Modelling light conditions in forests using airborne laser scanning data

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Abstract

The amount of available sunlight in vegetated areas is an important factor influencing species composition, plant morphology and natural succession. It is therefore a significant parameter in forestry, ecology and other sciences dealing with biodiversity relevant studies. Research indicates a strong correlation between the quality and quantity of sunlight and the vegetation structure, both in horizontal and vertical direction. Due to the high complexity and variability of the canopy architecture, continuous area-wide data collection of light conditions in the understorey is needed for accurate modelling of light transmission. However, conventional ground based measurement methods are pointwise and time consuming, therefore not feasible for data acquisition of large areas.

The ability of small-footprint airborne laser scanning (ALS) to penetrate small canopy gaps makes this remote sensing method especially suitable for vegetation studies. Geometric information of the vegetation structure can be derived directly from the 3D point cloud. This allows for modelling of the distribution of sunlight-absorbing or intercepting parts of the foliage, which consequently cast shadows on the surrounding understorey vegetation or the ground. Light transmission through the canopy can therefore be described in a very direct way by employing this 3D structural information.

In this paper a methodology for modelling light conditions in forests using ALS data is proposed. The approach is based on a modified version of photogrammetric monoplotting. The parallel sun rays from variable sun positions act as projection rays being traced through the 3D point cloud (i.e. laser echoes) that represents the canopy. A defined size is assigned to each individual laser echo which casts a shadow of the respective size and shape. Shadowed areas are then derived by intersecting these projection rays with a digital terrain model and by rasterizing the projected point cloud. By employing ALS data from different acquisition times (leaf-on and leaf-off) the influence of vegetation phenology is explored. The derived shadow raster maps describe where a shadow is cast and how many intercepting parts of the canopy contribute to it. Consequently, these maps provide an excelent input for modelling the amount of available sunlight in vegetated areas, considering canopy gaps in arbitrary directions and also the seasonal variability of vegetation. The first results show that ALS is a time- and cost- efficient means for area-wide analysis of sunlight condition for forest floors, as well as for different understorey layers.

Keywords: *LiDAR, light transmission, vegetation structure, monoplotting, vegetation phenology*

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1. Introduction

The amount and quality of available sunlight in vegetated areas is an important factor having critical effects on sub-canopy air temperature, photosynthesis and soil condition (e.g. soil moisture). It therefore influences species composition, plant morphology and natural succession, all of which are significant parameters for biodiversity relevant studies in order to assess, evaluate and monitor the vegetation's current condition. The scattering process and the interaction of sunlight within the foliage are of a highly complex nature, dependent on biophysical and geometrical features of the canopy [*Kimes and Smith*, 1980; *Woolley*, 1971]. It was found that the vertical and horizontal structure of vegetation, as well as the existence and size of canopy gaps have great impact on the distribution of light in vegetated areas [*Canham et al.*, 1990; *Comeau and Heineman*, 2003; *Lieffers et al.*, 1999; *Whitmore et al.*, 1993]. Knowledge about the canopy architecture, meaning the spatial composition of trees or bushes and the arrangement of their branches and leaves or needles, is therefore of critical importance for the modelling of light transmission.

Conventional methods of measuring the photosynthetically active radiation (PAR), describing the visible spectrum of sunlight that is intercepted (IPAR) or transmitted (TPAR) by the vegetation, are ground based (e.g. directly with quantum sensors or indirectly with hemispherical photographs) [*Hardy et al.*, 2004]. These measurements are time consuming, thus not feasible for area wide acquisition and sometimes requiring frequent repetitions due to seasonality effects [*Oshima et al.*, 1997; *Romell et al.*, 2009]. Modern remote sensing techniques provide a time- and cost-efficient way of data acquisition, enabling wide-area analysis of locations otherwise very hard to reach for ground based inventories. Especially small-footprint laser scanning, also referred to as light detection and ranging (LiDAR), is an observation technique well suited for the derivation of geometric information on the canopy architecture. Recent studies have investigated and successfully applied airborne or spaceborne laser scanning data for the determination of light transmission through the canopy [*Jochem et al.*, 2009; *Lee et al.*, 2009; *Parker et al.*, 2001; *Todd et al.*, 2003].

In this paper, a methodology for the modelling of light conditions in forests employing high-density full-waveform airborne laser scanning (ALS) data is proposed. A point cloud based approach is used to predict patterns of direct sunlight and shadow in a deciduous forest depending on the existence and location of canopy gaps in every part of the vegetation stratum. The proposed procedure is capable of deriving maps showing the distribution of shadowed areas for arbitrary sun positions. By analysing ALS data from different acquisition times the influence of vegetation phenology on the light and shadow distribution can be observed.

2. Study area and data set

The study site is located in the federal state of Burgenland in Austria. The area comprises a forest consisting mainly of deciduous trees and bushes of different stages of succession. For the purpose of this study, an area of 150 x 250 m² with loosely distributed vegetation of different height was chosen in order to have unobstructed areas where the results of the modelled vegetation shadows could be visually observed (see Figure 1). The analysed ALS data were acquired during two flight campaigns in 2010, which were kindly provided by the company *RIEGL Laser Measurement Systems GmbH* within the research project *TransEcoNet* [2011]. For the purpose of vegetation phenology studies the same area was scanned twice: in February under leaf-off and in June under leaf-on conditions. The mean point (i.e. echo) density in open areas was 12.5 pts/m², in overgrown areas sometimes twice this amount and more. A digital surface model (DSM) was derived from the first echoes by selection of the highest points within grid cells of 0.5 x 0.5 m². The digital terrain model (DTM) was calculated based on the last

echoes using hierarchic robust filtering [*Briese et al.*, 2002]. Additionally, a normalized DSM (nDSM) was calculated by subtracting the DTM from the DSM. All three models had a grid width of 0.5 m. Based on the DTM the normalized heights of all echoes were derived and only the echoes above 0.25 m were selected as vegetation echoes for the subsequent step of shadow projection.
For the modelling of light conditions also the position of the sun is needed. The MIDC SOLPOS calculator [2011] was employed to compute azimuth and elevation of the sun's location for hourly intervals and the period of a whole year (2010) for the location of the study site.

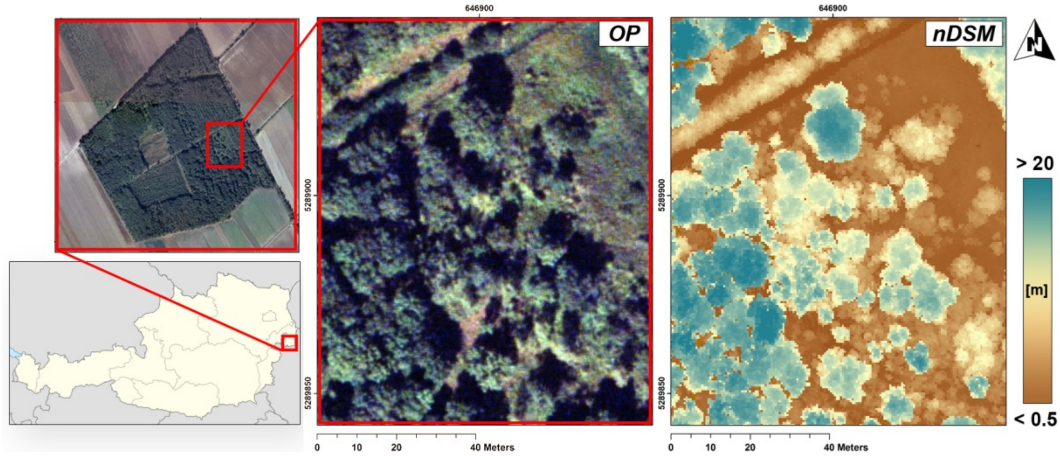

Figure 1: Location and overview of the study area. Central image shows the true-colour orthophoto (OP), the right image the normalized digital surface model based on the leaf-on data (nDSM = DSM - DTM).

3. Method

3.1. Basic concept

The advantage of ALS, as an active measurement system, compared to airborne and spaceborne imagery, is that the laser beams can pass through small gaps in the foliage. It can therefore retrieve information about overgrown smaller vegetation or objects and, in most cases, the laser beams also reach the ground itself. The author's hypothesis is that what is true for laser beams has to apply for sun rays, as well. Every gap the laser can penetrate, also can the sunlight and if the laser beam is intercepted by an object, e.g. a tree trunk or a branch, also is the sunlight. Consequently, a shadow is cast by the intercepting object. If this object is big enough to be covered by the entire footprint of the laser beam (a so-called *extended target*), the total emitted energy contributes to the backscattered signal. However, due to the conical shape of the laser beam, getting wider as it travels through space, it is likely that more than one object is hit with one shot. This is especially true in vegetated areas, where multiple echoes per emitted laser pulse are the norm (so-called *non-extended targets*) [*Wagner*, 2005]. As a result, the emitted energy is shared among the different scatterers. Due to the complex nature of the scattering process in vegetation we do not exactly know to which part each of the scatterers contributes, meaning we do not exactly know what spatial extent the intercepting objects have. This circumstance also influences the casting of shadows according to our hypothesis.
The basic concept is that a sun ray, considered as a projection ray, travels through space, meets a laser point with a defined spatial extent, which is subsequently projected onto the ground represented by a DTM. A shadow in the shape and size of his projection is cast onto the DTM. The definition of the point's size then relates to the before described problem of not knowing the extent of single scatterers. To deal with this fact it is assumed that for the case of an extended target the point size has to be equal to the size of the entire footprint area. The size of

non-extended targets is to be reduced according to the number of echoes in the shot. For example, if the shot produces three echoes, than the respective footprint area is divided by three and the size of the point is only a third, as is the shadowed area correspondingly. Hence, an extended target casts a bigger shadow than a non-extended, which also finds its trivial equivalent in nature: e.g. bigger branches cast wider shadows. Extensions of this straightforward assumption are presented in the outlook at the end of this paper (see section 5). For the task of projecting the laser points onto the DTM we decided to apply a monoplotting approach, which is explained in detail in the following section.

3.2. The monoplotting approach

The term *monoplotting* in photogrammetry refers to the analytical analysis of curved object surfaces using a single orthorectified image (orthophoto). It is based on the methods of projective geometry, considering the orthorectified image as a central projection of the terrain surface. The approach can be described by three main steps: (1) selecting a pixel of the orthophoto, (2) defining the projective ray through the projection centre and the selected pixel and (3) intersecting this ray with the surface model in order to interpolate the 3D surface coordinate [*Kraus*, 2007].

For the purpose of shadow projection in this study this monoplotting concept was utilized, however some adaptions to the usage with ALS data had to be made. The projection centre, analogous to the perspective centre of the lens in photogrammetry, in this case is the sun. Because of the large distance from sun to Earth the projection rays appear nearly parallel, compared to the more conical shape in the standard case. Furthermore, instead of pixels in a digital image, the 3D laser points are used to define the projection rays. They originate from the sun, go through each echo and project it down to the DTM (see Figure 2). According to section 3.1, the size of each projected echo is defined by the number of consecutive echoes resulting from an emitted laser shot and the respective footprint size of the laser beam. Calculated from the beam divergence of 0.5 mrad of the employed laser scanner [*RIEGL*, 2011] and an average flying altitude of 500 m above ground level during this campaign, the diameter of the footprint on horizontal surfaces results in 0.25 m and its area is 0.049 m². Even for the largest trees in the study area (around 21 m), the differences in footprint size due to differences in range are insignificant and therefore ignored. Hence, the same footprint size applies for the calculation of the size of all of the projected echoes.

3.3. Implementation and processing

The monoplotting algorithm was implemented in MATLAB [2011]. As input an ALS point cloud (column-wise in ASCII format including information on echo number) and a DTM (GeoTIFF format), as well as a set of desired sun positions (as described in section 2) for which the projection should be carried out, have to be provided. To be able to observe and discuss the influences of vegetation phenology on the resulting shadowed areas, the leaf-off data set together with the averaged sun positions from February and the leaf-on data set together with the sun positions from June were used. Altogether, the monoplotting had to be done for 10 hourly sun positions in February and for 14 in June. Although SOLPOS returns positions before dawn and after dusk, only azimuths between sunrise and sunset and above 10° of elevation were considered.

The desired accuracy of the interpolation can also be defined as an additional input parameter. For the current study it was set to 0.25 m, which is half the grid width of the DTM. The result of the MATLAB processing is one file for each sun position containing the 3D coordinates of the projected points (x,y,z_{DTM}) and their assigned sizes in m² in a four column ASCII format.

Subsequently, the ASCII files were imported into GRASS GIS [2011] using the module *r.in.xyz*, creating raster data sets with 0.5 m grid size where all the projected point sizes within one grid cell were accumulated. To reduce salt and pepper effects the resulting raster maps were smoothed with a mode filter using the module *r.neighbors* and a square kernel with a size of 3 x 3 pixels. Finally, the georeferenced shadow raster maps were exported with the module *r.out.gdal* to GeoTIFF format and visualized (see Figure 3 and Figure 4).

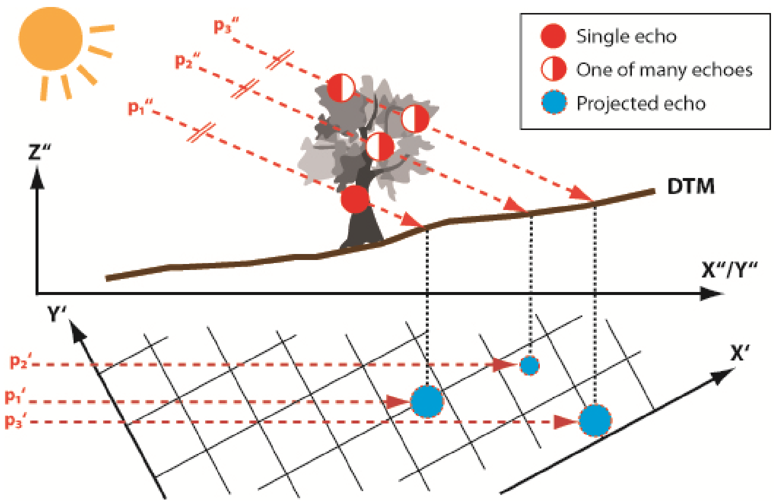

Figure 2: Schematic depiction of the proposed monoplotting approach in horizontal (X'/Y') and upright projection (X''/Y''). Parallel sun (projection) rays $p_{1,2,3}$ projecting the ALS points onto the DTM, casting shadows of different size according to the number of echoes within the respective laser shot.

4. Results and discussion

For leaf-on and for leaf-off conditions the shadows were computed for the months February and June, respectively. Figure 3 and Figure 4 each show three examples of the resulting shadow raster maps at three times of day. The informative value of the proposed methodology had to be verified visually, as no reference measurements, e.g. with a quantum sensor, lux meter or a similar instrument, were at hand. The maximum sun elevation angle calculated with SOLPOS for February was roughly 30°, which was around noon. At all other times of day, the sun irradiates in rather flat elevations angles, therefore creating very long shadows, especially for high trees. This can be seen in Figure 3a and c correspondingly, were the high tree in the centre of the image (red number 1) casts his shadow far away (marked as red ellipse), whereas the lower ones cast shorter shadows (compare tree heights in Figure 1). In June the sun elevation angles are steeper, therefore the shadows are generally shorter. This is true for the results shown in Figure 4, where the shadowed areas are smaller and at all times nearer to the shading object. It can also be observed that the differences in acquisition time influenced the result. In Figure 4 the shadows appear generally darker than in Figure 3, meaning that more or "bigger" echoes contributed to the respective shadowed area on the ground. Also Figure 4 creates the impression as if the tree tops cast the darker shadows. The obvious explanation is the fact that during leaf-on conditions the majority of laser echoes come from the top canopy, whereas during leaf-off conditions more penetration takes place and the echoes are more equally distributed over all height levels. For the present study area, 38 % of the vegetation echoes from the leaf-off data set were located above the 80th height percentile, while for the leaf-on data this number increased to 65 %. The sensitivity to the different input data sets suggests that the proposed method could be used for a seasonality dependent modelling of light conditions, thus considering the vegetation phenology in a functional relationship.

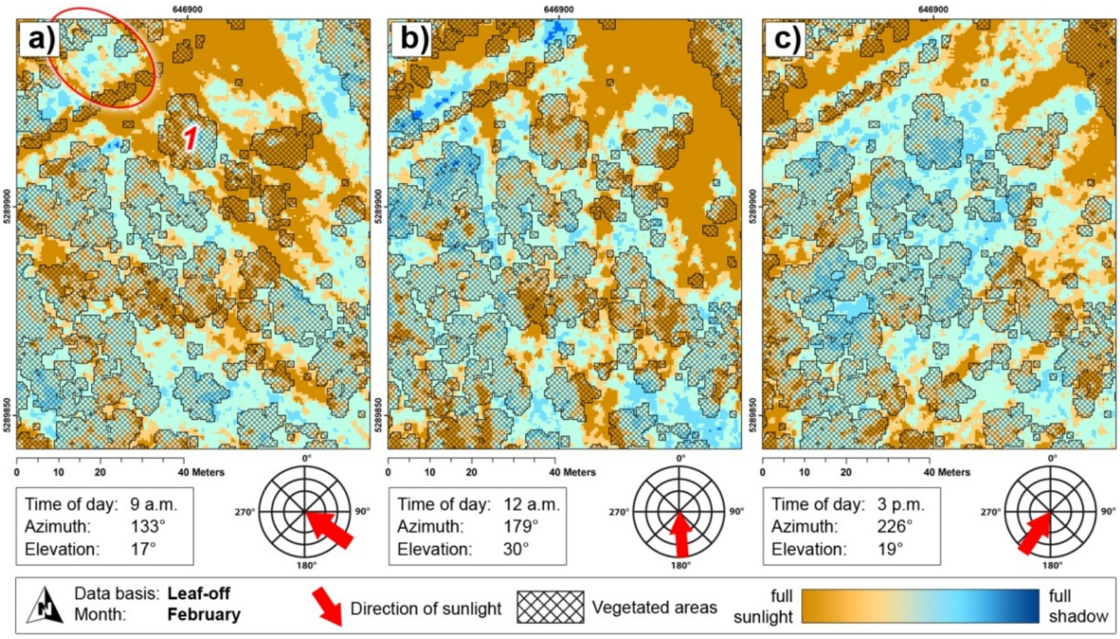

Figure 3: Shadow raster maps based on the leaf-off data (selected vegetation echoes only) and the averaged sun positions from February. Yellow means no shadow is cast, blue means the area is shadowed. The darker the blue, the more or "bigger" echoes contribute to the shadow.

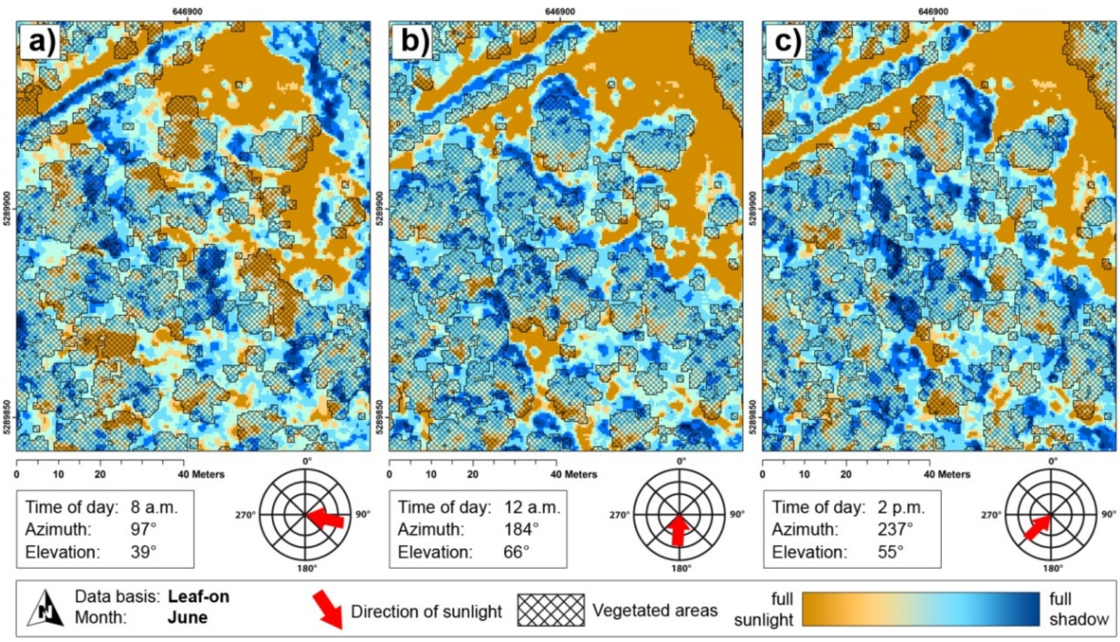

Figure 4: Shadow raster maps based on the leaf-on data (selected vegetation echoes only) and the averaged sun positions from June. The cast shadows are generally darker compared to Figure 3 due to the more dense distribution of the laser echoes in the tree crowns in the summer flight.

The proposed algorithm of shadow projection bears analogies to ray tracing, which was invented in 3D computer graphics for visible surface determination [*Agoston*, 2005]. As well as ray tracing, monoplotting is a computationally extensive procedure, especially as it was applied in this study for the 3D ALS point cloud. Therefore, the runtime of the MATLAB program with respect to the different employed data sets shall be noted. The leaf-off data consisted of 242595 echoes and the computation of the shadow raster maps took between 2.5 and 3.5 minutes for a single sun position. For the leaf-on data with 361119 echoes computing times ranged from 3.5 to 5 minutes. The differences in processing time within one data set resulted from the fact that the interpolation step, as it is currently implemented, tends to converge slower with shallow sun elevation angles. To speed up computation, binary input and output could be employed, which would speed up the I/O tasks in MATLAB significantly.

5. Conclusions and outlook

Methods for sunlight and shadow prediction have to consider the fact that shadows cast in overgrown areas are not continuous and of the same intensity or darkness. We applied a point cloud (i.e. vegetation echoes) based method which solves this task effectively and, as shown in the resulting shadow raster maps, quite successfully. The simplified assumption of the projected point sizes being dependent on the number of consecutive echoes in a laser shot (see section 3.1) can be further extended to better reproduce the natural conditions. According to Wagner et al. [2006] the backscattering cross-section, a measure which can be derived from full-waveform ALS data during the task of data calibration, can be referred to as the effective area of collision of the laser beam and an object. Therefore, the cross-section can be employed in order to derive the point size according to the proposed method, representing a much more adequate depiction of the intercepted area of the laser beam. Due to the currently used method of creating the raster maps (accumulating all the projected point sizes within a grid cell; see section 3.3), strongly inclined parts of the DTM would accumulate more points and thus produce darker shadows. This is also the fact for strongly varying point densities in case of heterogeneously distributed scan lines or strip overlaps. Inclined surfaces could be compensated by the introduction of the surface slope and aspect to the algorithm. Varying point densities may be considered by normalisation of the shadow values using a point density map. Furthermore, the topographic shadows, which are currently not considered, could be integrated by applying a line of sight analysis on the DTM. In this way, parts of the surface which are shadowed by others can be found. The total cast shadow then has to be the sum of the topographic and the vegetation shadow. However, these limitations are not significant for the presented study site, as the area is rather flat with low relief energy. On the other hand, the usage of a surface model as projection surface opens up interesting opportunities for the modelling of light conditions in different vegetation strata. A DSM comprising the herbaceous or shrub layer could be created based on selected laser echoes from the respective height levels. Consequently, the light situations in these different parts of the vertical structure could be examined, which provide valuable input for various biodiversity analyses.

Acknowledgements

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