Planimetric and height accuracy of airborne laserscanner data: User requirements and system performance

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ABSTRACT

Motivated by the primary use for the generation of digital terrain models with a point spacing of a few meters, the precision of airborne laserscanner data has often been specified solely as a height precision. Recent developments in data acquisition systems, however, have caused a strong increase of the point density of airborne laserscanner data. At the same time, the technique is increasingly being used for new applications fields in the generation of 3D GIS information from high density point data. In these applications based on high density datasets, height and planimetric accuracy of the data points are of equal importance.

The analysis of laserscanner system components as well as practical tests indicate, that the height precision of airborne laserscanner data is usually significantly better than the planimetric precision. While the height precision of a single ground point is often in the order of 10-15 cm, an almost linear dependence of planimetric precision on flying height above ground can be stated, with a typical precision in the order of 0.5-1.0 meter at a flying height of 1000 meter above ground. Both height and planimetry precision are affected by significant systematic effects, which are often larger than the stochastic errors.

1. INTRODUCTION

Airborne laserscanning (or 'lidar') has widely replaced stereo-photogrammetric approaches in the task of digital terrain model generation. The major reasons for this fact are the efficiency of the technique, the high precision and reliability potential and the capability of partly penetrating vegetation and thus delivering elevation data also in forest areas. The high reliability is accounted for by the character of an active measurement technique, which does not suffer from matching errors like automatic stereo-photogrammetric approaches. In addition to these 'classical' applications, airborne laserscanning has proven to be a valuable data source for automatic 3D GIS information extraction tasks such as 3D building model generation or corridor mapping.

Many theoretical considerations and practical tests have shown the high accuracy potential of airborne laserscanning. In the following, the accuracy potential of airborne laserscanning will be reviewed, consequently treating not only height, but also planimetric accuracy of data points and derived objects. After a discussion of individual error sources and their propagation into surface point precision, results of some practical tests will be discussed.

2. REQUIREMENTS TO HEIGHT AND PLANIMETRIC ACCURACY

Airborne laserscanning was introduced as a commercially available measurement technique in the early/mid nineties. In the beginning, the precision of laserscanner point data was solely specified as a height precision. Data providers often specified 10-20 cm, which was considered sufficient by most users. A better height precision, although desirable for some applications, seems unrealistic for most natural surfaces for the following two reasons:

- Early systems offered data rates of 2-10 kHz, leading to datasets with a point spacing of typically 3-4 meter. At this point spacing, the terrain representation error caused by sub-sampling will be larger than the actual measurement error for most terrain types.
- The laser ground spot diameter is typically in the order of 25 cm at a flying height of 1000 meter. In regions with significant terrain surface roughness, there will be a height amplitude of several centimeters within the spot.

Figures on the planimetric precision of laserscanner data points generated by early systems were known, but usually neglected, although in most systems the planimetric precision of laserscanner data is significantly worse the height precision. This reduction of the precision measure of laserscanner ground points (with three-dimensional coordinates) to only height precision was justified by two reasons:

- As the technique was mainly applied for the generation of digital terrain models over areas with limited terrain slope, planimetric errors of several decimeters were not very relevant in datasets with a point spacing of a few meters.
- Many users of laserscanner data prefer to work on digital terrain models in a regular grid (height image), obtained from irregularly distributed raw data points by interpolation and filtering. In this case, the character of raster data gives reason for the specification of only a height precision.

Nevertheless, with recent advances in laserscanner system performance and with new application fields of the technique, the interest in the planimetric accuracy of laserscanner point data is growing. Modern laserscanner systems offer data rates of 58-83 kHz, leading to datasets with a point density of one point per square meter or beyond. With these point densities, airborne laserscanner data is becoming increasingly relevant for 3D GIS information generation tasks such as 3D building model generation (e.g. Haala/Brenner, 1997, Maas/Vosselman, 1999). The position and shape parameters describing buildings or other 3D GIS objects will generally include all three coordinate directions rather than only height. It has for example been shown by (Maas, 1999), that 3D building model parameters can be obtained at a precision of 10-20 cm from high resolution airborne laserscanner data. Although these figures cannot be generalized, they define a requirement to the accuracy of laserscanner data, with planimetric accuracy being of the same relevance as height accuracy.

3. ERROR SOURCES

The major error sources influencing the accuracy of airborne laserscanner point data are the laserscanner instrument itself, the position and orientation determination system, the alignment between these two subsystems and possibly human errors in data handling and transformation.

- The precision of laserscanner slant distance measurement is primarily determined by the precision of time-of-flight measurement (most instruments) or signal phase measurement. In addition, distance measurement may be influenced significantly by the type of local ground coverage and the terrain slope (Kraus/Pfeifer, 1998). With most systems operating at narrow opening angles, errors in distance measurement propagate mainly into the height coordinate. The error budget of the scanning mirror device is described by the angular resolution and may also be influenced by mechanical problems such as vibrations or oscillations caused e.g. by interference with the aircraft engine. These errors will mainly propagate into the across-track planimetric coordinate.
- The position of the aircraft and the sensor is determined by differential GPS techniques. Depending on the GPS satellite configuration, the error of the GPS height coordinate will usually be larger than the error of the planimetric coordinates. An INS system integrated with the GPS system is used to interpolate and possibly smoothen the 3D trajectory and to determine the platform orientation parameters. Random errors or uncompensated drifts of the INS system will primarily lead to errors in the roll, pitch and yaw angles, which mainly influence the planimetric coordinates.
- Alignment errors between laserscanner instrument, aircraft body and GPS/INS system components as well as synchronization errors will cause systematic offset and tilt effects in data strips. Every data provider applies calibration schemes to determine these alignment errors and to correct for them. Nevertheless, remaining errors not revealed by the calibration process will cause systematic shifts or rotations of the data strips.
- Errors in the transformation to local coordinate systems may be caused by errors in reference points or by human error.

While errors in slant distance measurement are primarily of stochastic nature, errors introduced by the position and orientation determination sub-system cause systematic deformations of laserscanner data strips. These systematic effects may be of local nature, but may also cause constant shifts (e.g. as a consequence of GPS cycle slips), tilts or torsions of whole strips (Crombaghs et al., 2000). Generally, position determination errors cause ground point coordinate offsets, which are independent on flying height, while the effects of orientation parameter errors will increase linearly with flying height. Their effect will also differ between strip center and strip edges. The slant distance measurement precision will show a weak distance-dependence, while angular errors of the scanning mirror will propagate linearly into ground coordinates. As a consequence, the horizontal ground point coordinate precision will show an almost linear dependence on flying height, while the vertical ground point coordinate precision will be much less flying height dependent.

4. TRANSLATION OF SYSTEM PRECISION SPECIFICATIONS INTO GROUND POINTS

In the following, precision specifications provided by system manufacturers will be briefly outlined and translated into ground point precision in planimetry and height.

Optech as the world's largest manufacturer of airborne laserscanner systems specifies a height precision of 15 cm (1 sigma) for their ALTM system. This figure is also widely being used by laserscanning service providers and data distribution centers. The range accuracy of single shot laser slant distance measurement is specified with only 2-3 cm, with the rest of the height error contributed by the pose determination system and the scanning mechanism. The horizontal precision of the ALTM system is specified to 1/2000 of the flying height above ground. This translates to 1,50 m at the maximum operation height of 3000 meter or 50 cm at a flying height of 1000 meter, which is more realistic for projects with point density requirements in the order of one point per square meter as demanded by most applications with requirements to planimetric accuracy.

Applanix as a major manufacturer of GPS/INS position and orientation determination systems specifies the following parameters for their POS AV system after post-processing: 5-10 cm for sensor positioning, 0.005° for pitch and roll, 0.008° for heading. Due to the geometric constellation of GPS satellites, the major component of the platform positioning error is in height direction. This effect propagates directly into ground point coordinates. At a flying height of 1000 m, the orientation errors translate into planimetric errors of 10-15 cm for each of the three angles. The effect of the orientation errors on the height coordinates depends on the opening angle of the laserscanner system. With the opening angle being ≤20° in most systems, the effect is only about 3 cm at the strip boundaries. Adding these effects, one may expect an error of approximately 10-15 cm for all three ground point coordinates from the pose determination sub-system at a typical flying height of 1000 meter above ground.

TopoSys operates a laserscanner system which avoids scanning mirror error effects by a fix glass fiber system. They specify a planimetry precision of better than 0.5 meter, with the option of sacrificing planimetric accuracy for representation accuracy by e.g. choosing the lowest point in a mesh in digital terrain model generation applications (Katzenbeisser, 2003).

Disregarding the effects of the position and orientation determination sub-system, the accuracy characteristics of airborne laserscanning are different from conventional stereo-photogrammetric object point coordinate determination in the sense that laserscanning generally offers better height precision than planimetry precision, while airborne stereo-photogrammetry will - depending on the opening angle or the base-height ratio - usually produce a height precision, which is by factor 1.5-3 worse than planimetry precision. As a consequence, airborne laserscanning poses higher requirements to the platform height determination. This is in contradiction with the precision characteristics of GPS, but - assuming narrow scanner opening angles - in accordance with the precision characteristics of INS. In this sense, the requirements to the direct georeferencing system differ partly from the situation in photogrammetry. See e.g. (Cramer, 2001) for a detailed analysis of the potential of direct georeferencing in photogrammetry.

5. RESULTS FROM PRACTICAL TESTS

In the following, the results of a few practical tests are shown and discussed. Even though these tests are based on a limited number of datasets and do not represent all laserscanner systems, they show some interesting phenomena and depict a useful contribution in the verification of the considerations outlined in chapter 3 and 4.

Practical statements on laserscanner point coordinate precision can either be based on ground control points introduced as check points or on discrepancies between data in the overlap area of neighbouring or crossing strips. Like in conventional photogrammetry, the measurement of a large number of check points (e.g. by GPS or stereo-photogrammetry) is connected with a large effort, while a rather dense pattern of tie point discrepancies in strip overlap regions can be obtained semi-automatically or automatically from the actual data.

Height accuracy

The Netherlands were the first country to generate a nation-wide digital terrain model by airborne laserscanning. In the preparation phase of this project, a large number of practical tests were performed to verify the height accuracy of the data by ground control. As the individual laserscanner data point cannot be recognized in the terrain, flat regions such as parking lots or soccer fields (with their height determined by GPS) were used as ground control. In (Huising and Gomes Pereira, 1998), a height precision in the order of 15 cm is reported.

(Crombaghs et al., 2000) use ground control and semi-automatically measured height discrepancies in a relatively sparse distribution along the overlapping region between neighbouring data strips as input for a laserscanner strip adjustment scheme. Their results show strip height discrepancies of up to 15 cm, with an RMS of 7 cm; it has to be noted that these figures are derived from planar patches containing some 100 points, thus largely eliminating stochastic errors.

(Burman, 2002) also uses height discrepancies in strip overlap regions as input to a strip adjustment scheme, assuming a linear strip error model with three shifts and three rotations per strip. Vertical strip errors of up to 9 cm are reported.

(Maas, 2002) shows height differences in the overlap regions neighbouring strips in a rather dense pattern, with the distance between patches being smaller than the distance between successive dGPS aircraft position measurements. Height discrepancies are measured automatically by a least squares matching approach including robust estimation techniques. The results show height discrepancies of 10-20 cm in the overlap regions (Figure 1). Although there is a recognizable trend in some cases, rather strong local deviations from linearity along flight direction can be seen. This can probably be explained by the dominating effect of limited dGPS height precision. As a consequence, a linear strip deformation model, which is assumed by several authors, seems at least questionable.

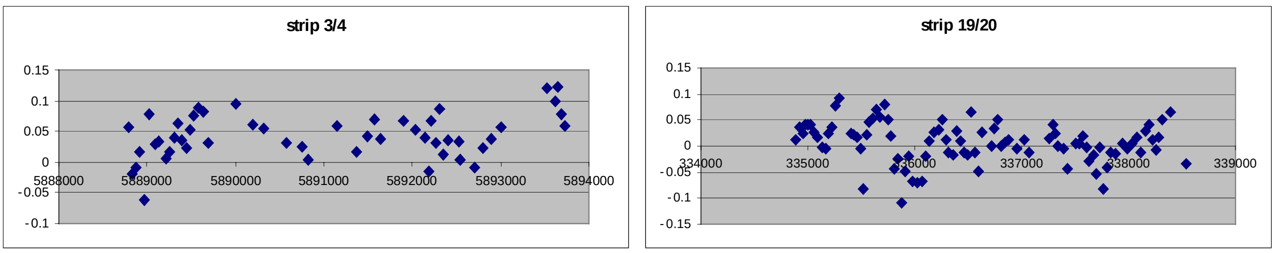

Figure 1: Height differences in strip overlap regions over 4-5 km strip length (Maas, 2002)

Figure 2 shows a zoom into Figure 1, where height discrepancy measurements are performed at distance intervals of about 5 meter, while the distance between successive dGPS aircraft position measurements was about 50 meter. The local smoothness of the discrepancy curve indicates a dominating influence of local dGPS aircraft height determination on the results.

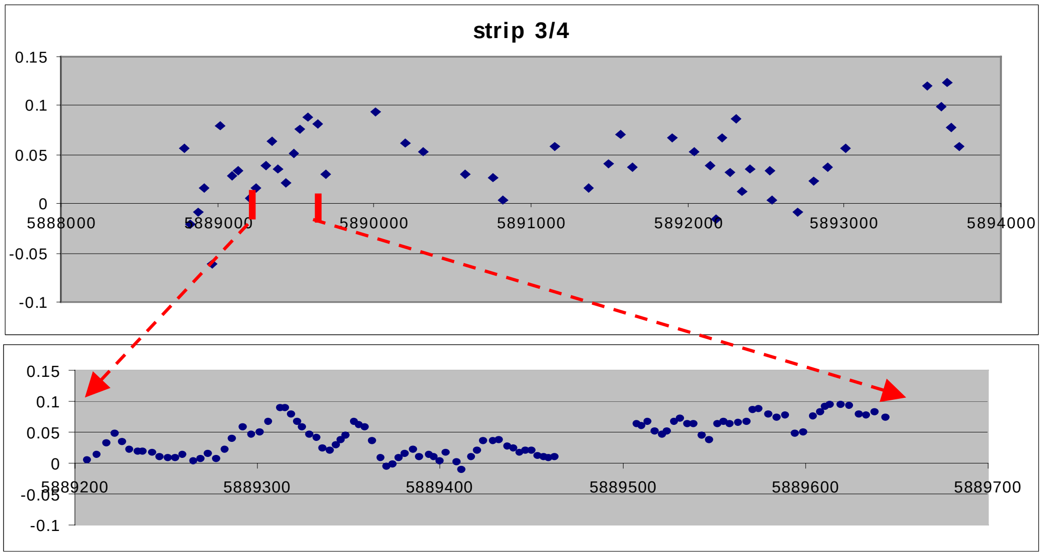

Figure 2: Height discrepancies between neighboring strips in [m]: Top: section of 5km (top), zoomed section of 450m (bottom)

These strip discrepancies are usually based on planar patches of a pre-defined size, containing multiple laserscanner points. Several publications address the local precision of a single laserscanner height measurement, unaffected by pose determination errors: (van der Wolk, 2000) reports a value of 4 cm for the nugget obtained from the covariance functions in a variogram analysis approach. (Maas, 2002) obtains a single point height standard deviation of 3-4 cm as standard deviation of unit weight in least squares matching applied to plane laserscanner data patches. These figures were obtained in data of flat terrain. (Kraus/Pfeifer, 1998) reveal a significant dependence of height precision on terrain slope, which is possibly caused by orientation errors and the poorly defined reflection of laser pulses with a finite spot size on tilted non-planar surfaces. The discrepancy between these figures on single shot precision and precision measures derived from ground control or redundant data indicates that, at least over flat terrain, the systematic errors in height data are larger than the stochastic errors. As a consequence, accuracy measures for objects obtained from multiple data points, which are simply derived by error propagation schemes based on the assumption of Gaussian distribution (e.g. Crombaghs et al., 2000), will usually be much too optimistic.

Planimetric accuracy

Like with height accuracy, measurements for the verification of planimetric accuracy can be provided by ground control or by discrepancies in redundant data. Generally, terrain surface changes are required to enable ground control check. As an alternative, laser pulse intensity information (generating a reflectance image) may be used in regions of poor height contrast (Maas, 2001).

A principal limitation in the selection and measurement of ground control for planimetric accuracy verification is posed by the undersampling characteristics of airborne laserscanner data, with the point spacing usually being significantly larger than the laser ground spot diameter. Suitable ground control will often be given by roof corners of buildings. Some data providers try to hit the antenna of their dGPS base station by a laser pulse in order to provide planimetric reference - a technique which will only work at rather high sampling rates.

(Kilian, 1994) and (Behan, 2000) use least squares matching, applied to laserscanner height data interpolated to a regular grid, to determine planimetric offsets between neighbouring data strips. While the advantage of this technique is the possibility of adapting existing software implementations, it can be shown that interpolation effects in regions with height discontinuities (e.g. tilted planes interpolated into the occlusion regions behind buildings) will cause large systematic errors in the strip offset determination (Maas, 2000).

As an option to solve for this deficiency, (Maas, 2000) shows an implementation of least squares matching to laserscanner point data in a TIN structure for the determination of three-dimensional geometric discrepancies between neighbouring strips. The technique yields a measurement precision in the order of $^{1}/_{10}$ - $^{1}/_{20}$ of the average point spacing in regions with suitable height contrast. Applied to a dataset with overlapping and crossing strips at a flying altitude of 500 m, planimetric shifts of up to 65 cm were detected. (Vosselman/Maas, 2001) report an RMS precision of 49/41/12 cm in X/Y/Z for the same dataset. As an extension of the technique, (Maas, 2001) describes the use of reflectance data (laser pulse intensity image, also in a TIN structure) replacing surface height texture in the determination of planimetric strip offsets in flat regions with sufficient surface reflectance texture.

(Burman, 2002) reports across-track coordinate discrepancies of up to 70 cm from a dataset acquired from a flying height of 700 meter above ground, derived from height difference measurements only.

Generally, defining ground control or tie points which are suitable for the determination of planimetric strip discrepancies turns out to be more difficult than defining height control. (Maas, 2000) shows that significant surface gradients in orthogonal directions are required to solve for both vector components, and that height jumps have to be handled with great care. In many regions, the only suitable objects are buildings with roof faces in orthogonal directions (e.g. L- or T-shaped buildings). To overcome this deficit, (Vosselman 2002) suggests to use linear and planar features obtained from a segmentation of the data. While each individual feature provides only partial strip discrepancy information, sufficient input for a laserscanner data strip adjustment procedure can be generated by local accumulation of partial strip discrepancy information.

Effects on object modelling

Obviously, systematic errors present in the laserscanner data propagate directly into object models (such as 3-D building models) derived from the data, while the effect of stochastic errors is diminished by the number of data points. Besides systematic shifts of reconstructed building models introduced by systematic errors, strip discrepancies both in planimetry and height may have severe effects on the performance of automatic building model generation techniques based on raw laserscanner data in a TIN structure. The interference of data from two strips with a significant offset on a tilted roof plane leads to triangle meshes with large slope errors, especially when dense laserscanner data are used. Figure 3 shows an example of a building covered by data points from two neighbouring strips. Triangle meshes formed by points from both strips in the triangulation of a merged dataset may show slopes which vary strongly from the average slope of their roof face, especially in datasets with a high point density. Negative effects of this interference on building reconstruction techniques based on a cluster analysis in TIN mesh parameter space are discussed in (Hofmann/Maas, 2003). Similar problems will occur when interpolation data to a regular grid, where strip discrepancies cause an effect denoted as 'ripples' (Crombaghs et al., 2000).

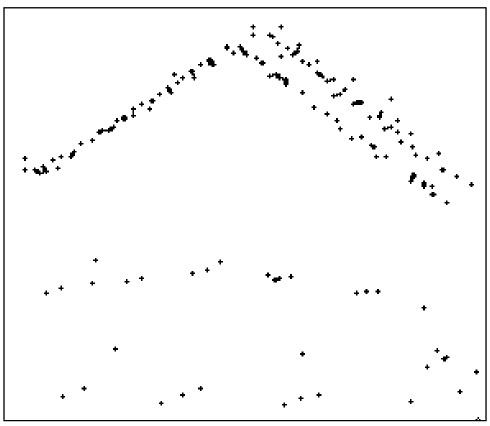

Figure 3: Horizontal and vertical laserscanner data strip offsets visualized at a saddle-roof building in an orthogonal point cloud projection

Potential of strip adjustment

Several authors have published laserscanner strip adjustment schemes trying to improve the overall accuracy of a laserscanner dataset based on manual or automatic measurements of ground control and tie points (Crombaghs et al. 2000, Vosselman/Maas 2001, Burman 2002, Kager/Kraus, 2003). Proper modeling of pose determination induced strip errors should correct the actual pose data. This can only be performed by the data provider, as the orientation data are usually not made available to the user. Instead, most approaches in laserscanner strip adjustment are based on deformations on laserscanner ground point data strips by linear or higher order polynomial models. Generally, it has to be noted that it is sometimes difficult to judge the magnitude of systematic strip errors and the accuracy improvement achieved by strip adjustment, because data providers often perform some interactive or semi-automatic strip adjustment before delivering data to their customers. If the data processing chain is not completely documented, the analysis of effects may be rendered difficult.

(Crombaghs et al., 2000) use a strip adjustment procedure to improve only the height quality of laserscanner data. Their strip deformation model is based on an offset and two tilts for each individual strip, with the along-track tilt being questionable for strip lengths of up to 30 km. They report an improvement of the residuals by 35% for a large block consisting of 300 strips; again, this result is based on strip tie point patches containing some 100 data points and thus largely eliminating single point noise.

(Kager/Kraus, 2003) use a low order polynomial strip deformation model based on automatic height difference measurement at small patches in 1000 meter intervals along the strip overlap region. As a result, rms strip height discrepancies were improved from 10.7 cm to 5.6 cm in a block of 56 strips. From an analysis of the polynomials and residuals, they derive a systematic (strip deformation induced) error of 6.0 cm per point and a random error of 3.1 cm per point.

The improvement of results by strip adjustment is also discussed in (Vosselman/Maas, 2001): They use a nine-parameter strip adjustment model allowing for three shifts, three rotations and three torsions (first derivative of rotation over strip length). The results of the technique applied to two datasets from rather different sensors show that the precision of ground point coordinates could be improved by approximately 40%, with the improvement in planimetry being significantly larger than in height.

These results show that the gain in precision obtainable by strip adjustment techniques is limited. Strip discrepancies show some systematic behaviour (offset, rotation and torsion of strips), but the limited GPS platform height determination precision and the difficulty of obtaining accurate planimetric strip discrepancy information disable further improvement. Future research should aim at also treating local errors caused by the dominating effect of GPS height precision, which are much more difficult to deal with in a calibration procedure. As a consequence of the fact that the gain in planimetry precision obtained by strip adjustment is bigger than the gain in height precision, laserscanner data strip adjustment may be even more important for the production of accurate 3D city models than for the production of DEM's.

6. CONCLUSION

Airborne laserscanning systems have faced a fast increase of their data rates in the past few years. Parallel with growing data rates, the technique is now applied to a wide range of new application fields. While in early DTM generation applications with a point spacing of several meters the primary focus was on height accuracy, planimetric accuracy of laserscanner data may be of equal importance in applications aiming at 3D GIS information extraction from dense laserscanner data.

Unlike in conventional stereo-photogrammetry, the height precision of surface points generated by airborne laserscanning is usually significantly better than the planimetric precision. As the planimetric precision potential is mainly influenced by the scanning mirror mechanism and the orientation determination system, there will be an almost linear dependence of planimetric precision on flying height above ground. In contrast, as the dominant factors influencing height precision are platform position determination by differential GPS (and possibly ground definition within the laser spot), height precision will be much less flying height dependent.

The precision figures for the height coordinate of airborne laserscanner data reported in the literature are mostly in the order of 10-15 cm. Less studies have been published on the planimetric accuracy of laserscanner data. Precision figures reported in the literature are in the order of 50 cm for flying heights of 500 - 700 meter. These accuracy figures are in accordance with the specifications provided by system manufacturers. Laserscanner data strip adjustment procedures may reduce systematic errors, but their effect is generally limited when using global strip deformation models and neglecting local systematic effects.

7. REFERENCES:

- Behan, A., 2000: On the Matching Accuracy of Rasterized Scanning Laser Altimeter Data. IAPRS, Vol. 33, Part B2, pp. 75-82
- Burman, H., 2002: Laser Strip Adjustment for Data Calibration and Verification. IAPRS, Vol. 34, part 3A, p. 67ff
- Cramer, M., 2001: Performance of GPS/Inertial Solutions in Photogrammetry. 'Photogrammetric Week 2001' /Eds. Fritsch/Spiller), Herbert Wichmann Verlag, Heidelberg, pp. 49–62
- Crombaghs, M., Brügelmann, R., de Min, E., 2000: On the adjustment of overlapping strips of laseraltimeter height data. IAPRS Vol. 33, Part 3A, pp. 230-237
- Haala, N., Brenner, K., 1997: Generation of 3D city models from airborne laser scanning data. Proceedings EARSEL Workshop on LIDAR remote sensing on land and sea, Tallinn/Estonia
- Hofmann, A., Maas, H.-G., 2003: Derivation of roof types by cluster analysis in parameter spaces of airborne laserscanner point clouds. ISPRS Workshop '3-D reconstruction from airborne laserscanner and InSAR data', Dresden/Germany (to be publ. in IAPRS Volume 34, Part 3/W13)
- Huising, J., Gomes Pereira, L., 1998: Errors and accuracy estimates of laser data acquired by various laser scanning systems for topographic applications. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 53, No. 5, pp. 245-261
- Katzenbeisser, R., 2003: Production and Types of DEM. TopoSys technical note (unpublished)
- Kager, H., Kraus, K., 2001: Height Discrepancies between Overlapping Laser Scanner Strips – Simultaneous Fitting of Aerial Laser Scanner Strips. Optical 3-D Measurement Techniques V (Eds. Kahmen/Grün), Wichmann Verlag
- Kilian, J., 1994: Calibration methods for airborne laser systems. IAPRS, Vol. 30, Part 1, pp. 42-46
- Kraus, K., Pfeifer, N., 1998: Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS Journal of Photogrammetry and remote Sensing, Vol. 53, pp. 193-303
- Maas, H.-G., 2000: Least-Squares Matching with Airborne Laserscanning Data in a TIN Structure. IAPRS Vol. 33, Part 3A, pp. 548-555
- Maas, H.-G., 2001: On the Use of Pulse Reflectance Data for Laserscanner Strip Adjustment. Accepted for ISPRS Workshop on Land Surface Mapping and Reconstruction using Laser Altimetry, Annapolis/Maryland, IAPRS Vol. XXXIV-3/W4
- Maas, H.-G., 2002: Methods for measuring height and planimetry discrepancies in airborne laserscanner data. Photogrammetric Engineering and Remote Sensing, Vol. 68, No. 9, pp. 933–940
- Vosselman, G., Maas, H.-G., 2001: Adjustment and filtering of raw laser altimetry data. OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Elevation Models, Stockholm, 1.-3. march 2001
- van der Wolk, M., 2000: Het Kansmodel van Digitale Hoogte Modellen. Master thesis, Department of Geodetic Sciences, Delft Technical University