Evaluating radar beam occultation and ground clutter in urban environment using laser scanner data

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1. Introduction

The United Nations expects that today's urban population of 3.2 billion will increase to nearly 5 billion by 2030, resulting in three out of five people living in cities worldwide. The growth of large cities has been rapid over the last half of the 20th century, and this trend seems set to continue to the extent that megacities - defined by the UN as cities with ten million or more inhabitants - have been called the "urban phenomenon of the 21st century "(United Nations, 2012). Rapid, uncontrolled spatial growth and densification create settlements in inappropriate areas most likely to be exposed to natural hazards. Moreover, according to the United Nations, among the 450 urban areas with a population of at least one million in 2011, almost 60% are exposed to the risk of a natural disaster. Heavy rainfall and flash floods are one of the main sources of risk in urban areas. Proper spatial and temporal scales in monitoring rainfall are faced by weather radars. In fact, up to 100-meters resolution quantitative precipitation estimation (QPE) is needed in order to be useful for pluvial flood forecast. Therefore, due to this spatial resolution requirement, weather radar for urban hydrology can not be placed far from the target area.
When the instrument is located within an urbanized area, several partial beam blockages and large return clutter are due to close obstacles like masts and buildings. As demonstrated in several studies - Krajewski et al. (2006), Kucera and Young (2004) and Fornasiero et al. (2006) - accurate radar visibility map can be obtained applying a beam standard propagation model (Doviak and Zrnic, 1984) with high resolution Digital Elevation Model (DEM). Krajewski also showed that, modelling radar visibility using accurate DEM data and Geographic Information System (GIS), the errors iin QPE can be reducted estimating the partial beam blockage. Unfortunately, buildings and infrastructures like masts, powerlines are not represented in DEM data by definition; hence, when the weather radar site is located in heavy urbanized areas, the derived radar visibility estimation tends to be optimistic, missing lage beam blockage caused by obstracles close to the radar antenna.
In the recent years Light Detection and Ranging (LiDAR) technology is proving to be the most promising data source to fill the gap between DEM data and actual surface. Recently evolved to the state-of-the-art technique for topographic data acquisition, Airborne Laser Scanning (ALS) data can provide small footprint diameters (10 - 30 cm), that allows accurate height determination of buildings, infrastructures and forest canopy (Shan and Sampath, 2008).
Analysing the three weather C-band radar located in the metropolitan area of Helsinki, Finland, this study investigates the benefits of using ALS data to quantitative estimations of partial beam blocking and return clutter. Standard propagation model results are compared with actual data to evaluate the effect of partial beam blocking due to man-made obstracles. The analysis is realized using Open Source GIS tools providing physical interpretation of the results.

2. Methods

Since 2005 the Finnish Meteorological Institute (FMI) and Vaisala have established and maintained the high resolution mesoscale network called Helsinki Testbed (`http://testbed.fmi.fi/`). The aim was to develop an internationally recognized platform where scientists could deploy their measurement devices and monitor small-scale weather phenomena (Koskinen et al., 2011). Recently, Helsinki UrBAN (Urban Boundary-layer Atmosphere Network, `http://urban.fmi.fi`) project has started a long-term intensive observational network to study physical processes in the atmosphere above the city (Wood et al., 2013). The network's key purpose is the understanding of the physical processes in the urban boundary layer such as fluxes of heat, momentum, exchanges of water vapour. Helsinki has emerged as the most pole-ward comprehensive urban research observation network in the world. Merging past and ongoing experiences, but moving beyond, *"Helsinki Next Generation Testbed"* will contribute to better understanding on urban areas and their atmosphere interactions by:

- providing better high resolution observations of precipitations, moisture, winds, and energy fluxes, ranging from micro-scale to mesoscale;
- building easy-to-access geo-database of measurements and relevant events;
- developing applications such as numerical models (NWP, nowcasting, air quality, and chemical transport), city planning, or energy use.

The new testbed experience will involve end-users of meteorological data, such as citizens, weather forecasters, researchers, city planners and emergency managers, and, into developing a paradigm for city planning and for meteorological hazards management in urban areas. Starting from results after 8-years operations, this study provides an comprehensive description Helsinki Next Generation Testbed and its highly-dense meteorological urban network and its long-term challenges.
Within this context in Helsinki three polarimetric C-band weather radar operate; their average distance is about 16 km. The Vantaa radar is located close to the international airport and it is operated by FMI; the Kerava radar is located 23 km far from downtown in North direction and it is operated by Vaisala Oyj. Finally the Kumpula radar is managed by the University of Helsinki and it is located in the university campus, few kilometers far from downtown. The antenna pointing accurary for all three radar is 0.1 degrees.
The following table summarizes the weather radar locations and their main characteristics.

Table 1: Main Helsinki weather radar characteristics.

Radar Name	Lon (deg East)	Lat (deg North)	Alt (m a.s.l.)	beamwidth (deg)
Vantaa	24.869	60.270	83	0.98
Kerava	25.114	60.388	59	1.00
Kumpula	24.269	60.204	83	1.05

According to Doviak and Zrnic (1984), the height of the beam h can be estimated by the following equation:

$$h = \sqrt{(r^2 + (k_e a)^2 + 2rk_e asin(\theta)} - k_e a + H_0 \quad (2.1)$$

where r is the distance from the antenna, a the Earth's radius, θ the antenna elevation angle, H_0 the antenna height; k_e depends on the refractive index n, which is function of atmospheric temperature and pressure. Observations demonstrate that the refractive index gradient in the first 2 km of the atmosphere is often constant and inversely proportional to the earth radius: these conditions are usually referred as "standard propagation conditions".
Assuming symmetrical antenna, a common approximation to calculate the integral of the emitted power is to assume a two-dimensional Gaussian illumination function:

$$f(\phi) = exp[-ln2((\phi/\phi_{3dB})^2)] \quad (2.2)$$

ϕ_{3dB} is the 3-dB beamwidth (half-power) along the principal axes, defined to be the angular distance across the main lobe where the power is reduced by one-half of the peak power. ϕ is measured from the point of maximum gain.
Nationwide airborne laser scanning (ALS) has been carried out in several European countries; in Germany large parts of the country has been scanned and the work is going on as federal basis. The benefits of ALS consist in significantly improved accuracy, lower processing costs and higher automation, and, thus, plans of performing national laser scanning are planned in many other countries (Ahokas and Kaartinen, 2013). According to this study, the quality obtained in all various surface types was better than 30 cm. ALS data are derived from an intensive campaign performed on 2008. Data are organized in 3 x 3 km^2 tiles with an average density of about 1.2 points per meter square. Both weather radar sites and ALS have been re-projected in the ETRS89 - ETRS-TM35FIN coordinate system. As the weather radar scan strategy does not allow negative elevation angles, ALS points having height less than radar heigh H_0 have been discarged.
The Figure 1 shows ALS tiles used in the analysis, ALS points considered according to their relative height. The potentiality of using this high resolution ALS data to extimate theoretical partial beam blocking is limited by refractivity of the atmosphere.

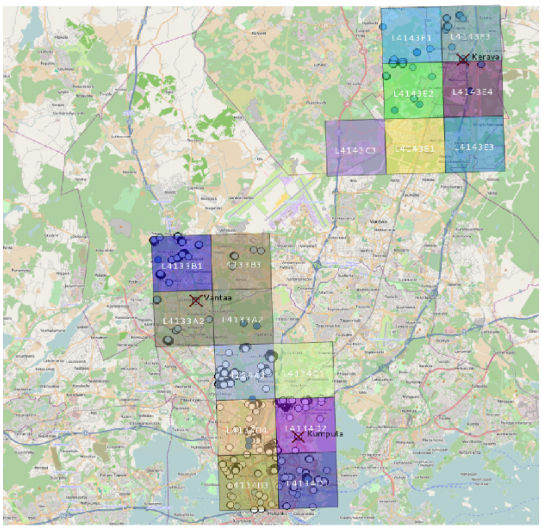

Figure 1: Weather radar position and ALS tiles considered in the study

All remaining ALS data have been checked to remove anomalous and isolated pointsare. Then, They are re-mapped in radar centric coordinates, i.e. distance from the radar and azimuth from North.

3. Results

Applying equations 2.1 and 2.2, antenna beam propagation in standard conditions, the beam propagation has been modelled varyng azimtuh and elevation in the range of 3-dB width by 0.01 degrees step. When the beam height is below the height of the ALS point, beam is considered blocked; the total expected blocking is derived are ratio between weighted un-blocked and blocked part of 3-dB beam. Figure 2 shows are example for Kumpula radar. Residential buildings in Pasila are located 1.4 km far from the radar at 253 degrees and they cause a large beam blocking for the first elevation (0.5 degrees) of the operational scan.

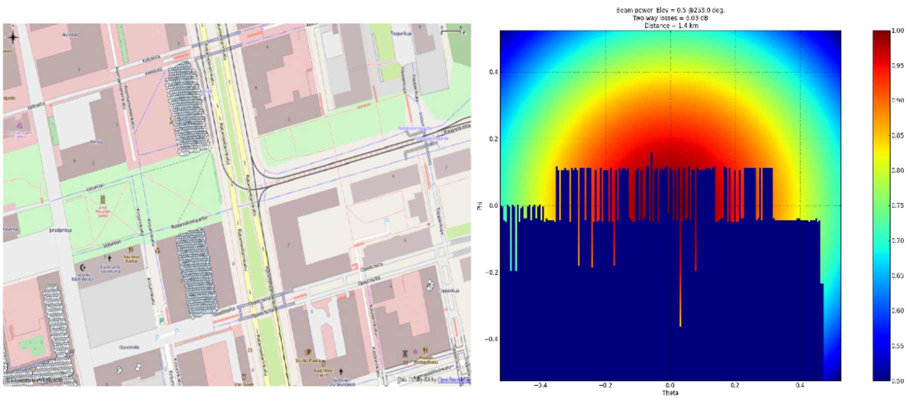

Figure 2: Kumpula radar beam blocking at 0.5 deg caused by 1.4-km far residential building in Pasila. a) GIS representation of building and ALS data; b) Expected partial beam blocking.

Figure 2a shows GIS map of Pasila residential buildings with OpenStreetMap (OSM, `http://www.openstreetmap.org`) layer: superimposed points are ALS data above the Kumpula radar antenna baese. The expected partial beam blocking derived from the model is for 0.5 elevation angle and 1-degree antenna beamwidth is shown in Figure 2b. Consisering 0.1 degrees pointing accuracy, the overall estimated blockage in standard propagation conditions is 6 ± 1.5 dB. The following Figure reports azimth of significant partial beam blockings for all the three weather radar in the Helsinki area.

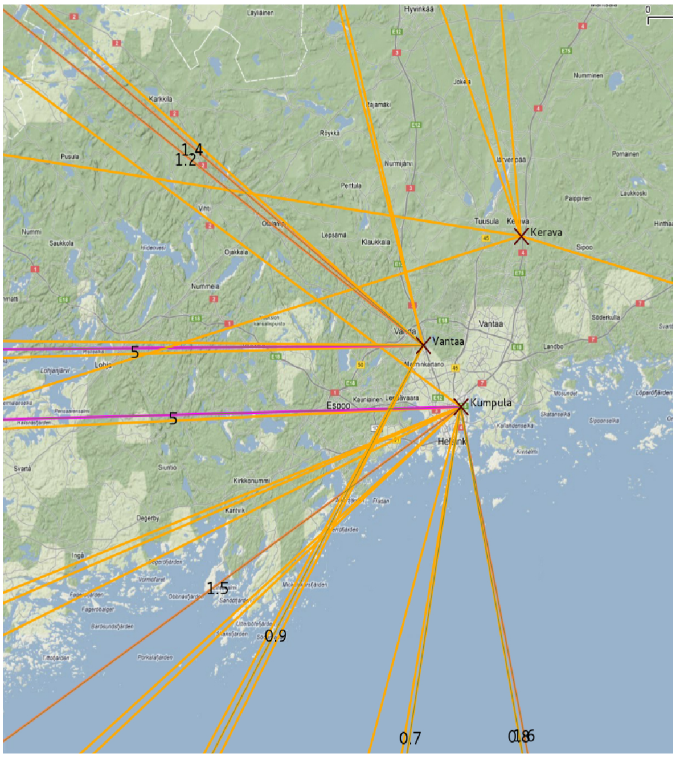

Figure 3: Expected partial beam blocking in dB for Helsinki weather radar. Pink lines represent blockage greater or equal to 5 dB.

Partial beam plocking often occurs for Vantaa and Kumpula radar in Westward direction. The main blockages for these radar are respectevely due to the a water tower (2.1 km far from the antenna) for Vantaa and due to Pasila residential buildings for Kumpula radar. Kerava radar is not affeted by relevant blockage in Helsinki direction. Comparison with 24-hours rainfall accumulation data collected by these radar in stratiform precipitation showed a good agreement between estimated partial beam blockings and rainfall underestimation.

4. Conclusions

In urban environment weather radar visibility methods that use DEM data, even with very high spatial resolution, underestimate partial beam blocking. The recent availability of ALS data over metropolitan areas can overcome this problem. The main uncertainties in this model are due to the actual atmospheric refractivity conditions; in fact, anomalous propagation conditions can lead to large errors. Nevertheless, analyzing Helsinki weather radar testbed, this study has demonstrated that accurate LiDaR data and GIS functionality can locate azimuthal angles where partial beam blockings occur and estimates quantitatively the strength. This results can be used to define the radar scan strategy, optimizing the elevation angles respect to obstacles close to the antenna. Moreover, this new tool can be used to evaluate the impact on weather radar measurements due to new buildings or infrastructures close to the antenna.

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