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Construction of Digital Elevation Models for a Southern European City and a Comparative Morphological Analysis with Respect to Northern European and North American Cities

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ABSTRACT

A morphometric analysis of a southern European city and the derivation of relevant fluid dynamical parameters for use in urban flow and dispersion models are explained in this paper. Calculated parameters are compared with building statistics that have already been computed for parts of three northern European and two North American cities. The aim of this comparison is to identify similarities and differences between several building configurations and city types, such as building packing density, compact versus sprawling neighborhoods, regular versus irregular street orientation, etc. A novel aspect of this work is the derivation and use of digital elevation models (DEMs) for parts of a southern European city. Another novel aspect is the DEMs’ construction methodology, which is low cost, low tech, and of simple implementation. Several building morphological parameters are calculated from the urban DEMs using image processing techniques. The correctness and robustness of these techniques have been verified through a series of sensitivity tests performed on both idealized building configurations, as well as on real case DEMs, which were derived using the methodology here. In addition, the planar and frontal area indices were calculated as a function of elevation. It is argued that those indices, estimated for neighborhoods of real cities, may be used instead of the detailed building geometry within urban canopy models as those indices together synthesize the geometric features of a city. The direct application of these results will facilitate the development of fast urban flow and dispersion models.

1. Introduction

In recent years we have witnessed an increase of urbanization worldwide. Over 50% of the world’s population (almost 80% in the United States and about 70% in Europe) live in cities and this ratio is still increasing. This is particularly evident in developing countries undergoing rapid urbanization: between 2000 and 2030, the urban population in Africa and Asia is set to double and, by that same year, urban dwellers will make up about 60% of the world’s population (United Nations, Department of Economic and Social Affairs, Population Division 2007).

Urbanization affects the environment within and beyond cities. Many economic and social activities, governmental operations, and extensive infrastructures are located in cities or in nearby areas. Air quality in urban areas is continually deteriorating because of many of these activities, particularly the increase of vehicular traffic. Moreover, the larger consumption of energy in cities may contribute to the formation of heat islands modifying the urban climate and causing pollutant entrapment zones. Pollution can injure human health, harm the environment, and cause building deterioration and property
damage. For these reasons, accurate prediction of pollution dispersion and of urban air quality are becoming more and more important with respect to legal regulations concerning acceptable pollutant levels, environmental planning, and the health of the citizens. Additionally, these and other related issues demand substantial studies of the impact of urban growth on climate change.

In particular, it is of interest to understand how the wind and turbulence fields change above and within the city as a consequence of airflow interaction with the urban agglomeration. In the idealized case of arrays of buildings of regular size and shape, the resulting flow structure can be roughly categorized in terms of the spacing among buildings into three flow regimes, which are: isolated obstacle flow, wake interference flow, and skimming flow (Oke 1988). In the case of a real city, the complex urban texture generates more complicated flow patterns with occurrence of flow separation. Numerical modeling, such as computational fluid dynamics (CFD) including large eddy simulation (LES) models, should be used for the prediction of such flows. However, in most cases, it is still not practical to calculate the flow around every obstacle. For this reason, a parameterization to represent the dynamical effect of an urban area is still required as it arises from many studies available in the mesoscale modeling community (see, e.g., Martilli et al. 2000; Brown 2000; Otte et al. 2004). The level of topographical or building detail depends upon the modeling scale, increasing from the regional scale, through the city and the neighborhood scales, up to the street scale (Grimmond and Souch 1994; Britter and Hanna 2003).

Various methods for determining aerodynamic parameters exist. Comprehensive direct measurements of wind and turbulence fields in cities are difficult. In fact, they require observations taken at several horizontal positions within the city and at various vertical levels, some of them well above the average building height. As an alternative, morphometric methods express the cities’ aerodynamics characteristics in terms of average building height $H$, planar area index $\lambda_p$, frontal area index $\lambda_f$, and other measurable parameters related to the urban morphology (e.g., Cionco and Ellefsen 1998; Grimmond and Oke 1999).

Urban morphometric analyses have been conducted more widely in the United States (Burian et al. 2007) than in Europe, especially in southern Europe. Such analyses require the characterization of the built elements, which is difficult because of the irregularity and asymmetry of the associated shapes. This heterogeneity can be found at different scales within the city and among cities, and the variability is partially related to geographic positioning, geomorphologic structure, and historical background of the specific territory in which the city has developed. For example, European cities have grown with successive additions of neighborhoods from the city center to the suburbs (Long et al. 2003). “Modern cities are often characterized by clusters of high rise buildings and wider streets, meanwhile older cities often have very narrow streets and densely-packed, few-storey high buildings” (Kastner-Klein et al. 2004). We are still some way from a systematic study that provides an extensive classification of different city types based on morphometric criteria.

In previous work, building statistics have been calculated according to different urban land use categories such as residential, commercial, industrial, and downtown core areas. Grimmond and Oke (1999) as well as Burian et al. (2007) performed such studies on several North American cities. Similarly, other authors derived relevant flow and dispersion parameters linked to the urban morphology for parts of some northern European cities, such as London, Toulouse, and Berlin (e.g., Ratti et al. 2002, 2006). However, little attention has been directed toward cities in southern European and Mediterranean regions even though their morphological, geographical, historical, and societal characteristics would be of considerable scientific interest, especially given their unique climate (e.g., Camuffo et al. 2000; Bolle 2003).

In the past, one of the main difficulties of the morphometric approach, particularly outside the United States, was the limited availability of data describing the urban texture. Grimmond and Souch (1994) were among the first researchers to develop an urban DEM; a few years later Grimmond and Oke (1999) and others (e.g., Burian et al. 2002; Ratti et al. 2000) employed this methodology to determine the aerodynamic properties of urban sites.

Burian et al. (2004) reviewed presently available data sources and data-collecting methods. Many techniques can be used to construct DEMs. Among those there are remote sensing techniques, such as satellite imagery (Tacket et al. 1991), aerial photography (Müller et al. 1999), stereophotography, and plane-mounted lidar (Baltavias 1999). Regardless of the technique used, DEMs are just two-dimensional (2D) matrices (raster structure) of height values where the position of each matrix element is implicitly associated with planar spatial coordinates. Therefore, DEMs contain three-dimensional (3D) information based on a 2D structure that can be stored in different formats. Among these, the raster image is a convenient format as it is commonly used and easily readable with most freely available software packages. Each pixel of the raster image represents a value of building height and can be displayed in shades of gray. However, DEMs are not yet available for many areas, in part because of their cost.

In this paper we show how raw data of building heights can be obtained at low cost to construct DEMs. We derive DEMs for parts of a southern European city to show...
their sensitivity to image resolution and data formats; we proceed to compare and comment on these DEMs with those available to us for other areas. DEMs are analyzed to calculate a number of morphological parameters. Specifically, we determine \( H \), \( \lambda_p \), and \( \lambda_f \), and then calculate the roughness length \( z_0 \) and other parameters for the city of Lecce, Italy, as an example of a typical southern European or Mediterranean city. The calculation is based on extensions of some available algorithms based on image processing techniques developed within the Matlab proprietary software environment as discussed by Ratti et al. (2000) and Ratti and Richens (2004). All algorithms are evaluated by means of sensitivity tests performed on idealized DEMs made up of simple arrangements of cubic and rectangular buildings for which an analytical calculation of the morphometric parameters is possible.

Three urban DEMs corresponding to different parts of the city of Lecce are analyzed and the morphometric and aerodynamic properties are compared with those of some parts of three northern European and two North American cities, noting their similarities and differences and their possible effects on wind and dispersion characteristics.

The Lecce study areas are described in section 2. Section 3 describes how DEMs were constructed and how the morphometric parameters were extracted using image processing techniques. Image resolution sensitivity tests are also discussed in this section. Section 4 shows the new algorithms for the calculation of \( \lambda_f(z) \) and its validation. The results are discussed in section 5. Conclusions are presented in section 6, and an appendix is included with details of the various image sensitivity tests.

2. Study areas

The study areas are located in Lecce (40°23’N, 18°11’E), a medium-size city, typical of southern Italy and of the eastern Mediterranean area. The city is in the middle of a narrow peninsula about 40 km wide and 70 km long. Lecce has about 100 000 inhabitants and is known for its important cultural building heritage. Urban pollution sources, such as heavy traffic and domestic heating as well as the presence of a large power plant and an industrial site about 50 km from the city produce poor air quality in Lecce. Figure 1 shows the location of the city (Fig. 1a) together with these two major pollutant sources (Fig. 1b). The city has an overall rectangular shape (7 km × 5 km) with the longer side along the northeast/southwest direction. The morphological structure reflects that of a southern European and Mediterranean city. It has developed around the historical center bounded by pre-Roman walls that enclose an area of about 2 km × 1.5 km. This older part of the city is characterized by densely packed buildings of two or three stories with irregular footprints, flat terrace-type roofs, and internal courtyards. Several churches and small courts separated by twisted alleys are also present.

Newer parts of the city generally have taller buildings that are mainly residential apartments or commercial buildings. Buildings here have a more regular shape than those in the historical center and they are less irregularly distributed but equally densely packed. Some minor industrial sites about 10 km from the city center are not considered here.

In this study we focus on three neighborhoods of 400 m × 400 m. This size has been chosen to facilitate the comparison with previously analyzed DEMs. All three neighborhoods are part of downtown Lecce where commercial, public office, and residential buildings are mixed together. Two of the areas (named Le1 and Le2) are in the same part of the city and include tall commercial buildings of rather regular shape (a rectangular footprint). In contrast, the third area (named Le3) includes the Public Gardens where about 140 trees up to 20 m high cover a
surface that is about 3% of the total area. Le3 includes a small part of the historical center, where buildings are arranged in a very complex manner with roads typically not perpendicular to each other. Overall this site has a less regular structure than the other two study areas. The building density is also greater than the other two. Most buildings in this area are public, including schools. This area was selected as it is different in structure from the other two and also because it is among the most polluted of the city’s neighborhoods. The choice of Le1 and Le2 was motivated by their planar building density being similar to those of London and Toulouse previously analyzed by Ratti et al. (2000).

3. Methodology

The methodology followed for the DEMs’ construction and their subsequent analyses starts with the collection of raw measurements of the building heights and proceeds with their processing and transformation into various image formats.

a. Building-height data collection

Building-height data collection took about three months for the three city areas. Planar dimensions of the buildings were available from 1:2000 scale planar maps stored in digital form. All buildings on the map were checked and identified on site. Building footprints were in some cases inaccurate and were corrected by measuring them on site. Building heights were measured from the ground level from two sides when possible. Building-height data were measured using a distance meter Leica DISTO mounted on a tripod at ground level, positioned 2–3 m from the building façade. This instrument is a laser diode consisting of a laser pulse of known frequency split into a reference beam and a measurement beam by a system of mirrors. Because of the delay time between the reference ray and the external trajectory of the ray of measurement, the difference of phase between these two signals is proportional to the distance between the distance meter and the reflecting surface. To make use of the full nominal accuracy of the instrument (2 mm) we placed it in front of each building facade and performed sets of three auxiliary measurements. Figure 2 shows the typical instrument setup with the three auxiliary measurements. The figure also shows photographs of one of the street canyons and the DISTO instrument. As the laser measuring points have to be on a straight line in a vertical plane, the use of the tripod avoids the possibility of shaky measurements. The second auxiliary measurement must be made perpendicular to the desired length. This can be done by using a bubble level allowing for a simple horizontal leveling of the instrument as the distance meter is provided with a magnetic support for attaching accessories. The estimated building height is the result of the three measurements combined through their squared, triangle geometrical relationships.

While the distance meter has a resolution of 2 mm, the laser dot resolution can be up to few centimeters for each
set of measurements. Errors introduced by the operator can be significant for very tall buildings as some difficulties may arise in performing the auxiliary measurement along a vertical plane (label 1 in Fig. 2). The instrumental errors are always negligible in comparison with those introduced by the operator. To minimize them, the distance meter was equipped with a telescopic viewfinder with fourfold magnification.

By performing some tests on building of known height we estimated that, for building heights less than 40–50 m, errors associated with the overall building height measurement are less than 1 m. Such measurement errors were considered acceptable for our research purposes.

For the representation of buildings on the map, some approximations were made:

• a porch inside a group of buildings was not represented;
• sparse trees, walls, roof overhangs, turrets of staircases at the top of some buildings, buildings under construction, etc., were neglected;
• over the whole study area, the road level was assumed to be horizontal;
• the representation of the dome of a church was also approximated. It was drawn as a cylinder of the diameter of the dome, but of smaller height to simulate a cylinder of similar volume;
• the trees of the Public Gardens were represented by a square plan shape with a constant height equal to the average tree height.

b. Construction of the DEMs

The construction of the actual DEMs consisted in displaying individual building heights on the original planar maps and in forming new vector layers where the basic units to be mapped were structures of different heights. Every building is described by a 2D polygon with specific attributes corresponding to its footprint and rooftop elevation. DEMs of the three study areas were manipulated using ESRI ArcView GIS 3.2 tools to convert them into a raster image, that is, in a form appropriate for the application of image processing techniques. Figure 3 shows the various phases of the DEM construction from the aerial photograph to the DEM in raster form. The intermediate phases consist of using planar building maps in digital form, editing building footprints if necessary with CAD software, adding building-height measurements to them and representing the maps as a vector DEMs. Once the DEMs are in raster form they can be analyzed using image processing techniques.

In this study we compute urban morphometric parameters (explained in the next section) by using previously developed computer programs and by developing new ones within Matlab’s Image Processing Toolbox in which images were represented as square matrices and pixels were coded using 8 bits (though higher resolutions could be used in principle).

In the vector to raster transformation, care should be taken in choosing the appropriate correspondence between image pixel and building height. This was done by using a grayscale so that each pixel has a level of gray proportional to the building height. For 8-bit images this corresponds to 256 levels of gray. Each image has its own scale so that the value 255, displayed as white on a raster structure, is assigned to the road level (0 m) and the 0 value corresponding to the black color is assigned to the maximum building height. Typically, if building-height accuracy is 1 m, not all 256 values of gray are used because buildings normally are shorter than 255 m. Instead, particular shades are used for a given building height in such a way to minimize the errors arising from the conversion from the grayscale to the building height. The choice of the shade interval can be made according to the building-height distribution histogram as done in remote sensing data representations. This way of assigning the pixel level makes full use of the range of gray shades and more clearly represents building heights.

A further point to make concerns the choice of the pixel size (this is separate from the issue above). One of
the problems related to the DEM construction in a raster form, obtained as a data conversion from vector structures, is that the pixel size should be small enough not to affect the positional accuracy of building footprints. This could be solved following general rules adopted in digital photogrammetry. On the other hand, the size of the pixel should not affect the values of the morphometric parameters to be calculated. From the theoretical point of view, one should choose the pixel size that satisfies both requirements and which is the lower of the two. However, in the context of this work, it is sufficient that the choice of the pixel size is made only in relation to the calculation of the morphometric parameters without taking into account the problem of the positional accuracy. This is further addressed below.

c. Estimation of morphometric parameters for three areas

The originally derived DEMs for the three areas Le1, Le2, and Le3 were analyzed to calculate building statistics as well as several building morphometric parameters. In particular, \( \lambda_p \), \( \lambda_f \), and \( z_d \) (the average height weighted with building frontal area) are calculated as

\[
\lambda_p = \frac{\sum A_{p,i}}{A_T}, \quad \lambda_f = \frac{\sum A_{f,i}(\theta)}{A_T}, \quad z_d = \frac{\sum H_i A_{f,i}(\theta)}{\sum A_{f,i}(\theta)},
\]

where \( H_i \) and \( A_{p,i} \) are respectively the height and the planar area of the \( i \)th building, while \( A_{f,i}(\theta) \) is its frontal area perpendicular to the wind direction \( \theta \). The \( A_T \) is the total site planar area. \( \lambda_f \) represents the total area of buildings projected into the plane normal to the incoming wind direction and is a function of orientation. For a given wind direction, \( \lambda_f \) is smaller if the wind angle is oblique, rather than perpendicular, to the front face of the building. That is, \( A_{f,i} \) is multiplied by a \( \sin(\theta) \) function dependent on wind angle relative to that building face.

In addition, we calculated four other statistical parameters: the average building height and its standard deviation, and the average building height weighted with the planar area and its standard deviation. The last two, more meaningful from the fluid dynamics point of view, are defined as

\[
\bar{H} = \frac{\sum H_i A_{p,i}}{\sum A_{p,i}} \quad \text{and} \quad \sigma = \sqrt{\frac{\sum (H_i - \bar{H})^2}{N-1}}.
\]

Starting from these parameters, we computed the zero-plane displacement height \( z_d \) and roughness length \( z_0 \) using the equations derived by Macdonald et al. (1998):

\[
z_d = 1 + (\lambda_p - 1)\alpha^{-\lambda_p} \quad \text{and} \quad \frac{z_0}{\bar{H}} = \left(1 - \frac{z_d}{\bar{H}}\right) \exp\left\{-\frac{0.5\beta C_D A_F}{\kappa^2}\left(1 - \frac{z_d}{\bar{H}}\right)^{-0.5}\right\},
\]

with \( \alpha = 4.43, \beta = 1.0, \kappa = 0.4, \) and \( C_D \sim 1 \).

As discussed previously, the particular technique used to derive those building morphological parameters requires an assessment of the influence of image resolution on the results. This is particularly relevant when using those parameters within urban dispersion models. One may find that an error of 10% on the calculated parameters is acceptable given the large approximations usually made in those models. More importantly, one may find that a variation of 10% in the value of the building morphological parameters is irrelevant from the fluid dynamics point of view. This needs to be evaluated through detailed numerical flow simulations.

As described in the previous subsection, the construction and analysis of DEMs consists of converting vector data into a raster image and then storing this image in a specific format. This format should be chosen in such a way to avoid, or at least minimize, loss of information relevant for urban morphometry analyses. For the same reason, image spatial resolution is important, also because it can affect the edge detection occurring in several algorithms; for example, those related to \( \lambda_p \) and \( \lambda_f \) calculations. As a consequence, it is appropriate to investigate how the image storage format may affect results before interpreting them. Indeed, even when DEM analysis by image processing techniques has been carried out (i.e., Ratti et al. 2006), a suitable sensitivity analysis has not always been done. We performed several tests on many building arrangements of different complexity to investigate how specific image formats, such as TIFF, BMP, JPEG, and GIF, as well as the image spatial resolution influence the accuracy of the calculated parameters. Details on the various tests and specific results of the sensitivity analyses are
reported in the appendix. In general, all formats except JPEG do not influence results but the image resolution does. The way image resolution affects the calculation accuracy is rather complex, because it depends on the specific building arrangements, shape, and orientation. The various tests performed suggest that to minimize errors, the original DEMs should be rotated in such a way as to get most of the building facades aligned with the external raster frame. This procedure allows us to reduce the effect of changing the intrinsic positional regularity of the pixels. The sensitivity analysis shows that the accuracy of the $\lambda_p$ parameter improves with increasing image resolution. This does not happen for all other parameters, which, instead, do not behave linearly with image resolution and appear to be more dependent on the specific building arrangement rather than the image resolution. To identify a general rule for handling errors due to image resolution, it is reasonable to adopt the criterion of choosing that image resolution that does not affect the value of $\lambda_p$. Errors on the other building morphology parameters are then calculated on the basis of the chosen image resolution. Table 1 summarizes the errors related to all calculated parameters for the case when $\lambda_p$ agrees with its theoretical value, at least within the first two significant digits. The errors can be large on both roughness length and displacement height. We anticipate that errors are more significant for cities that tend to have irregular building arrangements and orientations as it is typically the case of southern European/Mediterranean cities.

### 4. The frontal area index as a function of elevation

As a principal objective of this work, we now furnish some guidelines on the suitability of the calculated morphometric parameters within urban flow and dispersion models. Starting from the idea that a city can be represented as a superposition of neighborhoods each characterized by some lambda parameters, one may look for useful representations of the city’s neighborhoods in those models. Recent literature has shown how wind flow and dispersion characteristics can be derived from morphometric parameters, which are formulated as a function of the elevation $z$. For example, Di Sabatino et al. (2008) developed a simple model for spatially averaged wind profiles within and above real urban canopy layers where buildings are represented by the frontal area index as a function of $z$, $\lambda_f(z)$. This parameter has been calculated also by Burian et al. (2007) for several cities in North America. However, $\lambda_f(z)$ derivation from image processing techniques has not been explicitly addressed. As described in Ratti et al. (2006), the key element of the algorithm to calculate $\lambda_f$ for a given wind direction $\theta$ is the calculation of the overall building facade area along that direction. This involves the derivation of the unit vector perpendicular to the DEM surface on each pixel. By applying geometric relationships, $\lambda_f$ is calculated by summing all individual building façade areas projected into the given wind direction. A more detailed description of the algorithm can be found in Ratti et al. (2006).

We now present a modification of this algorithm in order to calculate the variation with height of the frontal area index, $\lambda_f(z, \theta)$, defined as:

$$\lambda_f(z, \theta) = \frac{\sum \Delta A_{f,i}(z, \theta)}{A_f}.$$  

For a given wind direction $\theta$ and a constant increment height interval $\Delta z$, $\Delta A_{f,i}(z)$ indicates the portion of the building frontal area in the region between $z$ and $z + \Delta z$. In other words, $\Delta A_{f,i}(z)$ is equal to $W_f \Delta z$, where $W_f$ is the width of the facade perpendicular to the wind of the $i$th building at the elevation $z$. Figure 4 illustrates the definition of the building scales: $H$ (height), $W$ (width), and $L$ (depth).

The original algorithm for $\lambda_f(\theta)$ is modified in order to select those pixels within the layer between $z$ and $z + \Delta z$ and to apply to those pixels the usual procedure for the calculation of $\lambda_f$. The result is such that the sum of $\lambda_f$ values calculated for every $\Delta z$ coincides with the total frontal area index for the given wind direction. The value of $\Delta z$ should not be smaller than the building height accuracy which for our case is 1 m.

The new algorithm was evaluated through several tests on idealized building arrangements for which a theoretical calculation of the morphometric parameters was possible. As an example, Fig. 5 shows the results for $\lambda_f(z)$ profiles calculated for very simple cases and their comparison with theoretical values. The first case is that
always denoted as \( W \).

An additional way to derive building shape information is by looking at polar diagrams of \( \lambda_f \) variation with wind direction \( \theta \). As an example, Fig. 9 reports \( \lambda_f(\theta) \) for
tree height in that specific area (32 m for Le1 and 28 m for the other two). To facilitate the interpretation of these images, building distribution histograms are shown for the three areas in Fig. 7, with and without the trees of the Le3 area. To more clearly emphasize the natural breakdown of building distribution in each neighborhood, a height interval of 3 m, which is typical for each storey in Lecce, was chosen. Focusing on the building height distribution only, without trees, it can be seen that Le1 is the most uniform among the three areas, with a similar number of short and tall buildings. Le2 has the highest number of short buildings and few tall buildings. Le3 is characterized by buildings of intermediate height. Overall, this area has a bell-shape building-height distribution around a mean value of 10–12 m, corresponding to three to four stories. This distribution is altered substantially by the trees. Trees act as additional obstacles to the flow, and therefore, they have been included in the basic building height statistics and, most importantly, in the derivation of fluid dynamics parameters as discussed in the next sections.

5. Discussion and results

In this section, DEMs originally derived following the methodology previously described for the three areas of Lecce, Le1, Le2, and Le3, are presented, discussed, and compared with three DEMs of three northern European cities and two DEMs of North American cities. The choice to compare cities according to their geographic location was considered relevant from the meteorology and climate points of view but other criteria could be used. The approach used in our analyses is not dependent on the specific choice of north–south cities, though specific results will be presented here in this framework.

a. Southern European DEMs: General description

Figure 6 shows DEMs in grayscale for the three areas of Lecce. We reiterate that each image has its own scale and that black corresponds to the maximum building or
Le2, Toulouse, and Salt Lake City, chosen to represent the three geographic regions (southern Europe, northern Europe, and North America) investigated in this study. The first two cities have a circular symmetry, with \( \lambda_f(\theta) \) almost constant with wind direction, while Le2 has an increase in the north–south direction because most building facades are oriented east to west. In addition to the particular shape of \( \lambda_f \) with orientation, the plot immediately shows the comparative difference in frontal area densities among the cities investigated. It further emphasizes the higher building densities of European cities with respect to the ones in North America.

As previously discussed, we also calculated \( H \), the average building height, and \( z_H \), the building-height weighted with the building frontal area. As pointed out by Ratti et al. (2002), \( z_H \) is the parameter that, in principle, should be used in the calculation of the aerodynamic roughness. This is because it explicitly accounts for some features of building shape, synthesizes the overall resistance to the wind, and, in this respect, is fluid dynamical relevant. By comparing the two building-height averages for the DEMs, we see that \( z_H \) is slightly smaller than \( H \) for Le1 and Le2, and typically larger for all DEMs analyzed. The difference between the two building-height averages is much larger for the two North American cities, with respect to the other DEMs. This is a first indication that the overall building frontal area of the European cities investigated here is smaller than that of the two North American cities. This also indicates buildings which are wider rather than taller in these European cities. The difference between \( H \) and \( z_H \) is reflected in the derived zero-plane displacement height, \( z_d \), and the roughness length \( z_0 \), calculated with Eqs. (6) and (7). First of all, \( z_d \) and \( z_0 \) calculated with \( z_H \) in place of \( H \) are not significantly different for the European cities. The difference ranges from about 3% for Toulouse and London to 9% for Berlin. Instead, significant differences are observed for the DEMs of the two North American cities for which the use of \( z_H \) instead of \( H \) in the \( z_0 \) calculation leads to an increment of about 46% for Salt Lake City and 68% for Los Angeles. This and the \( z_0 \) results for Lecce are consistent with Ratti et al. (2000) in that, although the use of \( z_H \) in Macdonald’s formulas is generally appropriate, it is not adequate for the North American cities analyzed.
here. The reason for this is that Macdonald’s formulas have been derived for cubic building arrays. They tend to underestimate $z_0$ for real cities, because those formulas do not take into account building-height variability. The use of $z_H$ is appropriate for cities characterized by relatively large $\lambda_p$ values. If $\lambda_p$ is very small, as in downtown areas of American cities, the use of $z_H$ is not required. This is confirmed by the agreement between the $z_0$ value for downtown Los Angeles, obtained by Ratti et al. (2002), using $H$ and independently calculated by Burian et al. (2002). In general, the size of the northern European and Lecce sites (400 m × 400 m), used in this study, would not be large enough to perform a $z_0$ calculation; however, this simplification can be accepted as these sites

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**FIG. 6.** DEMs of the three areas of Lecce, named (a) Le1, (b) Le2, and (c) Le3.

**FIG. 7.** Histograms of building heights for the three areas (left) including trees and (right) without trees of the Le3 area.
may be considered representative of larger urban areas with similar morphometric characteristics or neighborhoods with similar lambda parameters. It should be pointed out that even though the roughness length, calculated solely on the basis of geometric considerations, might be important in the derivation of some flow characteristics in urban environment applications, the use of $z_0$ is questionable. In general, the use of $z_0$ in urban flow and dispersion models should be avoided or limited. Its determination is controversial because of the intrinsic difficulty linked to limited fetch, typical in urban areas, which prevents the flow to be in equilibrium with the changing surface (Belcher et al. 2003). It is important to bear in mind that the derivation of $z_0$ based on geometrical considerations only, is a first estimate, but its aerodynamic properties need to be evaluated on a case by case basis. Additionally, doubts remain about the suitability of Macdonald’s formulas for $z_0$ in complex geometries. For this and other reasons, it is worth investigating other building morphometry parameters that can replace, among others, the use of $z_0$ in urban flow and dispersion models, as well as in urban representations within mesoscale models. Obviously, the choice of a particular set of building statistical parameters depends upon the specific application. In the following, we show how $\lambda_p$, and $\lambda_f$ as a function of elevation, are suitable for representing a city or neighborhoods in urban canopy models and mesoscale flow models. Obviously, other choices to represent a city based on morphometric parameters can be made. For example, one may use lookup tables of building and vegetation descriptors, including fractional weights of small versus tall buildings, vegetative fraction, and storage.
etc., as well as their spatial variations. In this context it is important to include intracity variations among neighborhoods through the variation of the lambda descriptors. An alternative way to describe a city is in terms of its population density and distribution. This might be used to derive anthropogenic heat fluxes within the city. Studies in this direction have been initiated by several research teams (Ching et al. 2009) with a focus on cities in North America. Studies on city’s morphology and city’s categorization based on the building distribution and other parameters in Europe and in other continents are isolated and far from being comprehensive.

c. Southern European cities versus northern European and North American cities: Further analysis

As discussed in the previous sections, lambda parameters $\lambda_p$ and $\lambda_f$, as a function of elevation, can be used directly in flow and dispersion models as recently done by Di Sabatino et al. (2008) and Solazzo et al. (2010, manuscript submitted to Bound.-Layer Meteor.). Even though the building statistics of city’s portions illustrated in this study is too limited to allow any generalization, we argue that the direct comparison of lambda parameters can be used to infer city building structure (wider or taller buildings) when detailed building data are not available. Also $\lambda_f(z)$ and $\lambda_p(z)$ synthesize the vertical distribution of a city. This is separate from having detailed building geometry. Specific information about building arrangements within urban areas or neighborhoods as well as building shapes can be derived directly from the analysis of $\lambda_f(z)$ profiles as shown in Fig. 10. We reiterate that $\lambda_f(z)$ describes the variation of the frontal area density with height, which illustrates the resistance to the wind at various heights. This has direct implications on drag force calculations at various heights. Looking at Fig. 10, we observe a spike close to the origin, due to the presence of tall buildings. This spike is very pronounced for the North American cities that typically have skyscrapers in their central business district. It is less evident for cities in northern Europe, and absent for Lecce, where building heights show little variation. Again, any generalization should be avoided because those features reflect those of the datasets analyzed. However, some broad indications of the different city configurations in the three geographic regions considered can be extracted based on Fig. 10. There is an indication of larger packing densities in Lecce with wide and low buildings. Note that all the profiles for $\lambda_f(z)$ are calculated for winds from the north. This particular orientation was chosen as winds blow primarily from this direction. The results may be easily extended to other wind directions. Similar curves are obtained for $\lambda_p(z)$ profiles as shown in Fig. 11.

If we focus on the three Lecce areas, we see that the $\lambda_f(z)$ profile for Le1 has a slightly different curvature than Le2 and Le3 profiles, which, in turn, are more markedly
discontinuous. This is of interest for investigation of intracity variations of the lambda parameters, considering that Le1 and Le2 are adjacent areas. Similar considerations can be made from $l_p(z)$ profiles. Overall, profiles are more similar among the European cities than those for Los Angeles and Salt Lake City. This may be an indication of common features among the European cities, which are generally more compact and less regular than the ones in North America. Other observations can be made from the derived statistical parameters keeping in mind that all datasets with the exception of Le2 include building heights only without trees or vegetation, and therefore some care should be paid in using the results directly.

d. Toward a synthetic representation of a city

The choice of a particular set of building statistical parameters to represent a city depends upon the specific application, which needs to be evaluated before using. For flow and dispersion modeling applications, as well as for mesoscale modeling, it is useful to describe an urban area or a neighborhood through a small set of parameters rather than explicitly include all buildings.

On the basis of $\lambda_f(z)$ and $\lambda_p(z)$ parameters, we can argue that different flow patterns may be expected within a city. Also, pollution dilution potential of a given city is linked to city’s breathability a result of the combined effect of flow transport and entrainment within the city (Buccolieri et al. 2010). This is expected to be dependent on $\lambda(z)$ parameters, their spatial distribution (intracity variation) and the vertical building height variability (e.g., $\sigma/H$ values). The following arguments clarify the previous statements. We explain how $\lambda_p$ and $\lambda_f$ parameters, as well as $\lambda_f(z)$ and $\lambda_p(z)$ can be used to extract information about the building distribution of a city, and the average shape of the “city’s building envelop.” The purpose is to show how a combination of those lambda parameters can be used to capture the important geometric features of a city, which in turn influences flow patterns within urban areas or within specific neighborhoods. First we consider $\lambda_f$ and $\lambda_p$, then we extend the analysis to $\lambda_f(z)$ and $\lambda_p(z)$.

One way of extracting information about building shape is by direct evaluation of the $\lambda_p$ to $\lambda_f$ ratio given by

$$\frac{\lambda_p}{\lambda_f} \sim \frac{B^2}{B H} = \frac{B}{H},$$

where $B$ is an average value between the width and the depth of buildings (see Fig. 4) and the overbar indicates the average over all azimuths. It shows that the combination of both lambda parameters can be used to determine whether a city has grown more horizontally or vertically. Based on the $\lambda_f$ and $\lambda_p$ values in Fig. 8, these ratios indicate that northern European cities and Salt Lake City are characterized by buildings with heights smaller than breadths (ratios between 1.3 and 2) whereas buildings in southern European cities and Los Angeles, have heights larger than, or comparable to, their breadths (ratios between 0.7 and 0.9). Additional information on the average building shape can be derived from these ratios as follows.

One may start by considering the $i$th building of height $H_i$, depth $L_i$, and width $W_i$. Here, $W_i$ always denotes the horizontal dimension of the building façade facing the incoming wind, while $L_i$ is the other horizontal dimension. Its planar area $A_{pi}$ is $L_i W_i$. For simplicity, we assume that the $i$th building is positioned in such a way that the building frontal area is just $A_{fi} = H_i W_i$. This simplification is not too restrictive, because one can always find a wind direction $\theta$ for which most of buildings have a façade in the direction perpendicular to the wind. Then, replacing $A_{pi}$ and $A_{fi}$ with the respective $\lambda_p$ and $\lambda_f$ definitions given by Eqs. (1) and (2) yields
\[
\frac{\lambda_p}{\lambda_f(\theta)} = \frac{\sum_i L_i W_i}{\sum_i H_i W_i} = \frac{T_w}{H_w}, \tag{10}
\]

where \(T_w\) and \(H_w\) are the average building height and the average depth of buildings weighted by their width, respectively. Similarly, if we considered the direction perpendicular to \(\theta\), that is, \(\theta_\perp\), the frontal area \(A_f(\theta_\perp)\) is \(H_i L_i\) and, therefore,

\[
\frac{\lambda_p}{\lambda_f(\theta_\perp)} = \frac{\sum_i L_i W_i}{\sum_i H_i L_i} = \frac{W_i}{P_i}. \tag{11}
\]

Consequently, the comparison of these ratios indicates approximately whether the buildings have square or rectangular footprints. By applying the above reasoning to all cities studied, we conclude that both northern European cities and Salt Lake City have mainly short rectangular buildings, while southern European cities and Los Angeles have mainly cubelike buildings. Even though some care should be taken in adopting this reasoning, because the averaging process might lead to wrong conclusions on the actual building shape, the specific result can be interpreted as the “average shape of the neighborhood building envelop” relevant to the flow. This needs to be appropriately assessed by detailed flow calculations using for instance CFD models.

Other observations can be made from the analysis of \(\lambda_f(z)\) and \(\lambda_p(z)\) profiles shown in Fig. 10 and Fig. 11 as discussed earlier. For example, it is clear that small values of both \(\lambda_f(z)\) and \(\lambda_p(z)\) indicate a low density of buildings with heights equal to or larger than \(z\). To highlight similarities and differences of the cities investigated, Figs. 12a,b show \(\lambda_f(z)\) and \(\lambda_p(z)\) profiles normalized with their corresponding value at the ground level versus elevation. The latter has been normalized with \(H_{\text{max}}\), the maximum building height. This choice is not arbitrary but it is relevant fluid dynamically as recently proven by Xie et al. (2008) who have shown that the tallest buildings within a neighborhood area have a dominant effect on the overall drag exerted on the flow. The normalization with \(H_{\text{max}}\) represents a way of showing how a city’s neighborhood is “seen” by the wind, facilitating the comparison with other cities and highlighting features that are common or not common between them. Looking at the figures, the difference between U.S. and European cities is apparent. The former have almost the same profile, while the European cities are characterized by a large spectrum of profiles. Although, once again any generalization should be avoided, this suggests that these European cities have different architectural features, while the two U.S. cities have similar ones. In Fig. 12a, three layers can be identified: the first layer for \(z/H_{\text{max}} < 0.2\), the second one for \(0.2 < z/H_{\text{max}} \leq 0.6\), and the last one for \(z/H_{\text{max}} > 0.6\). Near the ground, \(\lambda_f(z)\) is almost constant for European cities, while for U.S. cities, this is the layer where \(\lambda_f(z)\) varies the most. In the intermediate layer, the behavior of \(\lambda_f(z)\) for European and U.S. cities is reversed. Finally, at the highest elevations \(\lambda_f(z)\) is constant for both U.S. and northern European cities. Here, only Lecce shows a different shape; that is, \(\lambda_f(z)\) keeps on varying. Since \(\lambda_p(z)\) profiles show the same features of \(\lambda_f(z)\) profiles, we can derive important information about the vertical structure of the cities. The two U.S. cities can be thought of as having two main types of buildings: high-rise and very short buildings. However, the spike of the profiles near the origin shows that the majority of buildings belong to the second category, and only a few high-rise buildings are present. An opposite configuration appears for the southern European city, whose profiles confirm the presence of a considerable number of buildings distributed within a relatively large range of heights. The northern European cities can be
located between these two limits. London has a profile more similar to that found for two U.S. cities, because of the spike near the origin and the presence of a spectrum of $\lambda_f$ values in a restricted range of low $z$ values. The Toulouse profile shows a similar shape, but is shifted up, slightly. This fact, and a larger value of $\lambda_f$ near the origin, suggests a slightly larger number of tall buildings. Finally, Berlin is characterized by a very low variability of $\lambda_f$ and $\lambda_p$, indicative of the most homogenous city among all those investigated.

We further observe that all European cities have almost the same values of $\overline{H}$ and $\sigma/\overline{H}$, but different shapes of $\lambda_f(z)$ profiles. More explicitly, $\lambda_f(z)$ coupled with $\lambda_p(z)$ incorporate the information contained in $\sigma/\overline{H}$, and provides a description of building height spatial variability more like the real spatial configuration of a city. The U.S. cities are characterized by very large values of $\sigma/\overline{H}$, suggesting large building-height variability. However, lambda profiles show that these cities are rather homogeneous, despite the large $\sigma/\overline{H}$, the result of having few high-rise buildings.

The estimation of $\lambda_p$ and $\lambda_f$ parameters and the analysis of their profiles versus elevation, suggest how to represent a city in a compact and effective way. The two North American cities have a sparse (low values of $\lambda_p$ and $\lambda_f$) canopy of two building heights: tall buildings (cubelike shape for both), and short (compared their respective $H_{\text{max}}$) buildings (narrow for Los Angeles and wide for Salt Like City). Southern European cities have a dense canopy made up of tall (compared to their respective $H_{\text{max}}$) cubelike buildings. An intermediate configuration can be hypothesized for the northern European cities. For example, most buildings in Berlin have similar heights, with tall and wide buildings characterized by a low value of $\lambda_p$. For city configurations like this, it becomes difficult to conjecture a possible wind regime and its implication for city breathability. This case requires a quantitative evaluation of the building effects on flow and consequently on dispersion characteristics. The presence of a low spatial building-height variability (a negative effect with respect to city breathability) and a low value of built-up area index (positive effect) needs to be assessed to establish which one is the most dominant by using, for example, CFD models. Furthermore, intricacy variability of morphometry is expected to be relevant in this context. Cities are made up of different neighborhoods and the “physical neighborhood” might be identified by its lambda parameters. Possibly, cities may be better categorized by the types and distribution of neighborhoods.

The analysis presented in this paper has only hinted on the possibility of including the effect on the flow due to intricacy variations of the morphometric parameters. This is strictly dependent on the definition one adopts for the neighborhoods. Once this is done the lambda categorization presented here can be used as a framework to interpret the overall effect of the city on the flow. This aspect is expected to be especially relevant for large cities (including megacities), which typically incorporate many land-use types and require additional investigations. This is left to future research.

6. Concluding remarks

This paper describes the derivation and analysis of DEMs, with image processing techniques for a southern European city of medium size, and their comparison with other DEMs of portions of three northern European and two North American cities. North–south differences have been chosen because they are considered relevant for their climate characteristics but other choices can be made to differentiate between city morphometries without loss of generality.

In general terms, the focus of this work has been to promote and to improve city DEMs’ analyses, with a suggestion on how to represent a city in a compact way within mesoscale and urban flow and dispersion models. This has required investigating and combining results from different geographic regions, taking into consideration various aspects ranging from raw building data collection, image analysis, and their errors with respect to the building statistics calculations.

In summary this paper has three major contributions.

(i) A new DEM derivation methodology has been developed and successfully applied to three areas of Lecce, an example of a southern European–Mediterranean city. This has required the acquisition of raw measurements of buildings’ heights using low cost and low tech techniques.

(ii) Various sensitivity tests have been identified and used to study the effect of image format and image resolution on the calculated parameters. Their results show that a) DEM images should be stored in a proper file format such as TIFF; b) image resolution affects calculated parameters; c) the correct image resolution can be chosen, based on the resolution that does not alter the $\lambda_p$ value. Sensitivity tests on idealized building arrangements have confirmed the reliability of algorithms used to estimate morphometric parameters. Results from the tests can be used as benchmark data for real cities’ neighborhoods with similar morphometric features.

(iii) DEM analysis of Lecce and their comparison with DEMs of parts of three northern European and two North American cities have been presented and
discussed. Despite the several limitations of the datasets used (the majority of them do not include trees, population distribution, etc. and are not large enough to allow us to determine intracity variability of the parameters), these results showed that an effective parameterization of a real urban canopy could be derived from the coupling of \( \lambda_f(z) \) and \( \lambda_p(z) \) parameters.

(iv) In particular, the analysis of lambda parameters and their profiles versus elevation has indicated that the two North American cities are examples of sparse canopies, comprised mainly of short (compared with the respective \( H_{\text{max}} \)) buildings. On the contrary, Lecce is an example of a dense and very homogenous canopy with tall cubelike buildings, while the three North European cities appear to fall into an intermediate configuration.

To further develop this picture, it would be interesting to expand the statistics by considering both larger areas of each city and a larger number of cities. Regarding the latter, the DEM construction methodology described in this paper could be a useful support to the activity. With its twin advantages of low cost and low technology, this method could increase the availability of urban DEMs, especially in those areas of the world with weaker economies.

The final, but essential, step in this research is to assess and validate the ideas reported in this paper, using detailed building resolving flow models, a work in progress by the authors using CFD models.

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**APPENDIX**

**Sensitivity Analysis**

As described in section 3, the particular image technique used here poses some questions about the image processing itself. In particular, it is important to ask the question whether and how much both the image spatial resolution and the file format (e.g., JPEG, BMP, GIF, and TIFF) used to store images affect the value of the calculated morphometric parameters. As emphasized in the methodology section, this is an issue separate from error treatment in the DEM construction. The sensitivity analysis presented here can be applied whenever image processing techniques are used. In the following, several tests were applied to various geometries of different complexity. For each of these configurations, values of the morphometric parameters were determined using both our algorithms and theoretical formulations based on purely geometric considerations [see Eqs. (1), (2), and (4)].
a. Influence of image format

We made a comparison of different file formats of images of simple cubic arrangements and complex geometries (including Lecce DEMs). Except for the JPEG format, the various algorithms always gave the same results, regardless of their complexity and image resolution. A simple building configuration is reported in Fig. A1 as an example of these comparative analyses. From those tests TIFF was the preferred format for both the DEMs of Lecce areas and for sensitivity tests on the image resolution discussed in the next subsection.

b. Influence of image resolution

In addition to establishing which file formats were the most appropriate, sensitivity analyses enabled us to confirm the validity of algorithms and most importantly to investigate the influence of image resolution on the morphometric parameters. Several tests showed that even though no general relationship can be found, the image resolution always affected calculated parameters. Not all parameters were affected in the same way: as resolution increased, the $\lambda_p$ value tended to agree with its theoretical value very quickly. Instead, $\lambda_f$ and consequently $z_0$ behaved nonlinearly with the image resolution for a fixed wind direction.

For example, Fig. A2 is a simple configuration of cubic buildings of 16- and 32-m heights on a 400 m $\times$ 400 m area. The image dimensions range from 200 $\times$ 200 pixels to 3200 $\times$ 3200 pixels. For this image, named DEM_2, $\lambda_p$ agreed with its theoretical value on the second significant digit at the resolution of 40 pixel cm$^{-1}$, that is, for

![Fig. A2. Results of the image processing algorithms using different resolutions (in pixels) of the DEM_2. Theoretical values (denoted with the subscript theor) are also reported. The overbar denotes a value averaged on all azimuths (except for $\bar{H}$), in the other cases the values are calculated for wind coming from the North.](image)

![Fig. A3. As in Fig. A2, but for DEM_3.](image)
a pixel size equal to half the accuracy of planar building data. Instead, the $\lambda_f$ values agreed with its theoretical value on the second significant digit at much higher resolution. At this resolution, the value of roughness length is different from its theoretical prediction by 1%.

These discrepancies arise because the $\lambda_f$ algorithm is based on detection of building edges. The smaller the pixel, the better building contours are detected. Another example is image DEM_3 (Fig. A3). Again, $\lambda_f$ agreed with its theoretical prediction on the second significant digit at a resolution of 40 pixel cm$^{-1}$. However, the agreement of $\lambda_f$, $z_d$, and $z_0$ with their theoretical values got worse. The cause of this is the presence of many buildings with oblique edges. One should bear in mind that the treatment of oblique segments within a raster image is always a source of large errors in comparison to straight segments or lines. An example of this is shown in Fig. A4, where building facades have been rotated with respect to the external frame. More specifically, in the first case, represented by the DEM_2b, we used DEM_2 of Fig. A2 but with a wind direction equal to 45°. In the second case we used DEM_4 of FIG. A4. Results of the image processing algorithms using different resolutions (pixels) of the DEM_2b and DEM_4. Theoretical values (denoted with the subscript theor) are also reported. The values are calculated for northeasterly winds in DEM_2b and northerly winds in DEM_4.

![DEM_2b](image)

<table>
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<th>Parameters</th>
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<th>Le2 (300 pixel cm$^{-1}$)</th>
<th>Le3 (300 pixel cm$^{-1}$)</th>
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</table>

TABLE A1. Average mean building height ($\bar{h}$) and planar area weighted building height ($\bar{T}$) and correspondent standard deviations calculated with ArcView and their comparison with algorithm (Matlab) results. Comparison for $\lambda_f$ values is also listed.
Fig. A4. DEM_4 is just DEM_2 rotated of 45°. In this case the wind is coming from the north. Results for some sensitive morphometric parameters are compared in Fig. A4. Even though the original DEM is the same, the change of the building orientation led to more disagreement between \( \lambda_p \) and \( z_0 \) predictions and their theoretical values.

In conclusion, the sensitivity analysis showed that it is always suitable to rotate the DEM to get the largest number of facades parallel to the external frame of the image. Once this is done, it is necessary to identify the threshold of the “correct” resolution for each DEM image to proceed with the calculation of the morphometric parameters.

On the other hand, when the method is applied to complex urban textures, it becomes difficult to calculate the theoretical values of many of these morphometric parameters and consequently it is not possible to establish the level of accuracy of \( \lambda_p \), \( \lambda_f \), and the other parameters at a given resolution. A possible solution to evaluate the accuracy of the results is to choose \( \lambda_p \) as a control variable. This can be done because its theoretical calculation is generally easier than other parameters and can be derived in other ways. For example, ArcView allows one to extract the \( \lambda_p \) parameter in a very simple way.

Consequently, one could select that resolution for which the discrepancy between the calculated and the theoretical value of \( \lambda_p \) is of the order of 0.1%–0.2%. At this resolution, the values of \( \lambda_f \) will agree with its theoretical prediction on the second significant digit. In this case, \( z_0 \) will differ from the theoretical value only by 1%–2%. For lower resolutions, these parameters should be considered reliable only on the first significant digit.

Based on Lecce DEMs analyses, we conclude that in general if \( \lambda_p \) agreed with its theoretical value on the second significant digit, statistical parameters are always calculated accurately. The theoretical values of \( \lambda_p \) for the Lecce DEMs were calculated by ArcView and are listed in Table 1.

With ArcView, we also calculated the average \( \overline{H} \) and standard deviation \( \sigma \) of buildings’ heights with Eqs. (4) and (5). Just for comparison, we also calculated the non-area-weighted building-height \( \overline{H} \) and corresponding standard deviation \( \sigma_h \):

\[
\overline{H} = \frac{\sum_i H_i}{N} \quad \text{and} \\
\sigma_h = \sqrt{\frac{\sum_i (H_i - \overline{H})^2}{N - 1}}
\]

These results are reported in Table A1 and are compared with the values extracted by the algorithms with Matlab. There, we also listed the \( \lambda_p \) values obtained by ArcView, and for these cases we verified that to achieve an agreement of about 0.1%–0.2% between the calculated and the theoretical valued of \( \lambda_p \), \( 3600 \times 3600 \) pixels were required for Le1 image and \( 6000 \times 6000 \) pixels for both Le2 and Le3 images.

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