Spatial Estimations of Air Pollution in Street Canyons by LIDAR Measurements

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Abstract: Air pollution of urban areas can be explored by direct monitoring, mathematical modeling and physical simulation in the wind tunnels. Complex analysis requires using of all mentioned approaches together. To integrate the data inputs and outputs, which include spatio-temporal interactions, the Geographic Information System (GIS) is used for database management and spatial analysis. The geodatabase is primarily developed to support spatial interpolations of LIDAR measurements in the street canyons. The LIDAR measurements provide the information about the distribution of pollutants in the points along the beam trajectories. As the examples, the sets of NO_2 spatial measurements are performed in the area of the street canyon in Prague. To estimate the levels of concentrations in the neighbor points, deterministic methods (IDW) and geostatistical methods (ordinary kriging) are used in the frame of the GIS projects. The interpolations provide the distribution of pollutant concentrations in the vertical planes, which are used for better understanding of air pollution in the street canyons. In addition to the interpolated pollutant concentrations in the 3D space, the attached GIS layers represent digital terrain models with buildings and vegetation, aerial and satellite images, surrounding sources of pollution and other thematic map layers. The integration of all mentioned data enables to extend our knowledge of the pollutants distribution and consecutively the influence on living environment. The developed projects can be included into more complex approaches, which can help local and state authorities to improve their decision making management and to carry out risk assessment analysis.

Keywords: spatial modelling; GIS; LIDAR; air pollution

1. INTRODUCTION

During the last decades, road traffic has become the dominant source of air pollution in urban areas and industrial zones. In order to minimize the influence of air pollution on living environment, the lager cities started to develop regional monitoring services and information centres. Numerous studies based on systematic monitoring indicate that air pollution together with other environmental factors increases risk for developing cancer and allergy diseases or aggravate the condition of people suffering from heart diseases [Seinfeld, 1989].

Generally, computer based decision support systems are applied in a number of cities. These systems encompass air quality monitoring, emission inventories, air quality modelling, air quality mapping and air quality impact assessment for various control strategies [Elbir, 2004]. In the frame of the geostatistical analysis, spatial interpolation is common practice in a variety of environmental studies. The goal of interpolation is to explore the spatial patterns of pollutant concentrations by estimating values at unsampled locations based on measurements at sample points. The result is a surface map of air pollution concentrations. A number of the maps is typically produced to visualize the spatial distribution of air pollution and to estimate human exposure to pollution. Mostly, the inaccuracy exceeds required limits, because the surface map is based on a small number of spatial observations. One of possible solutions is represented by predictive mapping that involves the integration of geospatial databases, multi-temporal data together with multivariate statistical techniques [Diem, 2002].

In the local scale of street canyons, distribution of pollutants affected by turbulent dispersion and chemical reactions cannot be explored by conventional monitoring stations and data analysis. The advanced solution gives the monitoring by remote sensing detection of atmospheric pollutants, which can also estimate the 3D distribution and together with other techniques transport processes.

Besides the spatial data integration, numerical models can be included into the project to predict the transport of pollutants. The data sharing with other modeling systems or data created by physical modeling [Janour, 1999] can be used through the geodatabase [Matejicek, 2002].

2. METHODS OF DIAL TECHNIQUES

Remote sensing techniques focused on detection of atmospheric pollutants are based on spectroscopic interaction between laser radiation and the atmospheric matter that contains among others particles of air pollutants. Remote sensing techniques can be performed in the passive mode, which uses natural radiation sources, and in the active mode that operates with artificial radiation sources, such as the microwave spectrum (radar systems) or the laser (long-path absorption techniques, LIDARs). In case of DIALs (**DI**fferential **A**bsorption **L**IDARs), which represent the active remote sensing methods, the pulse LIDAR techniques can estimate the distribution of pollutants along the laser beam trajectory. The DIAL system is characterized by a selective light absorption of different pollutants in the atmosphere. The laser light pulses are emitted in two different wavelengths λ_{on} (resonance) and λ_{off} (reference). The wavelength λ_{on} is chosen within an absorption band of the measured air pollutant. Its intensity is being decreased when passing through polluted areas of the atmosphere. The decrease is higher than for the intensity of the laser light with the reference wavelength λ_{off} that is outside of the absorption band. A portion of the laser light covered by both wavelengths, which are scattered by molecules of gases (Rayleigh scattering) and by aerosols (Mie scattering), is returned back to the DIAL system and detected by the high time resolution detector. Consecutively, the pollutant concentration profile along the trajectory of the laser pulses is determined by comparing signal intensities on both wavelengths. The concentration $n(r)$ of the pollutant in the distance r along the trajectory of the laser beams can be computed using the differential equation:

$$n(r) = -\frac{1}{2\Delta\sigma}\left[\frac{d}{dr}\ln\frac{P(r,\lambda_{off})}{P(r,\lambda_{on})}\right],$$

where $\Delta\sigma$ is the difference of absorption cross-sections of the measured pollutant at the wavelengths λ_{on} and λ_{off}. $P(r, \lambda_{on/off})$ is the power of the back-scattered signal at the wavelength $\lambda_{on/off}$. The principle of the LIDAR system based on the DIAL type is in Figure 1. The DIAL system is managed by the rotary periscope that emits the laser beams and receives the backscattered signals from any direction. According to the motion of the rotary periscope, two-dimensional vertical and horizontal maps of air pollution distribution can be developed within few minutes. The estimates of pollutant concentrations in the neighbour of measured point concentrations are mostly created by deterministic methods. But the data can be transported into other computer systems in order to provide more sophisticated interpolations and integration together with other spatial data.

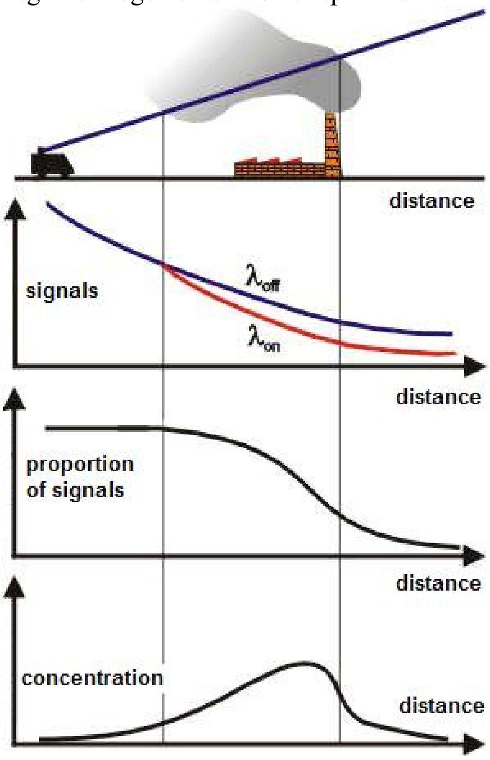


Figure 1. Principle of LIDAR-DIAL systems.

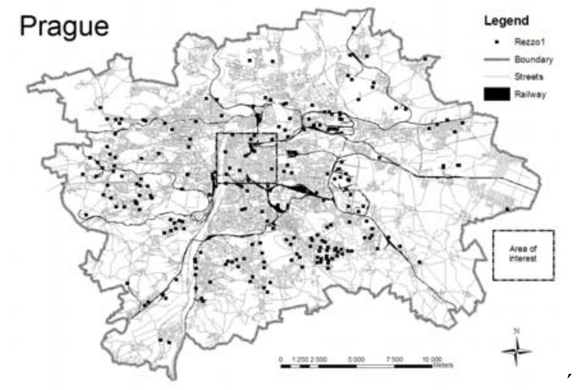
The DIAL system used for measurements in the street canyon is represented by the mobile LIDAR laboratory, which includes the DIAL LIDAR 510M (Elight Laser Systems GmbH, Germany) and the customary SODAR PA2 (REMTECH, France).

3. SPATIAL INTERPOLATION OF THE LIDAR DATA IN GIS ENVIRONMENT

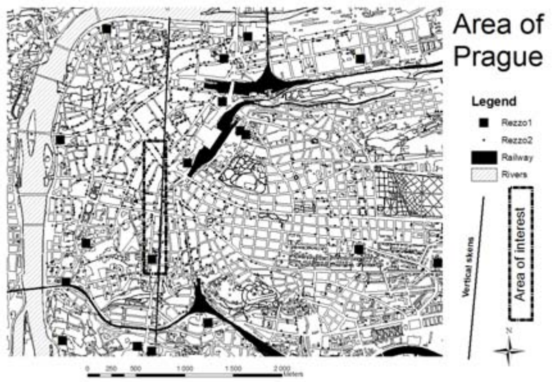
In spite of that many computer programs can solve spatial interpolations, Geographic Information System (GIS) offers more complex environment for geostatistical analysis, which represents just a part of analytical tools for a wide range of its spatial data formats. Generally, the interpolation software tools provide two groups of the interpolation techniques: deterministic and geostatistical. In case of the LIDAR data, the deterministic methods are primarily used for initial calculations. If the data distribution satisfies the requirements of geostatistical methods, the kriging techniques are preferred for interpolation and prediction of pollutant concentrations in the neighbourhood of the measured point concentrations. The deterministic techniques use mathematical functions for spatial interpolation. The geostatistical solutions rely on both statistical and mathematical methods, which can also be used for the uncertainty estimations in addition to the creating of the surfaces. Sometimes the concentrations for the measured locations contain a directional influence (anisotropy) that can be statistically quantified but perhaps cannot be explained by any known identifiable process depending on turbulent flows. The setting of the angle tolerance can modify the selection of points in the semivariograms to improve the final interpolation [Cressie, 1993].
The GIS modules, in addition to providing various interpolation techniques, offer many supporting tools that allow exploring of spatial data by Exploratory Spatial Data Analysis (ESDA), the interactive display of the analysed parameters together with objects in the map layers, calculation of the crosscovariance between spatial datasets, etc. [Johnston, 2001].

3.1 Description of spatial data in GIS

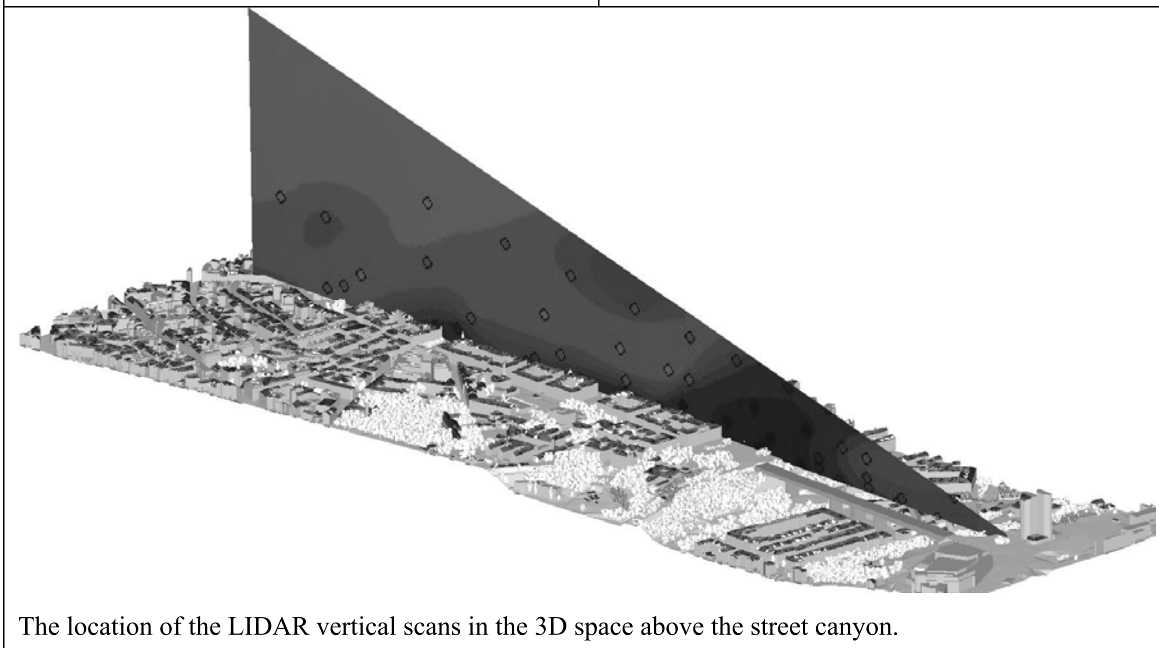
The area of interest is illustrated in Figure 2. Data



The street network in Prague.



The local area of the street canyon.



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

Figure 2. The area of interest represented by neighbourhood of the street canyon and by the vertical scan.

formats used in the presented projects are compatible with the vector formats, raster templates and TINs managed by ESRI-ArcGIS. The 3D spatial models of buildings, bridges and vegetation are compatible with the CAD data formats. The spatial data included in the projects focused on spatial interpolation of the LIDAR measurements are represented by a few groups of the map layers.

The basic data set contains topographical and thematic map layers of the studied area in Prague. These map layers are mostly administered and regularly upgraded by the Institute of Municipal Informatics in Prague. The spatial data are among others focused on the street network, the railway network, the main point sources of air pollution included in the national database (REZZO 1 -extra large and large pollution sources, REZZO 2 – medium-sized pollution sources). The small pollution sources are based on the local municipal development. The mobile pollution sources come out from the density of the municipal transport. They are represented by street sectors as the line pollution sources in the map layers.

The extensions of the basic data set are formed by aerial images, satellite images, digital terrain models of the selected area and 3D models of buildings, bridges and vegetation. In some cases, the CAD systems are used for visualization of more complex 3D data structures.

Other group of the spatial data represents map predictions of air pollution focused on concentration of sulphur dioxide, nitrogen oxides, ozone, organic compounds, heavy metals and suspended particles.

3.2 Description of the LIDAR data in GIS

The particular application of the LIDAR system is focused on the mapping of nitrogen oxides (NO_2) predominantly caused by the car transport in the street canyon. The measurements were carried out in November and December 2001. The point concentrations were located in the vertical scans above the midline of the street canyon (Legerova, Prague). The street represents a part of the arterial road in Prague. During the rush hours, the street canyon with heavy traffic represents the dominant source of air pollution with a rather high concentration of aerosols mostly near the bottom of the canyon. If the concentration of aerosols is higher, the DIAL method cannot be used, because the Mie scattering on aerosols influences more significantly the measurement precision of the nitrogen oxides. In order to minimize the inaccuracy of the DIAL method, the reference measurements of NO_2 were performed by two Horiba stations located in the street canyon with sensors 10 meters above the surface of the street. The measurements were also complemented by information about wind speed and wind direction.

Each LIDAR scan encompassed approximately six laser beams. Each laser beam included from ten to twenty points of the estimated pollutant concentrations. The final spatial interpolation are illustrated in Figure 3 (November, 2001) and in Figure 4 (December, 2001).

4. CONCLUSIONS

In the frame of the LIDAR measurements and GIS spatial modelling, the unique information about the three-dimensional structure of air pollution in the street canyon has been obtained. In addition to the conventional monitoring networks, the pollutant stratification above the street canyon was estimated. In case of NO_2, the concentrations were higher on the low levels. A few clouds with the higher air pollution by NO_2 were identified above the main crossroads.

5. ACKNOWLEDGEMENTS

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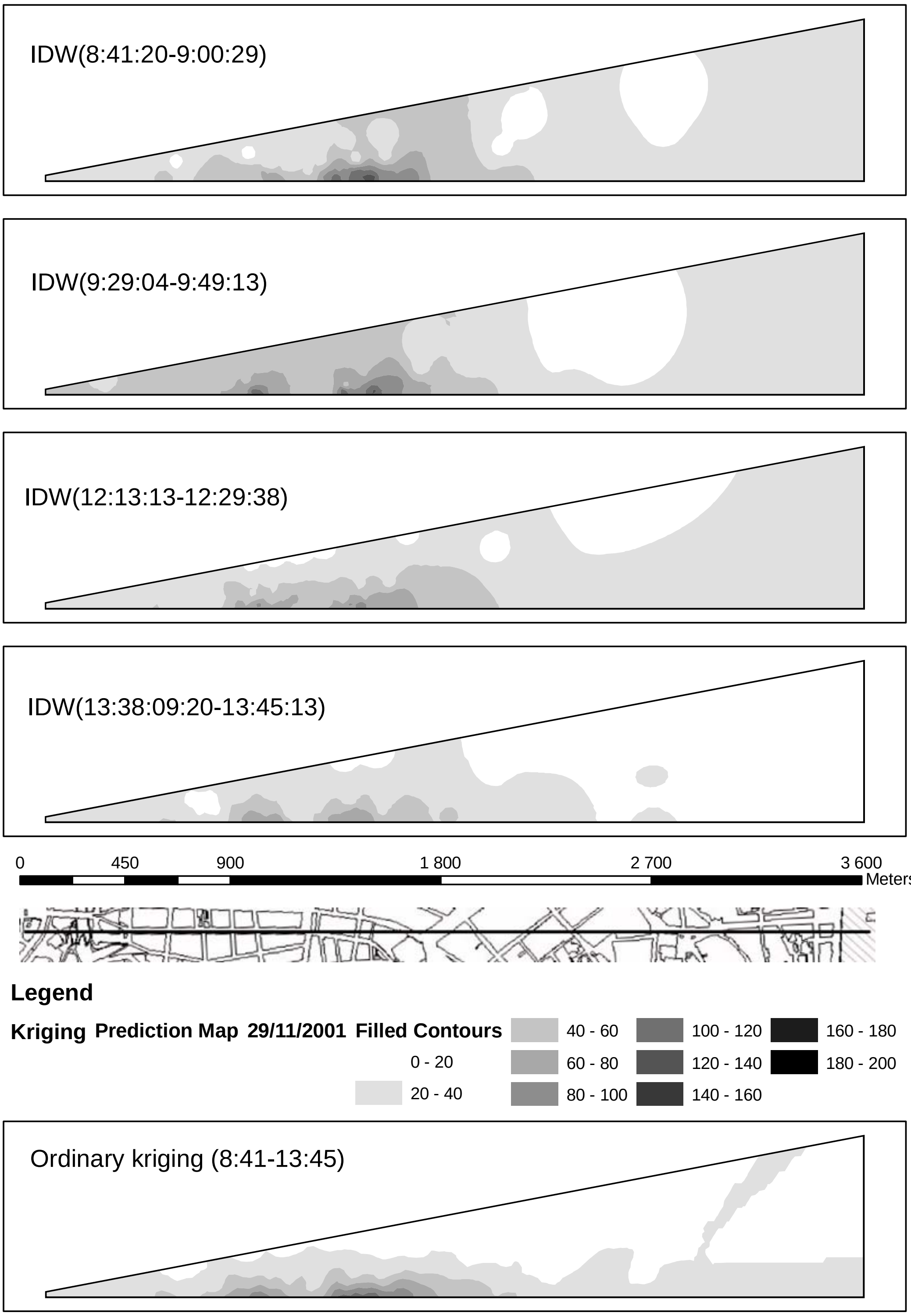

Figure 3. The LIDAR vertical scans with surface maps of NO_2 [µg] captured in November 2001, Prague, the street canyon of Legerova (four scanning seasons interpolated by IDW, one aggregated scanning season containing all previous measurements interpolated by ordinary kriging).

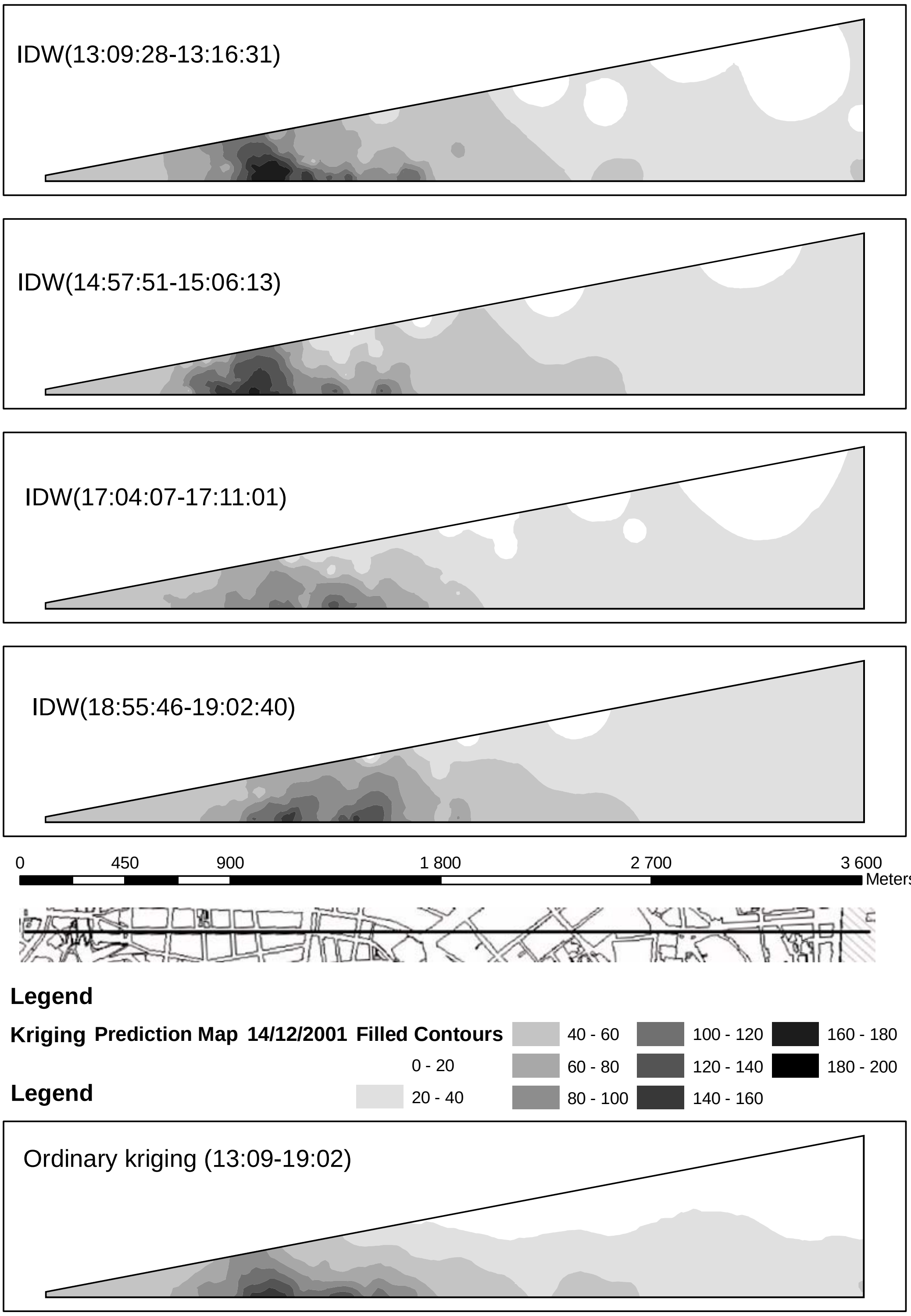

Figure 4. The LIDAR vertical scans with surface maps of NO_2 [µg] captured in December 2001, Prague, the street canyon of Legerova (four scanning seasons interpolated by IDW, one aggregated scanning season containing all previous measurements interpolated by ordinary kriging)