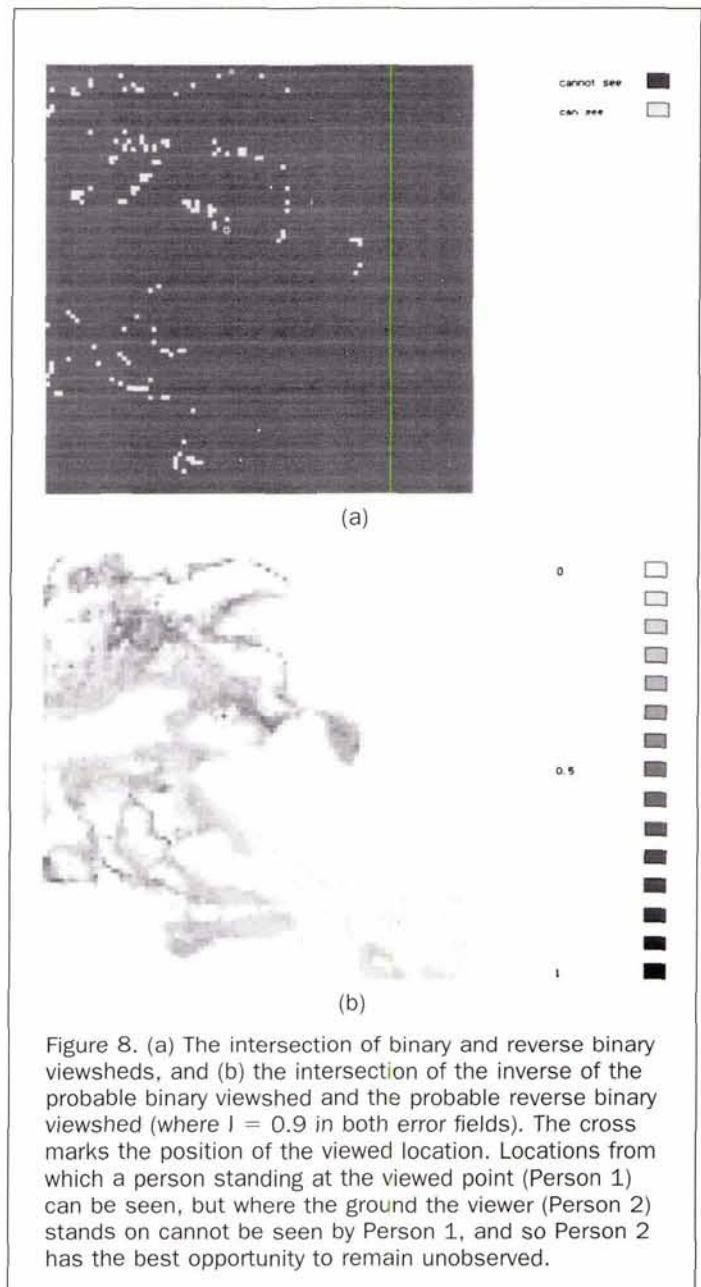


Figure 8. (a) The intersection of binary and reverse binary viewsheds, and (b) the intersection of the inverse of the probable binary viewshed and the probable reverse binary viewshed (where $I = 0.9$ in both error fields). The cross marks the position of the viewed location. Locations from which a person standing at the viewed point (Person 1) can be seen, but where the ground the viewer (Person 2) stands on cannot be seen by Person 1, and so Person 2 has the best opportunity to remain unobserved.

be sufficient to invalidate all analyses, but the resulting misapplication may well cause a growing feeling of distrust among users. That distrust will be to the detriment of the use of GIS in particular and computer technology in general.

In the work presented here, variants of a basic GIS operation have been summarized. It has been shown that the viewshed, as it is implemented within most GIS, has a limited suitability for the types of query it is frequently used to answer. The variants improve greatly the analytical potential of the viewshed operation, giving more appropriate answers to complex queries, well beyond those which motivated the research in the first place. Furthermore, not only do the variants provide complete and precise responses to the queries, the two offset variants also provide real number images of an area which allow flexible interrogation and changes in parameters of the query, without the need to re-calculate the viewshed, a computationally complex and time consuming process.

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