MODELING INSOLATION IN THE APPLICATION DOMAIN OF GIS

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ABSTRACT.
The estimation of insolation - exposure in direct sunlight - at various geographic locations in a certain context of time is extremely significant provided that solar radiation is the controlling factor for many natural processes on earth. Insolation is by nature a spatio-temporal phenomenon, which should be handled accordingly. This study presents an insolation modeling approach, which applies and extends the utilities offered by commercial Geographic Information System (GIS) software packages. A prototype system has been developed as an outcome of these efforts. This prototype is connected to a public domain server, which provides sun location for any temporal instance as related to the region of interest. If topography of this region is known, the corresponding insolation can be computed (based on a simplified computation model) and modeled for a specified temporal interval. This study can be also considered as a paradigm of modeling spatio-temporal phenomena with exploitation and extension of GIS functionality.

KEYWORDS. Insolation, spatio-temporal modeling, GIS functionality.

1. INTRODUCTION

The computation of the insolation is of vital importance for numerous applications, which examine the natural processes. Notice that the sun provides the 99.97% of the heat used at the earth's surface for all natural processes, while the annual mean energy received from the sun is 1.5 X 10^{18} Kwh (Henry and Heinke 1996).

At a *global scale* the latitudinal gradients of insolation, caused by the geometry of Earth's rotation and revolution about the sun, are well known (Boecker and van Grondelle 1995, CEC 1984). At *local scale* (landscape scale), the major factor modifying the distribution of insolation is topography (Kumar 1997). The main local gradients of insolation are caused by elevation variation, surface orientation (slope and aspect) and shadows cast by topographic features.

For most geographical areas accurate insolation data at this local scale are not available and their production requires dense field data collection, which is not applicable in extended areas because of high cost(Dubayah and Rich 1995)

Due to the dynamic nature of the earth-sun system, the insolation varies from location to location on the earth surface and from time to time. Hence insolation is a *spatio-temporal phenomenon* and should be handled accordingly.

The major fruit of technological evolution on the area of spatio-temporal data modeling are *geographic information systems* (GIS). Commercial GIS software packages, although rich toolboxes, they have limited capabilities in modeling and handling complex spatio-temporal phenomena. Specifically, it is widely recognized that these systems (Longley et al. 2000): do not accommodate the temporal dimension of geographic data; they provide a limited built-in analytical and modeling functionality; and their level of intelligence is inadequate.

This study makes an attempt to damp down these deficiencies by enriching the analytical functionality of a GIS. Specifically, an approach for modeling the spatio-temporal phenomenon of insolation in the application domain of GIS is investigated.

Notice that it is out of the scope of this study to provide a complete model for computing insolation. In the opposite, it assumes a rather simplified model and concentrates on the implementation methodology of this model. We argue that an integral model might be implemented in a similar manner.

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The discussion is organized as follows. Section 2 presents the simplified model for computing insolation in a spatio-temporal context. Section 3 presents a conceptual framework for computing insolation. Section 4 shows how a commercial GIS software package can be exploited to assist the implementation of the spatio-temporal procedure. Section 5 delineates the architecture of a prototype system for computing and visualizing insolation in a real-time environment. Finally, Section 6 concludes the discussion by summarizing the contributions of the study and giving hints for future research.

2. A SIMPLIFIED MODEL FOR COMPUTING INSOLATION

The intensity of solar radiation reaching the top of the atmosphere is estimated to be about 1367 W/m^2 measured at right angles to the solar beam (solar constant) (Henry and Heinke 1996). The radiation received at the earth surface is well below this value. The distribution of solar radiation is as follows: 17% absorbed by clouds and atmosphere gases, 30% is reflected back to space from clouds and atmosphere gases, and 53% reaches the ground (2/3 is direct sunlight and 1/3 is diffusion). These percentages vary due to local conditions (e.g., different humidity conditions, etc.). Notice that the actual mean intensity (averaged over 24 h) of solar radiation at ground varies from 250 W/m^2 in subtropical deserts to 80 W/m^2 in cloud subpolar areas. In low - mid latitude areas – as Greece – mean values are about 200 W/m^2.

As mentioned already the scope of this study is far from adopting a complete model for computing insolation. In contrary, it assumes a rather simplified model, which is presented next.

The simplified model adopted in this study for computing insolation is based on the following assumptions:

(a) The region under examination is relatively small. Hence its projection in a 2D plane is free of distortions.

(b) Provided the large distance of the sun from earth, the sun can be considered as a point light source for an observer on earth. In addition, sunrays reaching the region are parallel to each other.

(c) Only direct sunlight (about 1/3 of the total sun radiation) striking straightforward the earth surface is considered. Therefore, we ignore any light as result of diffusion, reflection, or cloud effects.

The earth is moving around the sun and turning around itself. Consequently, the insolation is variable and is a function of both *space* (location on the earth surface) and *time*. In our simplified model we assign to insolation a value, which is equal to the angle ϕ of the normal vector of a geographic location N and the direction of sunrays L at a temporal instance.

Referring to Figure 1, insolation value for point D at time t_1 is equal to the cosine of ϕ. Therefore insolation value varies from 0 to 1, which correspond to 90 and 0 deg, respectively. At time t_1, point A is assigned the value 1 ($\cos 0^\circ$). This value corresponds to the highest possible insolation. All areas not visible from the sun (due to the interpolation of a natural or artificial obstacle) are assigned the null value, which corresponds to no-insolation. Hence, all individual locations between D and F (e.g., location E) are assigned the null value for insolation.

Obviously, this model for assigning estimates of insolation is not exploitable as it is for a real world application. Parameters like the light diffusion, the season (i.e., distance between earth and sun), the existence of clouds or humidity, the reflectance of neighbor regions, etc., are omitted. Our main aim was not to present a new complete algorithm for insolation calculation, but to introduce a spatiotemporal modeling for insolation estimation in a GIS application domain.

3. A CONCEPTUAL FRAMEWORK FOR MODELING INSOLATION

The scope of this Section is to present a conceptual framework for modeling insolation. As stated previously, insolation is a spatio-temporal phenomenon. Therefore a *spatio-temporal model* should be applied to represent insolation values at different locations of the region under study during a temporal interval.

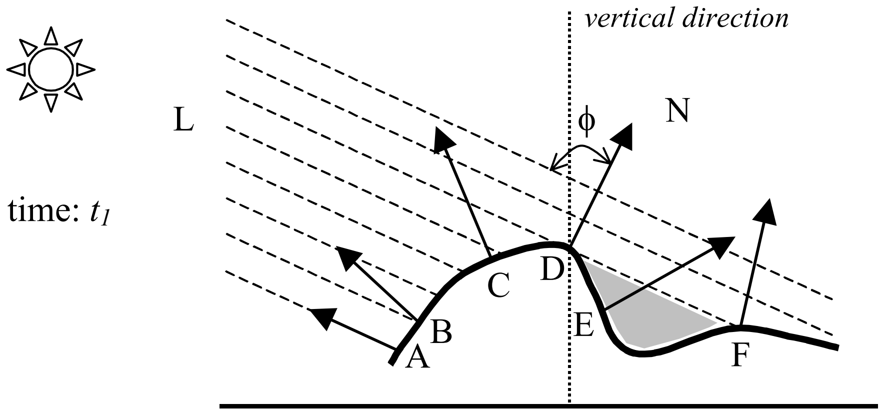


Figure 1. Relationship between normal vector of an individual location and direction of light.

The spatio-temporal model adopted in this study is based on a common *spatial model*, first introduced by Tomlin (1990), and later extended (Stefanakis 2001) to accommodate *time*. This model treats in an elegant manner both single and related collections of spatial entities; and can be used to define spatial operations independently on the fundamental models available in literature (Aronoff 1989): the vector model and the raster model.

The spatio-temporal model is defined as follows. Geographic entities are represented as a set of locations in *space-time* (the notion of "chorochronos") with a set of properties characterizing those locations. Depending on the application, space can be handled as a two- or three-dimensional domain. For a 2D space, provided that, time can be considered as linear, space-time is represented in a 3D modeling space. Two dimensions are reserved to describe the geographic location of entities (space) and one to describe their temporal status. Thematic data are associated to geographic entities and characterize them.

The data model can be viewed as a hierarchy of data. At the highest level, there is a space-time cube (2+1D modeling space), which is called *map*. The map is a library of space-time cubes, called *thematic layers*. Each thematic layer refers to a theme characterizing geographic entities. All thematic layers are in registration (i.e., they have a common space-time coordinate system, which coincides with map system). Each thematic layer accommodates the theme value of each *individual space-time location*. A space-time location is the smallest spatio-temporal unit of interest (and defined the generalization level) for the corresponding layer in the application domain. It is defined by the granularity in both space and time and can be generalized or specialized by applying appropriate operations. All individual locations with: (a) a theme value within a specified range [a,b], (b) a geographic location within a geographic space S, or (c) a temporal location within a temporal space T, constitute a *space-time zone*. Geographic entities of interest are represented by space-time zones and identified uniquely. Therefore, each entity is represented by a set of individual locations.

Figure 2 illustrates an example of the insolation thematic layer in Mykonos Island, Greece, during the winter solstice in 2001. Notice that each individual spatio-temporal location accommodates the corresponding insolation value, which has been in turn computed based on the model presented in Section 2.

A thematic layer, as defined in the previous paragraphs, is three-dimensional and represents a *dynamic* (spatio-temporal) theme, which characterizes a phenomenon. *Static* themes, for instance the hypsography of Mykonos Island, are modeled in a 2D (plane) layer as defined in the original Tomlin's spatial model (Tomlin 1990).

The operations for handling and reasoning on thematic layers (data interpretation operations) are done in a layer-by-layer basis. That is, each operation accepts one or more existing layers (cubic or plane layers) as input (the operands) and generates a new layer (cubic or plane layer) as output (the product), which can be used as an operand into subsequent operations.

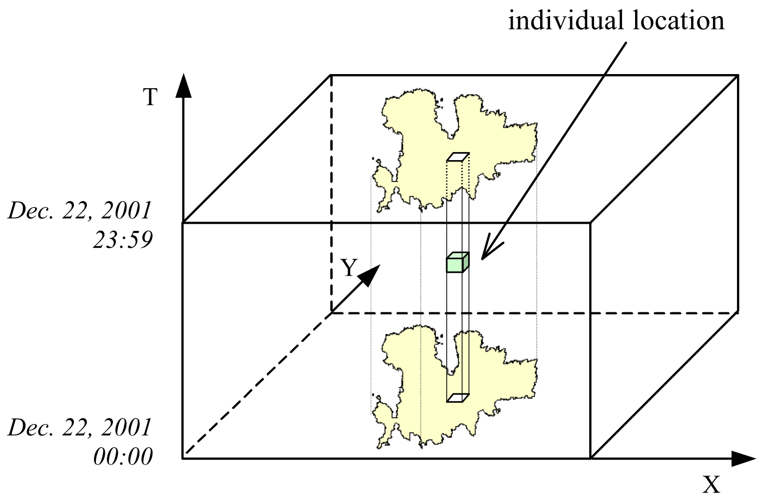


Figure 2. A spatio-temporal thematic layer representing insolation.

Figure 3 presents a procedure (sequence of operations) that results in the insolation thematic layer. The input of this procedure is the hypsography (plane) layer of the region under study and the sun position (cubic) layer for the temporal interval of interest. The procedure consists of two operations. The first (operation 1) is a pure spatial operation. It gets as input the hypsography layer and provides as output a plane layer of normal vectors. The second (operation 2) is a spatio-temporal operation. It gets as input the normal vectors (cubic) layer and the sun position (cubic) layer. The operation results in the insolation (cubic) layer, which is similar to the spatio-temporal cube shown in Figure 2.

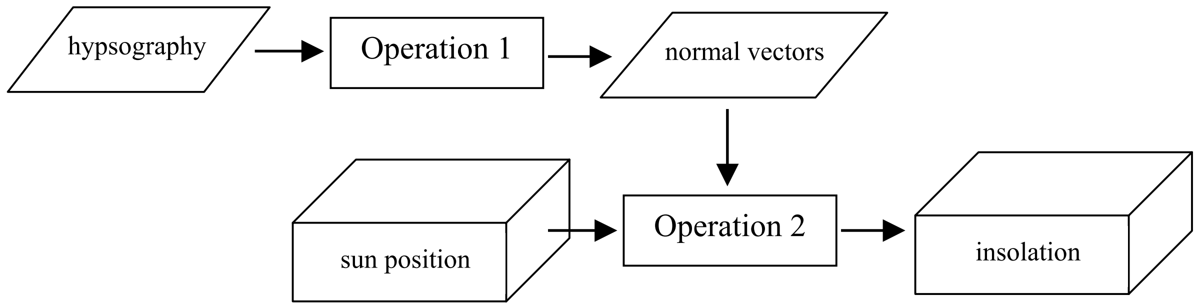


Figure 3. The spatio-temporal procedure to compute insolation thematic layer.

4. MODELING INSOLATION IN A COMMERCIAL GIS PACKAGE

Commercial GIS software packages do not provide any operation for computing insolation explicitly (Kumar et al. 1997). There are several reasons for this:

(a) The GIS package does not provide explicitly normal vectors for individual locations (in grid model) or triangles (in TIN model) used to represent the earth surface morphology (Burrough and McDonell 1998, Jones 1997).

(b) There is no model or utility available to compute the real-time position of the sun in a commercial GIS package.

(c) GIS software packages do not accommodate time explicitly. Snapshots are used instead to represent the evolution of a spatial phenomenon in time. Those snapshots constitute a rough generalization of temporal evolution. Additionally, the snapshots are independent to each other and they are not explicitly interrelated in the system.

Obviously, a GIS software package seems unable to conclude itself the application of insolation modeling. However, a commercial GIS offers several utilities, which might be useful in an attempt to develop a prototype system for computing and modeling insolation.

Specifically, a GIS usually provides utilities for computing *hill shading* from a digital terrain model (DTM) assuming a non-moving light source. The position of this light source is selected either artificially or based on the real sun position at a given time stamp. The former case, usually adopted in automated cartography, locates the light source at north-west and 45° above the horizon. This convention has much more to do with human optical perception than with astronomical reality (Burrough and McDonell 1998).

Additionally, a GIS package provides operations for computing slope and aspect values for each construct (grid cell of TIN triangle) of the DTM. Normal vectors of these constructs can be derived from the appropriate combination of slope and aspect values. The GIS package also considers shadow effects.

A prototype system for computing and visualizing insolation, which extends GIS functionality, is described next.

5. A PROTOTYPE SYSTEM FOR COMPUTING AND VISUALIZING INSOLATION

Figure 4 illustrates the architecture of the prototype. The core system consists of a commercial GIS software package supporting the grid data model (ArcView8 and Spatial Analyst Extension from ESRI). This software is extended with some external analytical functions (developed in a third-generation programming language) and communicates with a public domain server (http://aa.usno.navy.mil/ data/docs/AltAz.html), maintained from U.S. Naval Observatory, which provides the astronomical calculations as relates to sun position.

The DTM of the study region is created initially using GIS functionality and exploiting appropriate data (hypsography measures) from external sources. The user defines the related spatio-temporal parameters, namely the time interval and time step. The web server provides the system with the real sun position catalog (azimuth, altitude for each time step), based on the above parameters (Figure 5).

A special application has been developed to compute insolation snapshots, based on aspect and slope values provided by common GIS functionality in combination with sun position estimations.

A second application makes use of the insolation snapshots and generates shaded relief map series plus local insolation reports or animated maps.

Notice the extensibility that characterizes the prototype. Special applications can be also developed to support other decision-making processes using various other layers (vegetation, surface temperatures, etc.).

Figure 6 presents five snapshots, which corresponds to successive sun positions with a two-hour difference (approximately) during the winter solstice.

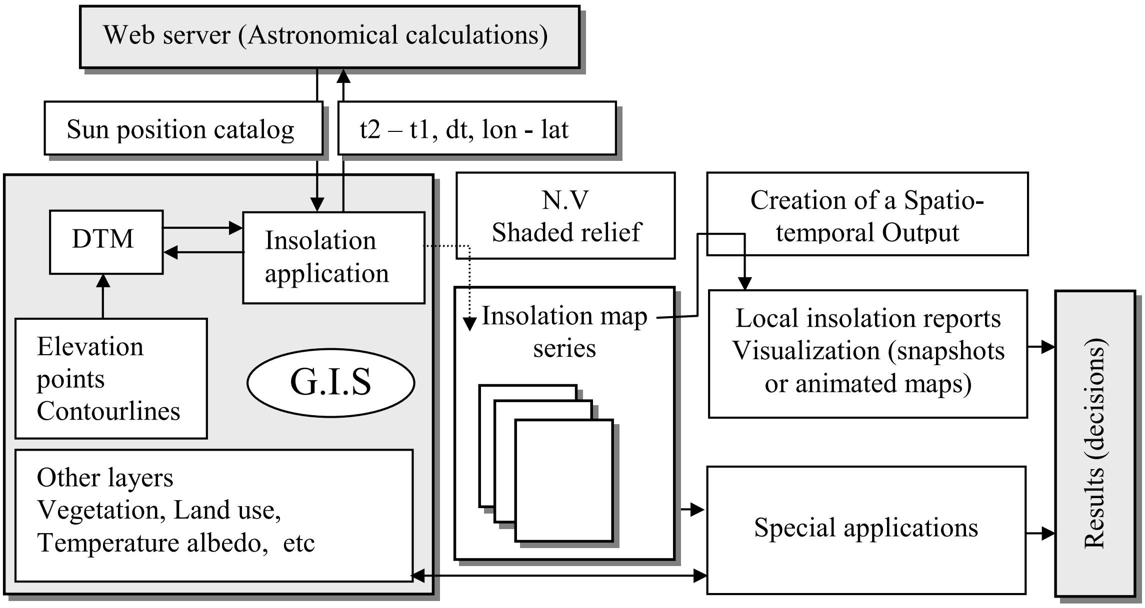
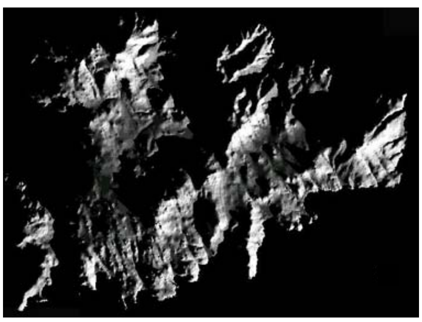


Figure 4. The architecture of the prototype system.

MYKONOS
Altitude and Azimuth of the Sun
Dec 22, 2001
Zone 2.00 East of Greenwich

h m	Altitude o	Azimuth (E of N) o
06:30	-11.4	110.9
07:00	-5.9	115.2
07:30	-0.7	119.6
08:00	4.6	124.3
08:30	9.2	129.3
09:00	13.6	134.7
09:30	17.6	140.5
10:00	21.1	146.8
10:30	24.0	153.5
11:00	26.3	160.7
11:30	27.9	168.2
12:00	28.8	175.9
12:30	28.8	183.8
13:00	28.0	191.6
14:00	24.1	206.3
14:30	21.2	213.0
15:00	17.7	219.3
15:30	13.7	225.1
16:00	9.4	230.5
16:30	4.7	235.5
17:00	0.1	240.2
17:30	-5.7	244.7
18:00	-11.2	248.9

Figure 5. Sun position catalog (Source: US Naval Observatory).



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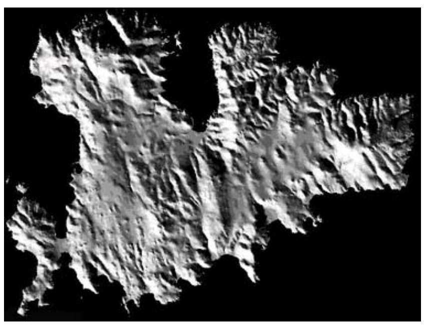

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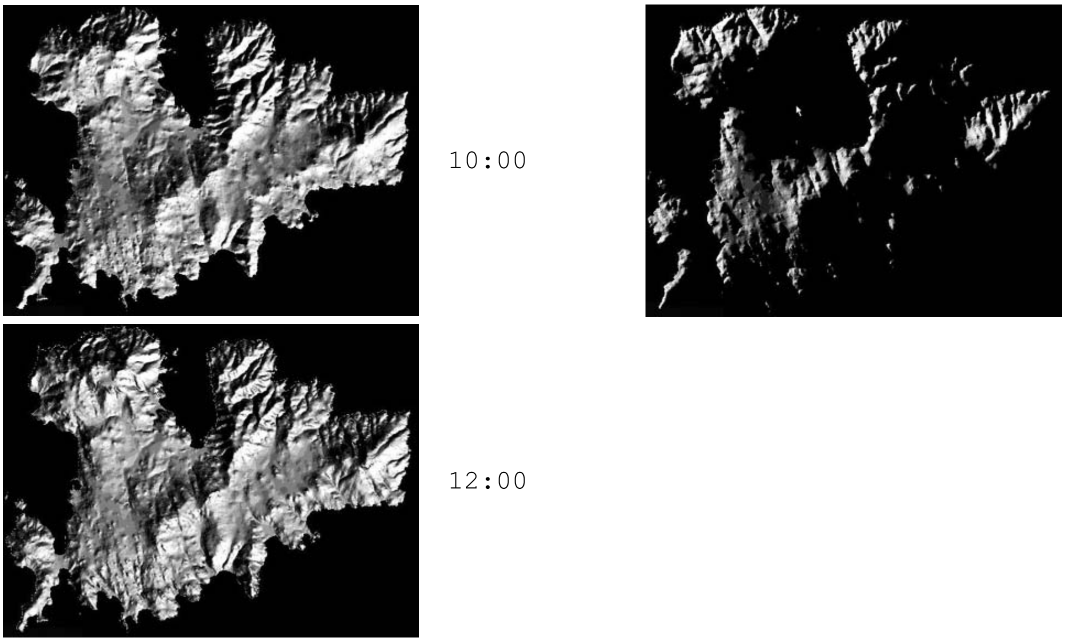

Figure 6. The shaded relief snapshots (Mykonos, Dec. 22, 2001).

6. CONLUSION

This study presents an insolation modeling approach, which applies and extends the utilities offered by commercial Geographic Information System (GIS) software packages. A prototype system has been developed as an outcome of these efforts. Apart for the wide significance of this approach to sciences examining natural processes, it can be also considered as a paradigm of modeling spatio-temporal phenomena with exploitation and extension of GIS functionality.

Our future research includes: (a) the efficient incorporation of time factor in GIS modeling and the extension of commercial GIS functionality in spatio-temporal data handling, and (b) the development of a more integrated insolation modeling approach involving quantitative estimations, correlation with field work data, validation on real situations, etc.

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