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Dual-Domain Visual Exploration of Urban Solar Potential

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Figure 1: *In dual-domain exploration the solar irradiation potential is computed and visually analyzed in the 3D spatial domain of the urban model as well as in a temporal domain. The latter is represented by two-dimensional temporal maps with* time of the day *on the horizontal axis and* day in the year *on the vertical axis.*

Abstract

Traditional methods for estimating the solar energy potential in buildings determine energy yields on an annual base and make use of highly aggregated geo-spatial data. This work proposes a method for detailed assessment of the potential solar energy yield in the temporal and spatial domain. Solar irradiance is evaluated using numerical methods based on hourly variation of solar irradiance and on actual building geometry. Results of our initial studies allow exploration of the variation patterns in solar yield depending on local and time-varying factors, which cannot be seen in coarse level solar planning tools. This helps identifying surfaces with good solar yield that are deemed unfavorable according to traditional planning practices.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—

1. Introduction

Planning for integration of widespread photovoltaic (PV) systems and solar thermal (ST) systems in the built environment requires knowledge of the solar irradiance levels on existing and planned buildings and individual building surfaces (roofs, walls, etc.). These analyses are useful for architects and construction engineers in design or retrofit of buildings or building areas. Information on the level of districts or whole cities is also useful for strategic city and regional planning, both as a way to determine suitable areas for solar integration and as a basis for predicting where energy distribution infrastructures might be in need of strengthening or extension. This information can be obtained with computer-based tools that determine and visualize the solar potential (mainly irradiance but also actual solar electricity and heat production and daylight availability). Meanwhile A variety of solar design tools exists to support architects and planners; a comprehensive review of them is provided in [HD12]. Most tools have the ability to provide detailed solar potential analyses, including shading and occlusion analysis. But as it seems, they are provided either as detailed snapshots for an instant moment or aggregated over time as integrated whole-year values. The challenge with solar potential calculations is to allow highly detailed analyses in the spa-

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tial as well as the temporal domain including complex shading effects. At the same time they have to offer the computational efficiency needed for real-time interaction. With reduced processing times, detailed analyses of solar irradiance could be performed and elaborated interactively while other architectural requirements are evaluated in the design process. Whole-year integration of irradiance availability as well as studies of fast irradiance fluctuations on building surfaces would also benefit from faster processing, as it would allow a more fine-grained time resolution.

1.1. Objectives

In this work a new conceptual approach for energy yield estimations is proposed, which encompasses simultaneous exploration of solar irradiance in the spatial and temporal domain with high resolution. The initial objective was to support planners and architects in the design of PV installations by providing intuitive temporal views of the expected solar yield for arbitrary points on the building facades. Hereby, spatial accuracy is to be limited only by the level of geometric detail of the available building models and temporal resolution should be in the range of a few minutes.

1.2. Contributions

The following sections describe our method for high-resolution energy yield estimations which utilize the processing capabilities of modern graphical programming units (GPU). By representing time-variable data as two-dimensional temporal texture maps we offload solar yield computations to the rasterization hardware of the GPU. While temporal irradiance maps have been proposed earlier to graphically express the results of solar yield calculations [Mar04], we are the first to treat the time-varying parameters as temporal texture maps to feed the computational parts of solar yield estimations on the GPU. Also, as solar irradiance is calculated on-the-fly, we link the display of temporal irradiance maps with probed 3D positions in the building model and hence provide the means for dual-domain visual exploration of solar irradiance.

2. Method

The general approach taken in our visual solar energy planning application is based on interactive dual-domain exploration, which implies simultaneous interactive exploration of different parameter spaces. It has been successfully used in different visualization applications such as in direct volume rendering and transfer function design [KKH01] or in information visualization [WHJK07]. For the purpose of solar energy planning, we let the user interactively sample visualizations of 3D models of the built environment and for any surface point in the city model we instantly calculate annual solar yield depending on the surface orientation, weather conditions, solar angles and other factors (see Figure 1).

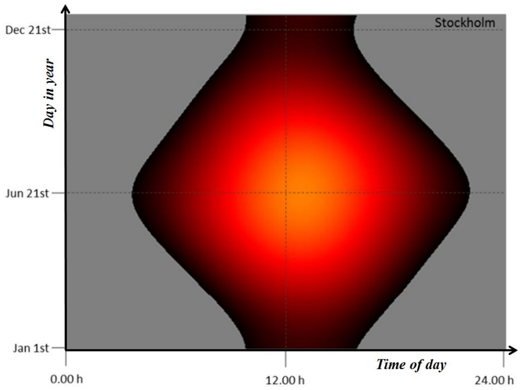

Figure 2: *A temporal map of theoretically available solar irradiance for Stockholm. Coordinates in the temporal map are* time during the day *and* day in the year. *Colors indicate the amount of solar irradiance for periods where sun is above horizon.*

2.1. Data representation

Our work is inspired by the idea of temporal irradiation maps proposed by Mardaljevic [Mar04] and later used for the analysis of daylight in buildings by Andersen et al. [AKY*08].

According to the notion of temporal maps our algorithms treat all time-varying parameters involved into solar yield computations as variables in a 2D domain with time of the day defining one dimension and day of the year the second dimension. This allows storing those variables as 2D textures which then can be used on the GPU to efficiently perform numerical integration over arbitrary time intervals. Likewise, the 2D representation of time varying variables and of computational results allows visualizing and exploring how the potential solar yield varies in the time domain [AKY*08]. Figure 2 is an example of a temporal map of solar irradiance (ideally) at a geographic position nearby Stockholm. It shows in an intuitive manner the characteristic variation of available solar intensity during the days (horizontal axis) of the year (vertical axis). For our computations we represent 480 time samples per day (3 minute intervals) for 365 days (in total 175200 samples per year), which are accommodated in a 512^2 sized texture.

2.2. Solar yield computation

The algorithms for determining solar irradiance availability on arbitrarily oriented surfaces are straightforward 3D vector operations which are ideally performed as fragment programs on the graphical processing units (GPU). Almost all time-dependent variables needed for the calculations (time varying solar position vectors, irradiance on the horizontal plane, cloudiness, etc.) are dependent on the geographic latitude/longitude and can therefore be pre-computed and stored

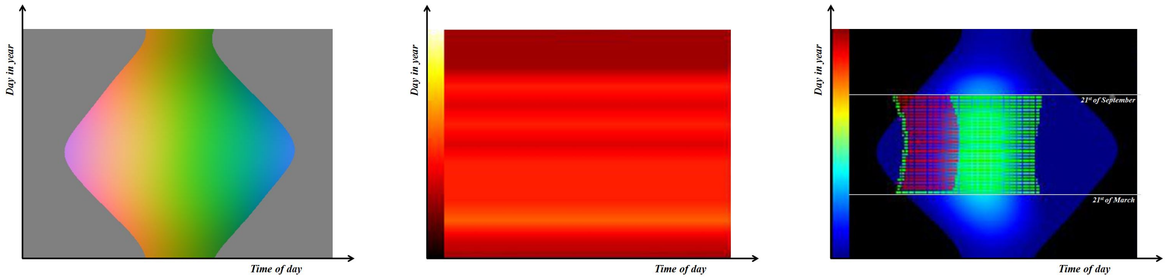

Figure 3: *Temporal maps are used to store solar angles (left), monthly cloudiness index (middle), and solar irradiance for a specific surface point (right). An overlay shows in green color the "time window" when the solar panel is directly exposed to the sun, while the red area indicates periods when the panel is shadowed by nearby building structures. In this example, the overlay is calculated and shown only between March and September.*

as 2D texture maps. Figure 3 shows the solar position over the year represented by solar azimuth and elevation angles which are encoded in a RGB texture (left). Similarly, a temporal cloud map texture represents the variation in relative cloudiness during the day and over the year (middle). An aggregation function, implemented as a graphical shader program, is used to combine data sampled from these textures to a final output value. Equation (1) expresses in a general form how solar irradiance I is numerically integrated by sampling and compositing several factors or functions depending on time within a specific interval. Figure 3 (right) shows the actually available solar irradiance computed from the previous textures and considering the orientation of the current surface in question. It can be seen that the panel surface faces south-east, as there is most yield before noon. Vertical elevation of the surface also affects the maximum available irradiance but is not seen here. The calculations of irradiance maps are performed in real-time, hence year-round solar potential (neglecting shadows) on an arbitrarily oriented surface can be computed and visually inspected simultaneously with the view of the spatial building models (see Figure 1). Occlusion of sunlight for specific points in a 3D model of a building requires ray-tracing the 3D scene over the hemisphere of the current surface point. This is a complex process that is not executed in real-time in our current system but is instead triggered on user demand. Figure 3 (right) shows the result of occlusion calculations between March and October as an overlay upon the temporal irradiance map. The red region is due to shadows cast by a nearby building.

$$I = \sum_{t=t_S}^{t_E} D(\vec{L}_t \cdot \vec{N}) \otimes O(\vec{L}_t) \otimes C_t \qquad (1)$$

where:

$\vec{L}_t$ solar position at time t
$\vec{N}$ normal vector at sampled surface position
C_t cloudiness index at time t
$O()$ occlusion function
$D()$ direct solar irradiance function
$\otimes$ some arithmetic or logical operation

2.3. System implementation

We have implemented our system for interactive visual solar irradiation estimation using the 3D development environment Vizard 4.0$^{\text{TM}}$by WorldViz. It is a 3D/VR authoring tool based on Open Scene Graph that allows rapid application development in Python. The time-critical code of our application is implemented as fragment shader programs in GLSL which are applied as material properties to proxy-geometries in the scene. 3D building models of our demonstration case are imported as Google Sketchup files from Trimble 3D Warehouse and aerial images are loaded as ground textures from Google Earth.

3. Results and discussion

Figure 4 shows three scenarios with different placements of a PV array on a building in a Swedish city. The obtained texture maps of the irradiance availability, with occlusion taken into account, are shown below each building 3D scene. These results were obtained from 3-min sampling of the texture maps and average monthly cloudiness data.

The main advantage of this approach is the implementation in the graphics hardware, which allows faster processing and rapid interactive comparison of solar yield for different surfaces in the urban model. The representation of available solar energy as texture maps also gives a highly resolved and comprehensive visualization of the year-round potential. The model can estimate the solar potential in any arbitrary point in space, which means that potential PV and solar thermal (ST) installations can be identified for both existing and projected buildings. This also holds for irregularly shaped surfaces, which will be of great importance as new flexible roll-to-roll polymer-based PV modules are under development [FCK09]. The qualitative spatio-temporal assessment of potential solar panel designs allows identifying local *windows* in time and physical space that lend themselves for small-scale or custom tailored PV installations. Occlusion calculations are in our system presently implemented as software

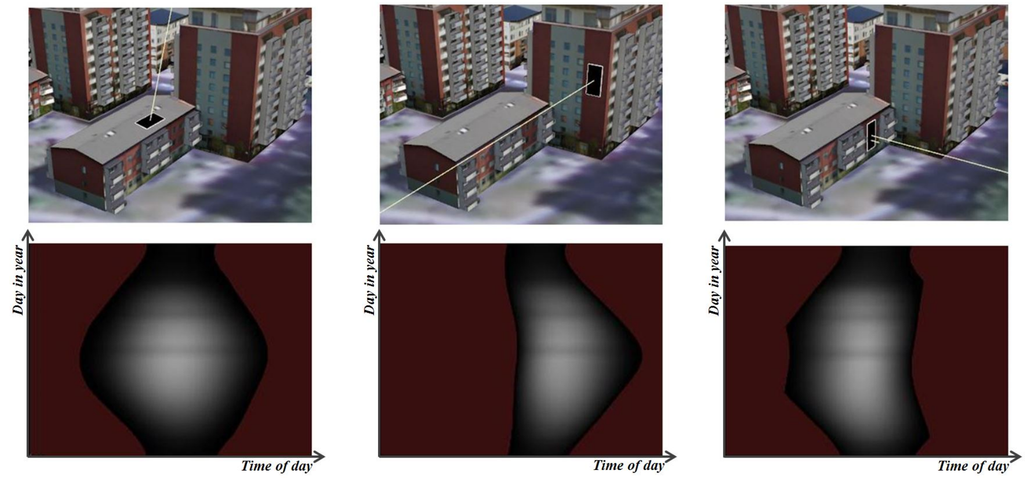

Figure 4: *Three different solar panel designs in an urban model are compared. The availability of sunlight in the temporal domain (see temporal irradiance maps in the bottom row) depends on the actual orientation of the solar panel and on daylight periods for a given geographic position. A solar panel oriented almost tangentially with the ground captures sunlight during the entire daylight period (left) even though sun-rays may impinge not perpendicular to the solar panel. The solar panel shown in the middle is facing west and does not capture the available sunlight in the morning hours. A vertical solar panel design on a facade facing south provides an ideal angle at noon when sunlight is most intense, but does not capture sunlight in the early morning and late afternoon hours during the summer (see bottom picture, right).*

ray-caster and are executed on user demand. A more efficient hemispherical GPU renderer dealing with curved triangles is one of our tasks in the near future. The current approach only considers direct beam radiation on the solar panel. A complete model for incident radiation must also consider diffuse radiation from the sky and from the surroundings. Considering that the diffuse fraction of the annual global incident radiation on the horizontal plane amounts to 40-50% for most locations in Sweden [Per00], this is an important improvement that will be included in our further work.

4. Future work

Also in further work our system will be complemented with cloud movement data from a high-resolution irradiance monitoring network. This network will consist of a large number of low-cost irradiance measurement devices that are time-synchronized and collect irradiance data on very fast time scales. Cloud patterns and movements will be monitored on the scale from individual buildings up to cities and can be included in the methodology, represented as texture maps as above. This will potentially allow predictions of expected output variability on different time scales from dispersed PV systems in the built environment. The proposed model will further on also be developed not only to deal with high-resolution solar irradiance potential, but also to study the coincidence between local, spatially distributed PV electricity production and the local aggregated electricity demand, which can also be represented in texture maps to show the yearly and daily distribution.

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