Making the invisible visible – the DTM modelling in complex environments

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Abstract- **Mapping of forested areas and water bodies was very limited in the past. Access to such areas with traditional survey techniques (total station, GNSS etc.), analogue/digital photogrammetry or radar technologies was very limited because of the dense and multilayer vegetation, very complex topography, swamps, narrow beach and steep cliffs, deep water, etc. Gathered data by survey or remote sensing, were used for generation of digital terrain models (DTM, sometimes with unknown accuracy. Implementation of airborne laser scanning technology (ALS; LiDAR - Light Detection and Ranging) to monitor complex environments which are very hard to see by human eye or other instruments in 3D space - opens new opportunities to identify precisely the vertical and horizontal structures, objects and magnitudes. Use of precision DTM based on ALS point clouds, is now a widely deployed method in many environmental applications including: morphometry analyses, landslide monitoring, geomorphological and hydrological modelling etc. Dense forest crown cover and undergrowth is limiting the penetration of laser beams but now the ground (DTM) can be "seen" very detailed if using high density of ALS data performed with narrow nadir-off angle and using full waveform as well. The bathymetric scanners operating with green light, can penetrate the sea or river water and can be used for bed mapping. Also the terrestrial laser scanning technology (TLS) can be used for 3D point cloud collection and modelling of underground structures (e.g. caves) and later integrated with ALS data to generate continuously surfaces of the DTM and some new "underground DTM's".**

I. Introduction

Forests and water areas are the basic environments presented on maps since the early days of cartography, but because of their high complexity, they are very difficult for detailed and real mapping. The wooded areas, especially those covered by multi-layer evergreen dense tree and shrub vegetation are a challenge for detailed modelling of digital terrain models, because of the lack of the survey data referring to the true ground. The traditional photogrammetry approach and the GNSS survey are very limited due to the dense canopy, undergrowth and multipath signal errors. Water bodies like: sea, lakes or rivers cause serious problems with the measurement of the bottom. Therefore the need of the development on state-of-the-art technologies for precision mapping and 3D modelling of wide-areas still exist. Nowadays various Remote Sensing technologies like: aerial and satellite stereo-photogrammetry, radar and especially the Airborne (ALS) and Terrestrial Laser Scanning (TLS) technology are used for the national-wide, regional and local mapping. The precise DTM models besides their role in: geomorphology, archaeology or landslide monitoring are crucial for the quality of the generation of ALS derived products like normalised Digital Surface Models (nDSM). Those models (called also Crown Height Model) are very important e.g. for: foresters, ecologists and landscape planers. DTM mapping of river and sea bottom using bathymetric scanners can deliver very important information concerning the natural environment and different hazards especially when the integration of multi-source information leads to continuous DTM data. Also the using of TLS and handy scanners opens new possibilities to capture and make 3D models of underground surfaces such as caves or mines that can be integrated with DTM based on ALS and spectral information gathered by airborne cameras.

II. Complex environments: forest and water

A. DTM in wooded areas

Modelling of the ground surface in the forest areas has always been difficult due to the visibility limitations for traditional

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measurement methods such as levelling, total stations or even airborne and terrestrial photogrammetry. Only in clear-cuts, deforested areas, post-fire or areas without tall trees alongside the roads and other logging routes and trails it was possible to establish surveying control lines and refer to them with further, more detailed measurements (mass points, soft and hard break lines, barriers etc). In the forest areas triangulation towers were also constructed as important parts of height measurements networks. Gradually the traditional methods of getting information on digital terrain model (DTM) were supplemented by GNSS techniques, but these, due to the specifics of forest areas (negative influence of dense crown cover, wood biomass on the propagation of signal; multipath errors) they could not provide precise information compared to open areas [1]. The accuracy ($RMSE_{XYZ}$) of marking co-ordinates with GNSS method under the canopy of oak-pine tree stand (age 140 years; H=28m, dense crown cover) ranged between 0.10m (receiver CHC-900) trough 0.28m (Trimble 6000 GeoXR) to as much as 1.94m (TOPCON GRS-1) at RTK observations [2]. The reference control line in this tree stand was marked with a total station series with a very high accuracy referring to the points measured in the open area in a GNSS measurement session lasting many hours (post-processing stations ASG-EUPOS; [3]). The limitations in airborne photogrammetry have existed since its beginning and did not disappear with the appearance of airborne digital cameras or the increase of their resolution (ground, spectral or radiometric). Even in the situation of making photogrammetric measurements in the "leaf-off" season, the airborne pictures of deciduous forests are difficult for the collection of points on the ground and used in generation of DTM. This is because the shadows made by the trunks and branches of trees very negatively influence the perception of the operator of the photogrammetric station or the work of the algorithm responsible for the matching airborne stereo-images [4]. Only in the situations of disasters (deforestation of large areas with removal of all the trees) it was possible to use airborne photogrammetry in precise DTM for a few years, until a young generation of forest covered the ground densely. Some solution in DTM generation for large forest areas, was the application of radar technology (Shuttle Radar Topography Mission - SRTM in 2000), e.g. model DTED-2 (3 arc) or the new global data TanDEM-X and TerraSAR-X. Unfortunately the DTED-2 (SRTM) model in the forested areas often runs above the true ground, which results from the influence of biomass of dense old-growth stands on radar propagation. The studies showed that the errors of DTED-2 model took place in Central European forest areas, sometimes reach to the half of the tree stand height [5]. The Airborne Laser Scanning (ALS) certainly became an innovative technology in the studies of forest environment. This technology was awaited for dozens of years. At first ALS system represented a profiler, which was basically a static laser telemeter put aboard the plane, but with the appearing of technology NAVSTAR-GPS and inertial navigation systems (INS) a technology was made, owing to which ALS point cloud is made, covering large areas in a short time [6]. Forest ecosystem is, however, a very complicated terrestrial ecosystem limiting the penetration of the laser beam during its way to the ground [7]. The registration of subsequent laser returns in a tree stand depends on a very large number of factors. The number of registered returns in the height profile of the tree stand, and first of all these reaching the surface of the ground, results first of all from the type of the tree stand. Almost all the evergreen coniferous tree species during the whole vegetation season, basically do not show large differences between all returns and first returns, or last returns. Thus for the whole year in coniferous tree stands, almost the same density of the number of points reaching the ground while preserving the same scanning density – and in the same way – similar quality of DTM models can be expected. In case of deciduous stands (beech stands - *Fagus sylvatica* L.) covered by ALS flights during the vegetation season (May 2012, Ojcow National Park; OPN; South Poland, Fig. 1) leaves significantly limit the penetration of the laser beam in the relation to the ALS ISOK project flights performed at the end of the growth season (“leaf-off”; 24. Oct. 2012; Fig. 2). The vegetation period, however makes possibility to generate digital surface model (DSM; Fig. 1) of a proper quality, which also does not remain without the meaning for the examined forest ecosystems. Upper layers of canopy have higher number of the individual returns of the laser, which causes the limitation of the echo of the signal on the ground caused sometimes high errors in approximated DTM (Fig. 3; “leaf-on” conditions). About 20-30% laser impulses reaching the ground under forest canopy (“leaf-on”), make good input for DTM modelling when properly choose of ALS point cloud density is done concerning to specific type of relief and vegetation (Fig. 4; “leaf-off” conditions). Often dense undergrowth layer cause that the last ALS returns are registered generally not from the real ground but from surface of vegetation what influence DTM with certain elevation error. A particularly difficult case is dense vegetation occurring on the rocks, which causes problems for the algorithm looking for the lowest LiDAR returns. In this case the problem with the right approximation of DTM appears (Fig. 3) where the rocks (“Krakow Gate”; Fig. 6) are classified as high vegetation (Fig. 5) and are not taken to approximation of the ground surface. The maximum DTM RMSE between the “leaf-off” (Fig. 3) and “leaf-on” (Fig. 4) arrived over 20m in the height even when the point cloud density in vegetation errors was 3 times higher (12 pts/m^2).

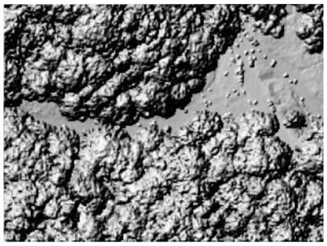

Figure 1. DSM of the “Krakow Gate” in Ojców NP (May 2012; OPN_ALS: 12 pts/m^2).

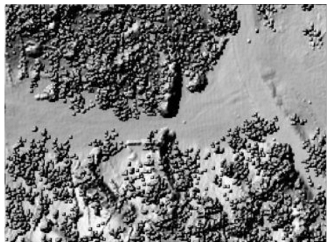

Figure 2. DSM of the “Krakow Gate” in Ojców NP (Oct. 2012; ISOK_ALS 4 pts/m^2).

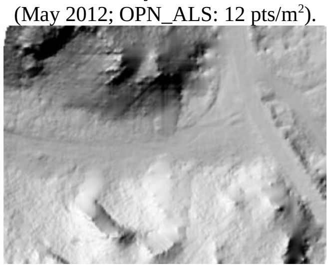

Figure 3. DTM of the “Krakow Gate” in Ojców NP with errors. (May 2012; OPN_ALS: 12 pts/m^2).

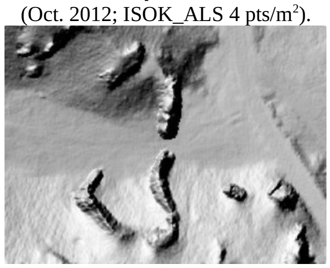

Figure 4. Correct DTM of the “Krakow Gate” in Ojców NP (Oct. 2012; ISOK_ALS 4 pts/m^2).

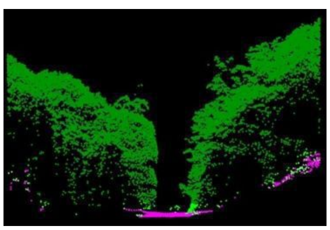

Figure 5. Wrong rock/ground classify-cation. OPN_ALS point cloud (May 2012; 12 pts/m^2).

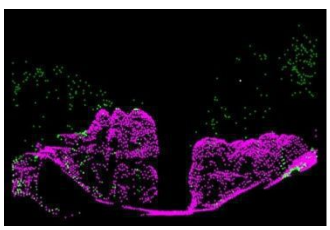

Figure 6 . Cross section through correct classified ISOK_ALS point cloud. (Oct. 2012; 4 pts/m^2).

Other authors in HIGH-SCAN project (point density 10 pts/m^2) reported RMSE in wooded areas on the level between 22 and 40 cm. Also the crown density was a crucial factor influencing the DTM RMSE showing the 14 cm in clear cut areas, 18 cm for lightly thinning forest and 29 cm for uncut old-growth forests [8].

Additionally factors influencing the DTM quality in the wooded areas can be: the lying dead wood, dense crown cover or windthrow areas after the hurricane disaster. It happens that the lying stems due to round shapes of trunks and tree crowns lead to the error in the ground detection algorithm and are counted to the triangles of TIN and as a result to DTM.

Horizontal and vertical crown cover of subsequent forest storeys results from preserving the natural character of the ecosystem (nature reserves) or silviculture treatments applied by the foresters. The crown cover is determined mainly by light requirements of the species and the mutual impact of the trees fighting for the space to live. In the situation of a great defoliation of trees (the fall of the LAI value), which is connected with their health status, the generated DTM are theoretically more accurate, but in some situations the growing access of light to the bottom tree stand causes the appearance of a dense layer of the ground cover or the undergrowth, making it more difficult to model the ground. To generate precise DTM models, ALS technologies in the deciduous stands should be perform in late autumn or winter (if there is no snow cover under trees). Other elements influencing the limitation of the number ALS points reaching the ground and their correct detection are: the nests of birds colonies, mistletoes, lichens, cones, acorns, clusters of fruit (in particular in the years of the abundance of seeds) or the occurrence of trunks and branches broken after hurricanes (microstructure). Single rocks or stones and their clusters can often make problems with generating proper DTM, which first of all results from the systematic approach to the approximated ground, and, on the other hand, make the work of algorithms detecting the ground more difficult, because of the shapes (e.g. round rocks in the river bed). The remaining elements or objects connected with DTM modelling in the forest areas are firmly connected with archaeology and the military remains (soil-made defence constructions: trenches, bunkers, war cemeteries, mass graves, remains after Nazi death camps etc.). It is estimated that in forest areas in Poland there are at least several thousand still undiscovered archaeological sites including: kurgans, hill forts, which are usually the element of DTM modelled from ALS data.

B. *Underground*

Another space invisible for the human eyes, even with the application of ALS are the objects under the surface of the ground or DTM. They can include: caves and cavities after the exploitation of resources (coal, silver, gold, salt etc.). Contemporary technologies of terrestrial laser scanning (TLS) and surveying (total stations + GNSS) not only allow getting full precise information, i.e. 3D cloud of TLS points, but also their integration with the ALS data. Due to this we obtain a continuous surface of „ground” under the real ground, which makes certain problems, even with the professional nomenclature. The example of such ALS integration can be both mobile laser scanning (MLS) or TLS data of underground car parks under the buildings or in rocks, tunnels in the mountains, but also caves (e.g. the “Łokietek Cave” in the Ojców NP). The integration very accurately allows non-invasive volumetric measurements or making profiles and first of all defining in the distances between subsequent galleries or chambers of mines or caves in 3D, including their distance to the real ground. Such a precise information obtained by the integration with ALS in the same system of co-ordinates gives the possibility of not only wonderful visualization for the needs of tourist information or the plans of protective tasks, but also undertaking all the rescue operations by respective services (e.g. making a rescue corridor).

C. The bottom of the water bodies

Until recently the only way to know and visualize the sea bed was the application of sonar technologies. Today there is however an alternative of using airborne laser scanning i.e. so-called bathymetric scanners. They vary technologically in the length of the applied light (green e.g. 532nm like VQ-880-G from RIEGL) from typical topographic scanners used to obtain information of the objects on the ground (close NIR; e.g. 1550 nm like LMS-Q680i from RIEGL). Bathymetric scanners usually are able to penetrate up to the depth of several dozen metres (max. 40-50 m). Of course, many conditions have to be fulfilled, such as: proper water transparency (connected with the suspension, presence of: waves or water foam, algae or plankton or even fish – to allow the laser beam reach the bottom and return to the detector aboard the aircraft or helicopter. Such solution gives wonderful possibilities of generating a continuous DTM runs through bank, cliff [9] and near shore which so far has been rather difficult to verify in the water bodies

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