|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **ESA STUDY CONTRACT REPORT**  **Deliverable 5 under WP3:**  **Report on definition of algorithmic structure of the toolbox** | | | | |
| ESA Contract No:  4000117034/16/NL/NDe | SUBJECT: **SURGE**: Simulating the cooling effect of urban greenery based on solar radiation modelling and a new generation of ESA sensors | | | CONTRACTOR:  Pavol Jozef Šafárik University in Košice, Institute of Geography |
| \* ESA CR( )No: |  | No. of Volumes: 1  This is Volume No: 1.0 | | CONTRACTOR’S REFERENCE: |
| ABSTRACT: This report summarizes the rationale and structure of the approach, which we adopted to simulate the cooling effect of urban greenery with Sentinel 2 data. The key component of the approach is the r.sun module implemented in the GRASS GIS open-source software, which is dedicated for calculating spatial distribution of global solar irradiance and irradiation incoming to the land surface. Grid-based digital elevation model of the land cover surface (DSM) is the main input of the module. The solar irradiation is calculated for the grid cells of the DSM. In the next step, a sequence of map algebra operations is executed to convert the solar irradiation to the land surface temperature. This procedure is based on the Stefan-Boltzmann Law, which describes the power radiated from a black body in terms of its temperature. The key inputs of the LST calculation comprise spatially distributed global solar irradiation of a DSM, convective heat transfer coefficient of the surface material, albedo of the surface and the emissivity of the material. We assumed ideal atmospheric conditions for deriving LST in various scenarios with and without urban greenery. The proposed algorithm is a novel contribution to modelling the land surface temperature in a GIS environment where tools for calculating temperature of surface have not been implemented to our knowledge to date. Despite the input variables, such as convective heat transfer coefficient and surface emissivity are difficult to ascertain with high degree of certainty and the transfer of heat in the environment being a complex phenomenon, the proposed approach provides means for assessing various scenarios of land cover in urban planning. Importantly, it enables to model surface temperature on a much finer scale than contemporary thermal sensors such as TIRS of Landsat 8 or SLSTR of Sentinel 3 sense it. We have demonstrated that Sentinel 2 data can be used in the algorithm for estimating the broad-band albedo, emissivity of surface material and transmittance of urban trees. It should be emphasized, that the resulting temperature values require validation in respect to more reliable data sets or methods. This aspect is to be discussed in the roadmap of the approach for future development. | | | | |
| The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it. | | | | |
| Names of authors: Michal Gallay, Jaroslav Hofierka | | | | |
| \*\* NAME OF ESA STUDY MANAGER:  DIV:  DIRECTORATE: | | | \*\* ESA BUDGET HEADING: | |

# 1 Introduction

## Contractual

This document has been issued by Institute of Geography, P.J. Šafárik University in Košice for European Space Agency under contract Nr. 4000117034/16/NL/NDe titled “Simulating the cooling effect of urban greenery based on solar radiation modelling and a new generation of ESA sensors (acronym SURGE)”.

## Purpose of the Document

This document presents our proposal of algorithmic structure of the toolbox. The toolbox should enable urban planners and researchers to mitigate heat risk based on solar radiation modelling and Sentinel-2A multispectral data for urban greenery parameterization. The proposed methods and procedures were tested using our test site in Košice City, Slovakia (Fig. 1). The here presented results address the following technical objectives (TO) as outlined in the proposal of the contract 4000117034/16/NL/NDe:

TO5: Identification of critical functions and characteristics of the proposed approach for implementation as a toolbox for simulating the cooling effect of urban greenery based on solar radiation modelling and defining its applicability (proof-of-concept).

|  |  |
| --- | --- |
|  |  |

*Figure 1. Location of the study area in the Košice City, Slovakia. The cyan line outlines the area subject to airborne lidar and photogrammetric mapping in a single mission, time series of the Sentinel 2 image coverage. The red outline delineates four sites selected for repeated terrestrial laser scanning of urban vegetation. The background maps are © Copernicus, Sentinel 2A image acquired on 7 September 2016.*

## 1.3 Motivation

Mitigation of urban heat islands (UHI) requires understanding the factors affecting the interaction of solar radiation and urban surfaces. Over the last two decades numerous studies have been published analysing the associations between solar radiation, reflectance, emissivity and other heat transfer parameters of materials of urban surfaces (Berdahl & Bretz, 1997, Mirsadeghi et al. 2013). The positive impact of urban vegetation on mitigation of urban heat islands is well known and documented. However, much less information is available on quantification of the impact in relation to urban vegetation parameters and temporal variation throughout the year depending on phenological phase of plants.

In this project we summarized supporting material from published studies why and how much vegetation in cities reduces solar radiation received by built-up areas. The most pronounced solar radiation loss determining the cooling of the local climate occurs during the summer time which is related to the full development of plants, especially trees with leaves. The D1 report (SURGE\_D1\_SOA\_MSVT) also showed that the normalized vegetation index (NDVI) is most frequently used for efficient parametrization of vegetation conditions despite the known shortcoming with saturation of high NDVI values. In modelling the solar irradiation of urban space, both atmospheric transmittance and geometric structure of urban space were shown to be critical model parameters. For the purposes of assessing the vegetation transmittance, NDVI and other indices cannot be directly used. Metrics expressing the nature of vegetation transmittance for the solar radiation comprise, for example, leaf area index (LAI), canopy cover, tree canopy closure, canopy gap fraction, etc. However, these are difficult to be measured directly from the satellite imagery. It has been shown by many studies that, into certain extent, NDVI and other indices are correlated with the metrics and can be used as a proxy for their calculation. Tooke et al. (2012) propose that opportunities exist for incorporating additional spectral data, especially for generating estimates of the reflected component of incoming solar radiation. The potential also exists for advancing estimates of radiation transmission by articulating the temporal, spectral and structural dynamics of the local vegetation. The multispectral imagery acquired by the Sentinel 2 mission has relatively high spatial, spectral and temporal resolution to capture the dynamic of vegetation phenology. In the D3 report we analysed the properties of this data to use it as a proxy of the vegetation transmittance on higher resolution.

In this report (D5) we analyse available solar radiation tools to assess the most important variable of the urban heat island - solar irradiance. Furthermore, we analyse the physical principles of heat transfer and land surface temperature directly impacting the air temperature. The most dynamic factor affecting the process is urban vegetation.

# 2 Spatial modelling of land surface temperature by solar irradiation modeling

Solar radiation received at the urban surface is a key input factor in many urban energy models and sustainable city designs. Examples include thermal and photovoltaic solar energy installations, passive heating systems or urban microclimate designs (e.g., Hofierka and Kaňuk 2009, Ratti et al. 2005, Lindberg and Grimmond 2011). However, solar radiation flows over urban surfaces are highly variable due to a complexity of urban morphology and interactions with various components of the urban environment. The use of adequate models and tools is therefore crucial for accurate assessments of spatial and temporal distribution of solar radiation in urban areas.

Over the last two decades several solar radiation models integrated with geographical information systems (GIS) were developed. These GIS-based solar radiation models provide estimates of spatial variations of solar radiation over large regions using digital terrain models (DTMs) and selected ground-based or satellite data reflecting atmospheric and land cover conditions (e.g., Hetrick et al. 1993, Dubayah and Rich 1995, Kumar et al. 1997, Fu and Rich 2000, Wilson and Gallant 2000, Šúri and Hofierka 2004). These solar radiation models can be used for two-dimensional (2-D) surfaces, such as land surface or rooftops. Hofierka and Zlocha (2012) also developed the v.sun model as a full 3-D solar radiation model for complex, three-dimensional (3-D) urban surfaces as an extension of the r.sun model.

## 2.1 The r.sun solar radiation model

One of the widely used GIS-based solar radiation models is the r.sun model implemented in the open-source environment of GRASS GIS as the r.sun module (Neteler and Mitasova 2004). Originally developed as a clear-sky model (Hofierka 197), it was later further substantially improved by Šúri and Hofierka (2004) to include diffuse and reflected components of solar radiation for clear-sky and real-sky conditions. The model is sufficiently robust and flexible over various scales and range of applications as presented, for example, in Romero at al. (2008), Steiniger and Hay (2009), Ruiz-Arias et al. (2009), Bergamasco and Asinari (2011). Perhaps the most popular application is the PVGIS online estimation utility (Šúri et al. 2005) available at <http://re.jrc.ec.europa.eu/pvgis/>. This web-based utility can be used to estimate the photovoltaic potential of a selected site in Europe and Africa. Hofierka and Kaňuk (2009) used the PVGIS tool and the r.sun methodology to assess a photovoltaic potential of urban areas. The rooftops of buildings in various urban zones have been mapped and analysed using a simplified 3-D city model for a possible installation of roof-mounted photovoltaic power plants.

The increasing number of applications and natural importance of urban areas has led to a growing number of urban studies using 3-D city models. This trend is also supported by a wider use of new geospatial data collection methods such as LiDAR and digital photogrammetry that also contribute to a wider availability of 3-D urban data. These technological advances also provide new opportunities for comprehensive 3-D approaches in solar radiation modelling (Carneiro et al. 2009). Moreover, the rapid development and greater use of various solar energy applications in urban areas even more necessitate accurate solar resource assessments including vertical surfaces, such as facades (Hofierka and Kaňuk 2010).

Solar radiation incident at the Earth surface is a very complex phenomenon. The extra-terrestrial solar radiation incoming to the atmosphere is attenuated here by scattering, refraction and absorption. Hence, the actual amount of radiation at the particular site at the Earth surface is dependent on the Earth‘s geometry and geographical conditions, such as elevation, surface inclination and orientation, and shadowing effects of the surrounding features (terrain, trees, buildings, etc.).

Global solar radiation at the Earth surface has 3 components: direct (beam), diffuse and reflected radiation (Fig. 2). The reflected radiation is available only on non-flat areas. In urban areas this component can be quite substantial due to complex morphology and high reflectivity of many urban surfaces (Muneer 2004). The maximum global radiation is obtained when the sky is absolutely clean and dry, relatively less radiation is received when aerosols are also present. The effect of attenuation is the strongest if clouds are present; however, modelling the effects of clouds requires a great deal of information regarding instantaneous cloud thickness, position and number of layers of clouds, as well as their optical properties. Therefore, simple empirical techniques are used to estimate the attenuation by cloud cover (Šúri and Hofierka 2004). Consideration of all factors of atmospheric attenuation in the calculation scheme results in real-sky (overcast) conditions. Omitting of the cloud attenuation results in clear-sky (cloudless) radiation values. While in most applications we need real-sky radiation values, a study of global radiation under clear skies is still very important and often a part of real-sky radiation estimation schemes.

The adequate GIS-based solar radiation models, such as the r.sun solar radiation model, should provide spatially distributed values of clear-sky as well as real-sky radiation based on the available input data. This model is available in the standard distribution of GRASS GIS as the r.sun module and command (GRASS 2012). The r.sun module uses a raster data model for data input and output, shadowing algorithm and all solar radiation calculations.

It can be very efficiently used for modelling the spatial distribution of solar radiation over various 2-D surfaces represented by a raster data model. A detailed description of the r.sun model and its methodology can be found in the study by Šúri and Hofierka (2004) with further information about the r.sun module in (Neteler and Mitasova 2004) and manual pages of GRASS GIS.

The solar radiation methodology used in the r,sun and v.sun models is based on the European Solar Radiation Atlas (ESRA) methodology (Scharmer and Greif 2000, Rigollier et al. 2000) also used in the r.sun solar radiation model (Šúri and Hofierka 2004). The calculation of the beam component is quite straightforward, the main difference between the various models available in the literature is the treatment of the diffuse component (Perez et al. 1987). This component depends on climate and regional terrain conditions and is often the largest source of estimation error. The diffuse component implemented in this solar radiation methodology is derived from European climate conditions. The reflected radiation contributes to global radiation only by several percents in open areas and depends strongly on the reflectance of surrounding surfaces. Higher contribution of this component can be expected in areas with insolated vertical surfaces.

The r.sun/v.sun model estimates the beam, diffuse and reflected components of clear-sky radiation after taking into account the attenuation of extraterrestrial radiation by air-mass effects and atmosphere turbidity. The real-sky radiation is approximated from the latter results using the clear-sky index, which represents the attenuation of clear-sky radiation by cloudiness. The spatial distribution of clear-sky index over large areas is usually estimated from ground radiation measurements by interpolation or from satellite-based predictions. Calculation of the irradiance incident on inclined surfaces requires estimation of beam and diffuse components of global horizontal radiation. Similarly to the clear-sky index, the ratio of diffuse and global radiation can be derived by spatial interpolation of ground-based data or by models based on satellite data.

The r.sun/v.sun module in GRASS GIS is able to compute instant values of solar irradiance for the specified time or sums of solar radiation over the selected period of time with a specified approximation time step. For example, daily sums of solar radiation can be calculated with an approximation time step of 1 hour which is sufficient for most applications.

The r.sun/v.sun module works in two modes. Mode 1 is for instantaneous calculations, for which vector-based 3-D data of solar irradiance [W.m-2] and solar incident angles [degrees] are obtained. In mode 2, the vector-based 3-D data provide daily sums of solar irradiation [W.h.m-2] and daily direct-sun duration [minutes]. These are computed from the integration of irradiance values (derived in Mode 1) that are calculated at a user-selected time step from sunrise to sunset. If such option is also selected, the computation can account for sky obstructions (shadowing). These two modes can be used separately or in combination to provide estimates of incident radiation for any desired time step or interval. This is done using a script (e.g., in the Linux operating system).

In summary, the r.sun and v.sun modules have the following key features:

• It is a raster-based (r.sun) and vector-based (v.sun) GIS program with selected solar input parameters defined as spatially variable in a raster/voxel format or as constants.

• It provides all components of clear-sky and real-sky solar radiation for irradiation [W.h.m-2] and irradiance values [W.m-2].

• Its calculations can be performed assuming solar or civil time.

• The spatial accuracy of calculation is defined by an easy-to-understand voxel size parameter defining the tessellation of the region volume and polygon elements.

• It is a free, open-source program with available source code for further improvement.

• Integration with the open-source environment of GRASS GIS provides other GIS tools for processing the input and output data directly within a single computing environment.

A growing number of solar energy application in urban areas along with a greater availability of 3-D city models representing a complex urban morphology attracted interest in adequate 3-D solar radiation modelling tools. While the topographic r.sun model can be applied to 2-D surfaces even in urban environment, vertical surfaces, such as facades must be excluded from the analysis, thus greatly limiting the accuracy and completeness of the solar resource assessment.

The original proposal in this feasibility study was to simulate the cooling effect of urban greenery using the Sentinel 2 data with the v.sun module. However, we realised that Sentinel 2 data could be implemented into such a geospatial modelling in a simpler fashion via the r.sun module which will be more convenient for the end user. The main argument for that is the two-dimensionality of Sentinel 2 data products which represent a 2D array of spectral radiance reflected from the earth surface and recorded by the MSI sensor on-board the satellite vehicle. The data products are 2D arrays by nature, i.e. raster datasets, therefore, more suitable for the r.sun module which was developed for 2D raster data.

Table 1 summarizes computation of the global solar irradiance in GRASS GIS for 4 scenarios for the 182th day of year and 10:20 of zonal time (30 June 2016). This day and time was selected for the availability of cloudless scenes of Landsat 8 for this moment and Sentinel 2 for previous day of 29 June 2016. The scenarios demonstrate the effect of urban greenery on the temperature of the land surface. Trees and shrubs taller than 1.5 m are considered for simulating this effect. Grass, lawns and small shrubs are considered as land cover of the ground surface. Figure 2 shows the input DSM data and the calculated morphometric parameters (slope and aspect). Figure 3 displays the calculated solar irradiance for the third scenario. The calculated global solar irradiance on horizontal surfaces such as roads (orange colour of global irradiance in Fig. 3) corresponds well with the measured global irradiance at the Košice airport weather station on (887.15 W.m-2) on 30 June 2016 at 10:00 zonal time. The final output of each of the four scenarios resulted in a sum of the beam, diffuse and reflected component which is the global irradiance raster layer. This dataset is one of the key inputs for modelling the temperature which is described in the following section.

*Table 1. Different scenarios of input parameters for modelling the global solar irradiance and the effect of urban greenery.*

|  |  |
| --- | --- |
| **Modelled scenario** | **Variable input parameters** |
| 1 | * Surface of the ground/terrain and buildings, and its slope angle and slope aspect * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * No transmittance of urban greenery, irradiation modelled for the canopy surface of urban greenery   r.sun --o elevation=DSM\_ground+buildings  aspect=DSM\_ground+buildings\_aspect slope=DSM\_ground+buildings\_slope  albedo=albedo\_182 beam\_rad=b182i1020 diff\_rad=d182i1020  refl\_rad=r182i1020 day=182 time=10.33 r.mapcalc "g182i1020 = b182i1020 + d182i1020 + r182i1020" |
| 2 | * Surface of the ground/terrain and buildings, * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Variable transmittance of urban greenery (coeff\_bh, 0-1), estimated with linear regression models of LAI\_TLS and S2\_NDVI for site 1   r.sun --o elevation=DSM\_ground\_buildings\_vegetation  aspect=DSM\_ground\_buildins\_vegetation\_aspect  slope=DSM\_ground\_buildins\_vegetation\_slope albedo=albedo\_182  beam\_rad=bveg182i1020r diff\_rad=dveg182i1020r refl\_rad=rveg182i1020r  day=182 time=10.33 coeff\_bh=real\_coeff20160914  r.mapcalc "gveg182i1020r = bveg182i1020r + dveg182i1020r + rveg182i1020r" |
| 3 | * Surface of the ground/terrain and buildings and urban greenery, and its slope angle and slope aspect * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * No transmittance of urban greenery, irradiation modelled for the canopy surface of urban greenery   r.sun --o elevation=DSM\_ground\_buildings\_vegetation  aspect=DSM\_ground\_buildins\_vegetation\_aspect  slope=DSM\_ground\_buildins\_vegetation\_slope albedo=albedo\_182  beam\_rad=bveg182i1020 diff\_rad=dveg182i1020 refl\_rad=rveg182i1020  day=182 time=10.33  r.mapcalc "gveg182i1020 = bveg182i1020 + dveg182i1020 + rveg182i1020" |
| 4 | * Surface of the ground/terrain and buildings and urban greenery, and its slope angle and slope aspect * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Variable transmittance of urban greenery (coeff\_bh, 0-1), estimated with linear regression models of LAI\_TLS and S2\_NDVI for site 1   r.sun --o elevation=DSM\_ground+buildings  aspect=DSM\_ground+buildings\_aspect slope=DSM\_ground+buildings\_slope  albedo=albedo\_182 beam\_rad=b182i1020r diff\_rad=d182i1020r  refl\_rad=r182i1020r day=182 time=10.33 coeff\_bh=real\_coeff20160914  r.mapcalc "g182i1020r = b182i1020r + d182i1020r + r182i1020r" |

|  |  |  |
| --- | --- | --- |
|  |  |  |
| *Elevation [ma.s.l.]* | *Slope angle* | *Slope aspect* |
|  |  |  |

*Figure 2. Lidar based digital surface model (DSM) of the area of Moyzesova street in Košice (site 1 in Fig. 1) including buildings (upper row) and vegetation (bottom row) which was used to calculate global solar irradiance. The area size is 200 m by 400 m. DSM cell size 0.50 m.*

|  |  |  |
| --- | --- | --- |
|  |  |  |
| *Digital surface model, elevation [ma.s.l.] including vegetation and buildings* | *False colour infrared aerial orthoimage* | *Global clear-sky irradiance [W.m -2]* |
| b207i12 | d207i12 | r207i12 |
| *Beam (direct) irradiance [W.m -2]* | *Diffuse irradiance [W.m -2]* | *Reflected irradiance [W.m -2]* |

*Figure 3. Lidar based digital surface model (DSM) of the area of Moyzesova street in Košice (site 1 in Fig. 1) including buildings and vegetation used to calculate global solar irradiance (W.m -2) with its components using the r.sun model in GRASS GIS for 30 June at 10:20 zonal time. The area size is 200 m by 400 m. The resulting data layers were derived at 0.50 m spatial resolution.*

## 2.2 Calculation of land surface temperature of urban surfaces

The land surface temperature is predominantly controlled by the solar radiation income. Therefore, the outputs of the approach described in Section 2.1 are the key inputs for modelling the heat transfer from the Sun to the land surface. Urban landscape comprises materials which absorb and reradiate the thermal energy in a distinct way from the rural landscape. If the urban landscape extends over a sufficiently large area, the urban heat island (UHI) phenomenon occurs in such an area. We showed that UHI occurs even in such a small city such as Košice (Onačillová & Gallay, 2018). There are two types of UHIs: surface and atmospheric UHIs. Surface UHIs usually develop during hot, sunny summer days. The sun heats dry, exposed urban surfaces, like roofs, roads and pavements, to temperatures 25 to 50°C hotter than the temperature of the ambient air mass. The magnitude of surface UHIs varies with seasons, due to changes in the sun’s intensity as well as ground cover and weather. As a result of such variation, surface UHIs are typically largest in the summer. Warmer air in urban areas compared to cooler air in nearby rural surroundings defines atmospheric UHIs. These are usually divided into two different types: canopy layer UHIs which exist in the layer of air where people live, from the ground to below the tops of trees and roofs and boundary layer UHIs that start from the rooftop and treetop level and extend up to the point where urban landscape no longer influences the atmosphere (Oke 1973). This region typically extends no more than 1.5 km from the surface. Surface temperatures have an indirect, but significant, influence on air temperatures, especially in the canopy layer, which is closest to the surface. For example, parks and vegetated areas, which typically have cooler surface temperatures, contribute to cooler air temperatures. Dense, built-up areas, on the other hand, typically increase the air temperature. The relationship between land surface and air temperatures is not constant and linear because air mixes within the atmosphere. Therefore the air temperature typically varies less than the temperatures of the land surface across an area. In this section, we focus on surface UHIs and LSTs which directly contribute also to the development of atmospheric UHIs.

The most important factor contributing to development of surface UHIs is the amount of solar irradiance. It consists of three components: beam (direct), diffuse and reflected irradiance. The most important component is beam radiation because usually it is about 50-60% of global radiation and even more during sunny days. Beam radiation depends on solar and local surface geometry and therefore it can be computed quite straightforwardly. Diffuse radiation is anisotropic, i.e., it varies over the sky depending on direction of solar rays. The ground-reflected component of solar radiation is usually quite small (e.g., several percent of global radiation). It depends on topography and ground surface reflectance. The reflectance of urban surfaces is expressed via ground albedo. In flat areas, the ground reflected radiation is almost non-existent, i.e. reflected; however, it may become significant in urban areas with buildings and vertical walls.

Land surface temperature (LST) is generally defined as the radiative skin temperature of the ground derived from solar radiation. LST is a key parameter in the physics of land surface processes, combining surface-atmosphere interactions and energy fluxes between the atmosphere and the ground. Properties of urban materials, in particular solar reflectance, thermal emissivity, and heat capacity influence the LST and subsequently development of UHIs, as they determine how the sun’s energy is reflected, emitted, and absorbed.

Generally, a built-up area exhibits a variable thermal pattern with hot and cold peaks, corresponding to low and high reflectivity impervious surfaces, respectively. A solar-reflective surface is typically light in colour and absorbs less sunlight than a conventional dark-coloured surface. Mitigating UHIs requires lowering the average surface temperature of the city so that there is less surface-to-air heat transfer. Urban vegetation is one of key components of this effort as the greenery maintains cooler surface temperatures, mainly by the process of evapotranspiration and shading. For building and pavement surfaces in the sun, surface characteristics such as albedo, emissivity, and roughness, are also relevant. For a surface under the sun and insulated underneath, the equilibrium surface temperature, *Ts* is obtained from the equation based on Stefan-Boltzmann Law which describes the power radiated from a black body in terms of its temperature (Bretz et al., 1998):

 Eq. 1

where  is unitless solar-reflectivity or albedo of the surface varying from 0 to 1, *I* is the total solar radiation incident on the surface in W.m-2 which is the output from the r.sun model, is the emissivity of surface,  is the Stefan-Boltzmann constant, 5.6685 × 10-8W.m-2K-4, *Ts* is equilibrium surface temperature, K, *Tsky* is the effective radiant sky temperature, *hc* convection heat transfer coefficient, Wm-2K-1, *Ta* air temperature, K (ASHRAE, 1989).

Using this equation, the surface temperature *Ts* can be approximated by Newton's iteration method. In GRASS GIS using a shell script this approximation has the following form:

#!/bin/sh

#lst.stefan-boltzman.sh

echo "Global irradiance file"

read irr

g.copy rast=$irr,gi

echo "Albedo file"

read alb

g.copy rast=$alb,albedo

echo "Convection coefficient file"

read cc

g.copy rast=$cc,h\_c

echo "Initial estimation of land surface temperature (e.g., 300)"

read temp0

echo "Ambient air temperature (e.g., 293)"

read T\_a

echo "Radiant sky temperature (e.g., 287)"

read T\_sky

echo " initialization of parameters..."

r.mapcalc --o "epsilon = 1. - albedo"

r.mapcalc --o "c = -epsilon \* 0.000000056685 \* $T\_sky \* $T\_sky \* $T\_sky \* $T\_sky - h\_c \* $T\_a - (1 - albedo) \* gi"

r.mapcalc --o "lst0 = $temp0" #initialization of LST

r.mapcalc --o "y = lst0\*lst0\*lst0"

r.mapcalc --o "lst = (3\*epsilon\*0.000000056685\*y\*lst0 - c)/(4\*epsilon\*0.000000056685\*y+h\_c)" #1st iteration

i=2

while [ $i -le 10 ]

do

echo "Iteration" $i

g.copy --o rast=lst,lst0

r.mapcalc --o "y = lst0\*lst0\*lst0"

r.mapcalc --o "lst = (3\*epsilon\*0.000000056685\*y\*lst0 - c)/(4\*epsilon\*0.000000056685\*y+h\_c)"

i=`expr $i + 1`

done

echo "Finished."

This approximation requires the first estimation of LST (e.g., roughly close to measured air temperature, sunny, overcast day, etc.). Then 10 iterations produce the results with sufficient accuracy. The GRASS GIS implementation assumes that ambient air temperature *Ta* and radiant sky temperature *Tsky* are also known. Air temperature is usually measured by meteorological stations, often even within the city. Radiant sky temperature can be estimated using one of the available approximation methods published, e.g. in (Algarni, 2015), depending on the cloudiness. In this study, we use fairly simple clear sky and cloudy sky direct temperature models where *Tsky = Ta - 20* under clear-sky conditions (Garg, 1982) and *Tsky = Ta* *- 6* under cloudy conditions (Whillier, 1967). Of course, any other temperature model can be used depending on available data to improve the accuracy of assessment. However, to evaluate the algorithmic structure of our solution it is sufficient to use even these simple formulas. The dominant parameters which determine the maximum LST are solar reflectance (albedo), thermal emissivity of the surface and convection heat transfer coefficient *hc*.. Berdahl and Bretz (1997) demonstrated a fairly linear correlation between albedo and thermal emissivity of the surface for typical metal roof coatings and in most cases emissivity can be roughly approximated by .

The relationship between albedo and thermal emissivity is generally called Kirchoff's Law saying that surfaces with high reflectivity (or, roughly, high albedo) have low emissivity and vice versa. Based on this law, we assume for an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity of the incomming electromagnetic energy.

*absorption = emissivity at a specific wavelength*

Despite it is known that this assumption does not rigidly hold it can be used for approximating the emissivity in case other more accurate data do not exist. Moreover, emissivity can be calculated from Sentinel 2 data by deriving broad-band albedo as described in Section 2.3.

The convection coefficient *hc* is usually the most difficult parameter to estimate. It depends strongly on wind speed and direction, geometry of the building and surroundings objects, height of the roof above ground level, building material texture (roughness) and surface to air temperature difference (Mirsadeghi et al., 2013). In sunlight, with zero wind speed, *hc*, is determined by natural convection. It is a weakly increasing function of temperature difference, and almost independent of surface size. For example, for *Tsky* - *Ta* = 30 K, estimates give *hc* = 6.6 Wm-2K-1. For wind speeds above 1 m.s-1, the convection coefficient is determined by forced convection, and, *hc* rises from 2.5 to 3.0 W.m-2.K-1 at zero wind speed to about 15 to 20 W.m-2.K-1 at wind speeds of 7 m.s-1 with even higher values of *hc* for roofs and upwind surfaces (Liu et al., 2015). More accurate estimates of *hc* require complex modelling techniques using 3D city models, data on building material and 3D wind simulation. In this study, we use a uniform value of *hc* =10 W.m-2.K-1 for the whole study area but also spatially differentiated *hc* based on land cover type to account for spatial differences within the city or between the buildings. Table 1 and Figure 4 summarize how we assigned different land cover categories with the values of *hc* which was based on expert judgment supported by the values reported by Liu et al. (2015), Vollaro et al., (2015) and Amir et al. (2018). The values are estimated for typical hot summer atmospheric conditions with clear sky, small or no wind.

*Table 2. Convective heat transfer coefficient used in this study for modelling the surface temperature in the Košice city*

|  |  |
| --- | --- |
| **Surface material** | **Convective heat transfer**  **coefficient [W.m-2.K-1]** |
| roofs | 8 |
| dark grey and dark pink asphalt roads and pavements, red bricks, concrete, concrete paver blocks, concrete paver blocks with tram rails, crushed stone pavement, dark stone blocks pavement, loose pebbles pavement, gravel stones, red clay courts, railway, stone graves with grass | 10 |
| concrete channel with water | 12 |
| bare soil | 13 |
| grass, lawn, low shrubs | 15 |
| low shrubs | 15 |
| water surface | 20 |

|  |  |
| --- | --- |
|  |  |
| *Land cover in 21 categories representing the material of the ground below the trees and shrub for the entire study area and site 1 – Moyzesova street.* | |
|  |  |
| *Spatially distributed convective heat transfer coefficient* hc2 *(W.m-2.K-1) for the entire study area and site 1 – Moyzesova street based on land cover of the ground (Table 2).* | |
|  |  |
| *Spatially distributed convective heat transfer coefficient* hc2\_s *(W.m-2.K-1) for the entire study area and site 1 – Moyzesova street based on land cover of the ground (Table 2) and increased for the the tree and shrub vegetation based on vegetation transmittance and expert judgement.* | |

*Figure 4. Land cover of the ground surface and its reclassification into classes of spatially distributed distributed convective heat transfer coefficient* hc2 *and* hc2\_s*. The resulting data layers were derived at 0.50 m spatial resolution.*

Using the outlined algorithm (the lst.stefan-boltzman.sh script) in GRASS GIS, the land surface temperature was calculated for the four scenarios listed in Table 1 with the following inputs for land surface temperature calculation with the lst.stefan-boltzman.sh script as Table 3 summarizes. Figure 5 demonstrates the resulting surface temperature for the four scenarios using the detail of the study area of site 1. Figure 6 shows the result for the entire study area of Košice for scenarios 1 and 4.

*Table 3. Different scenarios of input parameters for modelling the land surface temperature and the effect of urban greenery.*

|  |  |
| --- | --- |
| **Modelled scenario** | **Variable input parameters** |
| 1 | * Global solar irradiance for scenario 1 as listed in Table1 * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Spatially distributed convective heat transfer coefficient *hc* for the land cover classes (Table 2) including urban greenery   sh lst.stefan-boltzman.sh g182i1020, albedo\_182, hc2  g.copy rast=lst,lst182i1020 |
| 2 | * Global solar irradiance for scenario 2 as listed in Table1 * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Spatially distributed convective heat transfer coefficient *hc* for the land cover classes (Table 2) excluding urban greenery (Fig. 3)   sh lst.stefan-boltzman.sh g182i1020r, albedo\_182, hc2\_s  g.copy rast=lst,lst182i1020r |
| 3 | * Global solar irradiance for scenario 2 as listed in Table1 * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Spatially distributed convective heat transfer coefficient *hc* for the land cover classes (Table 2) excluding urban greenery (Fig. 3)   sh lst.stefan-boltzman.sh gveg182i1020, albedo\_182, hc2\_s  g.copy rast=lst,lstveg182i1020 |
| 4 | * Global solar irradiance for scenario 2 as listed in Table1 * Surface broad-band albedo (albedo, 0-1) derived from Sentinel 2 for 29 June 2018 (day of year 181, 10:40 zonal time) * Spatially distributed convective heat transfer coefficient *hc* for the land cover classes (Table 2) excluding urban greenery (Fig. 3)   sh lst.stefan-boltzman.sh gveg182i1020r, albedo\_182, hc2\_s  g.copy rast=lst,lstveg182i1020r |

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | lstveg182i1020 | lstveg182i1020r |
| DSM with buildings,  Albedo of ground land cover,  No trees  lst182i1020 | DSM with buildings,  Albedo of ground land cover,  Solar transmittance of trees  lst182i1020r | DSM with buildings and trees,  Albedo of land cover  lstveg182i1020 | DSM with buildings and trees,  Albedo of land cover  Solar transmittance of trees  lstveg182i1020r |

*Figure 5. Modelled temperature of ground surface (kelvins) in site 1 - Moyzesova street, without and with implementing vegetation transmittance downscaled from linear regression model os S2\_NDVI vs. LAI\_TLS for 30 June 2016 at 9:20 AM of UTC, 10:20 zonal time. In the first two images DSM of terrain and building surface is used and albedo is derived for the ground land cover below the trees. In the latter two images, DSM of terrain, buildings and trees is used and albedo of the land cover canopy surface was used.*

|  |  |
| --- | --- |
| lst182i1020_full_KE_area |  |
| DSM with buildings,  Albedo of ground land cover,  No trees  lst182i1020 | DSM with buildings,  Albedo of ground land cover,  Solar transmittance of trees  lstveg182i1020r |

*Figure 6. Modelled temperature of ground surface (kelvins) in the entire study area of Košice without and with implementing vegetation transmittance downscaled from linear regression model os S2\_NDVI vs. LAI\_TLS for 30 June 2016 at 9:20 AM of UTC, 10:20 zonal time.*

We recognize that the heat transfer is a complex phenomenon and therefore it is difficult to ascertain realistic values of the input parameters of the proposed approach of converting solar irradiance to land surface temperature. Nevertheless, the algorithm provides means for assessing various scenarios in urban planning for mitigating urban heat island or summer heat waves in general. Most importantly, the outlined approach enables to model the surface temperature on a much finer scale than it is sensed by contemporary thermal sensors such as TIRS of Landsat 8 or SLSTR of Sentinel 3. Both sensors record the LST phenomenon on a different and broader spatial scale than was modelled by the proposed algorithm lst.stefan-boltzman.sh. The two kinds of LST data products are therefore difficult to compare for the modifiable area unit problem (MAUP) which his demonstrated by Figure 7. Atmospherically corrected LST was derived from a Landsat 8 scene acquired on 30 June 2016 10:20 zonal time using the approach presented in Onačillová & Gallay (2018). The LST was modelled by the lst.stefan-boltzman.sh algorithm for the same date and time for comparison. The image on the right side of of Figure 6 spatial resolution of 0.5 metres, but for comparison with Landsat 8 LST it was resampled 30 meters. It can be seen that the larger areas of low temperatures associated with urban greenery but also elongated area of high temperatures in the west associated with railway station are represented in both datasets. However, Landsat 8 does not capture the variations of LST existing on a finer scale which the lst.stefan-boltzman.sh modelled with a fine detail. Therefore, the scatterplot of both types of LST does not show any trend or linear relationship. Figure 5 and 6 demonstrate the cooling effect of urban trees and shurbs. Missing urban greenery in case of lst182i1020 causes the modelled LST of the ground surface to be about 20-40 K hotter than in the case of lst182i1020r, lstveg182i1020, lstveg182i1020r, where the tall vegetation is involved in modelling present. This is supported by the areas of cooler LST of vegetation canopy as derived from the Landsat 8 data in Figure 7.

Inclusion of tall vegetation into urban spaces is thus one of the means for mitigating the UHI phenomenon. At the same time, it is necessary to avoid low-emissivity materials, such as bare metals and aluminum coatings. Most urban surfaces that are not metallic exhibit high emissivity. The most practical parameter in the outline algorithm to alter on a large scale is albedo (Yang et al. 2015). With high albedo, reflective materials redirect more radiation and reduce surface temperatures, which in turn lead to lower air temperatures. However, reflected solar radiation can increase the temperature of the surrounding built environment and consequently increase its cooling load, such that overall benefits of reflective pavements and roofs can be less than expected. Reflected UV radiation, glare, and thermal discomfort are concomitant with the reflected radiation that attention is required to their impact on human health. In terms of energy consumption, reflective materials results in cooling savings and heating penalties, whose relative magnitude depending on complex interactions of many urban environmental factors, including building characteristics, urban morphology, geographical locations, local climate, etc. Reflective materials on different urban spatial locations can lead to opposite effects with regards to energy consumption. When applied at a large scale, reflective materials have positive impact on urban air quality directly and indirectly. However, the consequent reduction in precipitation, runoff, and soil water content requires special attentions, especially in arid and semi-arid regions.

At this stage, it is not possible to judge whether the modelled temperatures by the lst.stefan-boltzman.sh algorithm are more realistic. This would require validation against spatially distributed reference temperature measurement, e.g. high resolution thermal data, point monitoring of surface temperature. Despite the current limitations of the algorithm, the resulting temperature simulations enable quantitatively explain the effect of different land cover scenarios in a GIS software environment.

|  |  |
| --- | --- |
|  |  |
| Modelled temperature with main inputs:  DSM with buildings and trees,  Albedo of land cover (including trees)  Resampled to 30 m | Landsat 8 land surface temperature at the bottom of the atmosphere |
| differences_L8_20160630_LST_Kelvin_sjtsk30m_clip_vs_lstveg182i1020r_res30m |  |
| Differences between the Landsat8 observed and modelled temperature in degrees Kelvin | Scatterplot of modelled temperature and temperature sensed by Landsat 8 TIRS Band 11 resampled to 30 m spatial resolution |

*Figure 7. Modelled temperature of land cover surface (left) derived for 30 June 2016 at 9:20 AM of GMT 10:20 zonal time and land surface temperature at the bottom of the atmosphere (right) as sensed at the same time by Landsat 8 TIRS, band 11. The spatial resolution (raster cell size) is 30 m, the units of temperature are degrees Kelvin.*

## 2.3 The role of Sentinel 2 in LST calculation

Sentinel 2 mission provides multispectral imagery in visible and infrared spectrum at spatial resolutions of 10, 20, and 60 metres. The spectral range approximately covers the wavelengths from 440 nm to 2,200 nm. Thus, no direct means of thermal sensing is possible with Sentinel 2 sensors. However, several data types can be derived from the Sentinel 2 imagery which can be used in the proposed algorithm of land surface temperature calculation described in section 2.2. We experimented with the surface albedo and NDVI parameters for deriving input raster layers for the LST calculation. Given the temporal resolution of the Sentinel 2 mission, such data products can be provided and updated every 5 days.

The first useful parameter is, ***the broad-band surface albedo*** which was calculated as the integration of at-surface reflectance across the shortwave spectrum (D'Urso and Calera, 2006):

Eq. 2

where *α* is albedo, *ρbi* is surface reflectance for a given band *bi* at Level-2A Sentinel-2A surface reflectance, obtained using the ESA's Sen2Cor algorithm (Version 2.3.1), *ωbi* is the weighting coefficient representing the solar radiation fraction derived from the solar irradiance spectrum (Thuillier et al., 2003) within the spectral range (spectral response curves) for bands *bi* as indicated with *Esun* in Table 2. This approach of surface albedo calculation was applied by Vanino et al. (2018) in the study of evapotranspiration and irrigation requirements for tomato crop in Central Italy. The Sen2Cor algorithm (Müller-Wilm, n.d) processes S2 Level 1C data to an orthoimage bottom-of-atmosphere (BoA) corrected reflectance product (Level 2A). The algorithm is available within the Sentinel Application Platform (SNAP), which is a software package tailored to the Sentinel-2 characteristics, developed by ESA (<http://step.esa.int/main/toolboxes/sentinel-2-toolbox/sentinel-2-toolbox-features/> ). The SNAP is provided free of charge and other added value products such as various land cover indices or biophysical biophysical products can be derived from Sentinel-2 reflectance data.

*Table 2. Weighting coefficients for the calculation of broad-band albedo from Sentinel 2 data.*

| **Band**  **Number** | **Spatial resolution**  **(m)** | **Center λ**  **(μm)** | **Spectral width Δλ**  **(μm)** | **Esun**  **(W m−2)** | **ωbi** |
| --- | --- | --- | --- | --- | --- |
| **1** | 60 | 0.443 | 0.020 | 1893 |  |
| **2** | 10 | 0.490 | 0.065 | 1927 | 0.1324 |
| **3** | 10 | 0.560 | 0.035 | 1846 | 0.1269 |
| **4** | 10 | 0.665 | 0.030 | 1528 | 0.1051 |
| **5** | 20 | 0.705 | 0.015 | 1413 | 0.0971 |
| **6** | 20 | 0.740 | 0.015 | 1294 | 0.0890 |
| **7** | 20 | 0.783 | 0.020 | 1190 | 0.0818 |
| **8** | 10 | 0.842 | 0.115 | 1050 | 0.0722 |
| **8a** | 20 | 0.865 | 0.020 | 970 |  |
| **9** | 60 | 0.945 | 0.020 | 831 |  |
| **10** | 60 | 1.375 | 0.030 | 360 |  |
| **11** | 20 | 1.610 | 0.090 | 242 | 0.0167 |
| **12** | 20 | 2.190 | 0.180 | 3 | 0.0002 |

For the purposes of the LST algorithm the surface albedo was calculated in the map algebra calculator r.mapcalc of GRASS GIS using the Eq.1 and the coefficients *ωbi* from Table 2 with the command:

*(Float("B02.tif")\*0.1324+Float("B03.tif")\*0.1269+Float("B04.tif")\*0.1051+Float("B05.tif")\*0.0971+Float("B06.tif")\*0.0890+Float("B07.tif")\*0.0818+Float("B08.tif")\*0.0722)/10000*

The resulting albedo raster layer was resampled to 10 m by cubic convolution. This product is used to approximate the surface emissivity in the proposed algorithm. Figure 8 shows the example of both the albedo and emissivity for the acquisition from 14 September 2016.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| *S2 natural colour composite 10m* | *S2 broad-band surface albedo10m* | *S2 surface emissivity 10m* |
|  |  |  |
| *Aerial orthoimage of Site 1 Moyzesova street as natural*  *colour composite 0.5 m* | *S2 broad-band surface albedo 0.5m* | *S2 surface emissivity 0.5 m* |

*Figure 8. Surface albedo and surface emissivity derived from Sentinel 2 Level 1C product for the entire study area (2 by 2 km) and for the site 1 in the detail (yellow outline) for 14 September 2016.*

|  |  |
| --- | --- |
|  |  |
| *Mask of urban greenery as trees and shrubs extracted from ALS and aerial orthoimagery.* | *Surface albedo derived from S2 L1C data overlaid by urban greenery mask* |
|  |  |
| *Land cover as 20 categories representing the material of the ground below the trees and shrubs.* | *Ground surface albedo calculated as zonal mean within the ground land cover classes after masking the trees and shrubs* |

*Figure 9. Surface albedo derived for different classes of the ground land cover from Sentinel 2 Level 1C product for the entire study area (2 by 2 km) for 14 September 2016.*

Simulation of the cooling effects of the urban greenery requires data on the ***properties of the ground cover material***. We approximated such properties by calculating zonal mean albedo for each ground land cover class after masking the trees and shrubs above 1.5 m high. Furthermore, continuous raster layer of ***albedo of the urban trees*** can be extracted using the urban trees mask and the surface albedo layer. Figure 9 shows the example.

***Vegetation transmittance*** of solar radiation to the ground surface was the third product derived from the Sentinel 2 data for our purposes of simulating the cooling effect of urban greenery. The rationale behind was in applying the linear regression models of the estimated leaf area index derived from TLS time series and Sentinel 2 NDVI time series (SURGE\_D4\_VEGMETR). Figure 10 shows the scatterplots and liner models between the two variables. The spatial coverage represents the spatial extent of the four sites displayed in Fig. 1. The LAI\_TLS was calculated at 10 m cell size directly from the TLS point clouds to match the resolution of Sentinel 2 NDVI. For particular date of scanning with TLS, figure 6 shows cell values of LAI\_TLS from all 4 sites binned together and plotted against corresponding values of S2\_NDVI. Apparently, there is no meaningful relationship between the two variables. However, locally there is. For example, site 1 (Moyzesova street) exhibits relatively strong relationship for summer months (Fig. 11). Despite the distribution of the variables around the regression line is very bimodal (clustering of low and high values), we used the linear model for 14 September 2016 and 23 November 2016 to demonstrate how the S2\_NDVI could be used to roughly estimate the LAI\_TLS to approximate the effect of urban trees solar transmittance (Fig. 12), i.e. to downscale the S2 vegetation metrics to higher resolution urban tree layer. Other indices should be used and more robust approaches statistical exploited to search for a stronger and more convincing linear relationship than the one here presented. Anyway, it can be seen that the effect of leaf-on season is still present in September blocking the sun light while there is the leaf-off season in November. Clearly this is related to the temporal variation in NDVI. The main reason why the NDVI does not correlate with the LAI TLS is very likely in different manner of how the two variables are sensed by the sensor. With TLS the 3D geometry of a tree is very realistically modelled while the vegetation indices derived from passive multispectral satellite sensing of subvertical to vertical field of view capture only reflected radiation from the top parts of the tree canopy. The amount of biomass is thus saturated in the higher NDVI values and also spectral signal of trees is mixed with the ground cover for the cell size relatively larger to the size of an average tree in urban environment. In the site 1, this effect of spectral mixing is probably reduced, i.e. cells values are clean signal from the ground.

|  |  |
| --- | --- |
|  |  |
| S2\_NDVI = 0.315067 - 0.005879\*LAI\_TLS  N = 470, R = -0.091573, R2= 0.008386, F = 3.957623 | S2\_NDVI = 0.570006 + 0.005166\*LAI\_TLS  N = 459, R = 0.165156, R2= 0.027277, F = 12.814894 |
|  |  |
| S2\_NDVI = 0.568160 + 0.003706\*LAI\_TLS  N = 460, R = 0.097329, R2= 0.009473, F = 4.380093 | S2\_NDVI = 0.585870 + 0.001443\*LAI\_TLS  N = 461, R = 0.033652, R2= 0.001132, F = 0.520395 |
|  |  |
| S2\_NDVI = 0.495079 + 0.003274\* LAI\_TLS  N = 469, R = 0.069697, R2= 0.004858, F = 2.279580 | S2\_NDVI = 0.253445 + 0.002576\* LAI\_TLS  N = 463, R = 0.192262, R2= 0.036965, F = 17.694775 |
|  | S2\_NDVI = 0.149407 + -0.001163\* LAI\_TLS  N = 459, R = -0.021266, R2= 0.000452, F = 0.206775 |

*Figure 10. Scatter plots and liner regression models with statistics for estimated leaf area index derived from TLS time series and NDVI derived from Sentinel 2 imagery, both parameters are calculated for 10 m spatial resolution for all 4 sites merged together.*

|  |
| --- |
|  |

*Figure 11. Scatter plots and liner regression models with statistics for estimated leaf area index derived from TLS time series and NDVI derived from Sentinel 2 imagery, both parameters are calculated for 10 m spatial resolution for site 1Moyzesova street. The colour represents the value of probability density of the plotted points.*

|  |  |
| --- | --- |
|  |  |
| *Normalized transmittance calculated for trees based on linear models between S2 NDVI vs LAI TLS for 14 September 2016* | *Normalized transmittance calculated for trees based on linear models between S2 NDVI vs LAI TLS for 23 November 2016* |
|  |  |
| *Detail of site 1 Moyzesova stree for 14 September 2016* | *Detail of site 1 Moyzesova stree for 23 November 2016* |

*Figure 12. Normalized transmittance predicted for urbane greenery (trees and high shurbs)based on linear models between S2 NDVI vs LAI TLS for the entire study area and for the site 1 for 14 September 2016 and 23 November 2016 (Fig. 11). Note the change in transmittance due to leaf-off season in November while leaves are still present in September.*

# 3 Resulting algorithmic structure of toolbox

The result presented in this report comprise the design of the algorithm, i.e. workflow, of how the we approached the modelling of the cooling effect taking into account the information extracted from the Sentinel 2 mutlispectral imagery (S2). Partial outcomes of this workflow are presented as example output data layers for selected days within a year. The summary of results does not contain output layers derived from all acquired input datasets (TLS or S2 data) or all possible scenarios.

During this project we have conducted the following steps that lead to our estimation of LST and surface UHIs including the representation of cooling effects of urban greenery in the Košice city:

* creation of a 3D city model representing urban surfaces such as buildings, roads, urban greenery in the form of digital surface model (digital terrain model + buildings + trees) or a full 3D model
* evaluation and parameterization of trees for effects on solar radiation (shadows, albedo) and heat transfer using lidar and Sentinel data;
* preparation of input data in a vector and raster data formats for solar radiation modelling using r.sun/v.sun for the selected time horizons;
* land surface temperature estimation using Stefan-Boltzmann equation using assessment of solar irradiance and irradiation, land cover parameterization and meteorological data;
* evaluation of various scenarios reflecting a different state of urban greenery using GRASS GIS to assess the best ways to mitigate UHIs.

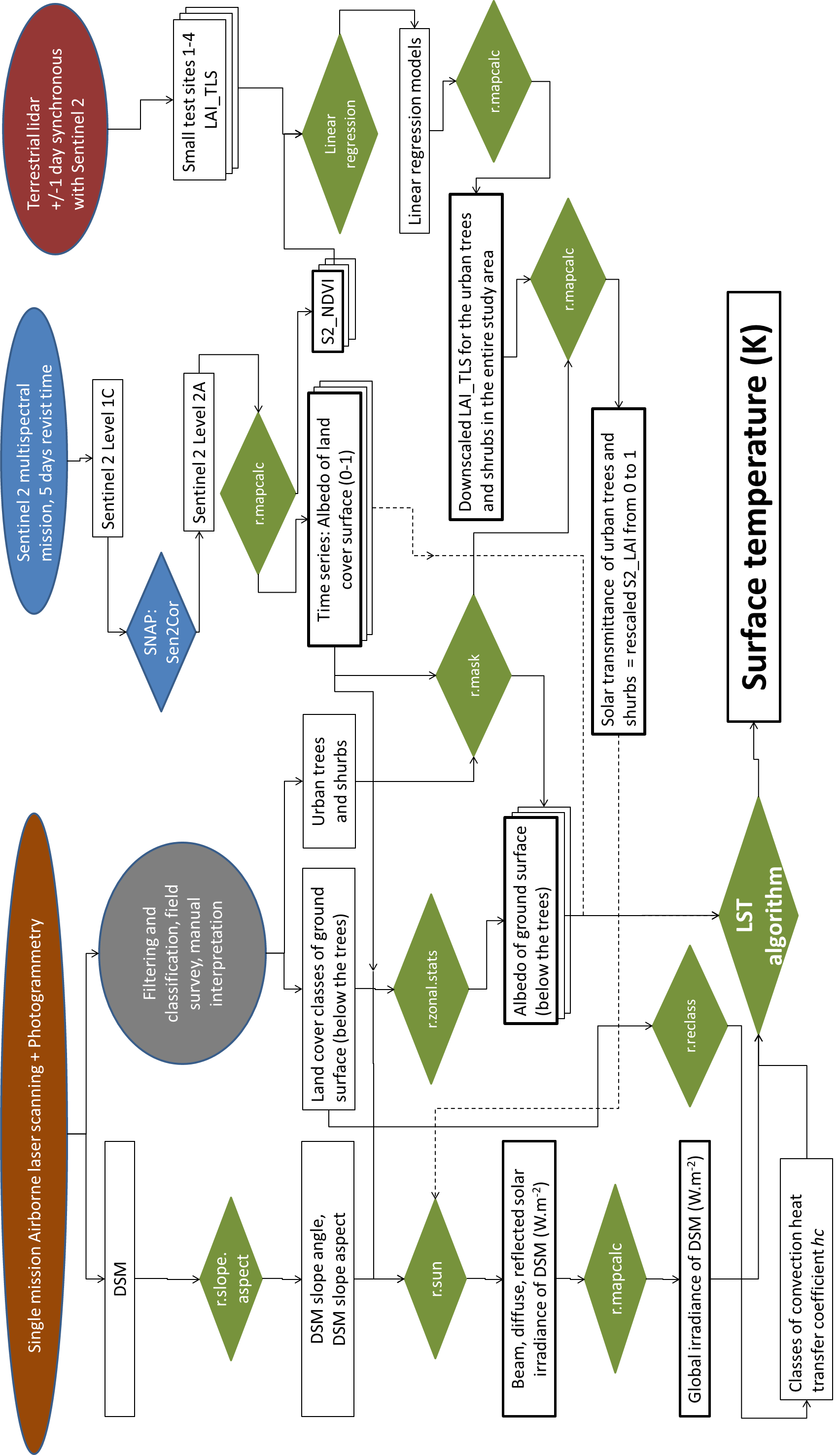
These steps define these major components of the algorithmic structure for the future toolbox:

1. Data component: 3D city model (vector format), input GIS data (vector/raster), meteo data (vector-point)
2. Simulation/modelling component: r.sun/v.sun solar radiation models a Stefan-Boltzmann land surface temperature model
3. Prediction component: Based on actual data, the simulation component will produce data on predicted LST, thus providing information on expected LST in any location within the city. Evaluation of various scenarios based on different input data parameters will help to better plan counter UHI measures, such as changing roof colour paintings to increase albedo or planting trees in UHI hotspots.

The suggested toolbox consists of the following tools implemented in GRASS GIS:

1. Data component: v.in.gdal, r.in.ascii, r.slope.aspect
2. Simulation component: lst.stefan-boltzman.sh, r.sun, v.sun, r.mapcalc
3. Prediction component: r.mapcalc

The workflow used in our study is graphically outlined in Fig. 9. The role of Sentinel 2 data products is highlighted by thick outline. The main contribution of Sentinel 2 data in surface temperature calculation is in the estimation of albedo of the land cover surface. This parameter is important in modelling the global solar irradiance and in approximating the surface emissivity. The use of Sentinel 2 data in ascertaining the solar vegetation transmittance is a more complex task. In the study, the relationship between NDVI and LAI\_TLS for corresponding dates was found to be weak and insignificant.



*Figure 12. Schematic workflow of preparing the inputs for the land surface temperature modelling. Elipses denote the data acquisition methods, rectangles denote the data layers or products, pinacoids denote processes. Green colour is marks the processes in the GRASS GIS environment, blue colour marks the SNAP environment for processing Sentinel 2 products. Thick outline marks the data layers derived from Sentinel 2 products.*

# Conclusions

The presented report provides the following findings and solutions:

* Sun is the main source of heat energy on the Earth.
* Spatial distribution of solar energy income can be modelled based on physical and geometric principles in a relatively straightforward and accurate way. Tools enabling spatially distributed solar modelling are available in contemporary GIS, but no such tools exist to convert the calculated solar energy income into land surface temperature (LST).
* The open-source GRASS GIS comprises one of the most robust tools for solar irradiation modelling such as r.sun on which one of the members of the SURGE project team collaborated. We used r.sun as a base for calculating the solar energy income and we developed an algorithm based on the Stefan-Boltzmann Law, which describes the power radiated from a black body in terms of its temperature.
* The key inputs of the LST calculation comprise spatially distributed global solar irradiation of a DSM, convective heat transfer coefficient of the surface material, albedo of the surface and the emissivity of the material. While solar energy income can be calculated with a high degree of reliability, the latter three parameters are difficult to be measured directly by remote sensing instruments in such a fine resolution as the solar irradiation can be computed.
* We have demonstrated that Sentinel 2 data can be used in the algorithm for estimating the broad-band albedo, surface material emissivity and urban trees transmittance.
* We have tested the NDVI derived from Sentinel 2 data products as a proxy for ascertaining the transmittance of solar energy by urban trees and shrubs which we parametrized by LAI derived from time series of TLS point clouds. It seems linear regression model is not sufficient to describe this relationship or it is the modifiable area unit problem for which the relationship could not be specified. Further testing and more robust geostatistical approaches need to be exploited.
* The toolbox can be used for testing on any other geographical area or city providing that the following datasets exist: gridded DSM, land cover classification, land cover of the ground (below the trees), spatially distributed broad-band albedo, e.g. from Sentinel 2 data products, convective heat transfer coefficient, ambient air temperature, equilibrium surface temperature, and effective radiant sky temperature.
* The resulting algorithmic structure of the toolbox for surface temperature calculation requires further testing in terms of validating the calculated temperature values in respect to more reliable data sets or methods. This aspect is to be discussed in the roadmap of the approach for future development.

# References

ASHRAE (1989). Handbook Fundamentals, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, Georgia.

Algarni, S. A. (2015). Modeling Radiation Heat Transfer for Building’s Cooling and Heating Loads: Considering the Role of Clear, Cloudy, and Dusty Conditions in Hot and Dry Climates.Theses and Dissertations. 1231.

Alonzo, M., Bookhagen, B., McFadden, J.P., Sun, A., Roberts, D.A. (2015). Mapping urban forest leaf area index with airborne lidar using penetration metrics and allometry. Remote Sens. Environ., 162, pp. 141-153.

Amir, A.K., Katoh, Y., Katsurayama, H., Koganei., M., Mizunuma, M. (2018). Effects of convection heat transfer on Sunagoke moss green roof: A laboratory study. Energy and Buildings 158, 1417-1428.

Becker, S. (2001). Calculation of direct solar and diffuse radiation in Israel. International Journal of Climatology, 21: 1561-76

Berdahl, P., Bretz, S. E. (1997). Preliminary survey of the solar reflectance of cool roofing materials. Energy and Buildings, 25, 149-158.

Beyer, H. G., Costanzo, C., Heinemann, D. (1996). Modifications of the Heliosat procedure for irradiance estimates from satellite images. Solar Energy 56: 207-12

Beyer, H. G., Czeplak, G., Terzenbach, U., Wald, L. (1997). Assessment of the method used to construct clearness index maps for the new European solar radiation atlas (ESRA). Solar Energy 61: 389-97

Bonafoni, S., Anniballe, R., Gioli, B., Toscano, P. (2016). Downscaling Landsat Land Surface Temperature over the urban area of Florence. European Journal of Remote Sensing, 49(1), 553-569.

Bretz, S., Akbari, H., Rosenfeld, A. (1998). Practical issues for using solar-reflective materials to mitigate urban heat islands. Atmospheric Environment, 32, 95-101.

Campbell, J.B., Wynne, R.H., (2011). Introduction to Remote Sensing. 5th Edition, The Guilford Press.

Dubayah, R., Rich, P. M. (1995). Topographic solar radiation models for GIS. International Journal of Geographical Information Systems 9: 405-19

D'Urso, G., Calera, A. (2006). Operative approaches to determine crop water requirements from earth observation data: methodologies and applications. AIP Conf. Proc., 852 (2006), pp. 14-25

Fogl, M., Moudrý, V. (2016). Influence of vegetation canopies on solar potential in urban environments. Applied Geography, 66, pp. 73-80.

Henrich, V., Krauss, G., Götze, C., Sandow, C. (2012). IDB - www.indexdatabase.de, Entwicklung einer Datenbank für Fernerkundungsindizes. AK Fernerkundung, Bochum, 4.-5. 10. 2012.

Hetrick, W. A., Rich, P. M., Barnes, F. J., Weiss, S. B. (1993). GIS-based solar radiation flux models. American Society for Photogrammetry and Remote Sensing Technical papers. GIS, Photogrammetry and Modeling 3: 132-43

Hofierka, J. (1997). Direct solar radiation modelling within an open GIS environment. In Proceedings of the 1997 Joint European GI Conference, Vienna, Austria, 575–584.

Hofierka, J., Gallay, M., Kaňuk, J., Šupinský, J., Šašak, J. (2017). High-resolution urban greenery mapping for micro-climate modelling based on 3D city models. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Archives), XLII-4/W7, pp. 7-12.

Hofierka, J., Kaňuk, J. (2009). Assessment of Photovoltaic Potential in Urban Areas Using Open-Source Solar Radiation Tools. Renewable Energy, 34, 2206-2214.

Hofierka, J., Zlocha, M. (2012). A New Solar Radiation Model for 3-D City Models. Transactions in GIS, 16, pp. 681-690.

Huete, A.R. (1988). A soil-adjusted vegetation index (savi). Remote Sens. Environ, 25, 295–309.

Jiang, Z.; Huete, A.R.; Didan, K.; Miura, T. (2008). Development of a two-band enhanced vegetation index without a blue band. Remote Sens. Environ., 112, 3833–3845

Jensen, J.R., (2006). Remote Sensing of the Environment: An Earth Resource Perspective. 2nd edition. Pearson.

Liu, J., Heidarinejad, M., Graci, S., Srebric, J. (2015). The impact of exterior surface convective heat transfer coefficients onthe building energy consumption in urban neighborhoods withdifferent plan area densities. Energy and buildings, 86, 449-463.

Klingberg, J., Konarska, J., Lindberg, F., Johansson, L., Thorsson, S. (2017). Mapping leaf area of urban greenery using aerial LiDAR and ground-based measurements in Gothenburg, Sweden. Urban Forestry and Urban Greening. 26 (2017). pp. 31-40.

Mirsadeghi, M., Costola, D., Blocken, B., Hensen, J.L.M. (2013). Review of external convective heat transfer coefficient models in building energy simulation programs: implementation and uncertainty, Applied Thermal Engineering, 56, 134–151.

Muneer, T. (1990). Solar radiation model for Europe. Building Services Engineering Research and Technology 11: 153-63

Neteler, M., Mitasova, H. (2004). Open Source GIS: A GRASS GIS Approach. Second Edition. Boston, Kluwer Academic Publishers.

Oke, T. R., 1973. City size and the urban heat island. Atmospheric Environment, 7 (8), 769-779.

Onačillová, K., Gallay, M. (2018). Spatio-temporal analysis of surface urban heat island based on LANDSAT ETM+ and OLI/TIRS imagery in the city of Košice, Slovakia. Carpathian Journal of Earth and Environmental Sciences, 13(2), 395 - 408.

Perez, R., Seals, R., Ineichen, P., Steward, R., Menicucci, D. (1987). A new simplified version of the Perez diffuse irradiance model for tilted surfaces. Solar Energy, 39, 221-231.

Rigollier, Ch., Bauer, O., Wald, L. (2000). On the clear sky model of the ESRA – European Solar radiation Atlas – with respect to the Heliosat method. Solar Energy 68: 33-48

Richardson, J.J., Moskal, L.M., Kim, S.H. (2009). Modeling approaches to estimate effective leaf area index from aerial discrete-return LIDAR. Agric. For. Meteorol., 149, pp. 1152-1160.

Scharmer, K., Greif, J. (eds) (2000). The European Solar Radiation Atlas. Vol. 2: Database and Exploitation Software. Paris, (es Presses de l'École des Mines

Šúri, M., Hofierka, J. (2004). A new GIS-based solar radiation model and its application to photovoltaic assessments. Transactions in GIS 8, 175–190.

Šúri, M., Huld, T.A., Dunlop, E.D. (2005). PVGIS: a web-based solar radiation database for the calculation of PV potential in Europe. International Journal of Sustainable Energy 24, 55–67.

Tooke, T.R., Coops, N.C., Goodwin, N.R., Voogt, J.A. (2009). Extracting urban vegetation characteristics using spectral mixture analysis and decision tree classifications. Remote Sensing of Environment, 113(2), pp. 398-407.

Tooke, T.R., Coops, N.C. Christen, A., Gurtuna, O., Prévot, A., (2012). Integrated irradiance modelling in the urban environment based on remotely sensed data. Solar Energy, 86(10), pp. 2923-2934.

Thuillier, G., Hersé, M., Labs, D., Foujols, T., Peetermans, W., Gillotay, D., Mandel, H. (2003). The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions. Sol. Phys., 214 (1) (2003), 1-22.

Vanino, S., Nino, P., De Michele, C., Bolognesi, S. F., D'Urso, G., Di Bene, C., Pennelli, B., Vuolo, F., Farina, R., Pulighe, G., Napoli, R. (2018). Capability of Sentinel-2 data for estimating maximum evapotranspiration and irrigation requirements for tomato crop in Central Italy, Remote Sensing of Environment, 215, 452-470.

Vollaro, A., Galli, G., Vallati, A. (2015). CFD Analysis of Convective Heat Transfer Coefficient onExternal Surfaces of Buildings. Sustainability, 7, 9088-9099.

Yang, J., Wang, Z.-H., Kaloush, K. E. (2015). Environmental impacts of reflective materials: Is high albedo a ‘silver bullet’ for mitigating urban heat island? Renewable and Sustainable Energy Reviews, 47, 830-843.

Zelenka, A., Czeplak, G., D’Agostino, V., Josefson, W., Maxwell, E., Perez, R. (1992). Techniques for Supplementing Solar Radiation Network Data. Technical Report, International Energy Agency, # IEA-SHCP-9D-1, Swiss Meteorological Institute, Switzerland