Aerial thermography for energy efficiency of buildings: the ChoT project

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ABSTRACT

The ChoT project aims at analysing the potential of aerial thermal imagery to produce large scale datasets for energetic efficiency analyses and policies in urban environments. It is funded by the Italian Ministry of Education, University and Research (MIUR) in the framework of the SIR 2014 (Scientific Independence of young Researchers) programme. The city of Bologna (Italy) was chosen as the case study. The acquisition of thermal infrared images at different times by multiple aerial flights is one of the main tasks of the project. The present paper provides an overview of the ChoT project, but it delves into some specific aspects of the data processing chain: the computing of the radiometric quantities of the atmosphere, the estimation of surface emissivity (through an object-oriented classification applied on a very high resolution multispectral image, to distinguish among the major roofing materials) and sky-view factor (by means of a digital surface model). To collect ground truth data, the surface temperature of roofs and road pavings was measured at several locations at the same time as the aircraft acquired the thermal images. Furthermore, the emissivity of some roofing materials was estimated by means of a thermal camera and a contact probe. All the surveys were georeferenced by GPS. The results of the first surveying campaign demonstrate the high sensitivity of the model to the variability of the surface emissivity and the atmospheric parameters.

Keywords: ChoT project, Aerial thermal imagery, Surface emissivity, Radiometric calibration, Bologna (Italy)

1. INTRODUCTION

The implementation of energy saving policies at city level would require large scale databases, providing urban planners and stakeholders with information regarding the status of energy efficiency of the buildings. These data would enable decision makers to identify priorities of interventions and to monitor the effectiveness of the implemented actions. Among the tools which can be used to produce such databases, aerial thermography is one of the most prominent.[1,2] Even if thermography cannot provide a full characterisation of the energetic performances of buildings unless it is integrated with plenty of ancillary information, this technique has the capability of providing a synoptic view of large areas, allowing a comparison among the districts in a city and even among building blocks in a district.[3,4] Of course, a complex processing of thermal data is required to extract reliable surface temperature values from imagery and a complex modelling is necessary to use these values as indicator of energy efficiency.

In this perspective, the project entitled "the Challenge of remote sensing Thermography as indicator of energy efficiency of buildings" (ChoT) aims at analysing the potential of aerial thermal imagery to produce large scale datasets for energetic efficiency analyses in urban environments. In particular, the final outcomes are expected to quantify the achievable accuracy in the estimation of surface temperature with the proposed technique and its sensitivity to the main variables of the problem. The project is funded by the Italian Ministry of Education, University and Research (MIUR) in the framework of the SIR 2014 (Scientific Independence of young Researchers) programme (`http://sir.miur.it/`).

The city of Bologna (Italy) was chosen as the case study, exploiting the synergies between the University and the Municipality, which are also two important stakeholders owning a large number of buildings. The ChoT

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Figure 1. Track of the night aerial survey over the city of Bologna.

project plans for the execution of a series of aerial and ground surveys in the study area. The acquisition of aerial images in the thermal infrared band at different times of the day is one of the main tasks of the project. An other key task is the execution of several ground surveys with different techniques, in order to collect a dataset of information about the investigated surfaces which can be exploited for calibration and validation purposes.

Since ChoT project started in September 2015 and it is designed to last three years, the present paper aims at providing an overview of the first activities conducted for the project and to present some of the very first results.

2. MATERIALS AND METHODS

At the time of the writing, two aerial surveys were performed over an area of approximately ten square kilometres located in the city of Bologna. The area encompasses a portion of the city center and some residential and productive districts. This choice was made to ensure that a wide range of building typologies could be investigated. In fact, the city center is mainly composed of historical buildings and the dominant roofing materials are clay tiles, while in the peripheral districts a wide variety of coverings can be found, e.g. metal sheets, bituminous sheaths, concrete tiles. The flights were executed on 14 and 15 March 2016, the first during the night (approximately at midnight) and the second during the day. A NEC TS9260 thermal camera was used, operating in the 7.5-13 μm infrared interval, with a resolution of 640x480 pixels and a noise equivalent temperature difference of 0.06°C. Considering the narrow field of view of the optics (21.7x16.4°) and the desired ground sampling distance of 0.5 m, the flight height was set to about 800 metres above the ground and more than 2,500 frames were acquired for each flight. The track of the flight is shown in Figure 1.

The derivation of reliable surface temperature values of building roofs from aerial imagery is a very critical task, because it involves an in-depth modelling of at least three main aspects: the atmospheric layer between the surfaces and the sensor, the radiative behaviour of the different materials which constitute the observed surfaces and the geometry of the acquisition.

In general, a sensor installed on-board an aircraft registers a signal which is composed by different emitted and reflected contributions.[5,6] The total spectral radiance reaching the sensor (l_S) is given by:

$$l_S = \tau \epsilon l_B + l_u + \rho \tau F l_d + \rho \tau (1 - F) l_{sr} \tag{1}$$

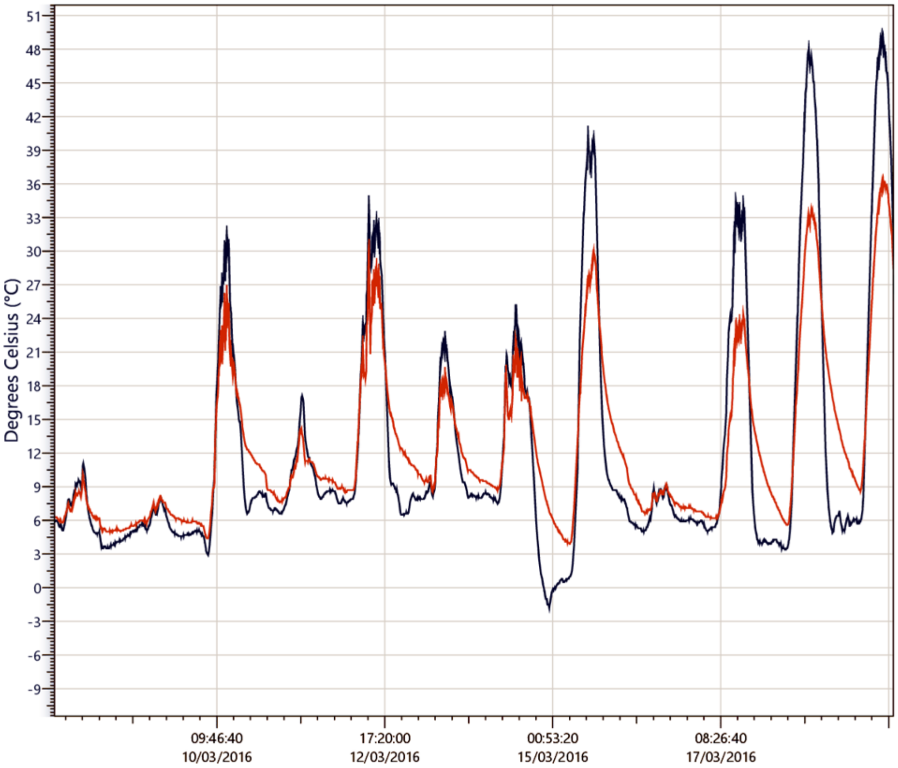

Figure 2. Examples of recordings from two thermocouples placed on the roof of the School of Engineering and Architecture of the University of Bologna.

The first contribution is the radiance emitted by the observed surface (l_B), which is function of the surface temperature according to Planck's law; the quantity is multiplied by the surface emissivity (ϵ), because the surface is not a black-body, and it is attenuated by the atmosphere transmittance (τ). The second term is the upwelling radiance (l_u) emitted upward by the atmosphere layer between the surface and the sensor. The last two terms are radiances reflected by the observed surface toward the sensor: l_d is the downwelling radiance from the entire atmosphere column and l_{sr} is the radiance emitted toward the observed surface by the surrounding objects. To simplify the problem, a lambertian behaviour is assumed for all the surfaces, thus surface reflectance ($\rho = 1 - \epsilon$) is considered dependant on the wavelength only and not on the observing geometry. Finally, F is the sky-view factor, ranging between zero and one.

Very often, however, the lack of essential ancillary data over large areas necessarily requires a simplified approach. In order to address, at least in part, these issues, some operations in the field were established and some ground truth data were collected for calibration and validation purposes.

Two FLIR P620 thermal cameras and several thermocouples were used to determine surface temperature and emissivity of some roof and road paving surfaces, performing the measurements at the same time when the aircraft acquired the thermal images. Where the access was impossible at the time of the flight (for example on certain roofs), fixed thermocouples were placed, which registered temperature data continuously with a sampling rate by five minutes (Figure 2). In one case also a thermal camera was installed on a fixed position registering data continuously (Figure 3), in order to check the agreement between data provided by thermal images and by thermocouples. For all the other points, only one image and one measurement with a contact probe were collected contemporary to the flight. All the surveys were georeferenced by GPS.

Some thermocouples, however, were positioned a few months before the flight, in order to observe the thermal behaviour of roofs and daily temperature oscillations. The optimal timing of the flights, in fact, would be when temperature gradients of roof surfaces are minimal, in order to reduce temperature variations between the beginning and the end of the survey. The actual time of the flights, however, is necessarily a compromise with

Figure 3. The installation of a thermal camera in a fixed position for the continuous monitoring of surface temperature.

the requirements of the aerial traffic control, especially when an important airport is located close to the area of interest, as is the case of Bologna.

Additional ground surveys were performed with the thermal camera, in order to measure the variation of emissivity depending on the viewing angle. The measurements of some surfaces were acquired with the thermal camera positioned at nadir and at progressively inclined views, till 30 degrees between the observing direction and the plane of the surface. The sequence of inclined measurements was repeated along two orthogonal directions, in order to verify also variations due to the observing azimuth. An example of the observed behaviours can be seen in Figure 4, where the data referred to two roofing materials are shown: one is a more uniform plain sheath, whilst the second is a more irregular rough tiled cover.

The framework for the orthorectification of aerial images was provided by the technical cartography of the Municipality of Bologna and the digital surface model (DSM) derived by LiDAR data (Figure 5).

The DSM was used also to derive sky-view factor (SVF) maps, which are essential for the radiometric processing of thermal images. This parameter, ranging between zero and one in value, expresses the proportion of radiation that comes directly from the sky as to the total radiation impinging on the observed surface.[7] SVF accounts for the complex geometry of the urban environments, which influences heat exchanges and radiation fluxes at each point of the urban texture. For this work, three software applications were tested, SkyHelios,[8] ENVI SVF Tool[9] and Solweig.[10] All of them exploit a DSM as the main input and produce a SVF map, according to different definitions and computation strategies.

Two main problems are evidenced in literature regarding the processing of thermal imagery:[11] the atmospheric correction necessary to compute radiance at ground level, and the combined effects of surface temperature and emissivity on the above mentioned radiance, that must be properly modelled in order to estimate both the variables.

Atmospheric correction is one of the most troublesome problem in remote sensing, since the distributions and intensities of atmospheric effects are often inadequately known.[12] This is true also for thermal imagery, where atmospheric correction means (according to equation (1)) the estimate of at least three parameters: atmospheric transmittance, which accounts for the molecular absorption processes, the upwelling and downwelling

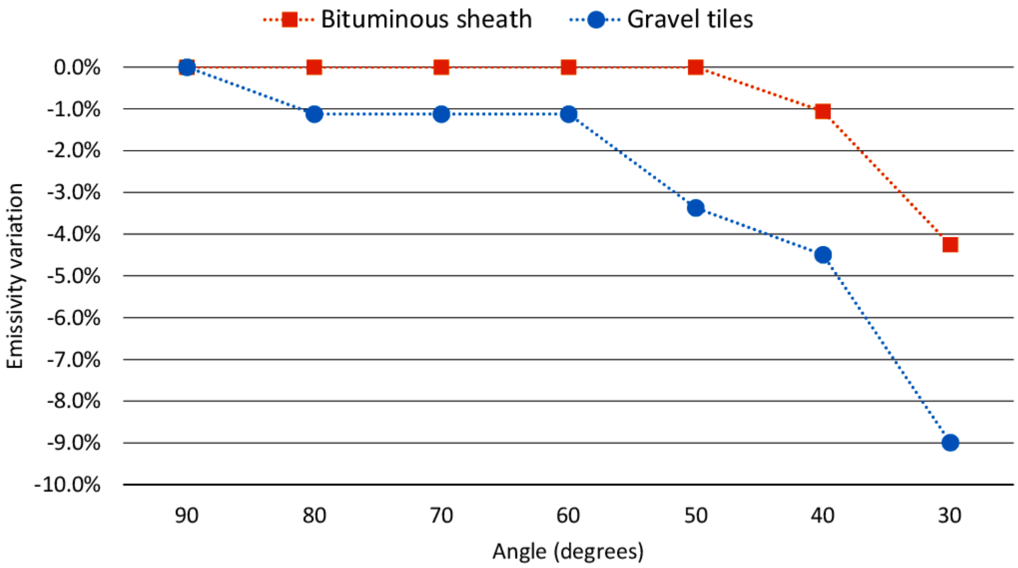

Figure 4. Emissivity variation with the observing direction for two roofing materials.

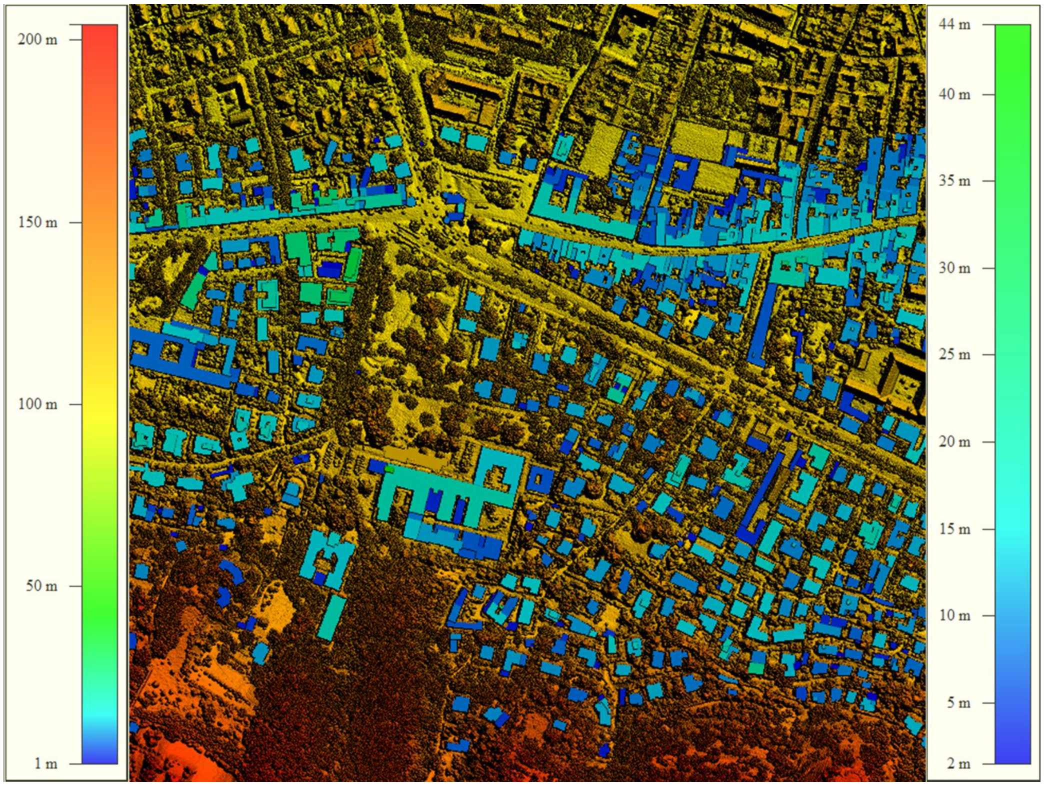

Figure 5. Technical numerical cartography superimposed on the digital surface model of a subset of the study area. The legend on the left refers to the DSM, while the one on the right refers to the elevations of the building eaves above the ground derived from the cartography.

radiances, which account for the emission processes toward the observing sensor and the observed surfaces, respectively. Two possible approaches can be followed. An option is the detailed modelling of the radiative transfer along the atmosphere column above the observed surfaces, which can be obtained using specific codes, such as Modtran 5. This modelling can produce accurate results but a lot of information about the physical and chemical state of the atmosphere is required. In particular, atmospheric profiles derived from radiosoundings or from satellite data, such as MODIS, can be used, together with meteorological ground data. However, these data are not always available or they are not accurate enough for the proposed application. In particular, radiosoundings can be located too far from the studied area and satellite data can have a too coarse spatial resolution, especially in consideration of the complexity of urban micro-climate. The second option is the use of ground surveys of temperature and emissivity on a relatively limited number of surfaces to estimate the atmospheric parameters through an empirical adjustment. In this case, the main limitation is that the accuracy and validity of the retrieved parameters are closely related to the accuracy and distribution of the ground measurements. Furthermore, the adjustment procedure relies on the assumption of lateral invariance of the atmosphere (at least above a small area) and the estimated values may absorb eventual systematic errors occurring in the measurements.

Even if in most investigations the importance and potential impacts of urban surface emissivity were ignored, often due to data unavailability, for accurate quantitative temperature analysis they must necessarily be considered.[13] Several methods can be followed to separate the effects of both surface emissivity and temperature on the radiance at ground level; however, even with multi-spectral sensors with N thermal channels available, the system composed of N radiative transfer equations (one for each channel) remains mathematically unsolvable, because there will always be $N + 1$ unknowns, corresponding to the N emissivities in each wavelength and the surface temperature.[11]

On the basis of the number of thermal infrared channels available, the methods to derive the land surface temperature were categorized in four main groups:[14, 15] single channel methods, double channel (or split-window) methods, two angle methods and other methods, developed for sensors operating in more than two infrared channels or based on different techniques. In more recent classifications,[11] the methods to derive the land surface emissivity from space are divided in three groups: (semi)empirical methods, multi-channel temperature/emissivity separation methods, and phisically based methods. In general, single channel methods require the assessment of surface emissivities in order to compute surface temperatures, although for some new temperature retrieval methods the emissivity is not strictly necessary.[13] In addition, they are very sensitive to atmospheric effects and can become unusable with high water vapour contents in the atmosphere column (higher than 1 g/cm^3 for flights at an height of approximately 1000 m above the ground).[14]

When using a single thermal channel, only empirical methods can be applicable in practice for the estimation of surface emissivities:[13] this category can generally be furtherly divided in classification-based methods and spectral index-based methods, even if hybrid procedures combining them both were also applied. For the former category, the accuracy of classification and the representativeness of the emissivity values associated to the different classes result very important, especially for dry atmosphere conditions when a 0.01 error in emissivity may generate an error of 0.6 K in temperature.[13]

Even if spectral libraries containing emissivity values for several man made materials are available and can be used (such as the ASTER Spectral Library version 2.0,[16] the Modis Emissivity Library and the spectral library of impervious urban materials at London Urban Micromet Data Archive LUMA[17]) at the moment they do not completely represent the huge variety of anthropogenic materials actually present in urban areas; moreover, they are generally sensor dependant.[13] For a valuable use of a comprehensive spectral library in thermographic applications, more samples of anthropogenic materials collected in different urban areas under different climatological and geographical backgrounds are necessary, anyway that would require a long work with high professional skills and specialized equipments. At the moment, an *a priori* knowledge of the materials (and their surface conditions) present in a specific urban area is suggested as a more suitable way if compared to spectral libraries,[13] and described as definitely beneficial for surface emissivity estimation (at least for satellite analysis).

Following this recommendation, the identification of the more widespread roofing materials present in the urban area of Bologna, and the subsequent assessment of the emissivity values in the same spectral range

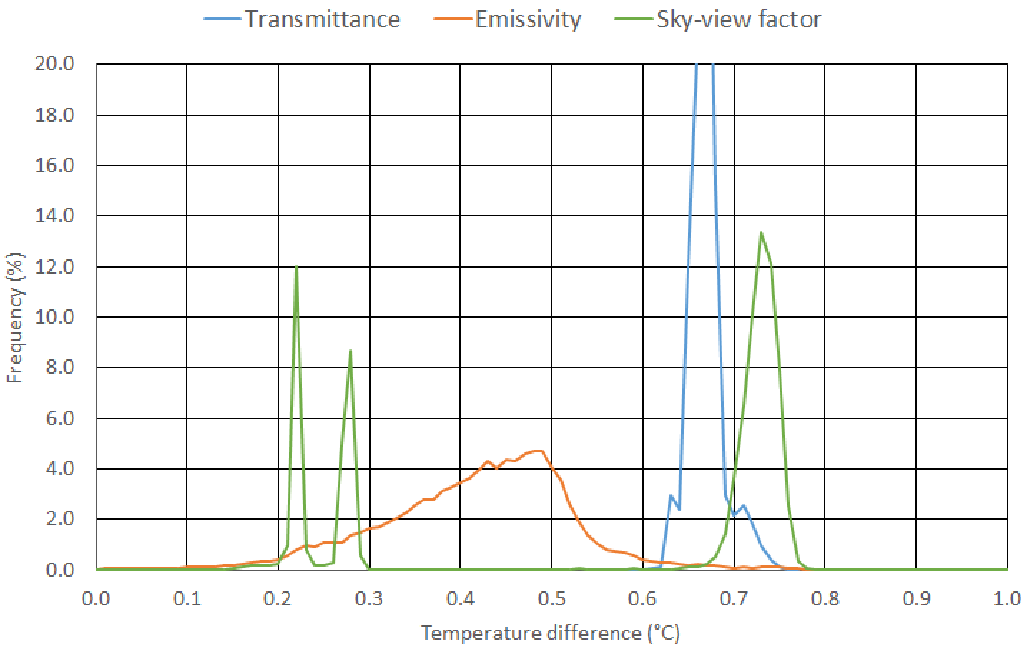

Figure 6. Temperature differences for the test area obtained by varying by 1% the values of atmospheric transmittance and surface emissivity and by 10% the SVF.

acquired by the aerial infrared sensor are among the activities of the ChoT project. For the present paper, a very high resolution satellite image was used. An object-oriented supervised classification was applied to distinguish among the major roofing material types and an emissivity value was assigned to each class according to ground measurements, if available, or literature data.

3. RESULTS AND DISCUSSION

Data acquisition and processing is still ongoing, but the results of the first surveying campaign were used to analyse the sensitivity of the model to the main parameters, considering a test area of about 0.5 km^2. Regarding the atmospheric parameters, a variation of 1% in transmittance produced an average difference in surface temperature of 0.7°C with a standard deviation by 0.02 (Figure 6). However, it must be noted here that atmospheric parameters are strongly correlated and a different transmittance always corresponds to different upwelling and downwelling radiances.

A variation of the same entity (1%) in emissivity, instead, caused an average decrease in temperature of 0.4°C (STD 0.11). This result is in good agreement with the outcomes of previous studies.[3, 18] Finally, it was found that to produce a similar mean difference in temperature (0.7°C, STD 0.55) the sky-view factor must vary by 10%.

It is worth to mention that the sky-view factor varies significantly, according to the method used for the computation. Differences up to 20% are possible starting from the same digital surface model, however their effect on the retrieved temperature is limited. On the other hand, neglecting completely the effects of the different exposure of each surface composing the scene would produce an overestimate up to three or four degrees.

These first results suggest that great efforts should be spent in emissivity estimation, because it has a strong impact in the surface temperature retrieval process and it has also a great variability on the observed surfaces. In fact, emissivity may range from values lower than 0.5 for metal covers to values higher than 0.9 for bituminous pavements. Furthermore, even for the same material, the emissivity may vary as a consequence of weathering and ageing effects.

Regarding the directional effects, some ground surveys suggest that the emissivity value viewed from an inclined observing direction can diverge significantly from the value at nadir when the elevation angle of the sensor is lower than 60 degrees. However, the actual observing angle is affected also by the tilting of roof surfaces; therefore, a camera with a narrow field of view is to be preferred for this kind of surveys, in order to avoid very low angles of observation.

Future developments of the researches in the framework of the ChoT project will certainly encompass a detailed mapping of the main roofing materials occurring in the study area and an accurate characterisation of each material in terms of emissivity. Furthermore, the different algorithms for the computation of sky-view factor will be tested, in order to verify which definition is the most appropriate for the retrieval of surface temperature from thermal imagery.

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