TOWARD A RIGOROUS METHODOLOGY FOR AIRBORNE LASER MAPPING

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ABSTRACT:

Airborne laser mapping (ALM) provides as primary product a 3D point cloud. Currently, a rigorous method that provides a thorough accuracy control for the primary ALM product is lacking. ALM products are usually only empirically evaluated for accuracy by comparison with ground truth. This paper presents a method, analogous to the photogrammetric block adjustment, for controlling the accuracy of the point cloud. It uses the redundancy in the overlapping areas of flight lines to estimate corrections for the observations and instrument parameters. The goal is a geometrically correct laser point cloud, one that is free of blunders and systematic errors and for which the accuracy is predictable, and given in form of standard deviations for the individual laser points.

1. INTRODUCTION

For an Airborne Laser Mapping (ALM) flight mission over a given project area, ALM provides a 3D point cloud as a primary product. The point cloud describes the shape (relief) of the earth surface; its manifold forms (natural and man-made), as well as temporary forms (e.g. cars, materials on construction sites). Algorithms are applied that assign object and form attributes to the individual points (e.g. bare earth/terrain, vegetation, building, power wire, etc.), thus resulting in a classified point cloud. Points of interest for a particular application, i.e. points having a certain attribute or set of attributes, are eventually extracted from the classified point cloud for creating an application dependent product.

Over the past decade, the achievements in ALM instrument development have been substantial. Their measurement rates have increased from 2 kHz to 100 kHz; they are capable of recording the full wave-form of the return signal instead of either the first or the last return; their AGL[1] operating altitudes have increased from 1 km to 3 km, and they are available integrated with digital cameras. The achievements in developing appropriate ALM data processing software, however, have been rather marginal. Numerous research papers and theses have been written on all aspects of ALM, however, the transfer of the research into commercially available software products has only rarely occurred.

The success of ALM, i.e. its rapid development into a standard technology for topographic mapping, has to a very large degree been due to the ALM service providers; companies who operate an ALM instrument and provide end-users with point clouds or derivative products. These companies put a tremendous amount of effort into data processing. For example, for generating a geometrically correct point cloud, data-processing-to-data-acquisition time ratios of 10:1 up to 14:1 are reported. For classifying a point cloud into terrain (bare earth) points and others, ratios of up to 20:1 are common. These numbers depend, of course, on the quality requirements of the actual projects. However, they clearly demonstrate the need for much better data processing tools, in order to exploit the full potential of ALM.

Apart from obvious benefits that would accrue from better processing tools, the ALM community would gain enormously from a commonly accepted methodology. A methodology is, generally, a body of procedures and methods relating to a given discipline. An accepted methodology would imply a common understanding of the methods, of the results they produce and of how these results are to be interpreted. It would include a clear definition of the ALM products, and of their respective quality attributes. This would be beneficial for both service providers and end-users, especially when it comes to acceptance tests for specific projects. To avoid possible misinterpretations, it is emphasized that a methodology does not mean overly restrictive directions that are to be followed, and complied with for every step, so as to ensure that a project is accepted. It rather aims at the opposite. A well understood set of methods does not require meticulous control of the process.

From the discussion in the above first paragraph, two key ALM products and a group of derivative products can be distinguished:

- Laser point cloud
- Classified laser point cloud, and
- Digital terrain models, surface models, city models, etc.

Each of these products has its own specific quality attributes. Quality, in general, is the compliance of a product with the expectations of the user, as those are expressed in product requirements. Requirements such as meeting schedule and completeness, point density, compliance with any mission restrictions (e.g. snow-levels, water-levels, etc.), can be met relatively easily with appropriately executed project management. The most important quality attribute, however, for ALM as for any other surveying technique, is accuracy. Accuracy requires considerable effort to achieve and to demonstrate.

This paper focuses on the accuracy of the laser point cloud, the primary product of ALM. Section 2 provides a discussion on the meaning of accuracy as it is relates to the differences among

[1] Above ground level

the various ALM products. Section 3 presents a methodology that aims at ensuring the generation of a geometrically correct point cloud with predictable accuracy characteristics. Section 4 provides a brief summary, and an outlook for further work.

2. CONSIDERATIONS OF ALM PRODUCT ACCURACIES

2.1 Review of Accuracy related Terms

Three types of errors can generally be distinguished during a process of measurement: blunders (gross errors), systematic errors, and random errors. Blunders are significantly larger in magnitude compared to the other two types. They can be detected and eliminated with use of redundant observations. Systematic errors are caused by imperfect instruments, or deficiencies in the mathematical model used to compute the desired parameters from the observations. With appropriate surveying methods they can either be eliminated during the observation process, or determined and corrected. This requires redundant observations, and to some extent, independent control. Random errors are always present and can never be eliminated. They can, however, be minimized, again by redundant observations.

Accuracy describes the closeness of an observation (measurement value) to the "true" value of the parameter (quantity) being observed. The difference between an observation and the "true" value gives the true error. For empirical accuracy tests, the "true" value is usually determined with an instrument, the accuracy of which is better by an order of magnitude than that of the one being tested. The root-mean-square (RMS) of the derived "true" errors gives a measure of the accuracy, also referred to as absolute accuracy. Mathematical statistics provides methods for determining estimates for the errors from redundant observations. The standard deviation (σ) of the derived estimated errors provides a measure of the theoretical accuracy, also referred to as precision. For the case where the estimated errors are purely random, i.e. neither blunders nor systematic errors exist, the theoretical accuracy and the absolute accuracy are equivalent.

2.2 Laser Point Cloud Accuracy

Applied to ALM, laser point accuracy describes the closeness of the computed laser point position to the position of the actual laser footprint in the terrain, i.e. the position at which the laser return pulse was generated. Laser point accuracy depends solely on the accuracy of the observations (laser-range, scan-angle, sensor position and orientation) and on the validity of the mathematical model used to compute the laser point.

For each laser point the theoretical accuracy can be computed by applying error (covariance) propagation. Assuming that blunders and systematic errors can be eliminated, and that the theoretical accuracies of the observations (laser-range, scan-angle, sensor position and orientation) are given and proven to be valid, the resulting standard deviations will be a valid measure of the laser point accuracy. This is demonstrated in figures 2.1 for simulated data.

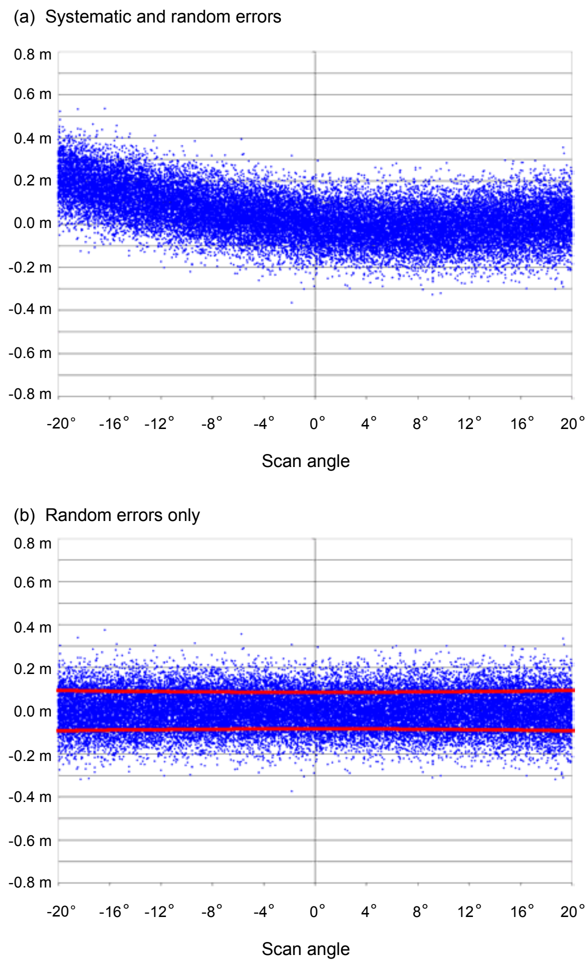

Figure 2.1: Both, (a) and (b) show the true errors of laser point heights in blue. Part (b) shows, too, the standard deviations, $+\sigma_H$ and $-\sigma_H$ of the height in red. For both examples, ALM observations were simulated with random errors (GPS position $\sigma_X = \sigma_Y = 5$cm, $\sigma_Z = 8$ cm, IMU attitudes $\sigma_{Roll} = \sigma_{Pitch} = 0.005°$, $\sigma_{Heading} = 0.02°$, laser range $\sigma_r = 5$ cm, scan-angle $\sigma_\Theta = 0.05°$). For (a), incorrect instrument parameters were used (scan-angle offset $\Delta\Theta=0.008°$, scanner scale error $\Delta s=0.001$) for computing the laser points. The flying height was 1000m.

2.3 Classified Laser Point Cloud Accuracy

Classifying a laser point cloud aims at assigning an attribute to each individual point, describing the type of object which reflected the laser beam at that measured location. The classification accuracy is usually determined empirically by comparing the classification results to ground truth, locally in selected areas. It is expressed in percentage values, e.g. number of correctly classified points as fraction of the total number of points in a particular category (e.g. Park 2002, Sithole, Vosselman 2004). Theoretical classification accuracies, for instance in the form of a probability value for the correctness of the assigned attribute, have not yet been provided by the available classification algorithms.

2.4 DTM Accuracy

The accuracy of the digital terrain model (DTM, bare earth model) is briefly discussed here as an example of a derivate product; firstly, because it is still the most frequently created derivate product of ALM, and secondly because of the link of the DTM to the empirical tests for laser point accuracy.

DTM accuracy describes the vertical closeness of the DTM surface to the true physical terrain surface (Ackermann 1994). It depends mainly on how well the terrain is represented by the data used to generate the DTM, i.e. on the distribution and density of the measured terrain points and the existence of break/form lines. The terrain surface roughness[2] and the accuracy of the terrain points determine the best-case limit of the DTM accuracy.

2.5 Accuracy Summarized

The different ALM products discussed above (laser point cloud, classified laser point cloud and DTM) have quite distinct accuracy characteristics. For all products, the accuracy evaluation is done only empirically, by comparison to ground truth data (disregarding the new developments for DTM -Kraus et al 2004). This approach provides absolute accuracy measures, but only locally for small control areas.

It should be noted that empirical analyses often do not acknowledge the difference between laser point and DTM accuracy. As the true laser footprint is invisible, most laser point accuracy tests are based on interpolating check points into a DTM, derived from measured laser points or vice versa, interpolating laser points into a control DTM. The height differences provide accuracy measures. Depending on the surface roughness of the actual terrain, these measures can either come very close to the actual laser point height accuracy, or actually be representative of the surface roughness and, thus, more a measure of DTM accuracy. This interdependency between measured laser point accuracy and the DTM accuracy needs to be considered when interpreting the results; however, it is frequently overlooked. It also needs to be taken into account when analyzing the height differences between the points of overlapping flight lines.

3. LASER POINT CLOUD

Currently, a rigorous method that provides a thorough accuracy control for the primary ALM product, the laser point cloud, is lacking, not just locally for control areas, but for the entire project area. The aim of such a method is a geometrically correct laser point cloud, one that is free of blunders and systematic errors and for which the accuracy is predictable and given in the form of standard deviations for the individual laser points.

3.1 Proposed Approach

The approach presented is analogous to the photogrammetric block adjustment. It is assumed that a project area is covered with flight lines that overlap to some extent. As well, additional cross flight lines are flown. The overlap areas provide redundancy, not on a point to point basis, but with respect to the surface scanned. Instead of tie- and control points, as in aerial triangulation, tie- and control features are proposed. A least-squares adjustment is formulated that minimizes the weighted quadratic sum of the observation residuals at the tie- and control features by estimating correction parameters of the mathematical model for the laser point computation.

The most prominent feature in the terrain is the planar feature (Filin et al 2001, Filin 2001, Filin, Vosselman 2004, Kager 2004, Schenk 2001), and it has, therefore, been the choice for the initial implementation. Linear features have been used by others (Vosselman 2002a, 2002b), and will be considered in future implementations.

The approach proposed herein requires that the following elements be implemented: an appropriate mathematical model for the laser point computation, algorithms for extracting planar features per flight line and for establishing the correspondence between the identical planes in the overlapping areas, as well as a process for selecting appropriate tie-planes; finally, an implementation of the least-squares adjustment model.

The optimal implementation of the approach would have a high degree of automation (with minimum of user interaction), would work for standard flight missions, would require a minimum of additional flying (e.g. cross lines) and a minimum of ground control, and would be capable of handling large projects with several flight missions.

3.2 Laser Point Computation

Mathematical models for computing the laser point position have already been reported in a number of publications (e.g. Lindenberger 1993, Filin 2001, Schenk 2001). They differ only slightly with respect to chosen corrections and notation. In the present case, the model is split into two components: a generic geo-referencing part and a sensor specific part. This has the advantage that the geo-referencing part needs to be implemented only once and can be used for different sensors. Both the functional model and the stochastic model, i.e. the computation of the covariance matrix for the laser point, are given.

3.2.1 Geo-Referencing

The laser point position in a local reference frame can be computed as:

$$\mathbf{X}_P^F = \mathbf{X}_G^F + \Delta\mathbf{X}_G^F + \mathbf{R}_L^F \Delta\mathbf{R}_I^L \mathbf{R}_I^L \Delta\mathbf{R}_S^I \mathbf{R}_S^I \left(\mathbf{X}_P^S - \mathbf{X}_E^S - \Delta\mathbf{X}_E^S\right) \quad (1)$$

where

$\mathbf{X}_P^F$ Laser point in a local reference frame

$\mathbf{X}_G^F$ GPS antenna position in a local reference frame

$\mathbf{X}_P^S$ Laser point in the sensor frame (equation 3)

$\mathbf{X}_E^S$ GPS antenna eccentricity in the sensor frame

$\mathbf{R}_S^I$ Rotation of the sensor frame into the IMU frame

$\mathbf{R}_I^L$ Rotation around IMU attitudes roll, pitch, heading

$\mathbf{R}_L^F$ Rotation into a local reference frame

$\Delta\mathbf{X}_G^F$ GPS position corrections

[2] Roughness is here understood as the smallest irregularities of a surface (e.g. the irregularities of a freshly plowed field).

$\Delta \mathbf{X}_E^S$ GPS antenna eccentricity corrections

$\Delta \mathbf{R}_I^L$ IMU roll, pitch, heading corrections

$\Delta \mathbf{R}_S^I$ Corrections for the rotation from sensor- to IMU frame

The geo-referenced laser point is a function of (indirect) observations, instrument parameters and corrections. The (indirect) observations are the laser point in the senor frame, the GPS position and the IMU attitudes. Instrument parameters are the relative orientation between the ALM sensor frame and the IMU frame, and the GPS antenna eccentricity[3]. They are the result of (manufacturer) lab calibration and aircraft installation procedures, respectively. Corrections are added to account for residual systematic errors in the position and orientation data and for uncertainties in the instrument parameters. These are unknown and need to be determined (section 3.4).

The covariance matrix of the geo-referenced laser point can be computed as:

$$\mathbf{C}_P^F = \mathbf{C}_G^F + \mathbf{J}_I \mathbf{C}_I \mathbf{J}_I^T + \mathbf{J}_P \mathbf{C}_P^S \mathbf{J}_P^T \quad (2)$$

where:

$\mathbf{C}_P^F$ Covariance matrix of the laser point in the local reference frame

$\mathbf{C}_G^F$ Covariance matrix of GPS position in the local reference frame

$\mathbf{C}_P^S$ Covariance matrix of the laser point in the sensor frame

$\mathbf{C}_I$ Covariance matrix of the IMU attitudes

$\mathbf{J}_I$ Jacobian matrix for the IMU attitudes

$\mathbf{J}_P$ Jacobian matrix for the laser point in the sensor frame

The covariance matrices for the GPS position and the IMU attitudes are obtained from prior processing, typically from one form of least-squares. For the time being, the correlations between the position and the attitudes are neglected. The covariance matrix of the laser point with respect to the sensor frame is derived from the respective sensor model (equation 6).

3.2.2 Sensor Model

Sensor models depend on the specifics of the actual hardware comprising the sensor; and on their geometrical relationship to each other. The following is a simplified, generic model for a single scanner sensor.

$$\mathbf{X}_P^S = R_\Theta \begin{bmatrix} 0 & 0 & r_P \end{bmatrix}^T \quad (3)$$

$$r_P = r_{obs} + \Delta r_{LC} + \Delta r \quad (4)$$

$$\Theta_P = \Theta_{obs}\left(s_{LC} + \Delta s\right) + \Delta\Theta_{LC} + \Delta\Theta \quad (5)$$

where:

$\mathbf{X}_P^S$ Laser point in the sensor frame

R_Θ Rotation around scan-angle(s)

r_P Corrected laser range

Θ_P Corrected scan-angle

r_{obs} Observed laser range

Θ_{obs} Observed scan-angle

Δr_{LC} Range offset from system calibration

$\Delta\Theta_{LC}$ Scan-angle offset from system calibration

s_{LC} Scan-angle scale factor from system calibration

Δr Range offset correction

$\Delta\Theta$ Scan-angle offset correction

Δs Scan-angle scale factor correction

The laser point position with respect to sensor frame is a function of the observations scanner angle and laser range, calibration parameters from the manufacturer and corrections to account for possible changes in the calibration parameters. The corrections are to be determined (section 3.4).

The covariance matrix of the laser point in the sensor frame is given by:

$$\mathbf{C}_P^S = \mathbf{J}_A \cdot \mathbf{C}_A \cdot \mathbf{J}_A^T \quad (6)$$

where

$$\mathbf{C}_A = \begin{bmatrix} \sigma_R^2 & \\ & \sigma_\Theta^2 \end{bmatrix} \quad (7)$$

and

$\mathbf{C}_P^S$ Covariance matrix of the laser point in the sensor frame

$\mathbf{C}_A$ Covariance matrix of the ALM observations

$\mathbf{J}_A$ Jacobian matrix for the ALM observations

σ_R Standard deviation of the laser range observation

σ_Θ Standard deviation of the scan-angle observation

3.3 Tie Surface Extraction

3.3.1 Plane Extraction

The planar surface extraction is done on a flight line by flight line basis. The topology of the laser points is provided by the scan-line geometry. The laser points are organized in an array of which each row contains the points of one scan-line (Kager 2004). The columns represent scan-angle intervals. Filters can be applied while reading the laser points and filling the array. The filters select points that fulfill certain conditions, e.g. only points for a given scan-angle range, or only those from single returns. Thus, with suitably chosen filters, the plane extraction can be done for the whole flight line, or just for the overlapping areas.

The plane extraction starts with a least-squares plane fit through a subset of laser points. The size of the subset is user selectable. The adjustment minimizes the weighted quadratic sum of the

[3] Sensor positions from combined GPS/IMU processing refer to the origin of the IMU frame and not to the GPS antenna center. For such, the eccentricity refers to that of the origin of the IMU frame with respect to the sensor frame.

distances[4] of the laser points to the plane (Lee, Schenk 2001). The standard deviation of unit weight σ_0 can, therefore, be interpreted as the standard deviation σ_D of the shortest distance of a point to the plane. The plane is accepted if σ_0 is smaller than, or equals, a threshold. The threshold is the average standard deviation of the distances to the plane computed by error propagation from the standard deviations of the laser point positions tested for the plane fit. For a horizontal plane it is just a function of the z-components, and thus influenced only by the accuracy in z. The steeper the slope of the plane, however, the greater will be the effect of the x and y planimetric components. If a plane is accepted, the neighboring points are tested statistically for the fit to the plane. If the fitting error remains smaller than the given threshold, the points are used to update the plane parameters using sequential least-squares.

Intensive simulation studies have demonstrated the suitability of the algorithm. Figures 3.1 to 3.3 show examples from first empirical tests.

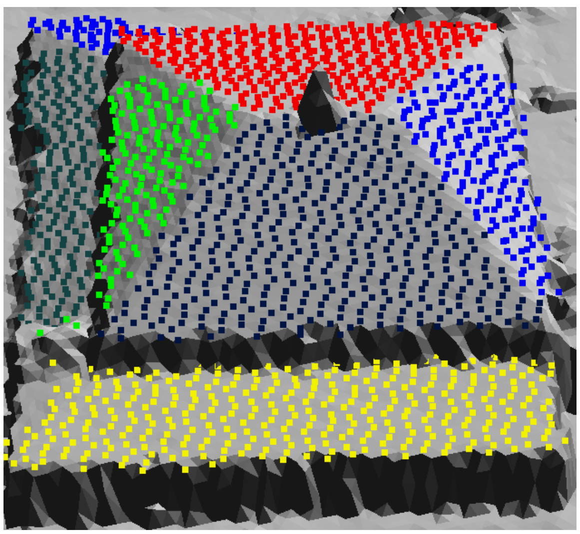

Figure 3.1: Points of extracted planar surfaces for a building; a different color for each of the planes.

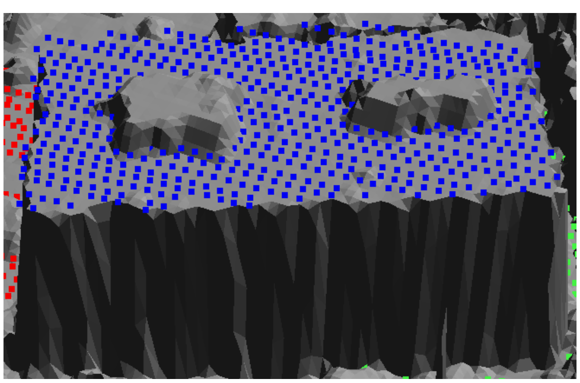

Figure 3.2: Points of one single roof plane. Obstacles are removed without splitting-up the plane.

[4] Distance along the direction of the plane normal.

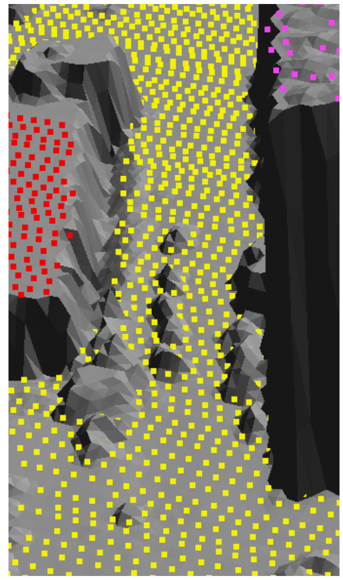

Figure 3.3: Points on a street that fit a plane. It demonstrates how the plane extraction can support laser point classification; non-plane points describe obstacles (e.g. cars).

3.3.2 Plane Correspondence

Establishing the correspondence between planes of overlapping flight lines is largely a software engineering problem, and can be solved in a satisfactory fashion with appropriate data file structures. One possibility is to establish a grid covering the project area. As planes are identified, the plane centers are sorted into the respective grid cells, while keeping the links to points and plane parameters. Such an approach not only allows for fast retrieval of the planes for a given sub-area (e.g. for graphical display purposes), but also for readily identifying those cells that contain planes from more than one flight line. Planes from two flights, co-located to within an acceptable tolerance, are then tested for correspondence, i.e. for representing the same physical plane. Thus far we have tried overlap criteria and statistical parameters analysis criteria to determine the correspondence. Choosing an optimal set among the possible approaches in the tests for correspondence will require further, extensive empirical studies.

3.3.3 Plane Selection

For the laser point adjustment, a set of appropriate tie-planes is to be selected from all available corresponding planes. Potential selection criteria for a tie-plane are size and shape, number of laser points, slope, orientation with respect to the flight direction, location within flight line and fitting error. All these criteria have an effect on the parameter estimation, as they determine the geometry of the adjustment. For the selected tie-planes, the related observations and parameters are to be retrieved from the various data files, and then passed to the adjustment program.

Some questions still remain, however, regarding what the optimal configurations are, with respect to number of planes, sizes, shapes, slopes, orientation and location within the flight line.

3.4 Adjustment Model

The adjustment is based on implicit least-squares. The applied observation equation is given as:

$$\mathbf{g}(\mathbf{l}+\mathbf{v},\mathbf{x}) = \mathbf{n}_{PN}^{F} \bullet \left(\mathbf{X}_{P}^{F} - \mathbf{X}_{PC}\right) = 0 \qquad (8)$$

where:

$\mathbf{l}$ Observations
$\mathbf{v}$ Residuals
$\mathbf{x}$ Parameters (unknowns)

$\mathbf{X}_{P}^{F}$ Laser point (equation 1)
$\mathbf{n}_{PN}^{F}$ Normal vector of plane
$\mathbf{X}_{PC}$ Plane centre
$(\bullet)$ Denotes dot product

The linearized observation equations take the form:

$$\mathbf{g} + \mathbf{Dv} + \mathbf{Ax} = 0 \qquad (9)$$

where:

$\mathbf{D}$ Partials with respect to observations
$\mathbf{A}$ Partials with respect to unknowns (design matrix)

This leads to the normal equation system:

$$\mathbf{A}^{T}\left(\mathbf{DC}_{vv}\mathbf{D}^{T}\right)^{-1}\mathbf{A}\hat{\mathbf{x}} = \mathbf{A}^{T}\left(\mathbf{DC}_{vv}\mathbf{D}^{T}\right)^{-1}\mathbf{g} \qquad (10)$$

where:

$\mathbf{C}_{vv}$ Covariance matrix of observations

Each laser point of the tie-planes provides one equation of type (9). There are 8 observations for each point: the laser range, the scan-angle, the GPS antenna position and the IMU attitudes (roll, pitch and heading). The covariance matrix of the observations is a block matrix, comprising the covariance matrix of the ALM observations (equation 7), of the GPS position and of the IMU attitudes. Correlations between the GPS position and the IMU attitudes can be taken into account, if provided. Control plane information can either be entered in the form of observations for the plane parameters, or in the form of control (plane) points.

The vector of unknowns contains the plane parameters for each of the tie-planes, one range correction for the observations of the entire block (equation 4), one set of scan-angle corrections (equation 5), and one set of antenna eccentricity and sensor to IMU orientation corrections (equation 1). The GPS position corrections and the IMU attitude corrections can be introduced as unknowns either per flight line, or per a group of flight lines (e.g. one set per block).

As several unknown parameters are highly correlated, they would lead to a singular (or near-singular) normal equation system, if all were entered as free unknowns. Therefore, for each of the unknown parameters, pseudo-observations can be added, which allow for a simple technique of controlling which parameter to estimate and which one to fix, depending on the actual geometry. The choice of which parameters are to be unknowns can be automated. When preparing the input for the adjustment (section 3.3.3), the geometry given by the available planes can be analyzed and the unknown parameters chosen accordingly. In addition, the least-squares adjustment itself offers information that can be used during the iterations to control which of the unknown parameters are to be solved for and which are to be fixed.

3.5 Discussion

The method presented here addresses all types of errors related to ALM observations: blunders, systematic and random errors. Blunders in the laser range can only be detected in the context to surrounding points, as there is no redundancy for a single laser point. The planar surface extraction algorithm provides this context when neighboring points are analyzed for fitting a plane. Thus, when applying the planar surface search for the whole flight line, instead for just the overlapping areas, outliers can be detected and flagged accordingly within in the entire data set. The block adjustment (equations 8 -10) eliminates systematic errors in the laser points by estimating corrections for the sensor positions and orientation and for a set of instrument parameters and provides estimates for the random errors of the observations.

Least-squares offers a variety of possibilities for analyzing and testing the results. Tests can be performed to check if the residuals are randomly distributed, thus, if all systematic errors are removed. The estimated standard deviation of unit weight allows for proofing the correctness of the a priori assumptions for the observation accuracies. Measures for the internal and external reliability can be used for blunder detection and for accessing the geometry of the adjustment. They show how much single observations contribute to the estimation of the unknown parameters and how much a single observation is controlled by the other observations of the network. Blunders in the individual observations are not expected to be present, as they are detected during the plane search. However, the blunder detection in the laser point adjustment would reveal if planes used as tie-planes didn't match.

Re-processing the laser points with the corrections determined in the adjustment results in a geometrically correct point cloud of which the accuracy can be described by the standard deviations derived by error propagation (equations 2, 6). At each of the tie-planes the laser point accuracy can be verified, by computing the planes' normal vectors through the individual laser points. This gives the residuals in all three components x,y,z, together with the length of the normal vector, i.e. the distance of the laser point to the plane.

Preferably, the presented approach will prove to work satisfactorily for standard ALM production flights. It still remains to be shown empirically, though, whether a sufficient number of appropriate tie-planes (different slopes, different orientation) will be found for most types of terrain in most of the flight lines. However, even if the above does not materialize, the method presented in this paper can always be applied for special calibration areas that fulfill the requirements with respect to tie-planes and that can be flown at the beginning and/or at the end of a production mission.

4. SUMMARY AND OUTLOOK

ALM products are usually only empirically evaluated for accuracy. This is done locally in areas with independent control measurements (ground truth). The available techniques (interpolation) typically provide accuracy measures for the height component only and, moreover, do not always allow for a clear differentiation between laser point and DTM accuracy.

Each of the ALM products requires its individual method for accuracy evaluation. Kraus et al (2004) describe methods for assessing DTMs. This paper presents a method for controlling the accuracy of the point cloud, the primary ALM product. It uses the redundancy in the overlapping areas of flight lines to estimate corrections for the observations and instrument parameters, and thus produces a geometrically correct point cloud. For each laser point, standard deviations are computed by error propagation. The residuals at the tie-planes provide information for verifying the theoretical laser point accuracies.

The implementation of the approach into software is complete. The planar surface extraction has been tested intensively with simulated data, and in a preliminary fashion with empirical data. A series of empirical studies for a variety of terrain types has to follow. Repeatability is going to be tested using data from two flight lines flown in opposite direction over the same area. Apart from providing tie-planes for the laser point block adjustment, the plane extraction can support laser point classification. The planar surface correspondence algorithm has also been proven with simulated data and awaits testing with empirical data. The laser point block adjustment has been tested with simulated data, mainly for correctness of the implementation. An extensive simulation study is planned for analyzing the determinability of the unknowns as a function of the distribution, slopes and orientation of the tie-planes within a block, as well as the number and distribution of required control surfaces. The results of this study will show under which conditions which set of unknowns can be reliably estimated. This is not only necessary to get the best understanding of the laser point block adjustment, but also for understanding how best to automate the whole approach (section 3.3.3). The empirical studies of the planar surface extractions will show if the conditions can be met in practical applications.

In addition to the effort of developing a robust method based on tie-planes, the extraction of other tie-features (e.g. lines) will be investigated. Finally, it is noted that in the case where aerial photographs are taken during an ALM mission, the ALM- and photogrammetric observations can be processed together in one simultaneous block adjustment.

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