Airborne thermal remote sensing: the case of the city of Olomouc, Czech Republic

Tomáš Pour, Jakub Miřijovský and Tomáš Purket
Department of Geoinformatics, Palacký University, Olomouc, Czech Republic

ABSTRACT
This paper describes the process of very high-resolution thermal mosaic acquisition using low-altitude airborne remote sensing and the basic analysis of data regarding urban climate research. The process of data acquisition from flight planning to final mosaicking is described. A broadband thermal camera was mounted to a Cessna aeroplane for two flights over the city; one performed in the morning and one in the afternoon. The ground resolution of the final mosaic fluctuates between 90 and 105 cm. Gathered data had to be processed to acquire kinetic temperature values. The processing consisted of radiometric, geometric, atmospheric and emissivity corrections. As a result, two mosaics covering the city were created. The difference between the building canopy layer and ground level was investigated, and a 5°C increase was found during the day on the rooftop level. It was confirmed that natural materials do not heat as much as artificial ones. Local Climate Zones were used in the analysis as the spatial unit for comparison of the thermal regime at the neighbourhood level. To summarise, the possibilities of extreme resolution thermal remote sensing data acquisition and analysis are demonstrated.

Introduction

According to a United Nations report (United Nations, 2016), 54.5% of the world population lived in cities in 2016. By 2030, the urban environment will be home to 60% of the global population. A third of the people living in urban environments will live in cities with populations of over half a million inhabitants. “In 28 countries or areas, more than 40% of the urban population is concentrated in cities of more than one million inhabitants”, the report further elaborates. In central Europe, up to 85% of the population lives in cities or urban agglomerations. Cities are not only vulnerable to natural disasters, such as hurricanes, typhoons, flooding and earthquakes but also directly impact the severity of events such as heatwaves. Therefore, it is pivotal to explore the environment that has recently become our habitat. Thermal remote sensing in extremely high resolution is one of the fields that can help to understand our surroundings at the neighbourhood or even single-building level.

Thermal imaging becomes more popular as one of the non-traditional methods of remote sensing. The recent decrease in the price of thermal cameras based on the micro-bolometer principle has also raised the interest of the scientific community. While satellite thermal imaging has been well established, airborne and drone thermal imaging remain small fields. In recent years, there have been only a few major articles regarding low-altitude thermal remote sensing. In those articles, thermal infrared remote sensing has been used mainly in urban remote sensing for energy efficiency purposes (Hay et al., 2011), urban climatology (Oltra-Carrió, Sobrino, Franch, & Nerry, 2012; Rigo & Parlow, 2007) and environmental applications (Zemek, 2014).

There are a vast number of different thermal sensors that can be used in airborne remote sensing. These sensors can be roughly classified into a few groups based on their means of data acquisition – camera and scanner – and their output data type – single-band (broadband) and multi-/hyperspectral. Each approach has certain advantages and specifics. Data from the hyperspectral scanner allow the usage of more sophisticated algorithms exploiting the multi-band approach when dealing with emissivity and corrections, in general. Advantages of multi-band methods were evaluated by Sobrino, Jiménez-Muñoz, Zarco-Tejada, Sepulcre-Cantó, and de Miguel (2006). The advantages of broadband sensors are usually the price and size along with easier corrections. (Zemek, 2014)

One of the major projects resulting in multiple scientific papers was realised by Hay et al. (2011). Their project is called HEAT and focuses on heat loss in residential buildings in Calgary. For this...
project, a thermal hyperspectral scanner TABI 1800 was used. The team published many articles regarding different steps in thermal remote sensing processing. One of them discusses thermal mosaicking with the GEOBIA approach presented by Rahman et al. (2012), which solved issues regarding the elimination of features during the mosaicking process. Another significant study was conducted by Rahman, Hay, Couloigner, and Hemachandran (2014) regarding the elimination of microclimate influences on the sensor. In this work, the microclimatic influx was identified using the homogeneity of the road network temperature. Another long-term research study was performed by Sobrino et al. (2009). Their work concerns all aspects of thermal infrared imaging including different sensing platforms, sensors, and data processing approaches (Sobrino, Jiménez-Muñoz, & Paolini, 2004; Sobrino et al., 2006; Sobrino & Romaguera, 2004).

There is considerably more scientific material regarding urban thermal remote sensing from satellites, with broader applications as well. Multiple satellites usually carry single- or multi-spectral radiometers. These sensors are, for example, ASTER and MODIS onboard the TERRA satellite, TIRS on Landsat 8, ETM+ on Landsat 7, NOAA-AVHRR, and SLSTR, newly deployed on Sentinel 3. The range of applications are broader in the field of satellite imagery as well. Estimation of land surface temperature is described, for example, by Chrysoulakis and Cartalis (2002). Parlow (2003) describes the application of heat budget system analysis based on thermal satellite data. Rigo and Parlow (2007) extended the topic even further by modelling the heat budget. The topic was developed by Chrysoulakis et al. (2016) with a new approach for heat flux estimation from space. Another significant study was performed by Liu et al. (2015) regarding urban heat island analysis on two different scales using satellite thermal data.

This paper aims to evaluate the possibility of low-altitude airborne thermal remote sensing of urban areas and to describe current possibilities using low-cost thermal imaging cameras. It is the groundwork for further analysis regarding urban climate research, which is briefly outlined in the results section. The work consists of flight campaign planning, radiometric, atmospheric and emissivity corrections, mosaicking and data descriptions followed by data analysis based on land cover, material types and verticality.

Thermal image processing begins with digital number values representing, in the case of a microbolometric camera, the electrical resistance on the sensor. These values are recalculated into temperature using a camera-specific equation with values acquired during calibration. This temperature is called the brightness temperature (sometimes called apparent radiant temperature (Hay et al., 2011) or apparent temperature) and represents the object temperature without emissivity correction, having already been corrected for radiometry, geometry and the atmosphere. When the temperature is corrected for the object emissivity, it is called the radiant temperature or kinetic temperature, or even true kinetic temperature. For precise terminology, we followed Norman and Becker (1995), that is, we use brightness temperature and kinetic temperature. Authors also point out that, in literature, these terms are commonly replaced by vague terms such as surface temperature or land surface temperature (contrary to ocean surface temperature).

Methods and data

In this chapter, the process of the production of a high-quality extreme resolution thermal mosaic of the city of Olomouc is discussed. This mosaic contains the kinetic temperature of the surface at two different times during the day. This process includes flight planning, data acquisition, data correction and photogrammetry processing.

Flight campaign

The aeroplane Cessna 172 was mounted with a photogrammetric sensor Phase One iXA-R 180 and thermal camera Workswell Thermal Vision Pro (based on a FLIR Tau2 core). This version of Tau2 is mounted with 13 mm, f/1.25 optics. That allows a field of view of 45° × 37° with an iFoV of 1.308 mrad. The flight campaign consisted of thermal and visible spectrum imaging. The flight height and spectral resolution was chosen considering primarily the thermal sensor because of its smaller iFoV. Different scenarios were created to satisfy the need for overlap and fine spatial resolution. After spatial resolutions from 30 cm to 130 cm were considered, the final decision was to aim for a 100-cm spatial resolution per pixel edge. Based on this decision, the rest of the variables were calculated, as shown in Table 1. The size of the scene was 512 m × 640 m, and the average flight height was set to 769 m above sea level.

The area of interest is about 10 km × 8 km in size, which required 22 flight lines; visualized in Figure 1. The flight was carried out on 10 July 2016. Because the closest airport does not allow night take-offs and

| Parameters | Value |
|------------|-------|
| Average flight height | 769 m AGL (Above Ground Level) |
| Map scale | 1:58,824 |
| Scene size | 512 × 640 m |
| Distance between images | 307 m |
| Distance between flight lines | 384 m |
landings, the early flight started as soon as possible; that is, right after civil dawn, which was at 4:55 CEST for that day. The second flight time was aimed at the highest possible stored temperature, which in this case took place at about 17:00 CEST. Both flights took about 180 min and consisted of approximately 2135 thermal images.

**Image processing**

Thermal imaging requires similar corrections as other conventional remote sensing methods do. According to Zemek (2014), we can divide these corrections into four main groups – geometric, radiometric, atmospheric and emissivity corrections.

**Radiometric correction**

Radiometric correction originates from a camera calibration based on imaging a black body object of known temperature. In our case, this calibration was performed by the manufacturer with results shown in Table 2.

![Figure 1. Flight lines and ground control locations over the city of Olomouc.](image)

Table 2. Accuracy protocol after the calibration for the thermal sensor FLIR Tau2.

| Radiation temperature (°C) | Sensor measurement (°C) | Deviation (°C) |
|---------------------------|------------------------|---------------|
| 0.0                       | 1.5                    | 1.5           |
| 20.0                      | 21.0                   | 1.0           |
| 40.0                      | 40.4                   | 0.4           |
| 70.0                      | 68.9                   | -1.1          |
| 120.0                     | 118.4                  | -1.6          |

However, off-axis vignetting compensation still had to be performed, which is, according to Li and Zhu (2009), a phenomenon commonly present in thermal imaging. Vignetting appears on all images, be it optical or from a near-infrared sensor. In thermal imaging, this effect is usually very strong due to the low contrast of imaging systems (Li & Zhu, 2009). The further the object is away from the system’s axis and the larger the field of view, the more serious the vignetting becomes, as seen in Figure 2.

![Figure 2. Off-axis vignetting effect.](image)
Four images were acquired to compensate for the vignetting effect. An object with a smooth, unpolished surface with constant emissivity and temperature was used. The images were taken from a strictly orthogonal position from approximately 40 cm away.

Figure 3 demonstrates the presence of off-axis vignetting in our system. However, it does not seem to increase with distance from the emitting object in this case; it maintains the same pattern and same difference on airborne images as on close-range images. Another fact is that it does not represent a linear gradient from the nadir to the sides but rather shows an irregular pattern. Although the temperature appears lower especially in corners in what corresponds to the off-axis effect described previously, in the lower-right corner, the effect is much stronger than in the rest of the corners, and the effect is stronger in the lower part of the picture, in general. Another inconsistency appears in the upper-central area. According to the theory, there is no possibility that the data near the upper edge of the image is similar to those in nadir, due to conditions mentioned earlier.

Images were to be exported to raw numbers because the camera produces images already recalculated to temperatures. At the raw-number level, the largest pixel value was subtracted from each pixel value in the entire image to obtain the vignetting mask. This was performed on four images. A low-pass filter was applied afterwards to smoothen the differences in the mask. In the next step, the masks of the four images were averaged to secure the most suitable outcome; the result is shown in Figure 3. The final mask was added to all images.

The results are satisfactory, regarding visual comparison and value comparison. After applying the vignetting mask, the same objects show highly similar values as many other images in different parts of the image, as shown in Table 3.

**Atmospheric corrections**

Atmospheric corrections are based on modelling the atmospheric signal loss and the atmospheric emission. Main atmospheric characteristics affecting thermal imaging are air temperature and air humidity.

Two meteorological data sources were available as the auxiliary data source. One is a GNSS reference station operated by our department. The station provides reference GNSS data for VESOG and CzechGeo projects. Moreover, it provides basic information about the atmosphere every five minutes. The basic variables are air temperature, air pressure and air humidity. The other source comes from an amateur meteorological station located near the city borders. The station provides information about air temperature, air pressure and air humidity as well as solar irradiation.

In the study, we used an algorithm developed specifically for FLIR cameras integrated as an R package called Thermimage (Tattersall, 2018). This package recalculates data from raw values to

![Figure 2. The off-axis vignetting principle shown in a two-lens system. The signal originating in nadir (A) is captured as A' with full strength. On the contrary, the signal originating further from nadir (B) is mitigated (B') while passing through the lens system. Source: Li and Zhu (2009).](image)

![Figure 3. Off-axis vignetting pattern based on mean from four images of homogeneous objects from a short distance.](image)

| Position in the image | Image centre | Image corner (before correction) | Image corner (after correction) |
|-----------------------|--------------|----------------------------------|---------------------------------|
| Metal roof tile       | 42.941644    | 38.007835                        | 42.590748                       |
| Cobblestone           | 38.29468     | 33.39945                         | 38.268635                       |

Table 3. Comparison of the same materials in different parts of the image before and after correction (in °C).
temperature based on calibration constants acquired during the calibration, applies corrections for atmospheric transmission loss based on distance from the object, compensates for radiance emitted from surrounding objects (reflected temperature) and compensates for emissivity.

The algorithm uses equations from Minkina and Dudzik (2009) to simulate the signal passing through the atmosphere using atmospheric constants and humidity recalculated to water vapour pressure. Water vapour pressure is calculated from atmospheric temperature and humidity based on Equation (1).

\[
WVP = \left( \frac{RH}{100} \right) \cdot \exp(1.5587 + 0.06939 \cdot AT - 0.00027816 \cdot AT^2 + 0.00000068455 \cdot AT^3)
\]

(1)

The equation also uses atmospheric constants ATA1, ATA2, ATB1, ATB2 and ATX, as seen in Equation (2), which generates the TAU value later used in the calculation. The values of atmospheric constants can be found in the package documentation (Tattersall, 2018).

\[
TAU = ATX \cdot \exp\left(\frac{OD}{2}\right)^2 \cdot \left(ATA1 + ATB1 \cdot \sqrt{WVP}\right) + (1 - ATX) \cdot \exp\left(\frac{OD}{2}\right)^2 \cdot \left(ATA2 + ATB2 \cdot \sqrt{WVP}\right)
\]

(2)

For brightness temperature, the algorithm uses the following equation

\[
BT = \frac{B}{\ln\left(\frac{R1}{R2(S + O)} + F\right)}
\]

(3)

where BT is brightness temperature in Kelvin, S is original raw data in 16-bit form, and R1, R2, B, F and O are constants acquired during the calibration of the camera.

**Emissivity corrections**

Emissivity is a characteristic of the viewed object which affects the resulting temperature in a major way. Emissivity is defined as the ratio of emitted thermal radiation of the object to thermal radiation of a blackbody. Emissivity is unique for each material and wavelength.

Emissivity corrections are of special importance in thermal remote sensing because they may cause the highest amount of error in the data (Minkina & Dudzik, 2009). In particular, low emissivity objects such as aluminium rooftops appear as very low-temperature objects, which is not the case in reality. Even though most objects have a similar emissivity of about 0.95, the remaining objects must be corrected to analyse the data further.

To compensate for emissivity correctly, we should know the emissivity of every object in the image. At the satellite image level, this issue is solved by estimating emissivity from NDVI with which it correlates. At the fine scale level, however, low emissivity objects are very significant, especially for analysis following the imaging, and are not recognised in the NDVI image. Therefore, at a finer scale, we have to compensate for emissivity for each object separately. This problem has no easy solution and is still quite new because there were not many thermal campaigns solving this issue.

Our proposed approach combines usage of auxiliary GIS and satellite imaging data to access the land cover. We used our national system RUIAN, which manages certain land cover classes. After some minor corrections, it captures building, roads and sidewalks well. A simple threshold for NDVI based on QuickBird satellite imagery was created to separate vegetation and non-vegetation classes. When combining the data, we created an easy hierarchy rule saying that vegetation can overlap roads, pavements and buildings, and that buildings can overlap roads and pavements. After this mash-up was created, we semi-manually tied these objects with their respective material emissivity number. This approach allowed us to eliminate cold spots that might corrupt further analysis results.

When calculating *kinetic temperature*, the radiance reflected from surrounding objects must be calculated first. The same equation is used except that the raw value (S) is replaced with the reflected temperature (RT). Thus

\[
RAW\_refl = \frac{B}{\ln\left(\frac{R1}{R2(RT + O)} + F\right)}
\]

(4)

and emissivity of the object is applied

\[
RAW\_em = \frac{S - RAW\_refl(1 - E)}{E}
\]

(5)

where E is emissivity of the imaged object. Now, the *kinetic temperature* can be concluded using the original equation while replacing raw data with the new value corrected for reflected radiance and emissivity.

\[
KT = \frac{B}{\ln\left(\frac{R1}{R2(KT\_em + O)} + F\right)}
\]

(6)

**Photogrammetric processing**

The biggest challenge of the mosaicking part of the study was the fact that plenty of images were corrupted due to blurring caused by the slow shutter speed of the camera and high aeroplane speed. Moreover, the aeroplane was considerably light. Therefore, it suffered from heavy wind and was unsteady in general.

Agisoft Photoscan Professional and Trimble INPHO software was used for the photogrammetric
process. The entire process is shown in Figure 4. The basic method for image orientation and calculation of the exterior orientation parameters is Structure from Motion (SfM). This approach includes a few methods like “Stereo matching” or “Multi-view stereo – MVS”. Stereo methods can be global or local. Semi-global matching methods are implemented in Agisoft Photoscan Pro. The main fundamental difference between SfM and classic photogrammetry is the use of a new generation of image matching algorithms, which allow for unstructured image acquisition. While classic photogrammetric methods typically rely on strips of overlapping images acquired in parallel flight lines, MVS was designed to reconstitute the three-dimensional geometry of buildings and objects from randomly acquired images (Fonstad et al., 2012). The multi-view matching method performs very well for oblique images as well as for classic aerial images with forward- and side-overlap.

Also, different settings and digital elevation models were tried. Namely, we used an automatically generated elevation model created by Agisoft with semi-global matching method, digital surface model and digital elevation model. The low overlap of the images in combination with corrupted images caused serious damage to the mosaic. The algorithm could not identify a large number of images and created gaps in the mosaic or, in the worst case, tried to distort images to fill the gaps. This process was unsatisfying, but most of the corrupted images were located outside the city or in the suburbs. Therefore, we decided to reduce the area of interest to only the city centre, which was of high quality in the images in general. The final mosaic was created by just 117 images in the case of the morning flight and 115 in the case of the afternoon flight.

Results and discussion

This work resulted in four raster datasets representing two flight campaigns (morning and afternoon) with two temperature scales (Celsius and Kelvin). The final mosaic covers approximately 75% of the area due to bad overlaps in the corner regions. Along with the flight campaign, a ground survey using a hand-held thermal camera FLIR E60 was performed. From this measurement, a control dataset was created with six locations gathering data for four materials. The locations were manually chosen, so they are evenly distributed over the area of interest. The presence of a water body and the feasibility of data acquisition at the same time as the aerial sensor was desirable. The location of ground measurement was recorded using a GPS receiver. As illustrated in Table 4, the final error after corrections is around one degree Celsius, which is very satisfactory given the base error of the camera. The classes with the largest error are water and asphalt. This phenomenon might have been caused by the heterogeneity of the material and the difficulty of measuring water.

In the analytical part, several land cover types were investigated with emphasis on the difference between morning and afternoon datasets. These were divided into five thematic groups, each consisting of several common land cover types. In Figure 5, the morning surface temperature and the afternoon surface temperature is visualized as well as the difference between these two times. The special
class – Globus – is a mixture of ground and rooftop material from the largest supermarket in the city. For all land cover types, 10 sample values were collected throughout the city with an emphasis on unified material throughout the class. For example, for regular rooftops, only the typical “red roofs” were considered.

We have confirmed that natural materials do not heat up as much as artificial ones throughout the day (Figure 5). Cobblestone seems to be a slightly better material than asphalt in terms of heating capacity. The orientation of the rooftop has a significant impact on the thermal regime. Very interesting is the temperature difference between the two rivers in the city. While river Morava is a wide, slow and deep river, Bystřice is very shallow, narrow and fast river, which also projects into the thermal regime.

In certain applications for urban climate research, such as surface urban heat island or city thermal comfort, it is very important to distinguish between the ground level and building canopy layer clearly. Heated rooftops have minimal influence on the thermal conditions in street canyons and near the ground; therefore, these two cases need to be separated. For that reason, we created two masks and compared mean temperatures for these cases in the morning and in the afternoon, as shown in Figure 6. While having a similar mean temperature in the morning, the rooftop level has a 5°C higher mean temperature than the ground level.

The extreme resolution of the dataset is a huge improvement from the very coarse resolution of satellite imagery. The resolution proved valuable when distinguishing between ground and building canopy layer (Figure 6), which would not be possible with satellite data without using a downscaling method. It also demonstrates that rooftops, in general, tend to heat up much more than the ground level. Lower ground surface temperatures are caused mostly by natural materials and shading. Nevertheless, the effect of the surface urban heat island is not as strong at the ground level during the day.

For further evaluation, we adapted the Local Climate Zone (LCZ) typology described by Oke et al. (2017), originally published by Stewart and Oke (2012). LCZs are neighbourhood-size units that have a specific thermal regime and, in general, specific local climate. For this case study, the four most

### Table 4. Comparison of ground- and airborne-gathered data.

| Material | Cemetery | Residential | Shopping mall | Monastery | Suburbs | Industrial | Average |
|----------|----------|-------------|--------------|-----------|---------|------------|---------|
| Asphalt  | Ground   | 18.9        | 20.2         | 21.0      | 22.2    | 23.2       | 21.1    |
|          | Airborne | 17.1        | 20.6         | 20.5      | 19.5    | 20.9       | 19.7    |
|          | Difference| **1.8**      | **0.4**      | **0.5**   | **2.7** | **2.3**    | **1.54**|
| Grass    | Ground   | 12.5        | 16.3         | 16.3      | 16.8    | 17.6       | 18.0    |
|          | Airborne | 14.9        | 16.0         | 15.9      | 15.7    | 18.2       | 17.8    |
|          | Difference| **2.4**      | **0.3**      | **0.4**   | **1.1** | **0.6**    | **0.83**|
| Concrete | Ground   | 16.1        | 21.0         | 21.0      | 23.2    | 20.1       | 19.2    |
|          | Airborne | 15.1        | 20.0         | 20.0      | 22.4    | 19.2       | 19.2    |
|          | Difference| **1.0**      | **1.0**      | **1.0**   | **0.8** | **0.93**   | **1.10**|
| Water    | Ground   | 23.2        | 16.2         | 18.4      | 17.3    | 18.8       | 18.8    |
|          | Airborne | 22.2        | 18.8         | 18.2      | 17.9    | 19.3       | 19.3    |
|          | Difference| **1.0**      | **2.6**      | **0.2**   | **0.6** | **0.2**    | **1.10**|

**Figure 5.** The Thermal regime of various materials and land cover types. Lighter colour represents morning data; darker colour represents afternoon data. Both are related to the left scale. The grey background represents the difference between the values for easier understanding; the values can be read on the right scale.
common LCZs have been manually delineated and visualized (Figure 7). Sample number 5 within LCZ A differentiates from other samples because it is a floodplain forest and lies outside of the city border, while other samples are parks within the city.

The use of LCZs allowed us to investigate the difference between different types of neighbourhoods. The compact mid-rise (LCZ 2) neighbourhood represents a typical middle-European city centre with narrow streets made of cobblestone and very high density. The lack of green and blue spaces in this neighbourhood contributes the most towards the highest mean temperature during the day. Open neighbourhoods are very much dependent on the building to greenspace ratio. Therefore, the mean temperature fluctuates in the morning as well as in the afternoon.

Conclusion
In this study, we have created a dataset consisting of four mosaics and provided a basic analysis of the results. We have successfully applied radiometric, geometric, atmospheric and emissivity corrections, resulting in a kinetic temperature of the surface. The radiometric correction was performed using a custom vignetting mask and default calibration. Atmospheric correction was based on measurements of two meteorological stations in the area. Unlike most of the other studies (Li et al., 2013; Nichol, 2009; Oltra-Carrió et al., 2012; Sobrino et al., 2012), we have decided to compensate for the emissivity by simply attaching a known emissivity to certain object types. This methodology required some manual work and would not be
possible in a large-scale area or an area without any auxiliary data. In the final step, we have used the structure from the motion method to do geometric corrections and mosaicking.

In the following basic analysis, we have presented a few possible ways to investigate the data. The detail of the data allowed us to distinguish between building the canopy layer and ground level and will be crucial in the future to evaluate the precise effect of the urban environment on public health. The study of material types in the urban environment might be another direction for future studies and might reveal interesting facts about used materials. In the third analysis, LCZs were applied to evaluate the thermal regime of various neighbourhoods. It might be very interesting to combine the methods and evaluate only ground temperatures within the neighbourhoods to precisely find out the near-ground effect on human health.

This study also shows the large potential in this field of study. Further research may focus on either more measurements throughout the day or multiple campaigns throughout the year. In the first case, the research would contribute to the material regime as well as the cooling/heating abilities of the surface. Imaging the city multiple times per year would allow a more detailed description of the material behaviour in different weather conditions. The accuracy of the data may be further improved by using a contact thermometer for the ground campaign.

**Disclosure statement**

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