

Short communication

An open-source 3D solar radiation model integrated with a 3D Geographic Information System



Jianming Liang ^{a, b}, Jianhua Gong ^{a, b, *}, Jieping Zhou ^{a, b}, Abdoul Nasser Ibrahim ^{a, b},
Ming Li ^c

^a State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, P.O. Box 9718, Beijing 100101, China

^b Zhejiang-CAS Application Center for Geoinformatics, Zhejiang 314100, China

^c Jiashan Metrological Bureau, Zhejiang 314100, China

ARTICLE INFO

Article history:

Received 9 May 2014

Received in revised form

13 November 2014

Accepted 17 November 2014

Available online

ABSTRACT

Photovoltaic energy has become a popular renewable energy source for sustainable urban development. As a result, 3D solar radiation models are needed to facilitate the interactive assessment of photovoltaic potential in complex urban environments. SURFSUN3D is a visualization-oriented full 3D solar radiation model that has been shown to achieve efficient computation and visualization for 3D urban models. The present paper introduces a framework to integrate SURFSUN3D into a 3D GIS-based application to interactively assess the photovoltaic potential in urban areas.

© 2014 Elsevier Ltd. All rights reserved.

Keywords:

Photovoltaic energy

3D urban models

3D solar radiation model

3D GIS

Software availability

The program is a freeware licensed under terms of the GNU General Public License (GPL) and runs under Windows operating systems with hardware and software support for NVIDIA CUDA and OpenGL. A minimum of 4 GB system memory and 1 GB video memory is recommended. The full source codes for SURFSUN3D and the demonstrated prototype system is available at <https://code.google.com/p/surface-mapping-based-3d-solar-radiation-model/>.

1. Introduction

With growing concerns over climate change caused by increasing fossil fuel consumption, sustainable energy sources, such as solar, wind and hydroelectric energy, are expected to contribute to climate stabilization and energy efficiency improvements (Hoffert et al., 2002). To ensure that urban energy needs are produced locally as much as possible via solar energy, it is

necessary to assess and monitor the spatial–temporal distribution of solar radiation over urban areas and to consider solar energy as a design parameter in urban planning (Kanters and Horvat, 2012).

Worldwide, the installed photovoltaic capacity was estimated to reach 102 gigawatts (GW) by the end of 2012; 32.340 GW was installed in 2012 alone (Schuetzeemail, 2013). Building-integrated photovoltaics (BIPV) can make full use of building surface space to gather solar energy by replacing conventional building materials with photovoltaic materials; thus, it is a very promising technology (Azadian and Radzi, 2003). A successful integration of solar energy technologies into the existing energy structure depends on the detailed knowledge of the potential solar resource (Šuri et al., 2005). Estimating photovoltaic (PV)-suitable spaces on building surfaces is a key factor in determining the technical potential of PV (James et al., 2011).

An interactive modeling tool that supports geospatial data integration and 3D visualization can facilitate the assessment of photovoltaic potential in urban environments. Currently, few open-source 3D solar radiation models or computing frameworks exist that can be integrated into 3D GIS and interactive visualization systems. In this paper, we present an open-source framework to incorporate SURFSUN3D (Liang et al., 2014) into 3D GIS to support urban solar potential assessment.

* Corresponding author. State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, P.O. Box 9718, Beijing 100101, China. Tel./fax: +86 010 64849299.

E-mail address: gongjh@radi.ac.cn (J. Gong).

2. Related research

One of the most well-known solar radiation tools for estimating the spatial–temporal distribution of PV potential is PVGIS ([Šúri et al., 2005](#)), which is a GIS-based web database that integrates various related data sources, including ground meteorological records, the SoDa web service ([Wald, 2000](#)) and USGS GTOPO30 DEM, as input parameters for the GRASS r.sun model ([Hofierka and Suri, 2002](#)) to calculate solar irradiation. The PVGIS service can be accessed via web applications to calculate and display the solar potential for given geographic areas. A new commercial solar radiation service known as the SolarGIS was developed to provide more reliable and accurate model estimates ([Šúri and Cebecauer, 2010; Cebecauer et al., 2010](#)). Nevertheless, traditional GIS-based 2D solar radiation models, such as r.sun, do not take into account complicated shadowing effects present in urban environments and cannot accommodate building facades due to the limitations of 2D data representation; full 3D methods must be employed to accurately estimate PV potential in urban areas.

Recently, several 3D solar radiation models ([Hofierka and Zlocha, 2012; Catita et al., 2014; Erdélyi et al., 2014; Liang et al., 2014](#)) were presented to meet such needs. The v.sun model ([Hofierka and Zlocha, 2012](#)) is a vector–voxel 3D solar radiation model that segments 3D vector objects into smaller polygonal elements using a voxel-intersecting rule. The SOL algorithm ([Catita et al., 2014](#)) generates hyperpoints on facades that are assumed to be 2.5D vertical planes, limiting its applicability to full 3D building models. The SORAM ([Erdélyi et al., 2014](#)) combines an accurate ray-tracing algorithm with the adjusted [Perez et al. \(1990\)](#) model to calculate solar radiation incident on building surfaces.

SURFSUN3D ([Liang et al., 2014](#)) employs surface mapping techniques to transform 3D surfaces into 2D raster maps to facilitate conventional GIS operations and real-time rendering. Irradiation results from SURFSUN3D are presented in the form of raster maps and can therefore be visualized through graphics processing unit (GPU)-based real-time texture mapping. Because both of the 3D models are essentially an extension to the 2D r.sun model, the basic input parameters are the same as those for the PVGIS in addition to georeferenced 3D building models. Because the raster-texture data representation is specifically designed to fit into the GPU rendering pipeline, SURFSUN3D is especially suitable for

incorporation into 3D interactive applications. SURFSUN3D was also shown to provide an efficient computation with Compute Unified Device Architecture (CUDA)-accelerated shadow casting. CUDA is a GPU-based parallel computing architecture provided by NVIDIA Corporation. A shadow casting algorithm can gain significant speedup if it is appropriately implemented on CUDA.

3. Methodology

The SURFSUN3D computational and visualization pipeline is organized as shown in [Fig. 1](#). Basically, the 3D surfaces of building models are transformed into 2D raster maps to allow r.sun to perform actual calculations on a cell-by-cell basis.

The r.sun model was developed and integrated to GRASS GIS by [Hofierka and Suri \(2002\)](#) based on the European Solar Radiation Atlas (ESRA) ([Rigollier et al., 2000](#)). According to r.sun, the total radiation incident to the Earth's surface is known as the global solar radiation, which is equal to the sum of the three components: the beam, the diffuse component and the reflective component. The major parameters required by r.sun include the clear-sky index, linke turbidity factor, time period, hourly step, latitude, longitude, elevation, slope and aspect ([Hofierka and Suri, 2002](#)). In the SURFSUN3D framework ([Liang et al., 2014](#)), the surface orientation (aspect) and inclination (slope) are extracted from the building surface normal vectors, and the shadowing effect is calculated using a CUDA-accelerated ray-casting method ([Liang et al., 2014](#)).

The SURFSUN3D model presents the irradiation results in the form of 2D floating-point raster surfaces that can be mapped back onto the 3D building surfaces for visualization. A color ramp is used to render the irradiation raster maps into colored textures for GPU-based texture mapping.

Originally, SURFSUN3D assumed a common geographic position (longitude, latitude and elevation) for all raster cells. However, a large city can cover an extensive geographic area with a large vertical span due to a combination of topographic relief and building height differences, which leads to inaccurate parameterization for the r.sun model. Therefore, the geographic latitude/longitude used herein is specifically calculated for each individual building. The elevation is calculated on a cell-by-cell basis as the sum of the height above ground and the terrain elevation, if a terrain layer is available.

4. Implementation of a prototype system

The system is partitioned into five modules ([Fig. 2](#)): the 3D building model database, the graphical user interface, the SURFSUN3D computation engine, the spatial data engine and the 3D & 2D rendering engine as described below:

- 1) The 3D building model database provides geometric and textural content for computation and visualization. There are several approaches to acquiring 3D building models, including manual creation in computer-aided design (CAD) software,

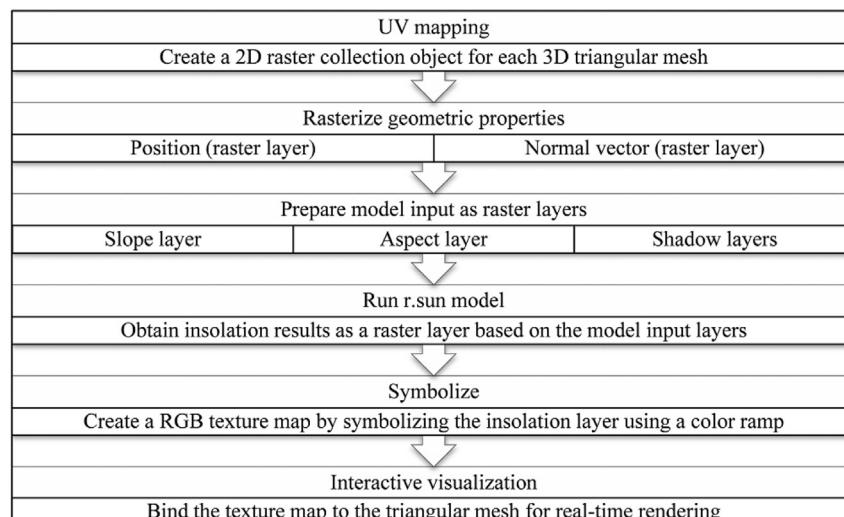


Fig. 1. Working procedures of SURFSUN3D ([Liang et al., 2014](#)).

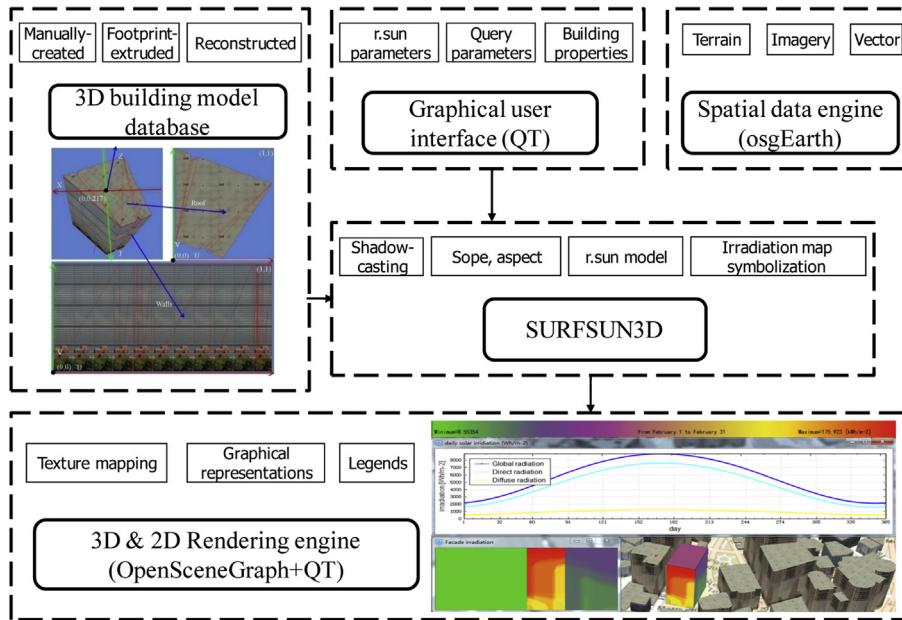


Fig. 2. Workflow of the prototype system.

building footprint-based extrusion, reconstruction from imagery or LiDAR point clouds. In the prototype system presented here, a building is simply split into two parts, namely a roof and façade, for potential retrieval by their spatial or semantic attributes.

- 2) Graphical user interface (Fig. 3). This module allows users to select buildings or building components for calculation and to specify the r.sun parameters, including the clear sky index, linke turbidity factor, time period and hourly step.

3) SURFSUN3D computation engine. A majority of the computation time of SURFSUN3D is spent on shadowing calculations due to the geometric complexity of 3D urban models. Therefore, a CUDA-accelerated high-performance ray-casting method has been implemented (Liang et al., 2014). Currently, only triangular meshes are considered in this shadowing algorithm, where trees can be modeled as triangulated objects to serve as shadow-casters. The SURFSUN3D model calculates solar irradiation for a 3D surface on a cell-by-cell basis using the r.sun model and

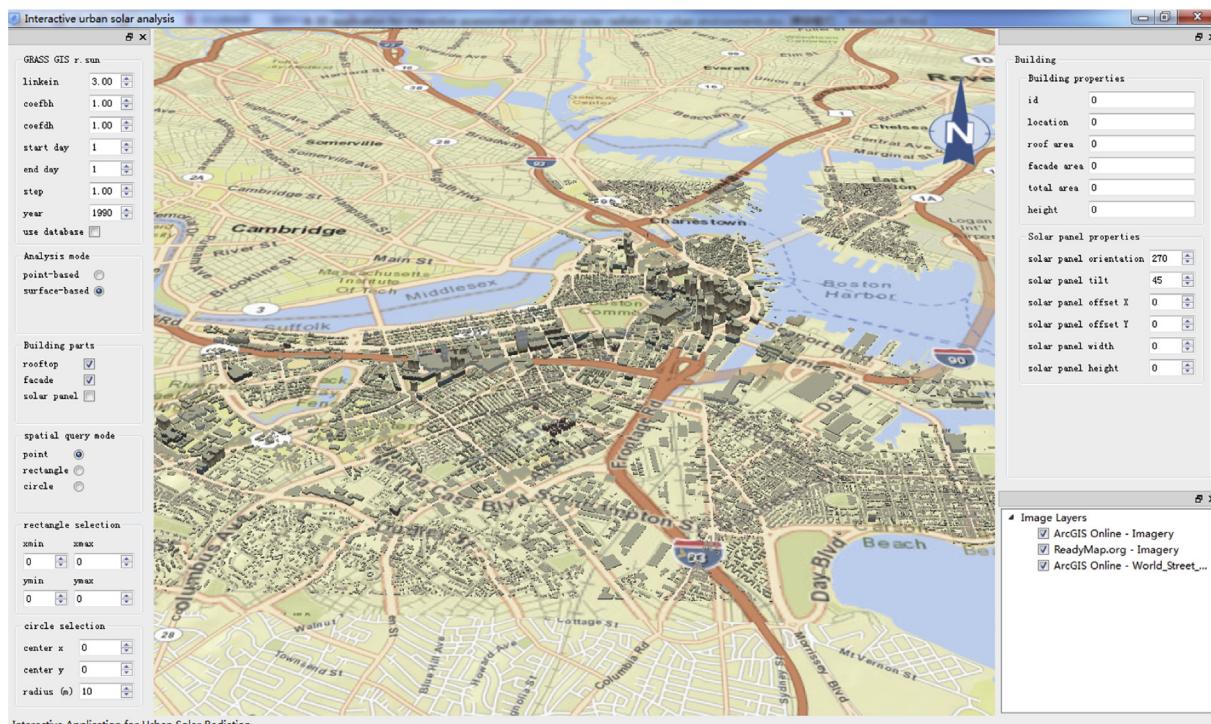


Fig. 3. Overview of the prototype system.

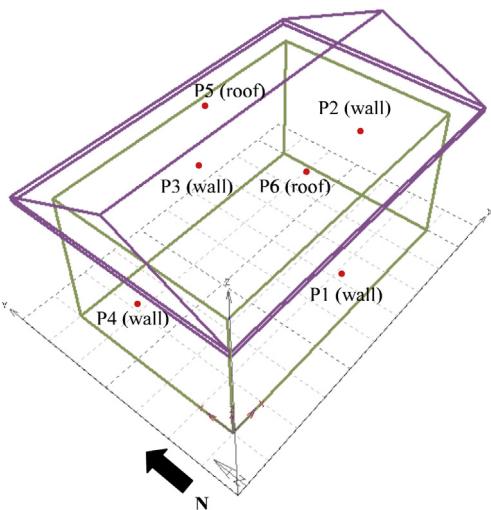


Fig. 4. A building with pitched roof created in Ecotect.

presents the results in the form of a 2D floating-point raster map, which can be shaded into an RGB-colored texture map for visualization by the 3D rendering engine.

- 4) Spatial data engine. The osgEarth is a 3D GIS system that enables access to local and internet-based raster and vector data sources. Georeferenced map layers from osgEarth are integrated into the system to provide a geographic context for urban solar energy analysis. Terrain layers can also be accessed via osgEarth to correct building elevation.
- 5) 3D & 2D rendering engine. The OpenSceneGraph-based 3D rendering engine offers a real-time interactive environment for users to explore 3D urban models that are georeferenced to osgEarth map layers. A combination of OpenSceneGraph and QT is used for rendering 2D graphs, legends, north arrows and annotations.

5. Model validation

The model has been validated against the commercial software Autodesk Ecotect Analysis, which is widely used for energy

analysis in the field of building design. Considering Ecotect an industrial benchmark, it's herein assumed a successful reproduction of Ecotect's results can serve as a measure of model validity.

A $5\text{ m} \times 8\text{ m} \times 4\text{ m}$ (width, length and height) flat building was created in Ecotect, and then a roof pitched at 25° was attached to the top (Fig. 4).

We chose 6 locations at the building surfaces to serve as reference points for comparison against Ecotect, including 2 points at the center of the two roof slopes and 4 points at the center of each façade. The building model constructed in Ecotect was later exported to text format and imported to SURFSUN3D for calculation. The climate data in EnergyPlus weather format for the city of Boston was downloaded from the U.S. Department of Energy website. The EnergyPlus climate dataset contains the observed hourly direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), which would later be used in both EnergyPlus and SURFSUN3D to estimate the cumulative global radiation incident on the tilted surfaces.

Global radiation estimates for the first day of each of the 12 months in a year were obtained for all the reference points using both Ecotect and SURFSUN3D. It can be seen from Fig. 5 that the estimates of SURFSUN3D agree well with those of Ecotect. Although the difference in the estimated global radiation can be as large as 10% sometimes, the average difference is less than 4% for all the reference points throughout the year.

Because pyrometer-based observational data for PV systems as well as for BIPV systems is difficult to obtain in complex urban environments, it is hoped that further case studies will contribute to model validation and improvement (Freitas et al., 2015).

6. Results

Tests and analyses were conducted to demonstrate the applicability of the prototype system. The test dataset is a 3D virtual city of Boston (Fig. 6) located at approximately $42^\circ 21' 28''\text{N}$ and $71^\circ 03' 42''\text{W}$ in Massachusetts, USA. The virtual city was extruded from 22,185 building polygon shapes downloaded from the website of the open-source project osgEarth. SRTM topographic data was used for this case study.

The tests described below were run on a machine with an NVIDIA GeForce GTS 450 graphics card and an Intel Core i5-2310 CPU. Using 1 m raster resolution and 1 h time step, the amount of

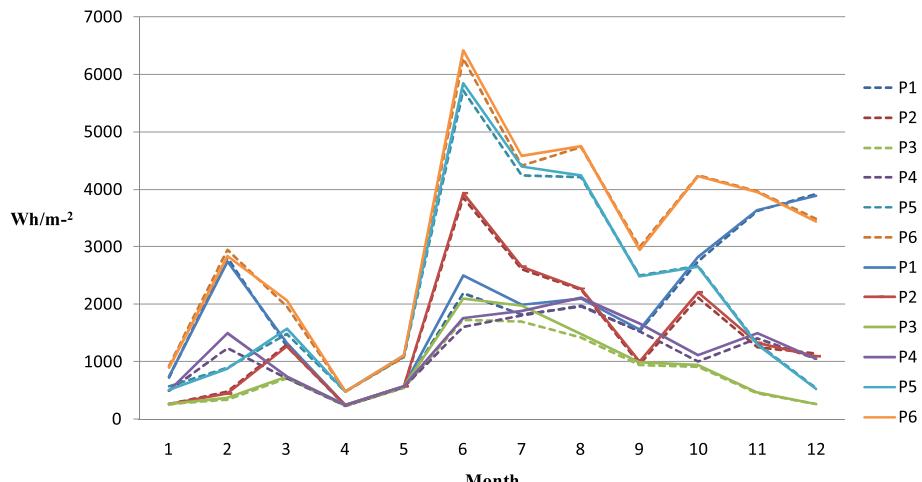


Fig. 5. Comparison of estimated daily global radiation (dotted lines are used for Ecotect).



Fig. 6. 3D virtual city of Boston (Liang et al., 2014).

time required to calculate daily radiation values for the whole Boston 3D city of 31 million m² in surface area was approximately 40 min.

Whole buildings, rooftops or façades can be selected from the virtual city for calculation and visualization using a spatial query. The spatial query allows users to numerically specify a region of interest (Fig. 7) or to interactively identify an individual building through mouse actions (Fig. 8). Three types of spatial queries are

available for users to select buildings of interest. Circle and rectangle-based queries are used for identifying multiple buildings.

An individual building can be identified through a mouse click-based point query. When an individual building is selected, the orientation and tilt of the rooftop solar panel can be adjusted to simulate the solar radiation received within the specified time period. Fig. 9 indicates how to find the optimum orientation and tilt angles through repeated trials.

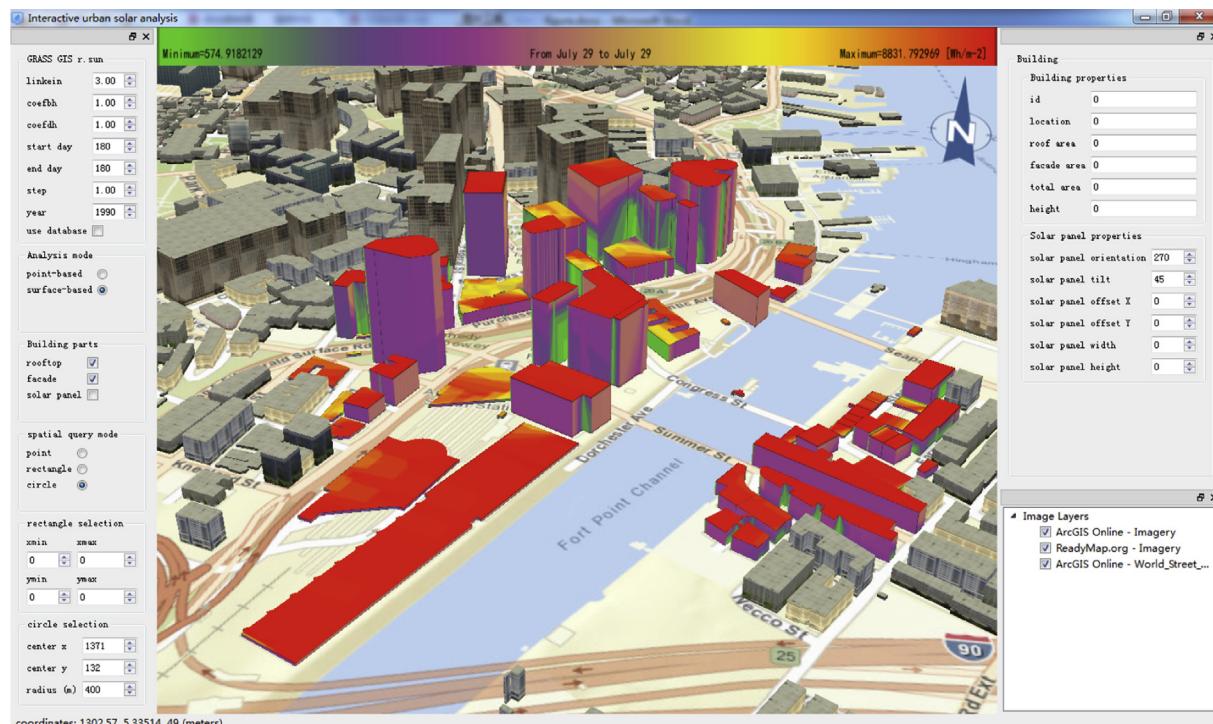


Fig. 7. Surface-based irradiation analysis for multiple buildings.

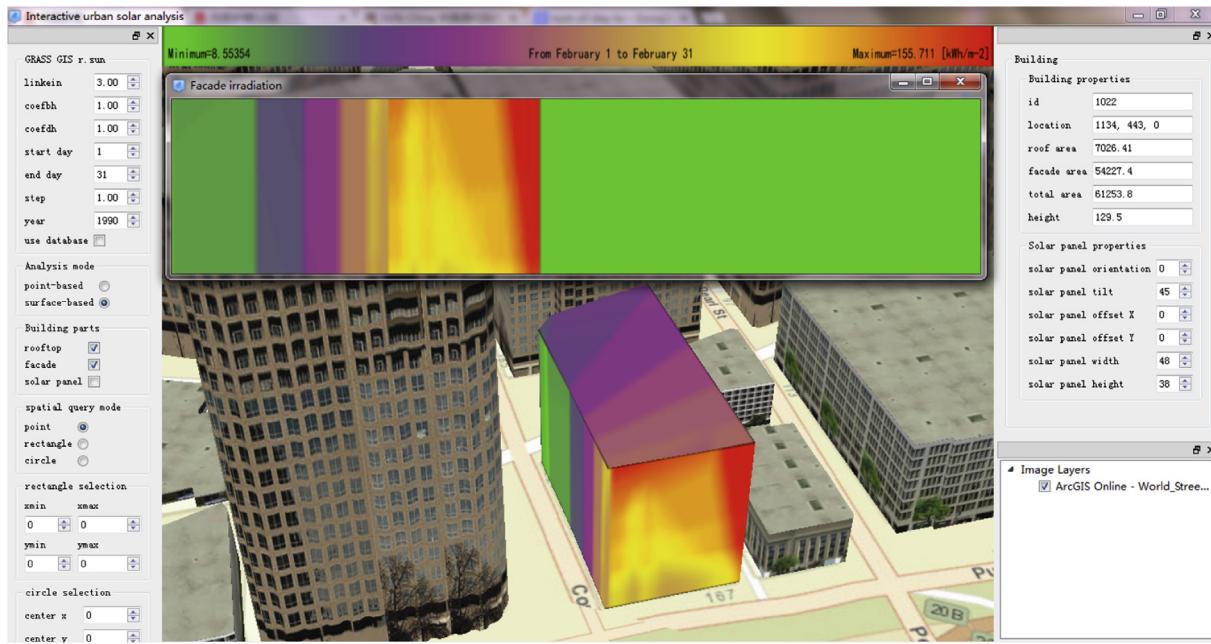


Fig. 8. Surface-based irradiation analysis for an individual building.

The user is required to interactively identify a position at a building, specify the r.sun parameters and specify the first and last days to be included in calculation. The result is presented in the form of a line graph that displays the irradiation against the number of days within the specified time period (Fig. 10).

Using the osgEarth spatial data engine, the buildings are accurately georeferenced and can be overlaid on various raster and vector map layers provided by online or local data sources. In Fig. 11, ArcGIS online satellite imagery and the street map provide an enriched geographic context for urban solar analysis.

7. Conclusions

To facilitate the assessment of photovoltaic potential in urban environments, we have presented a computing framework that can be used to develop 3D interactive applications with geospatial data integration capabilities. Compared to existing 3D solar radiation modeling tools, the presented framework has the following advantages:

- (1) The shadow casting algorithm can exploit GPU parallelism to gain speedup.
- (2) The surface mapping-based data representation is convenient for interactively visualizing the radiation attributes on building surfaces.
- (3) The integration with 3D GIS can facilitate the incorporation of multisource geospatial data in analysis and decision-making.

Because the application relies on real-time computations to produce irradiation maps, the computational cost tends to increase with the number of buildings intended for analysis. For instance, while calculation of daily radiation for a single building with 1 m raster resolution and 1 h time step may cost less than 1 s to a few seconds, the whole Boston 3D city of 31 million m² in surface area requires half hour to several hours depending on computer performance using the same time step and raster resolution. At the current stage, the program may be more suitable for early-stage assessment of photovoltaic potential since many practical factors regarding PV installation and engineering have not been addressed,

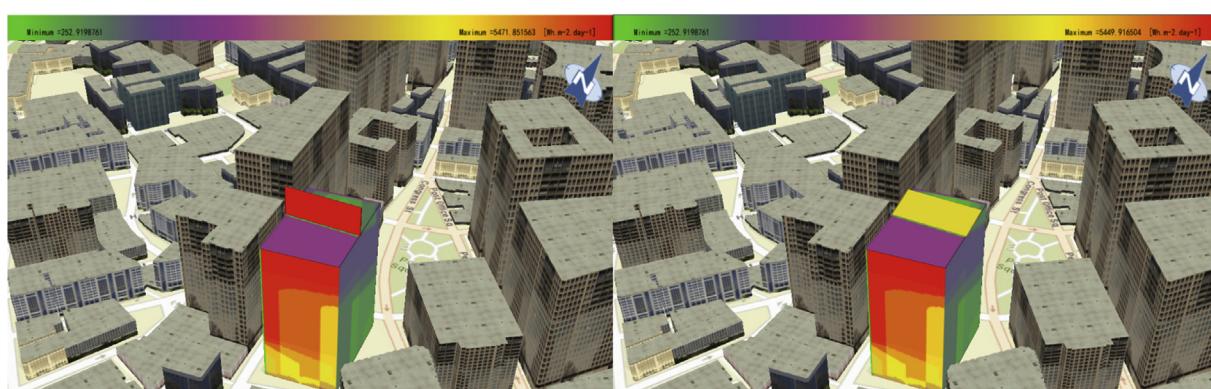


Fig. 9. Rooftop PV optimization for an individual building.

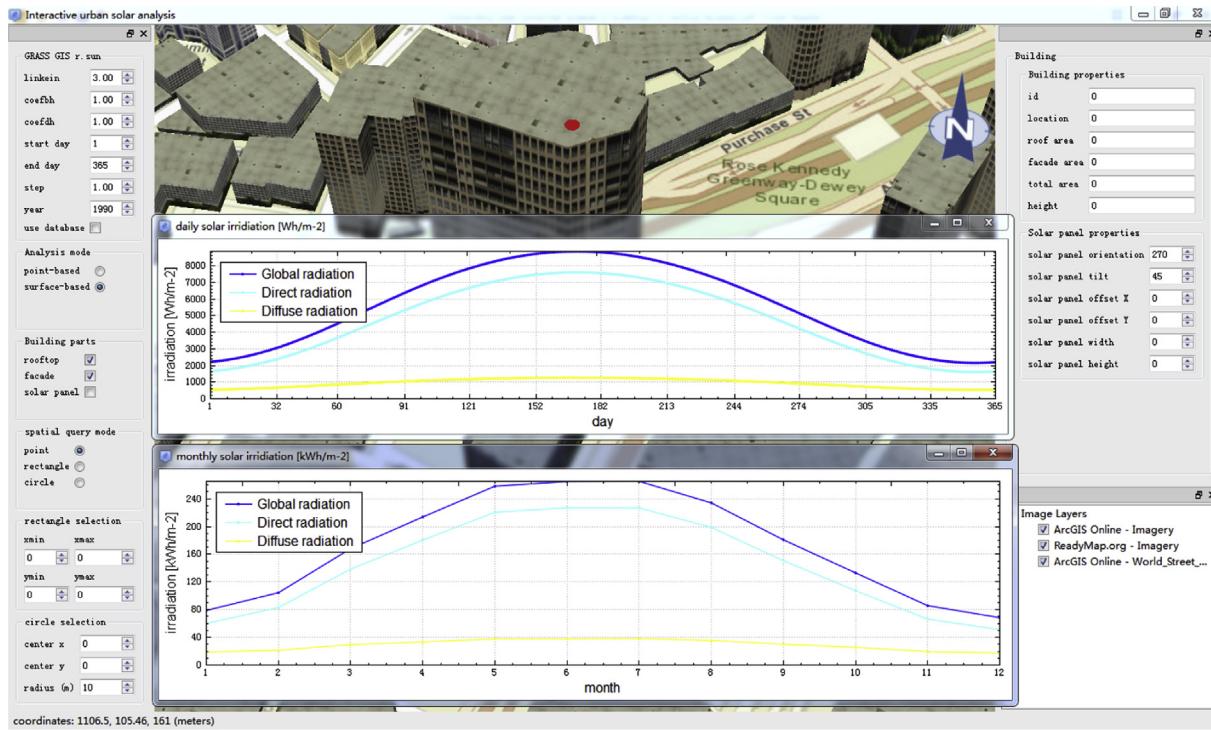


Fig. 10. Point-based irradiation analysis.



Fig. 11. Georeferencing to GIS data layers.

for example, the electrical behavior of a shaded PV generator, angular and dust losses.

Acknowledgments

This research was supported and funded by the Key Knowledge Innovative Project of the Chinese Academy of Sciences (KZCX2 EW 318), the National Key Technology R&D Program of China (2014ZX10003002), and the National Natural Science Foundation of China (41371387), and Jiashan Science and technology Projects (2013B07, 2013A60).

References

- Azadian, F., Radzi, M., 2003. A general approach toward building integrated photovoltaic systems and its implementation barriers: a review. *Renew. Sustain. Energy Rev.* 22, 527–538.
- Catita, C., et al., 2014. Extending solar potential analysis in buildings to vertical facades. *Comput. Geosci.* 66, 1–12.
- Cebecauer, T., et al., 2010. High Performance MSG Satellite Model for Operational Solar Energy Applications. *ASES National Solar Conference*, Phoenix, USA.
- Erdélyi, R., Wang, Y., Guo, W., Hanna, E., Colantuono, G., 2014. Three-dimensional Solar Radiation Model (SORAM) and its application to 3-D urban planning. *Sol. Energy* 101, 63–73.
- Freitas, S., et al., 2015. Modelling solar potential in the urban environment: state-of-the-art review. *Renew. Sustain. Energy Rev.* 41, 915–931.

- Hoffert, M., et al., 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298 (5595), 981–987.
- Hofierka, J., Suri, M., 2002. The solar radiation model for open source GIS: implementation and applications. In: Proceedings of the Open Source GIS—GRASS Users Conference 2002, Trento, Italy, 11–13, September 2002.
- Hofierka, J., Zlocha, M., 2012. A new 3-D solar radiation model for 3-D city models. *Trans. GIS* 16 (5), 681–690.
- James, T., et al., 2011. Building-integrated Photovoltaics (BIPV) in the Residential Sector: an Analysis of Installed Rooftop System Prices. National renewable energy laboratory. Technical Report NREL/TP-6A20-53103.
- Kanters, J., Horvat, M., 2012. Solar energy as a design parameter in urban planning. *Energy Procedia* 30, 1143–1152.
- Liang, J., et al., 2014. A visualization-oriented 3D method for efficient computation of urban solar radiation based on 3D-2D surface mapping. *Int. J. Geogr. Inf. Sci.* 28 (4), 780–798.
- Perez, R., et al., 1990. Modeling daylight availability and irradiance components from direct and global irradiance. *Sol. Energy* 44 (5), 271–289.
- Rigollier, C., et al., 2000. On the clear sky model of the ESRA, European Solar Radiation Atlas, with respect to the Heliosat method. *Sol. Energy* 68, 33–48.
- Schuetzeemail, T., 2013. Energies integration of photovoltaics in buildings—support policies addressing technical and formal aspects. *Energies* 6 (6), 2982–3001.
- Šúri, et al., 2005. PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe. *Int. J. Sustain. Energy* 24 (2), 55–67.
- Šúri, M., Cebecauer, T., 2010. SolarGIS: New Web-based Service Offering Solar Radiation Data and PV Simulation Tools for Europe, North Africa and Middle East. Conference EUROSUN 2010, October 2010, Graz, Austria.
- Wald, L., 2000. SODA: a Project for the Integration and Exploitation of Networked Solar Radiation Databases. European Geophysical Society Meeting, XXV General Assembly, Nice, France, 25–29 April 2000.