MODELING VISIBILITY THROUGH VEGETATION

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Abstract: The calculation of visibility patterns associated with past monuments and sites is an important element in modern landscape archaeology. These types of investigations have been limited by the inability of current viewshed routines to incorporate vegetation information. The following paper presents a new viewshed algorithm aimed at calculating the probability of locations being visible in the presence of vegetation. To this day little work has been done to address this limitation, a notable exception is Dean's *Permeability Index* Model (1997). A review of Dean's model is provided here in the light of the new proposed algorithm. The new algorithm is based on mathematical principles found in Beer-Lambert's Attenuation Law, a physics law governing the attenuation of light through a medium. In addition to common viewshed parameters, the routine requires a 3D model of a tree/plant and a layer indicating the spatial distribution and density of vegetation on the landscape. The possibility of varying both, the spatial and density distribution of tree/plants, and the three-dimensional model representing vegetation makes the model to be well suited to investigate the impact that vegetation may have on visibility patterns.

Keywords: Viewshed, Vegetation, Paleo-reconstruction, Landscape Archaeology

1. Introduction

In spite of the abundance of viewshed algorithms published in recent years the majority has focused almost exclusively on streamlining the line-of-sight (*los*) algorithm in order to make it faster. For the most part, the nature of the output has remained unchanged: classifying a location as being obstructed or not by topography. Moreover, these studies calculate visibility under identical environmental conditions often disregarding essential information, such as direction of light source, atmospheric refraction, vegetation, etc. This is rather unfortunate given the fertile ground that the resolution of these topics provides for new developments within GISc (Llobera 2006). Over the years, a few of these limitations have been addressed to various degrees of success, like the effect of illumination (Fisher 1995) or atmospheric refraction (see ArcGIS v9.1 documentation).

While few authors have made reference to some of these environmental factors (see Bishop 2000, 2003) these have seldom been the focus of formal models. The inability to incorporate vegetation remains one of the most important, if not the main, Achilles' heal surrounding GISc approaches to visibility analysis. Amongst the reasons for this shortcoming is undoubtedly the fact that a satisfactory solution cannot be attained using traditional GIS data structures. To be able to address this limitation it is necessary to resource to the use of three-dimensional information that has yet to be fully developed in commercial GIS.

The following paper discusses a theoretical model, a new algorithm, aimed at calculating the probability of visibility in a landscape populated with vegetation. The study arose in an attempt to address one of the main criticisms surrounding the use of viewsheds studies within landscape archaeology (Tschan 2000, Wheatley & Gillings 2000). Within this field, patterns of visibility generated by cultural features in the landscape (e.g. earthwork and megalithic monuments) are often associated with social and symbolic aspects within past societies. These patterns of visibility are often argued as being instrumental in the definition of territories or to questions regarding power and control (eg. Barrett 1994). The ability to assess how visibility patterns associated with prehistoric monuments may have been affected by existing vegetation would shed important light into these investigations. It is unlikely, however, that archaeologists will ever be able to reconstruct these patterns with any degree of precision. The best of palynological and other palaeo-environmental evidence can only provide us with information about the type of vegetation that was present at any point in time. It can also indicate whether people were actively manipulating their environment (eg. there is evidence of clearances around prehistoric round barrows in England). But it cannot tell us where exactly where trees or shrubs located in the past. Nevertheless knowing the type of vegetation, and its environmental requirements, it is possible to speculate with a good degree of certainty where certain type of vegetation may have been distributed in a landscape. These locations can then be populated with different vegetation densities ranging from few sparse trees to dense growth to allow us to determine in which areas visibility may have been affected, to what degree, and to investigate the effect of clearances in the past.

The following sections describe a new viewshed routine that enables the incorporation of this information when calculating visibility.

2. Preliminary work

To this author's knowledge, Dean's *Visual Permeability Method* (1997) is the only published work that has provided a tentative solution to this problem. In this work, Dean used two triangulated irregular surfaces (TINs) to represent tree coverage. Both TINs were used to delimit the height of the subcanopy (tree trunks) and the tree canopy above the terrain. Given a viewpoint, Dean calculated the probability of other locations being visible to be proportional to the length of the *los* that crosses both the subcanopy and canopy regions. Crossing through each of these regions reduces the probability by a certain amount (the *permeability coefficient*). Dean refers to this coefficient as the distance that a *los* traverses before it is obstructed entirely by tree coverage. In his article Dean acknowledged the difficulties of determining empirically this coefficient,

> Determining the visual permeability of a forest is not a trivial matter. It seems plausible that visual permeability is a function of many factors, including density, age, species composition, understory characteristics, and so on. This study made **no attempt to rigorously examine the issue of determining visual permeabilities**. Instead, **a number of possible visual permeability values were picked somewhat arbitrarily** and evaluated by using them in a visual permeability-based viewshed delineation analysis (Ibid: 973)[my emphasis].

Through a set of field experiments, Dean derived information that he later used to choose the appropriate permeability coefficient (Ibid. 974-5). The choice of this coefficient was based on the proportion of targets that were correctly classified in both, the field and his model. It is important to note that the use of empirical information ought to be considered as a way of fitting the viewshed model to a particular vegetation distribution than as an independent way of verifying the results of the algorithm.

While appealing for various reasons (its simplicity and relative computational efficiency) Dean's study has several important limitations:

- It does not provide a way to consider the effect of varying densities of vegetation. The presence of a TIN reflects the presence of absence of vegetation, and does not allow to discriminate patches with high or low vegetation density. Dean's permeability coefficient refers to the entire canopy and subcanopy, hence it is implicit that density is constant in these regions.

- The mechanisms to incorporate 'structural' differences because of tree typology are limited. The amount by which visibility is reduced is independent of the angle of incidence of the *los* on vegetation or nature of the canopy that it crosses (see fig. 4). The model could not easily differentiate between looking across tree tops or the middle of trees.

- It is very difficult, except through visual analogy with another environment, to use this model to predict visibility without conducting a priori field experiments needed in order to 'adjust' the value of the permeability coefficient a posteriori.

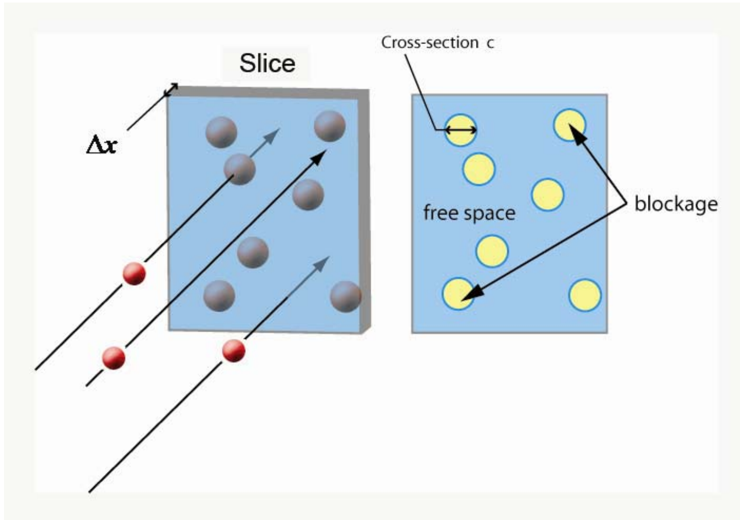
- More importantly, it assumes that the probability of seeing through a patch of vegetation decreases linearly (rather than exponentially) with distance. As I hope to show below, this is not correct from a probabilistic point of view. Furthermore, it stands in opposition to well establish principles in physics that describe the likelihood of a large scale particle (similar in this case to *los*) traversing any medium.

3. Model Description

The conceptual and mathematical basis for the model presented here is provided by *Lambert's Law of Absorption* (also known as *Beer-Lambert's Attenuation Law*). Reference to this law can be found in most elementary physics and meterological optics textbooks (Friedlander 2000, Halliday *et al.* 2004). Lambert's law provides a generic description on how large particles interact when crossing a certain medium. While some of the assumptions governing this law are not strictly met by the model, they still provide the guiding principles on which the following solution is built. A geometric explanation of this law is used in the next section instead of the traditional calculus one found in most physics textbooks in order to provide the reader with an intuitive understanding.

Beer-Lambert's Attenuation Law

We consider an imaginary thin sheet containing n number of particles per unit volume. Each of the particles in the sheet have a cross-section c (see figure 1). The thickness of this sheet, Δx, is thin enough in order to guarantee 'no shadowing' (i.e. no two particles within the slice can be found one behind the other). We now consider a stream of photons, a beam, traversing several of these slices.



<Fig. 1. Stream of photons traversing a thin slice. >

The probability that the slice will intercept an incoming uncharged particle is $P(int) = n \cdot \Delta x \cdot c$. For slices of the same thickness we expect that the 'blocked area', ie. the area blocked by the particles in the slice, is on average the same. It follows, that this probability also corresponds to the fraction f of uncharged incoming particles that are removed from the beam as they encounter each slice. In figure 1, f would correspond to the ratio of yellow area b (sum of circles) divided by the blue area A (free space).

Let $f = b/A$, it is clear that $0 \le f \le 1$. The chance that an incoming particle will survive traveling though a slice is $1 - f$.

If we put two slices in a row, the incoming particle stands $1 - f$ chance of going through the first slice and $1 - f$ of surviving the second one. Hence the total chance of getting though is $(1 - f) \cdot (1 - f)$. For m number of slices the probability will be $(1 - f)^m$.

If N_0 particles are launched we expect $N = N_0 \cdot (1 - f)^m$ to traverse the mth slice. The expected fraction of particles that will survive is $S = N/N_0$. That is S is the likelihood that any incoming photon will survive. Lets make S to be a function of the depth x. We can also relate the number of slices m to x since $x = m \cdot \Delta x$. We now have,

$$S(x) = (1 - f)^{\frac{x}{\Delta x}}$$

This expression can be further developed in order to get rid off Δx. If $b = (1 - f)$ then $0 < b < 1$. By imposing $x > \Delta x$ then $x/\Delta x > 1$ we now have,

$S(x) = \left(b^{\frac{1}{\Delta x}} \right)^x$. Given that b is a fractional number we can substitute $b = 1/a$,

$$S(x)=\left[\left(\frac{1}{a}\right)^{\frac{1}{\Delta x}}\right]^{x}=\left[\left(a^{-1}\right)^{\frac{1}{\Delta x}}\right]^{x}=\left[a^{\frac{1}{\Delta x}}\right]^{-x}$$

Given that $a>0$ and that $1/\Delta x>0$ and finite it follows that the entire expression between square brackets is always greater than 1. This expression clearly shows $S(x)$ decays exponentially. With some more elaboration and further substitutions we would obtain the *exponential law of attenuation*,

$$S(x)=e^{-\alpha\cdot x} \quad (\alpha>0,\ x>0)$$

Visibilty through vegetation

Beer-Lambert's Attenuation Law is adapted here to calculate the probability of seeing through vegetation. The following description refers to the 'visibility' between two locations only, i.e. a single *los*, but it can easily be generalized to an entire viewshed.

For the sake of simplicity the following example assumes that there is only one type of plant/tree, and that the observer and target location (i.e. where we are looking at) are both on the same leveled surface. Our ultimate goal is to derive the probability that a *los* will unite a viewpoint with a target location in the presence of vegetation.

To this end, the traditional representation of *los* as a line is extended in order to consider a rectangular solid, a beam (hereafter *los-beam*). This assumption is not unrealistic as are seldom interested in the visibility of a single point. The *los*, which would run through the center of the *los-beam*, is kept for reference. The ends of the beam are planes centered at the observer's and target location. The normal vector of both planes is defined by the direction of the *los*. The width (w) and height (h) of the *los-beam* are arbitrary. The *los-beam* can be thought of as being the result of launching a series *los* parallel to the original *los*, similar to the incoming particles in the previous description. The probability that the target location is visible corresponds to the chance that any *los* within the *los-beam* will pass unobstructed. This probability is a function of the amount of, or lack of, vegetation encountered along the *los-beam*. In the example described here we assume that vegetation intercepts the entire cross section of the *los-beam*, i.e. that the entirety of the *los-beam* is blocked by the vegetation. It is important to keep in mind that this does not need to be the case. In fact the vertical arrangement of vegetation along a *los-beam* will seldom be constant. In some instances the *los-beam* will intercept vegetation partially, or at different locations on the altitude changes along the *los*.

To estimate the likelihood of a target being visible we compute the proportion of the *los-beam* blocked by the intervening vegetation. We approximate the calculation of this value by dividing the length of the volume of the *los-beam* into smaller slices with length Δx analogous to the slices described in the original attenuation description. According to Lambert's law Δx must be thin enough in order to guarantee 'no shadowing', i.e. no two molecules (bits of vegetation in our case) within the thin slice can lie behind each other. For our purposes we define Δx to be the diameter of the circumference that delimits the canopy of an average plant/tree type when projected onto a horizontal plane, see figure 2. We then consider the net blocking effect that the tree has on the *los-beam*, ie, we flatten the tree in the direction of *los*.

<Figure 2. Diameter of a 3D model tree will be used to determine Δx >

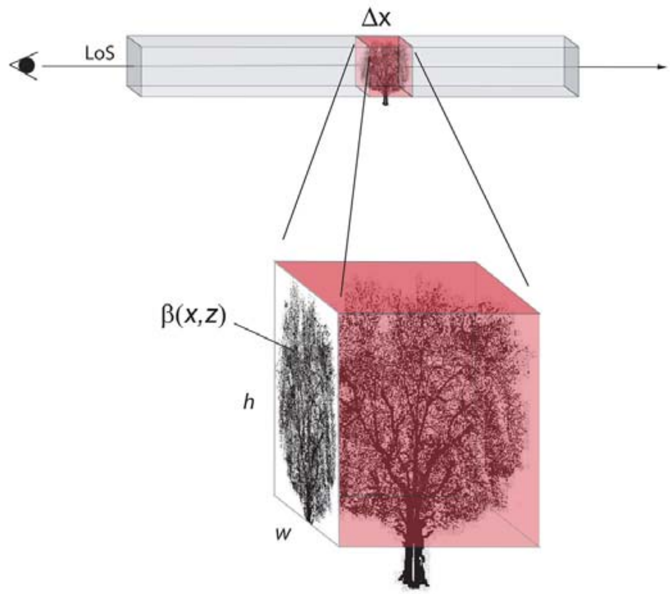
Strictly speaking, Lambert's Law assumes that the particles making up the material, or medium, are randomly distributed and that their number is more or less constant (enough for the mean density per volume of slice to be considered a good estimate). While this is not strictly true in the case of vegetation (ie, bits of vegetation are not randomly moving everywhere) we can relax this restriction which was put in place to simplify calculations and to define upper bounds of probability estimates

To find out how much blockage a *los-beam* will suffer at a distance *x* from the observer we need to consider various factors: the amount of vegetation that the *los-beam* will encounter, which is related to the density of vegetation along the beam, and how much the *los-beam* will be blocked given the angle of incidence of the beam on the vegetation.

Let α represent the cross-section area of the *los-beam* at any location along it ($\alpha = w \cdot h$). Let $\rho(x)$ be the density of vegetation (i.e. number of plants/trees per unit of volume) at a distance x from the observer. For obvious reasons, the number of trees in the volume, $\alpha \cdot \Delta x$, of one of our slices is equivalent to the number of trees found at the base of the slice, i.e. in the area $w \cdot \Delta x$ (see fig. 3). Let $\beta(x,z)$ be the area within α that is 'blocked' by a single average plant/tree located at a distance *x* from the observer and at a relative height *z* above/below the *los*. In this example β is always constant as the relation ground-tree-observer remains the same along the entire *los* length. However the relative height of the tree in relation to the observer is likely to vary in normal circumstances because of terrain variation along the *los* direction.

The ratio of area blocked by the vegetation to the total cross-sectional area of the *los-beam* at x can then be estimated as being,

$$\phi(x) = \frac{\alpha \cdot \Delta x \cdot \rho(x) \cdot \beta(x,z)}{\alpha}$$



<Figure 3. The volume in a *los-beam* is a divided into slices with Δx deep.>

The denominator is the cross-section area of the *los-beam* and the denominator is the area blocked by the vegetation at location *x* from the observer that is contained within a the volume $\alpha \cdot \Delta x$.

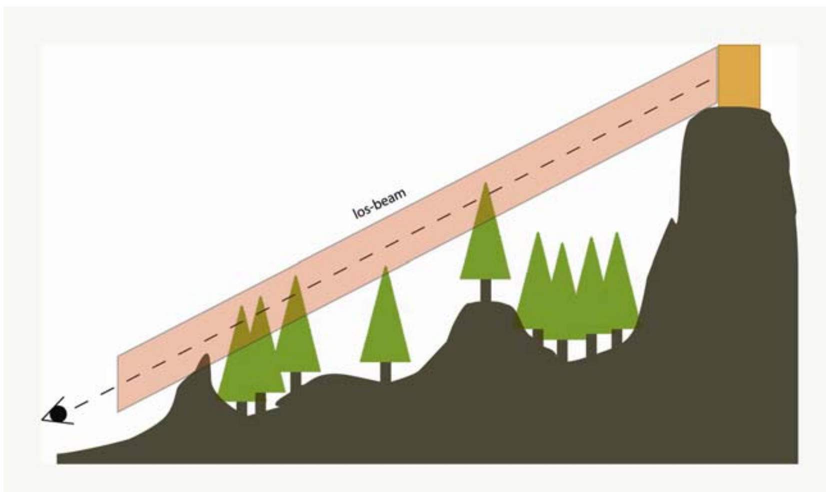
Given our choice of Δx, it follows that $0 \leq \phi \leq 1$. Using the same logic as the one used in the previous section we derive the chance of a *lo-beams* surviving a 'slice of vegetation' as being $1-\phi$. The probability that it will pass through a second 'slice of vegetation' is $(1-\phi)\cdot(1-\phi)$. For n slices, the proportion of *los* that will pass will be $(1-\phi)^n$. If we were to launch an arbitrary number of *los*, say N_0, $N = N_0 \cdot (1-\phi)^n$ of them would pass.

We can interpret the fraction $p(x) = \dfrac{N}{N_0} = (1-\phi)^n$ to be the probability that one of the original N_0 *los* will pass. Let this probability be $p(x)$.Thus we arrive to a similar expression to the one we obtained in the previous section which we could transform into an exponential equation.

$$p(x) = e^{-k(x)\cdot x} \quad (k \geq 0,\ x > 0)$$

x: Represents the distance from the observer along the *los*
k(x): Function based on the density of vegetation along the *los*.

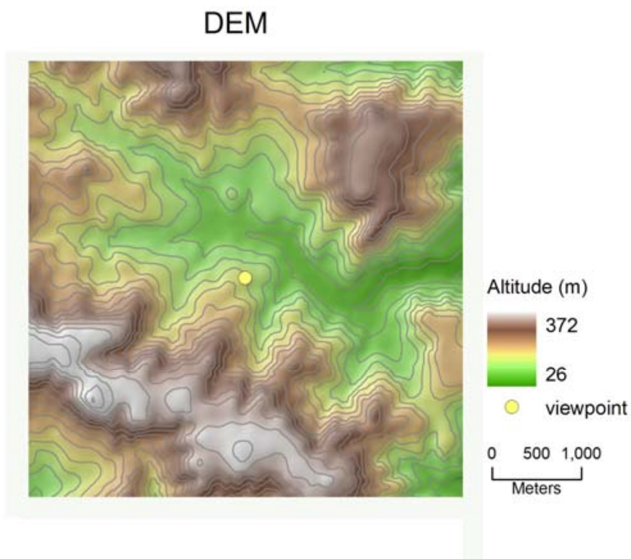
From the above it is clear that the probability of a target location being visible when looking across a volume of vegetation does not decrease linearly but exponentially. This is perhaps the single most important shortcoming of Dean's earlier work. This result is appealing because it coincides with what we experience in reality. As an observer looks towards a target location, vegetation closest to him/her will reduce the viewable area by a certain amount. The probability that the target location remains visible will decrease quite rapidly in the presence of additional vegetation given that all that is needed is that vegetation further behind blocks the remaining viewable area and so on. Note that this result does not imply that in order to calculate visibility through vegetation all we need to do is to incorporate a distance decay function to an ordinary viewshed. This approximation would be marginally correct only if we were on a plane field and the density of vegetation was constant. In order to calculate the probability we are interested in, it is necessary to compute blockage along the *los*. The proper calculation of this blockage is not straightforward as shown in the following sketch (fig. 4)



<Figure 4. Sketch showing a non-trivial blockage pattern along a *los-beam*.>

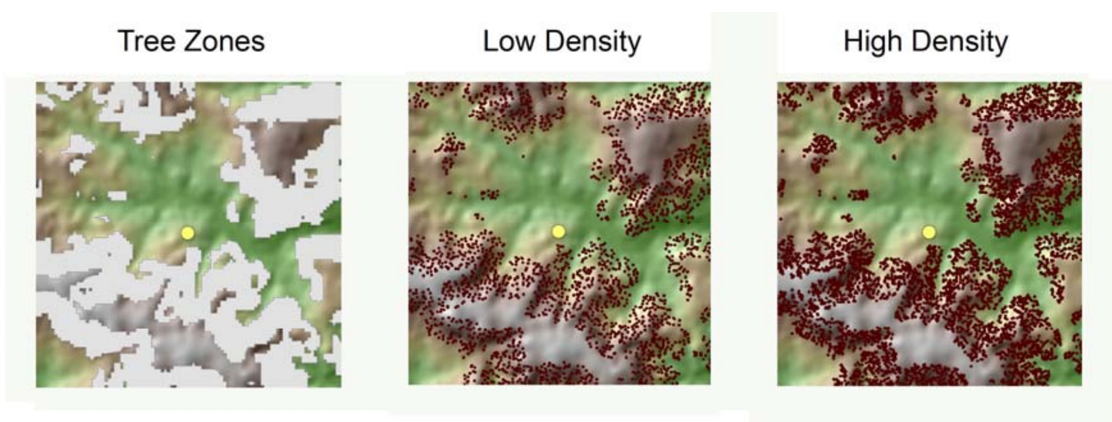
4. Modeling Results

A case study using a synthetic DEM (figure 5) is used to illustrate the application of the model. Several areas in the DEM were selected so that they could be 'populated' with trees (figure 6). In this example the selection is totally arbitrary but ideally it would be the result of a more elaborate (palaeo-)environmental reconstruction.



<Figure 5. Test DEM and observer location>

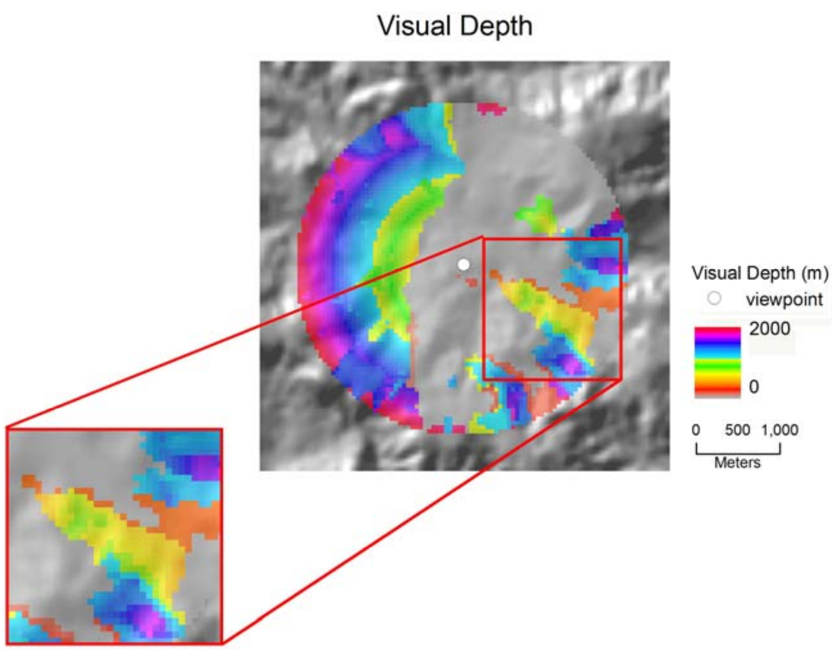
The ensemble of these areas defines a template onto which different levels of tree coverage are mapped. To test the new algorithm, we considered two different scenarios each of which corresponds to different levels of tree density: low, high (figure 6). These levels are constructed by filling the areas outlined by the template with a distribution of random values within pre-determined numerical ranges. The low density scenario is constructed by generating values between 0 and 0.30, while the high density scenario is made out of random values between 0.7 to 1.0. Rather than vegetation density (ρ), these values refer to tree coverage (c), so that a value of 1.0 corresponds to the unit area being totally covered by trees (however many there are) while a value of 0.25 would correspond to one quarter of the unit area being covered by trees.



<Figure 6. The spatial distribution of vegetation for two different levels of density coverage.>

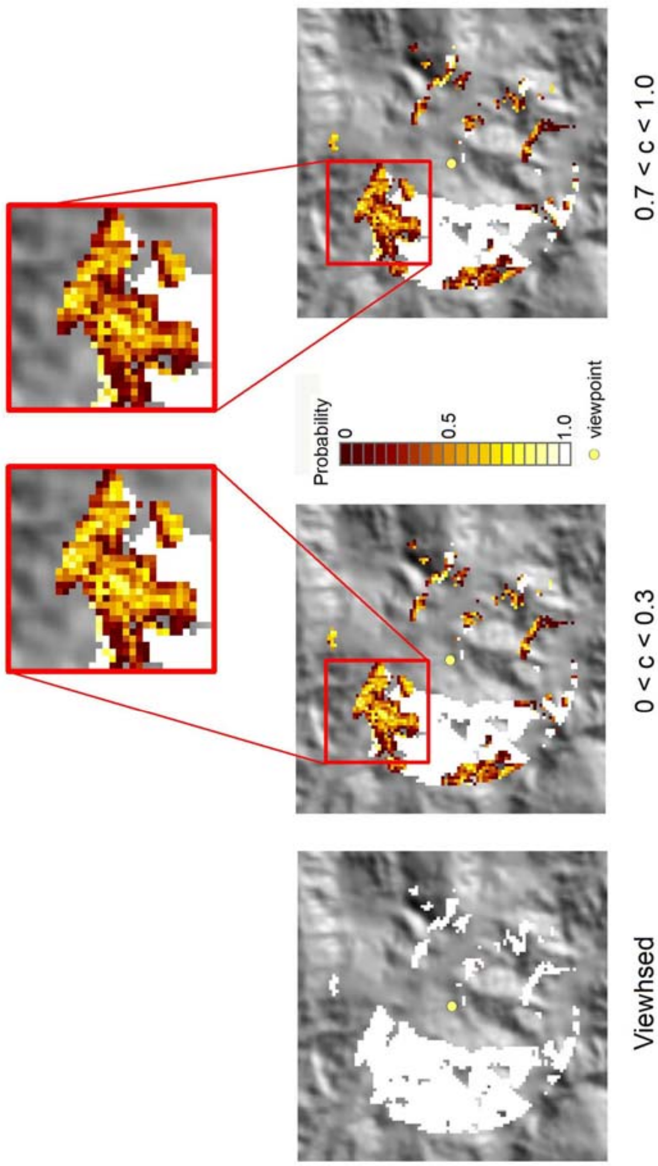
For this particular example, a three-dimensional tree with a volumetric size of 8.15 x 8.15 x 6.00 (meters) was generated. The tree can be thought as being made up by tiny voxels of an arbitrary size (5.0 cm^3 in this instance). It is envisaged that an extended version of this model would include a module dedicated to design and generate trees of different sorts. The possibility of being able to specify the characteristics of the tree provides great flexibility when exploring different possible scenarios as different types of trees and seasonal changes (in the case of a deciduous type) can be easily accommodated.

As a by-product of calculating the probability of visibility it is possible to obtain a raster representing the index of visual depth as shown in figure 7. This index, which is related to Dean's original *visual permeability* concept, represents the depth of view for each location within the viewshed as computed from the observer. It is calculated in planimetric terms, i.e. as the horizontal distance from the observer For any visible location the value of this index coincides with the horizontal distance between the location and the observer. This value will be different for locations that are not visible, either because they are hidden by topography or because their probability of visibility (when computed along the *los*) dropped below a certain threshold value (in this case this value was set to 0.001).



<Figure 7. Index of visual depth calculated for high density coverage (r=2000 m). The inset highlights target points where *los-beam*s were fully obstructed. The visual depth for these locations corresponds to the distance from the observer where the *los-beam* was totally obstructed.>

Finally, figure 8 displays the results obtained after running the new algorithm. The new routine was executed using the vegetation coverage layers described above. The effect that the different vegetation coverages have on visibility is clearly evident when their viewsheds are compared with a typical viewshed (far left in fig. 8). Differences in the probability of visibility between each vegetation coverage level can also be noticed . Except for very simple scenarios, it is hard to predict how these differences will affect the visibility probability. This value is the result of complex interrelationships between the observer, target location, the topographic nature of the area being covered by vegetation, the density at those locations, and how much obstruction the cross-section of the *los-beam* actually encounters. The procedure allows us to detect which areas are totally unaffected by the current vegetation layout in spite of the presence of vegetation. For those affected areas, it provides a measure of the mitigating effect that different vegetation coverages have on visibility. For some locations, the increase in vegetation coverage has a minimal effect as opposed to others.



<Figure 8. Probability of visibility given different vegetation coverages (r=2000 m).>

5. Conclusions and future work

This new algorithm extends current GIS viewshed capabilities by allowing the user to incorporate into the visibility calculation information about the nature of the vegetation (via a 3D model), its spatial distribution and density. As part of a more comprehensive palaeo-environmental reconstruction model, this procedure can be used to explore the effect that different spatial distribution of trees (or other vegetation) and tree densities, may have on the visual quality of a landscape.

The underlying rationale for using the approach was based on cost effectiveness and uncertainty surrounding environmental information. It is simply very difficult, or not worth the effort, to determine where exactly each tree or plant might be located in a landscape. Even if we did have this information we are likely to be more interested in how changes to the layout and density of trees would affect visibility. This is certainly true in the case of landscape archaeology where, except for a few point locations, we can only reconstruct in broad terms the trees and plants that existed at a certain period in time.

There are several ways in which this study and the model presented here can be improved. In spite of the fact that the model presented is based on sound physical principles (derived from Lambert's attenuation law) the model remains theoretical in so far that it has not been tested empirically. Testing this model would require access to a study area with certain characteristics and availability to specific information:

- An area dominated by a single type of tree.
- An area for which an estimated tree/vegetation coverage layer could be calculated with some degree of accuracy.
- A good quality DEM.

It is hoped that this information will be available in a near future and that testing will take place soon after.

The algorithm itself can be extended and improved in other ways; for instance, it could be altered to consider the effect of different types of vegetations and their associated densities simultaneously. It could also be expanded to incorporate random versions of the three-dimensional model representing each tree type (by introducing random changes in foliage and size). Other improvements may be achieved by substituting the *los-beam* by a solid angle, and simulating the *visual fusion* of distant objects. At the moment the cross-section area of the *los-beam* remains constant throughout the length of the *los*. The introduction of solid angle (i.e. rectangular based pyramid with its apex theoretically located at the observer's eye) would have the effect of reducing the cross-sectional area closer to the observer. This in turn, would put more weight on vegetation nearest to the observer. Visual fusion, the effect of merging distant objects into a pattern, may also be simulated by dynamically altering the resolution used to map trees onto the *los-beam*. Trees further away would be mapped into larger 'chunks' of the *los-beam*.

While the principles of the model are better understood in stochastic terms, the implementation of the model is not 100% stochastic. Indeed a purely stochastic model would not be satisfactory. Human vision has developed to spot order within nature. An algorithm that was 100% stochastic would not, for this reason, be appropriate. The model is constructed using a mixture of random and non-random elements. This combination allows us to address within the same modeling framework both the structural and variable character associated with vegetation in a landscape. Landscape variability may be introduced using different spatial distributions of vegetation patches and different density levels. The structural component is incorporated through the use of three-dimensional representations of the vegetation that capture, to various degrees of complexity, the specifics of different vegetation types.

The algorithm presented here had a very concrete goal: to calculate a 'probability' viewshed given a certain spatial distribution and density of trees. While the results presented here are thought to be valuable in their own right, the impact and wider implications of this algorithm can only be fully understood when we consider the routine as being part of a wider modeling effort, and further empirical tests have been undertaken.

Acknowledgements

I would like to acknowledge Prof. Tim Sluckin (School of Mathematics, University of Southampton, UK) for clarification of some of the key concepts in the Physics literature. Dr. Lee Hazelwood (National Air Traffic, UK) for pointing out the resemblance of some of my early work with Lambert's Attenuation Law, and Dr. Steven Goodreau (Anthropology, University of Washington, USA) for checking through my work and providing much valued suggestions in the face of some obstacles and two anonymous referees for several insightful comments.

References

BISHOP, I.,D., 2002 Determination of Thresholds of Visual Impact: the Case of Wind Turbines. *Environment and Planning B* 29, 707-718

BISHOP, I., D., WHERRETT, J., R., & MILLER, D., 2000. Using Depth Variables as Predictors of Visual Quality. *Environment and Planning B* 27, 865-875

DEAN, D., J., 1997, Improving the Accuracy of Forest Viewsheds Using Triangulated Networks and the Visual Permeability Method. *Canadian Journal of Forest Research* **27**: 969-977

FISHER, P., 1995, An Exploration of Probable Viewsheds in Landscape Planning. *Environment and Planning B* **22**, 527-546

FRIEDLANDER, K., S., 2000, *Smoke, dust and aerosol: fundamental of aerosol dynamics*. New York: Oxford University Press

HALLIDAY, D., RESNICK, R., and WALKER, J., 2004, *Fundamentals in Physics*. New York: Wiley & Sons.

LLOBERA, M., 2006, Seeing is believing: GISc and the visual. In *Classics IJGIS* edited by P., Fisher, (London: CRC Press)

WHEATLEY, D., W., AND GILLINGS, M., 2000. Vision, Perception and GIS: Developing Enriched Approaches to the Study of Archaeological Visibility. *Beyond the Map* edited by G. Lock, (Amsterdam: IOS Press), pp. 1-28

TSCHAN, A., 2000. Perception and Viewsheds: Are They Mutually Inclusive?. *Beyond the Map* edited by G. Lock, (Amsterdam: IOS Press), pp. 29-48