The time-in-daylight land-surface parameter

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Abstract—**Time-in-Daylight (TiD) estimates the portion of total daylight over a time span that a location experiences direct radiation. This paper describes a method for estimating TiD using horizon angle maps derived in a range of azimuths and information about the sun's position during the time span. TiD is evaluated as a potential land-surface parameter (LSP) for relief mapping and solar radiation modelling applications. The use of horizon angle to map shadow areas in calculating TiD makes this LSP conceptually similar to both openness and sky-view factor (SVF). However, TiD differs most significantly in the pairing of horizon angle maps with a dynamic model of sun position. The findings showed that TiD is well suited to applications in relief visualization, particularly with digital surface models (DSMs) in urban areas. The ability to estimate TiD with specific date/time ranges also makes it better suited for solar radiation modelling applications than either openness or SVF.**

I. Introduction

Shaded-relief mapping, or analytical hillshading [1], is one of the most common land-surface parameters (LSP) derived from digital elevation models (DEMs). Hillshading is often used for topographic visualization and as a predictor in environmental modelling applications involving solar radiation [2]. Despite its widespread use, there are issues with the application of hillshade maps in both of these areas. Interpretation of the terrain is highly sensitive to the light-source-viewer orientation—under some conditions, relief can appear inverted, with elevated sites appearing to be low-lying and vice versa, a phenomenon known as the pseudoscopic illusion [3]. Furthermore, the degree to which topographic features are apparent in hillshade maps is very dependent upon their orientation relative to the light source. Some researchers have also argued that the use of a single light-source direction with the traditional hillshade method results in near-complete loss of detail both within the darkened areas sloping away from the light source and in over-exposed areas directly facing the light, although this deficit can be addressed by applying a weighted average of multiple light-source directions in a multi-directional hillshade [4]. Lastly, because hillshading is based solely on the local topographic properties of slope gradient and orientation, it cannot account for shadowing from distant terrain [5].

These issues have led some researchers to develop alternative LSPs that overcome the limitations of hillshading, including the openness index [6] and the sky-view factor (SVF) [5, 2]. Both of these alternatives have found broad application, particularly in archeological surveying [7]. This paper describes a new LSP, called Time-in-Daylight (TiD), that can be used as an alternative to hillshade maps in relief visualization and solar modelling applications.

II. Time-in-Daylight (TiD)

A. *Definition*

TiD is defined as the portion of the total daylight period over a span of time that a location experiences direct radiation. TiD ranges from 0 (full shadow) to 1 (full sun). Thus, it is effectively the result of the integration through time of a dynamic Boolean shadow/sunlight model. Fig. 1 shows an example of a TiD map derived from a 10-m lidar DEM of an area south of Brantford, Canada. TiD has been calculated in this example using the full day and full year. Darker areas represent sites that experience more shadowing throughout the year.

B. *Estimation and implementation of TiD*

Whether or not a site is contained within a shadow area at a particular time is determined by the sun's position (altitude and azimuth, θ and φ respectively) and the horizon angle (ω) in the direction of φ [5]. ω is the maximum vertical angle between the horizontal plane and the topography (i.e., the horizon) in a direction. When θ is lower than the local horizon angle, the site is within a shadow cast by a distant object. Thus, thresholding a ω-map for a particular sun position will produce a shadow model for an instant in time. TiD can be estimated by deriving a series of ω-maps from a DEM corresponding to the sun positions for a specified time span and then, for each grid cell, determining the portion of maps (or duration) the cell is in sunlight. We only consider times when the sun is above the nominal horizon, i.e., $\theta > 0$, which ensures that TiD ranges from 0 to 1.

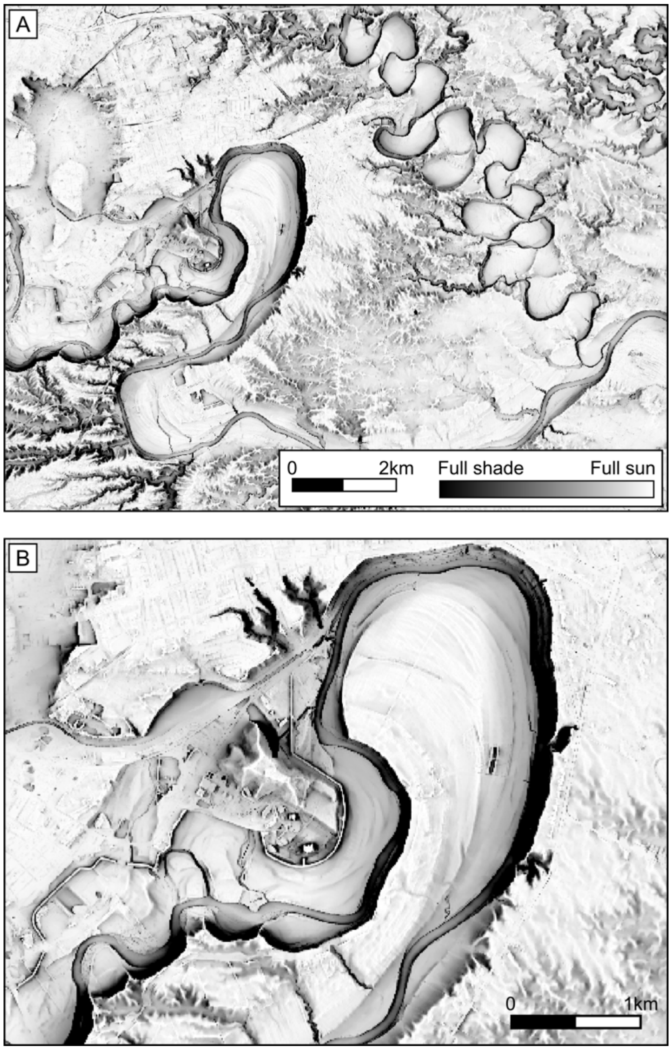

Figure 1. TiD for a site south of Brantford, Canada. TiD should be displayed using a greyscale with lighter colors associated with brighter areas.

Because it is impractical to sample time continuously, there are two approaches to estimating TiD. A TiD implementation may either discretize time, sampling at regular intervals and estimating the ω-maps at each individual time stamp, or φ may be discretized, i.e., sampling at a constant azimuth interval and then calculating the times at which the sun is located at each φ value for each day in the time span (if the span includes multiple days, there will be multiple times). The first approach has the advantage that, because each sampled time is of equal duration, one merely needs to count the portion of ω maps in sunlight to estimate TiD. However, each sampled time is likely to have a unique φ, and because ω must be calculated to correspond to φ, potentially a very large number of ω-maps will need to be estimated (one for each sampled time over the span). The second approach offers the main advantage that there are significantly fewer ω-maps that must be calculated (360 divided by the φ-interval minus the φ-intervals for which the sun is never above the horizon during the time span). However, because the rate of change in φ is not constant during the day, each sampled φ-interval represents a varying duration, and a time-weighted sum must be used to estimate TiD. Ultimately, of the two main computational tasks involved in measuring TiD, i.e., tracking the change in solar position during the time span and calculating ω-maps, the latter is by far the more computationally intensive. Thus, the second approach is recommended, and it is this method that is used in the TiD tool implemented in the WhiteboxTools open-source GIS software [8].

In applying the WhiteboxTools TiD tool, the user must specify the φ-interval, the maximum search distance used for calculating ω, the location (latitude and longitude) of the mid-point of the input DEM (used to calculate sun positions), and the time span. The search distance and φ-interval parameters both impact processing times, although performance is more sensitive to the later parameter (Table I). The span is provided as starting/ending days of the year and starting/ending times of day. Therefore, TiD can be estimated for a range of days, e.g., a season or the whole year, or for specific times of day, e.g., mornings or afternoons. For instance, Fig. 2 shows TiD maps for different time spans derived from the same 0.5-m lidar digital surface model (DSM) of a suburban neighborhood in Guelph, Canada. The WhiteboxTools TiD tool is currently limited to application with projected DEMs and does not account for Earth's curvature. It is therefore best applied to surface models with less than regional-scale spatial extents.

TABLE I. PROCESSING TIME ON M1-MAX PROCESSOR TO CALCULATE TID WITH VARYING PARAMETER VALUES FOR A 47.5 MILLION GRID CELL DEM.

Parameter Values	*Time (mm:ss)*
100-m search distance, 15° φ-interval	03:46
50-m search distance, 15° φ-interval	03:13
10-m search distance, 15° φ-interval	02:32
50-m search distance, 5° φ-interval	09:20
50-m search distance, 10° φ-interval	04:46
50-m search distance, 30° φ-interval	01:42
50-m search distance, 45° φ-interval	01:16

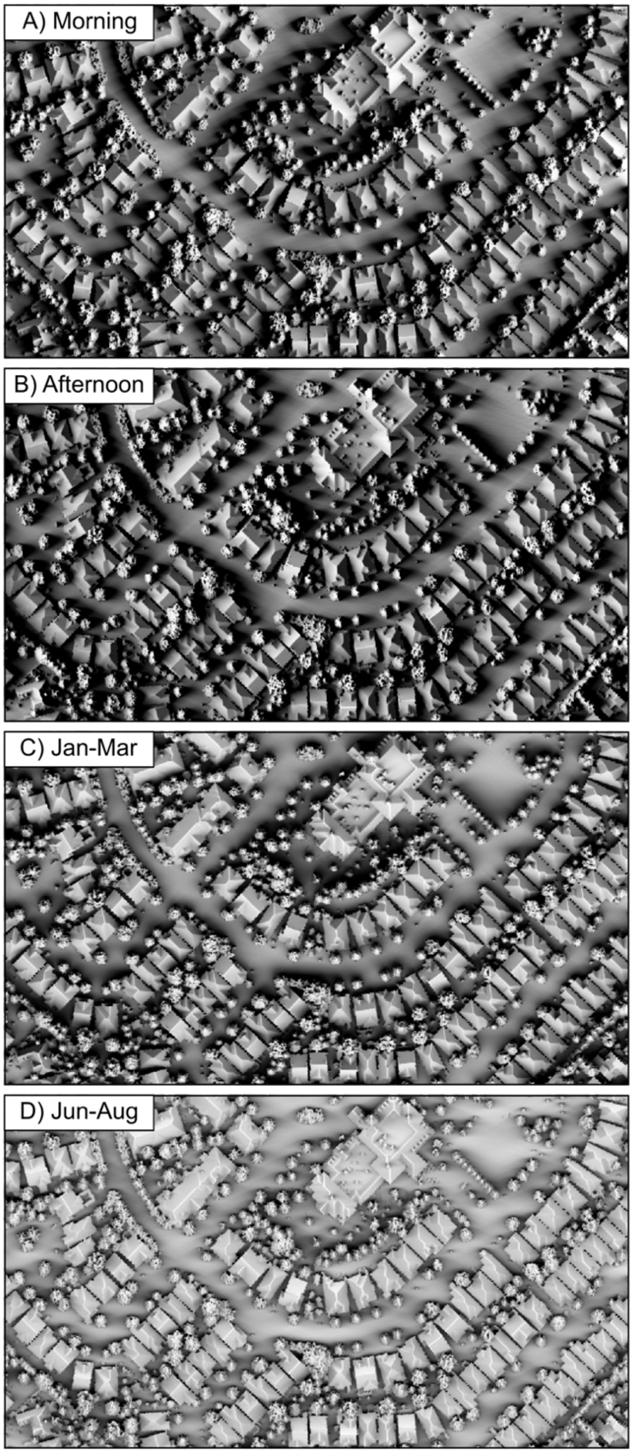

Figure 2. TiD calculated for A) sunrise to 09:30 (full year), B) 15:30 to sunset (full year), C) January to March (full day), and D) June to August (full day). In each image, lighter colors indicate fuller sunlight.

The tool has been implemented using the Rust programming language and uses parallelized code for calculating ω-maps to improve computational performance. The use of a maximum search distance parameter (also used in the calculation of openness and sky-view factor) improves the performance of the tool. The ω algorithm also only estimates the slope between the source grid cell and cells along the search line when a new maximum elevation is detected, since comparing elevations is faster. Lastly, the search for ω for a grid cell can be cut short before the maximum distance is reached if a ω-value greater than a threshold (set to 80-degrees) is encountered. Such high slopes can only typically occur when the obstruction cell (horizon) is located near the query cell and a substantial increase in elevation would be necessary for a more distant grid cell to form the actual horizon. This short-circuiting can improve algorithm performance, particularly when applied to DSMs in urban areas containing numerous buildings and vegetation.

C. *Comparison with hillshade, openness, and SVF*

The WhiteboxTools TiD algorithm was found to be faster than the Saga GIS SVF tool when applied with similar parameter values, although both LSPs took considerably longer to process a 47.5 million grid cell test DSM of the Guelph area than either hillshade or positive openness (Table II).

TABLE II. PROCESSING TIME ON M1-MAX PROCESSOR TO CALCULATE VARIOUS LSPS FOR A 47.5 MILLION GRID CELL TEST DEM.

LSP	*Parameters*	*Time (mm:ss)*
Hillshade	$\theta = 30°$, $\varphi = 270°$	00:01
Openness	100-m search distance	00:12
SVF	100-m search distance, 10° φ-interval	10:33
TiD	100-m search distance, 10° φ-interval	05:58

Fig. 3 compares hillshade, positive openness, SVF, and TiD for an area of the University of Guelph campus. It is evident that as a relief visualization technique, hillshade is less satisfactory than the other LSPs for this dataset; it appears flat by comparison and its basis on local 3x3 neighborhoods makes it unable to capture the relative height differences among the many off-terrain objects in the DSM. Positive openness, SVF and TiD appear similar, although TiD is most like openness (Figs. 3D and 3B). TiD does appears smoother than openness, but this is solely due to the finer φ-interval used in its calculation, which is also the primary reason why openness is faster to estimate (Table II). Unlike openness and SVF, TiD appears less omni-direction in illumination, which is apparent where one side of buildings is more brightly lit than the reverse side. The SVF raster has a strong dependency on local slope, which is something that has been previously observed about the LSP [7].

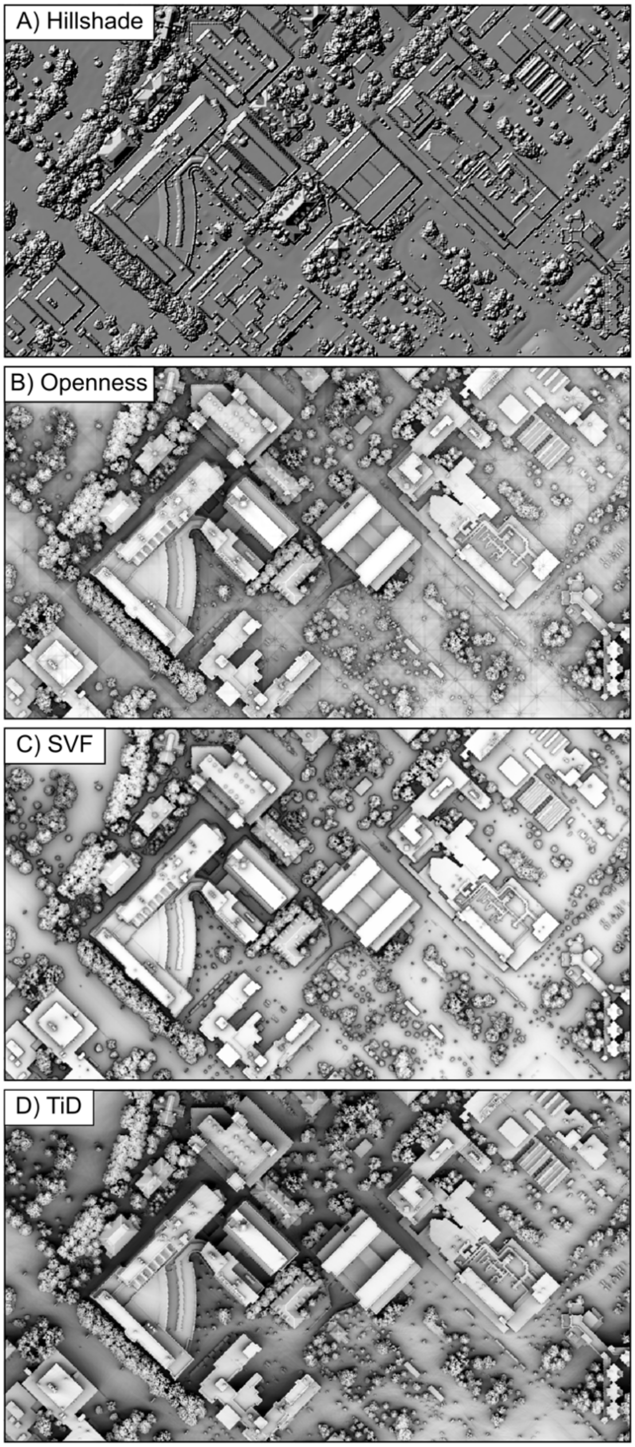

Figure 3. Hillshade (A), positive openness (B), SVF (C), and full-year TiD (D) for an area of the University of Guelph campus. In each image, lighter colors indicate higher LSP values.

III. Discussion and Conclusions

For relief visualization mapping, positive openness, SVF, and TiD are each better suited than traditional hillshading for application to DSMs in complex urban settings. The extended neighborhoods used to calculate distant horizons can encode information about the relative heights of buildings and vegetation, which means that they generally appear less flat than hillshade maps (Fig. 3). Full-year TiD has a directional lighting that is dictated by the local solar almanac and, therefore, has less omni-directional illumination than either openness or SVF. Whether or not this property provides advantages for relief mapping visualization is debatable and in practice all three LSPs (openness, SVF, and TiD) provide similar looking relief maps.

TiD has advantages over similar LSPs, however, for modelling the spatial pattern of solar energy potential. TiD is a measure of the direct solar radiation potential while openness and SVF are more related to diffuse radiation. The ability to restrict TiD calculation to specific day ranges (Fig. 2) could be useful for crop growth modelling, where TiD could be calculated over the growing season for specific crops in a region. Similarly, the ability to restrict TiD to certain times of day (Fig. 2A) could be useful for power utility companies engaged in residential rooftop solar-panel installation. For example, it would be possible to estimate TiD from lidar DSMs of residential neighborhoods during peak-demand times to help utilities target residences with suitably exposed properties for rooftop solar panel installation.

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