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Spatial Estimations of Air Pollution in Urban Areas by LIDAR Measurements

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Abstract: Spatial analysis and visualization of data focused on air pollution in urban areas can be more efficiently explored by geographic information systems (GISs). Data originating from direct monitoring, mathematical modelling and physical simulation in wind tunnels are represented by a wide range of data formats that, together with spatial objects on the surface of studied areas, form heterogenic structures. Thus, to solve spatio-temporal analysis and numeric models, a complex computer system is needed to manage the data and a number of user oriented procedures. In the case of this contribution, a GIS project is developed to examine the GIS abilities to integrate and analyse data collections from LIDAR measurements in the urban areas of Prague. The LIDAR data contain spatial measurements of pollutants located in points along the laser beam trajectories. As regards the mechanical system, the laser beams are mostly arranged into a horizontal or a vertical scan. In the case of the LIDAR system used, one data collection contains 3D scanning of O$_3$ in the horizontal planes and the other collection includes scanning of NO$_2$ in the vertical planes. The horizontal scanning is located above a street network with heavy transport. The vertical scans are mainly in the direction of arterial roads mostly above their midlines. Spatial estimations are focused on spatial interpolation of pollutant concentrations by deterministic and geostatistical methods. Subsequently, the images, which illustrate the pollutant distribution, are included into the GIS project and visualized together with other spatial data that can support decision making processes and risk assessment analysis.

Keywords: spatial modelling; GIS; LIDAR; air pollution

1. INTRODUCTION

New techniques in air pollution monitoring, together with improvements of graphic subsystems, the growing capacity of memory units and the increasing speed of processors implemented in standard computer systems, enable processing of large data structures which are related to air pollution at global and local scales. Thus, more complex software tools and data are needed to take advantage of technological progress. One of the most useful software tools is represented by geographic information systems (GIS). In spite of the fact that data processing by GIS has been used for a few decades, it’s application in related scientific disciplines is now really rapidly progressing. This is enabled by the GIS ability to integrate spatio-temporal data in the framework of its spatial data formats. Thus, for example, instead of spatial interpolation of the altitude on the earth surface, other variables can be substituted to carry out images of pollutant distribution. In the case of air pollution, regular grids are used to map pollutant distribution. Each grid cell contains a parameter of the pollutant concentration. To map homogenous objects, which are differentiated from their neighbourhood, vector formats are used for bounding the objects by lines or polygons. The homogeneity is represented by homogenous pollutant concentration fields. Generally, GIS uses three general types of spatial objects which are represented by points, lines and polygons. In the case of air pollution mapping, the point objects are used for air quality measurements collected from monitoring stations, LIDAR measurements of selected pollutants, and point sources of pollution. Line or polygon objects are used to map air pollution from the street network, urban areas and industrial zones. In addition to the traditional GIS two-dimensional layers, 3D objects
or phenomena are shaped by a triangulated irregular network (TIN), which is mostly dedicated to mapping the surface. Other extensions represent 3D models of buildings, vegetation, or bridges. These are mostly used for mapping on local scales. In the case of spatial estimates of air pollution, street canyons need to be mapped with these extensions. The GIS objects can be associated by topological rules, which bring additional possibilities. Thus, the LIDAR data can be related with the surface, the street canyon or the air pollution measurements from the existing monitoring networks [Mitchell, 1999].

2. METHODS OF SPATIAL ESTIMATION

Spatial estimations of air pollution focused on interpolation techniques are accessible in a number of statistical packages. Thus, former GIS projects required export/import tools to include statistical results into the map layers. Recent GISs include a number of extensions that can solve the spatial interpolation, which results in better interoperability and more efficient data management. Among the various methods of geostatistical methods implemented in GIS (ESRI’s ArcGIS-Geostatistical Analyst), two methods have been selected to carry out the spatial interpolation of air pollution: Inverse Distance Weighting (IDW) and ordinary kriging.

2.1 Deterministic methods: IDW

The IDW is mostly used as a preliminary technique for a quick look at interpolated data or if the statistical requirements of geostatistical methods are not accomplished. The method assumes that each known value of the measured physical variable in space has a local influence diminishing with distance. In the case of point measurements of pollutant concentration, it weighs the points closer to the prediction location greater than those farther away. The general formula for prediction of the concentration at the location \( s_0 \) is:

\[
Z(s_0) = \sum_{i=1}^{n} \lambda_i Z(s_i)
\]  

(1)

where \( n \) is the number of the measured sample concentrations \( Z(s_i) \) surrounding the prediction location, and \( \lambda_i \) are the weights assigned to each measured concentration. The weights are based on the power parameter, which can be determined by minimizing the root-mean-square prediction error (RMSPE) [Johnston, 2001]. If there are directional influences on the weighted data, the shape of the neighbourhood can be an ellipse with the major axis parallel to the directional influence. Other setting extensions consist of partitioning the neighbourhood into sectors and limiting the maximum and minimum number of measured concentrations.

2.2 Statistical methods: ordinary kriging

Ordinary kriging represents one of the statistical methods that are based on statistical models that include statistical relationships among measured values of pollutant concentration. In addition to the prediction, some evaluation of accuracy can be also provided over the surface interpolation. Thus, ordinary kriging is used for final interpolations. The ordinary kriging model is described by:

\[
Z(s) = \mu + \varepsilon(s)
\]

(2)

where \( \mu \) is the constant mean for the data with no trends and \( \varepsilon(s) \) are random errors with spatial dependence. The general formula for prediction of the new concentration can be described like in the IDW by the equation (1). But the weights \( \lambda_i \) are calculated from kriging equations [Cressie, 1993]. In case of normally distributed errors, the 95% confidence interval can be calculated for ordinary kriging as:

\[
predictor \pm \sqrt{\text{var}}
\]

(3)

where the square root of the kriging variance is the kriging standard error. Like in the IDW, other parameters can set the neighbourhood to eliminate the directional influence and to limit the number of neighbouring points.

3. METHODS OF DIAL TECHNIQUES

Surface measurements have already become a routine activity in a number of industrialized countries in the framework of national regulations. But, to explore conversion of primary pollutants in the higher layers of the atmosphere, monitoring of air pollution near the ground should be extended with the data from higher layers. In the case of DIALs (Differential Absorption LIDARS), which represent active remote sensing methods, the pulse LIDAR techniques can estimate the distribution of pollutants hundreds of meters above the surface. The DIAL system is characterized by the selective light absorption of different pollutants in the atmosphere. The intensity of laser beams is decreased when passing through polluted areas of the atmosphere. The DIAL system is managed by a rotary periscope that emits the laser beams and receives the backscattered signals. By processing the received signals, two-dimensional vertical and horizontal maps of air pollution distribution can be developed within a few minutes.
The DIAL system used for measurements in the urban area of Prague consists of a mobile LIDAR laboratory, which includes the DIAL LIDAR 510M (Elight Laser Systems GmbH, Germany) and the customary SODAR PA2 (REMTECH, France). In the case of the DIAL mobile system used, the data of the pollutant distribution are organized in “beam files”, which can be transferred into other computer systems. This DIAL mobile system by itself offers just a limited prediction of concentration fields based on the average concentration of neighbour point measurements. Also, the data cannot be integrated together with spatial objects to carry out analysis of air pollution distribution in dependence on the environment of the urban area. Thus, the original pollutant measurements together with their locations along the laser beams are transported into GIS to provide extended spatial analysis.

4. AIR QUALITY INFORMATION SYSTEM

As an example, a part of the Prague information system interface is shown in Figure 1. The graph is extended by two levels of warning signals for regulations and for emergency services (the upper straight lines 180 [µg/m$^3$] and 240 [µg/m$^3$]).

Figure 1. An example of the Internet interface with the selected measurements of O$_3$ [µg/m$^3$] during the last 9 hour period extended by two levels of the warning signals (in Czech language).

The regularly collected air pollution data, emission inventories and deposition measurements in Prague are managed by the information system. The charts and maps, which illustrate the air pollution levels, are mostly processed by spatial analysis in GIS. The spatial interpolations are based on IDW and ordinary kriging. Subsequently, the map algebra can be used to provide the multifactor analysis for the support of decision making processes and risk assessment analysis [Matejicek, 2002, 2005a].

5. CASE STUDIES IN THE URBAN AREAS

The case studies are focused on a few urban areas of Prague with heavy transport, which are monitored by standard systems and by the LIDAR system. The air pollution is influenced mainly by traffic-related sources. The accumulation of air pollutants results in high concentrations of organic and inorganic compounds in the street canyons. In addition to data from the monitoring network and the LIDAR measurements, the GIS projects contain thematic map layers (street network, sources of pollution based on local inventories), which are extended by aerial images, satellite scenes and digital elevation models with buildings and vegetation. The aerial images are used to get more realistic views over the larger urban areas in Prague. At local scales of the street canyons, the map layers are extended by the 3D objects of buildings and vegetation.

5.1 Spatial estimation of air pollution from LIDAR horizontal scans

The 2D interpolations are based on point concentrations along the laser beams. The ArcGIS-Geostatistical Analyst is used for spatial interpolation by ordinary kriging. The LIDAR scans have been captured in three horizontal planes with elevations of 10°, 15° and 20°, Figure 2. Subsequently, the images with O$_3$ distribution can be draped onto the sloping planes in the 3D space. The ArcGIS-ArcScene assists in developing visualization of the interpolated laser scans. The spatial estimate of O$_3$ distribution above the larger urban area is illustrated in Figure 3. In the framework of the GIS project, the surface consists of the aerial image, which is draped onto the digital elevation model. The scene is completed by the map layer that includes the street network. Thus, O$_3$ distribution can be compared together with the potential sources of pollution. The results indicate the dependence of O$_3$ concentrations on urban traffic. The higher concentrations are above main crossroads in the higher layers above the surface. This documents new facts that could not
be explored by the Prague standard monitoring network, which can measure air pollutants just a few meters above the surface.

5.2 Spatial estimation of air pollution from LIDAR vertical scans

The spatial distribution of NO$_2$ in the street canyon and above the urban area is shown in Figure 4. The LIDAR mobile laboratory is located on the opposite side of the valley, which is spanned by the bridge directed into the street canyon. To check the accuracy of the measurements near the bottom of the canyon, reference measurements of NO$_2$ are performed by two Horiba stations located on opposite sides of the street. The 2D interpolations are based on the LIDAR scans, which are oriented vertically. Due to the statistically heterogeneous data structure of the measured NO$_2$ concentrations, the deterministic methods (IDW) are preferred for spatial estimations. Again, the ArcGIS-Geostatistical Analyst is used for spatial interpolation (IDW, ordinary kriging) and ArcGIS-ArcScene supports visualization. The digital model of buildings is used to illustrate the neighbourhood of the images together with the NO$_2$ distribution. In spite of the fact that measurements of the wind speed and direction are included in the reference measurements carried out by the Horiba stations in the street canyon and the SODAR system at the LIDAR mobile laboratory, the turbulent flows caused by the heterogeneous surface rather affect the homogeneity of the NO$_2$ distribution. Therefore, the effects need to be studied more precisely by numeric models or by physical modelling in wind tunnels [Janour, 1999].

5. CONCLUSIONS

Many air pollution studies have employed spatial interpolation methods based on samples from monitoring networks to make spatial prediction maps of air pollution concentrations. Mostly, the studies are based on similar interpolation techniques. These methods use coordinate information of sample points to perform interpolation and kriging’s performance, which is especially dependent on the presence of spatial autocorrelation. But due to the paucity of air quality monitors and their likely poor spatial distribution, the results have not been satisfying. Some studies offer the use of regression based on grid estimates of pollutant precursors [Diem, 2002].

In the case of LIDAR scans, the 3D distribution of pollutants in the layers above the surface can be studied, which offer a new quality in air pollution analysis. The spatial estimations of air pollution by the LIDAR measurements are done to extend standard data sets provided by the monitoring network on the surface of urban areas in Prague. The pollutant distribution in the higher layers is less influenced by the turbulent circulation near the surface. In case of O$_3$, the higher concentrations are approximately indicated above the crossroads and arterial urban streets in the higher layers. In the case of NO$_2$ and vertical scans, there is no clear indication of the distribution in the higher layers. In the street canyon, the higher levels of NO$_2$ seem to be near the major crossroads. The measurements are also more dependent on the heterogeneity of pollutant sources and turbulent circulation in the street canyons.

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6. REFERENCES

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Ord. kriging, elevation 10°, O₃ [µg/m³].

Ord. kriging, elevation 15°, O₃ [µg/m³].

Ord. kriging, elevation 20°, O₃ [µg/m³].

Figure 2. The LIDAR horizontal scans with the images of O₃ [µg/m³] captured above the urban area.
The LIDAR horizontal scans with the images of $O_3 [\mu g/m^3]$ captured above the urban area.

Visualization of two-dimensional images above the urban area (ArcGIS-ArcScene) [Matejicek, 2005b].

**Figure 3.** Processing of the LIDAR data in the environment of GIS.
The mobile LIDAR system on the opposite site of the valley and the bridge directed into the street canyon (the photography on the left side), the street canyon and two reference stations-HORIBA on the left and right side of the street (the photography on the right side).

The location of the LIDAR vertical scans in the 3D space above the midline of the street canyon.

The local part of the street canyon with the LIDAR vertical distribution of NO$_2$ concentrations together with the digital elevation model, buildings and vegetation.

**Figure 4.** The LIDAR vertical scans with the images of NO$_2$ [µg/m$^3$] captured above the street canyon.