Analysis of long-wave radiation from urban facets derived from time-sequential thermography (TST) and 3D city model

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Abstract

The surface of urban areas has complex three-dimensional (3D) structure, which creates strong micro-climatic contrasts of temperature. A new topic is the observation of the temporal processes in the transport of radiation and energy. Therefore, a fixed ground based oblique viewing thermal camera system is used to obtain time-sequential thermography (TST) data series of a test side in Berlin, Germany. The TST dataset is combined with a 3-D surface model of the building inventory. Through the navigation of the 3D Model into the viewing perspective of the thermal camera system, every angle within the system sun-target-sensor can be computed. Long-wave radiation flux from different roof facets of buildings are subjects of interest. The azimuth and zenith angles of the roof facets results in shifts in the temporal variation of long-wave radiation flux of these surfaces. The ability to absorb thermal radiation into the roof layer may give information about roof insulation. The study shows that the combination of TST and 3D city models offers new possibilities to analyze thermal characteristics of single building elements.

Key words: urban facet, photogrammetric computation, thermo-physical properties

1. INTRODUCTION

The transport of radiation and energy in the boundary layer and its interaction with urban surface is a general research topic in urban meteorology. Remote sensing holds the possibility of making these patterns available for visualization and analysis. Many studies focus on the intra-urban variation of surface temperature at relatively small scales (e.g. Eliasson 1992, Quattrochi & Ridd 1994, Ben-Dor & Saaroni 1997, Chudnovsky at al. 2004). These studies contribute to our understanding of thermal patterns created by individual components of the city such as parks, industrial complexes or vegetation covers. Nevertheless, temporal processes in the transport of radiation and energy are not in the focus of these studies. Therefore, we used in our study a fixed based terrestrial oblique viewing thermal-infrared (TIR) camera system observing the temporal variation of upward long-wave radiation in a complex structured urban environment in Berlin.
Because of recent advances in computer science, digital photogrammetry and remote sensing, databases of the 3-D geometry of city centre areas are now increasingly available (Ratti et al. 2002). Ali-Toudert & Mayer (2007), Kanda et al. (2005), Gastellu-Etchegorry et al. (2004) and Khan & Simpson (2001) adopted actual 3-D data as a modeling source in urban areas.
Image orientation and the navigation within the 3-D space is a new coming topic in meteorological science (Krayenhoff & Voogt 2007, Lagouarde et al. 2000, 2004). Temporal variability of upward long-wave radiation flux densities of building facets is addressable by combination of TST data series and 3-D surface model. We focus on upward long-wave radiation flux densities from the building structure itself by observing different oriented facets and demonstrate the thermal patterns emitted and reflected from those surfaces during a diurnal cycle.

2. METHOD

2.1. Research Area

A single high-rise building (called 'Steglitzer Kreisel') dominates the area. The concurrence of urban dense build-up areas to the north and south of the high-riser and a well-greened up mid dense build-up area to the west of 'Steglitzer Kreisel' characterizes the research site (SenStadt 2008). Figure 1 shows the field of view (FOV) of the TIR camera. The FOV focuses on a dense build-up area with a traffic junction and five to six-story perimeter block development. The building height is here around 22.5 m above ground, the typical Berliner eaves height. Some smaller buildings in the FOV have pitched roofs. Most of the other buildings have different kind of flat roofs.

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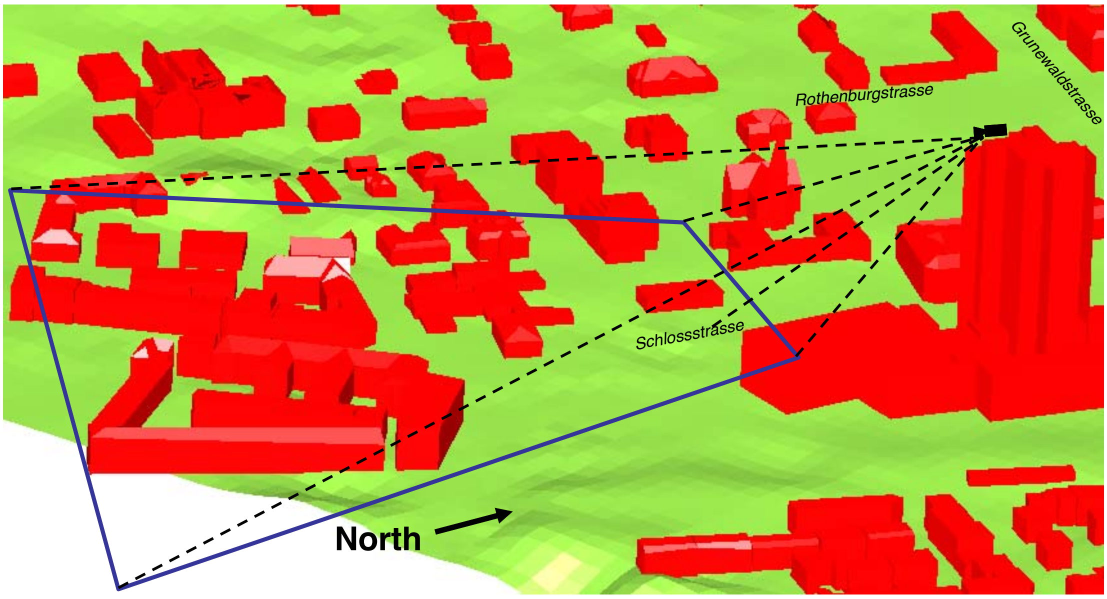

Figure 1: Detail of the 3-D surface model 'Steglitz' with the footprints of FOV as captured by the TIR camera system, mounted on the top of a 119 m high building ('Steglitzer Kreisel').

2.2. Data

The study uses two datasets, namely a 3-D surface model and a four-days TST dataset. The 3-D surface model is derived from aerial imagery. A raster surface model combined with a 3-D vector building model is called 3-D surface model and contains height information of both, surface ground and building facets. Both data products, namely a digital surface raster model and a shape file containing the buildings geometry, are derived by using aerial triangulation method. A RMSE of 1.72 m is the residual error for the overall aerial triangulation process. The buildings geometry is extracted as a vector files with vertices as bounds for each facet. The spatial resolution of the raster surface model is 10 m. The terrain of the research site is predominantly homogeneous with a slightly sloped hill in westerly direction. The 3-D surface model provides not only spatial extend of single facets but also associated parameters like facets orientation. If available, additional structural information (e.g. heat storage capacity, heat conductivity) can be associated with each facet.

A platform on top of the 119 m high-rise building 'Steglitzer Kreisel' carries a VarioCAM® head TIR camera system from InfraTec GmbH. The TIR camera system records the emitted and reflected long-wave radiation from urban surfaces. Table 1 lists detailed technical specifications of the TIR camera system.

Table 1: Technical specifications of the thermal-infrared (TIR) camera system

Camera manufacturer	InfraTec
Camera model	VarioCam® head
Spectral range	7.5 μm – 14 μm
Detector type	Microbolometer Focal Plane Array (320 x 240 pixel), uncooled
Temperature resolution at 30°C	better than 0.1 K
Measurement accuracy	± 2 K, ± 2%
Lens	Standard wide angle lens 12.5 mm
Field of View (FOV)	64° x 50°

The TIR camera recorded one image per minute over a period of 96 hours from 22th to 26th May 2008. The TST dataset are thus combined from 5760 single TIR images. Each image runs thought a four step pre-processing to convert the raw data to physical units. The pre-processing includes both calibration and correction of various lens distortions.

2.3. Image orientation

To address long-wave radiation flux densities from single urban facets, an interconnection in both ways between central perspective projected TST dataset and 3-D surface model is necessary. To realize this interconnection, the 3-D surface model must be oriented into the viewing position of the TIR camera system using photogrammetric equations. This orientation process is solved by defining the cameras absolute position in x-, y- and z-direction, the use of tie points (TP) and associated GCP within the FOV of the TIR camera system (Lagouarde et al. 2004).

For this task, the software package IDL and its capabilities in object-oriented visualisation is used. Ten TP are defined in the 2-D TIR image with 320 by 240 pixels and ten associated GCPs in the 3-D surface model. The solving of the photogrammetric equation depends on eight parameters. Two of them describe the interior orientation of the central perspective. Six of them belong to the exterior orientation, describing the position and bearing in space of the projection centre. The parameters of the interior orientation are known for the TIR camera system. The exterior orientation determines the relationship of an image to the ground coordinate system. Each image has six exterior orientation parameters, the three coordinates of the perspective centre in the ground coordinate system, and three rotation angles. Because the TIR camera system is fixed, our approach uses only two rotation angles around its own vertical and horizontal axis.

Three single tasks separate the process of perspective orientation to simplify the computational calculation. First, the fixed interior orientation is realized by the view port, which we assumed as stable for whole computation.

Second, the exterior orientation has to be established. The TIR image centre and the corresponding point within the 3-D surface model are used as a single GCP reference. For the orientation of the TIR images, the zenith angle between the original nadir locking view port and the first GCP is computed first. The 3-D surface model is then turned to this new horizontal angle. Then the azimuth angle between the north oriented view port and the first GCP is computed in order to adjust the 3-D surface model along its vertical axis at the azimuth angle.

Finally, we developed a software solution to link the 3-D vector representation of the buildings with the TST data directly. By just clicking to a vector facet, the software extracts the pixels in the TST dataset, representing the selected facet. This technique is able to extract both; single pixels as well as complete facet extend from the TST dataset.

3. RESULTS

The long-wave radiation, detected by the TIR camera system, depends on the angular position between the facet and the TIR camera system. Figure 2A shows the building environment as well as the surface heights in the FOV of TIR camera system. Blue color marks the detailed observed object. Figure 2B shows upward long-wave radiation flux densities, ranging from 400 W/m² to 520 W/m². The measurement was performed with the TIR camera looking in a southwestern direction. The image is taken at 12:00:10 23th May 2008 Central European Time (CET).

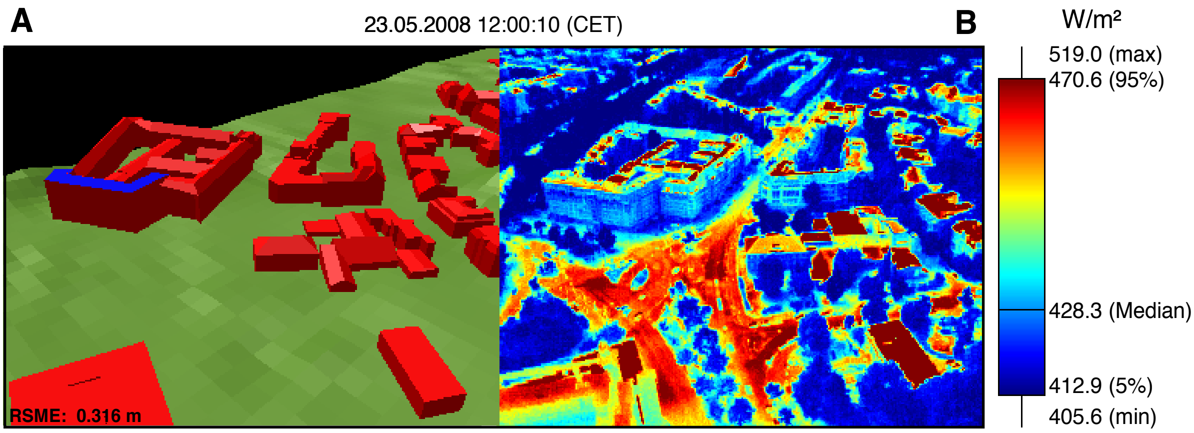

Figure 2 A: 3-D model ‘Steglitz’, in its perspective aperture as seen by the TIR camera system. The detailed observed building roof is marked in blue. The illumination of the 3D model equates to Sun’s elevation and azimuth at the acquisition time of the TIR image. B: TIR image at 12:00:10 23th May 2008, matching the 3-D surface model and recorded upward long-wave radiation.

Building roofs and sealed surfaces like streets show the highest upward long-wave radiation flux densities. Vegetation, especially trees, appears cooler in comparison to buildings or pavement ground due to evapotranspiration of vegetation. In particular, flat building roofs appear as warmest surfaces due to high sky view factors (SVF). Sky view factor refers to the ratio of diffuse sky irradiance at a given location relative to that on an unobstructed horizontal surface. Right-angled edges between building walls and the ground show adjacency effects (e.g. at the blue marked building, see fig. 2) on the vertical walls.

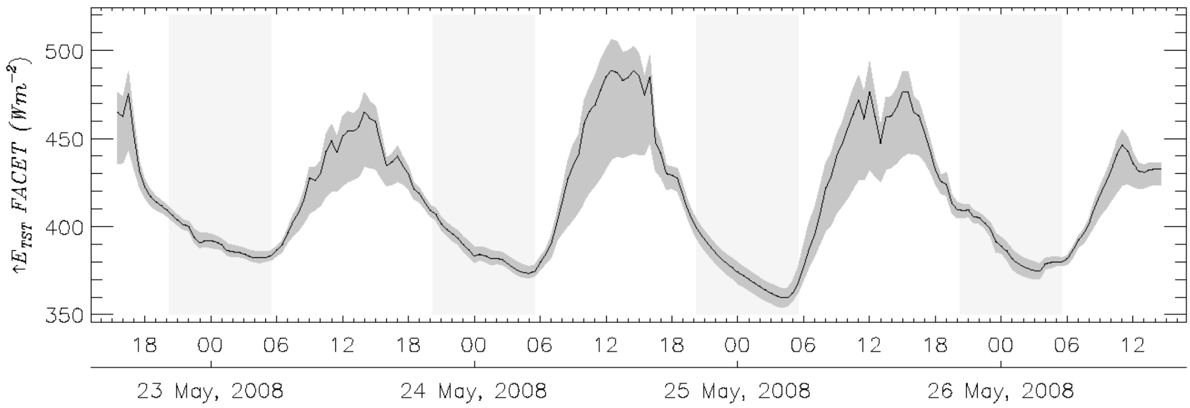

Figure 3: Median, 5% and 95% percentile of long-wave radiation flux of selected flat roof facet (compare Figure 2). Nighttime is marked in light grey.

Figure 3 shows exemplary the mean long-wave radiation flux of the roof facet marked in blue in figure 2 for the four-days period of the experiment. To avoid a mismatch of the results, a roof with no vegetation overlap in the camera-viewing path was selected as observed spot. The flat roof is represented in the TST dataset with a number of 479 pixels. The upward long-wave radiation flux is analyzed by computing statistical parameters like mean, median and 5% and 95% percentiles and displayed in figure 3. The black line the dark grey shaded area in Figure 3 represents the median while the 5% and 95% percentile is represented by upper and lower limits. In light grey, night times are represented in the figure.

In general, a strong diurnal variation of the upward long-wave radiant flux is obvious. The long-wave radiation flux increases rapidly in the morning hours and the majority of pixels show higher fluxes. Evening and nighttime is dominated by decreasing long-wave radiation fluxes and nighttime cooling until sunrise. Comparisons with other roofs show differences in temporal pattern of long-wave radiation flux. These differences may be correlated with thermo-physical properties of the observed roofs due to differences in roof insulation.

3. CONCLUSION AND OUTLOOK

We can conclude, that time-sequential thermography is a powerful tool for visualization of spatio-temporal patterns of thermal radiation. The combination of 3-D surface model and TIR image orientation with TST datasets allows process studies for single facets. Direct and interactive access to singe facets within the 3-D surface model and associated TST dataset is possible using photogrammetric approach.

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