AUTOMATING QUALITY CONTROL FOR AERIAL MAPPING USING DENSE POINT CLOUDS

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ABSTRACT

Quality control (QC) in aerial mapping is a predominantly manual process, carried out in various steps throughout the entire data processing chain. One of these steps is the verification of triangulation results, which comprises interactive measurements of control points for absolute accuracy as well as relative offsets in-between overlapping imagery. We present a way to automate this relative QC, using photogrammetrically derived point clouds. With panchromatic intensity and full color information added, these point clouds become "image point clouds". Computed pair-wise in overlapping areas, the combined geometric and radiometric information of such image point clouds enables the robust derivation of three-dimensional offsets. These are presented to the user along with reliability measures in condensed reports that provide comprehensive assessment of the relative geometric accuracy within a flight recording or block. This automated method, called "Shear Analysis", is used at North West Geomatics Ltd. (North West) to evaluate Leica ADS line-scanner data before and after aerial triangulation.
We outline the combined geometric/radiometric image point cloud matching approach and verify its results in comparison to manual measurements that are traditionally used in QC. The automatic Shear Analysis is discussed in detail for an ADS block from North West's production, comparing the orientations from Direct Georeferencing with two triangulation results, one of them based on manual image point measurements and the other using automatic point measurement (APM).

KEYWORDS: Point Cloud, Matching, Adjustment, Triangulation, Automation, Analysis, Quality, Industry.

INTRODUCTION

In recent years, the demand for faster product delivery has significantly increased in the mapping industry; therefore, optimization and automation of the production work flow is highly desirable. Using new technologies and ever faster computers, data processing can be highly automated, but it is still necessary for humans to perform many manual quality control (QC) steps throughout the photogrammetric processing chain. These include checks for ground coverage and image quality as well as geometric and radiometric accuracy of intermediate and final products.

A crucial part of QC is the verification of the georeferencing, which, for Leica ADS line-scanner data, is based on GPS/IMU measurements typically refined by aerial triangulation. The corresponding QC process is two-fold. Absolute block accuracy is verified with ground control points and relative agreement between individual ADS flight lines (strips) is determined from stereo measurements of well defined check points in the strip overlap areas. Currently all such points are manually measured, and the three-dimensional point offsets in-between adjacent strips are used to compute root mean square (RMS) values for the block. Because of the relatively large number of strip-to-strip check points required, this relative QC is a costly process in both elapsed time and man-hours.

In that regard, we present a way of automatically checking the relative geometric accuracy of aerial images, using point clouds rather than individual measurements. Such point clouds are based on the Semi-Global Matching (SGM) approach (Hirschmüller, 2005). The implementation for ADS by Gehrke et al. (2010) provides point clouds based on all panchromatic stereo bands in the resolution of the input imagery. Moreover, panchromatic intensity as well as full color information from ADS RGB and near infrared bands is assigned to each individual point, which turns a point cloud into an "image point cloud" that provides high-density and high-quality geometric and radiometric data (Gehrke et al., 2011). We utilize that information to match such image point clouds in overlapping ADS strips and automatically derive three-dimensional offsets for a large number of corresponding patches. Besides the obvious advantages that come with automation, the use of image point clouds moves this QC step closer to the final products by evaluating the very datum of the digital surface model (DSM) – which is a cleaned and gridded image point cloud – and, to a degree, also the ortho-imagery that is rectified with the DSM. This method has been coined "Shear Analysis" and is now becoming a tool for North West to automatically evaluate and verify the geometric quality of ADS data and products. The goal is to apply the Shear Analysis to flight recordings or image blocks before and/or after aerial triangulation.

The remainder of the paper will give an overview on how the relative offsets are computed and evaluated. The focus is on using the offsets for Shear Analysis, which will be demonstrated on a North West production block in Lansing, Michigan. We illustrate how the data can be utilized to judge the quality of the orientation parameters, whether based on Direct Georeferencing or triangulation results.

OFFSET COMPUTATION BY IMAGE POINT CLOUD MATCHING

The computation of relative ADS image offsets for Shear Analysis is based on the automatic definition, derivation, matching, and evaluation of image point cloud pairs for a large number of patches. The description of our approach is kept fairly brief in this paper; details are provided by Gehrke (2012).

Patch Derivation with SGM

Image point clouds used for Shear Analysis are collected by applying the Semi-Global Matching (SGM) technique on two stereo views available from the ADS sensor (nadir/backward and nadir/forward). SGM has been introduced by Hirschmüller (2005) and the adaptation to and implementation for ADS line-scanner data is described in Gehrke et al. (2010, 2011). The patches used here are computed with settings identical to a typical DSM collection, with the exception that for Shear Analysis the nadir and backward green bands are used in place of the nadir and backward panchromatic bands. While SGM delivers similar results for green/panchromatic combinations compared to panchromatic only, green intensities perform better than panchromatic in the geometric/radiometric integration that is described below.

SGM creates image point clouds of very high density in the order of the ground sample distance (GSD) of the input data. The high point density allows the use of small patches of a few hundred pixels square, which in turn enables the computation of a large number of localized three-dimensional offsets. Patch locations are determined along the center of each ADS stereo overlap (backward/nadir/forward) in a user-defined spacing, which depends on project requirements and terrain. Typical patch distances are 1000-5000 pixels; the example block as shown in Figure 2 was run with 2000 pixels.

Offset Computation by Geometric Point Cloud Matching

The ADS sensor has a high quality GPS/IMU and a well-known interior orientation, which results in two advantages for the point cloud matching: The expected offset between corresponding patches typically lies within a few image pixels or GSD units and the relative scale and rotations are negligible. This leaves 3 degrees of freedom: the offsets in X, Y and Z. Despite these simplifications, the matching must handle the fact that points in corresponding patches are derived near the image borders at very different view angles, which leads to different surface representations and especially to reverse gaps in case of occlusions.

There is a broad variety of point cloud matching or, respectively, iterative closest point algorithms; see overviews in Rusinkiewicz & Levoy (2001) or Akca (2007). A simple and robust method to match inherently close point clouds is based on point-to-plane distances, i.e. the local approximation of the surface by planes (cp., e.g., Chen & Medioni, 1991). For every point in the reference cloud, we fit a plane to those points of the corresponding match cloud that are located in a small radius around the reference point. The plane fits involve outlier elimination, utilizing the geometric standard deviations of the SGM-derived image point cloud. In case of too few points for a reliable plane fit, whether due to initial gaps or caused by eliminated outliers, the location will be ignored. All valid point/plane pairs are then combined in a single, highly redundant least squares adjustment, in which the average three-dimensional offset is derived. The solution is iterative, applying the previous offset to compute refined local plane fits (Gehrke, 2012).

Combined Geometric/Radiometric Matching

The described geometric matching will constrain the vertical offset in almost all practical cases. However, horizontal correlation becomes weak if patches lack significant gradients in different directions, which is obviously the case in flat terrain but also on oriented slopes such as building roofs, especially considering the small patch size. Similar to Maas (2002) and Akca (2007), we address this issue by utilizing the radiometric information of the image point clouds and integrate it with the geometric point cloud matching into a combined adjustment. This integration greatly benefits our offset computation, because intensity gradients tend to occur more frequently than height gradients; they can provide or complement the required information for the derivation of planimetric offsets. The functional models for geometry and radiometry are essentially identical, the first using height gradients (from local X,Y,Z planes), the second intensities (local X,Y,DN planes); the underlying idea is the well-known least squares (image) matching. Given the very high redundancy in our model, we are able to compensate radiometric differences in-between overlap intensities as part of the combined least squares adjustment (Gehrke, 2012).

During the iterative solution, the relative weighting of the geometric and the radiometric observation equations is continuously optimized based on their group variance components. We found that those can vary widely and even encountered factors greater than 1000 between different types of terrain.

Automatic Offset Verification

In order to provide reliable patch offsets for Shear Analysis, we automatically verify the results of the combined geometric/radiometric matching. First of all, the roles of corresponding image point clouds are switched between reference and match cloud, resulting in two independent offset computations that must agree within tight thresholds. Their average becomes the final result, provided that further indicators are meaningful. Those include a minimum number of point/plane pairs in a patch, reasonable radiometric corrections as well as a maximum number of iterations. Respective limits can depend on a variety of parameters, predominantly terrain and imaging configuration. Nevertheless, using rather tight general settings – e.g., a maximum of 5 iterations, based on at least 25% point/plane pairs in relation to the number of input image points in a patch (Gehrke, 2012) – might eliminate some correct results; but as long as offset are attempted to be derived in a fairly dense pattern, there will be sufficient data for a meaningful Shear Analysis. Most important is the elimination of false positives.

EXAMPLE DATA SET

Our Shear Analysis approach is demonstrated on an ADS block in the Lansing area, Michigan, that has been imaged and processed by North West. The block is shown in Figures 1 and 2.

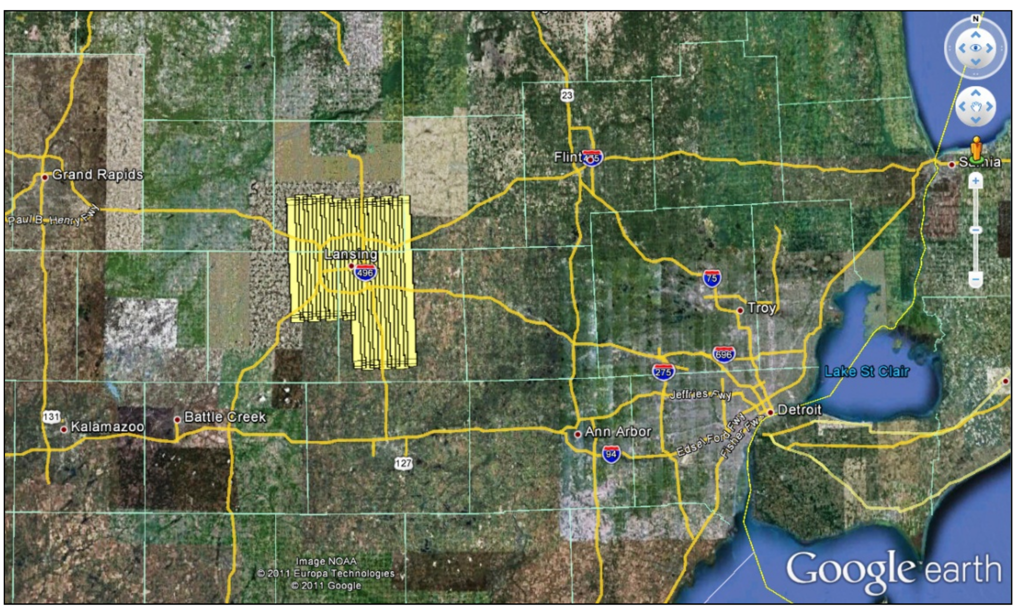

Figure 1. Location of the ADS block Lansing, Michigan, East of Detroit.

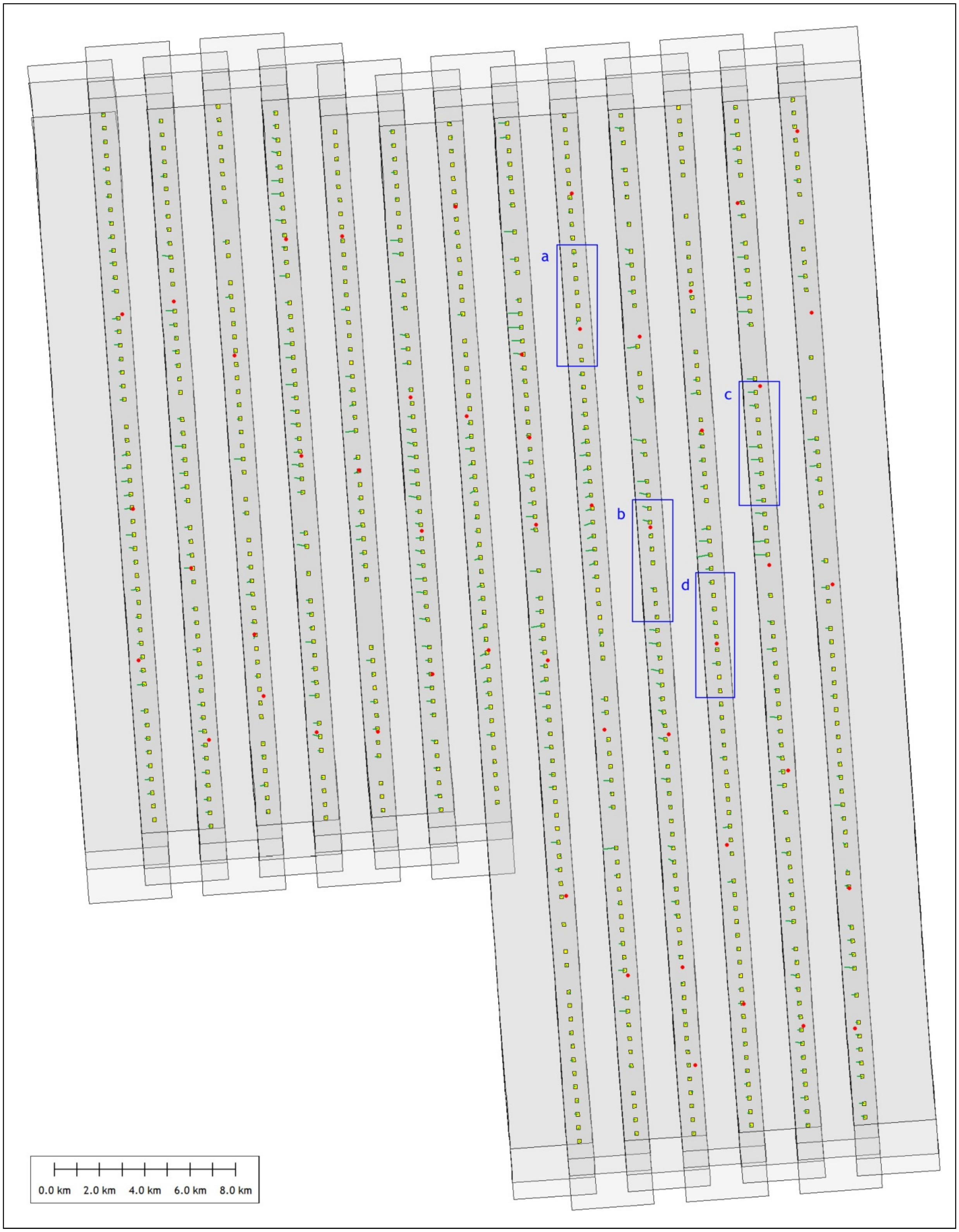

Figure 2. Lansing block overview: Footprints of ADS panchromatic bands; Shear Analysis results: patches and planimetric offsets (green, relative scale = 1000), based on the triangulation using manual measurements; QC check point locations (red dots); and example areas shown in Figure 5. ADS strips 001-014 from west to east.

Data Set: Lansing, Michigan

The Lansing block has been captured by North West with an ADS80 in fall 2011. It consists of 14 image strips (Figure 2), flown north-south within a single recording session. The nominal GSD is 0.30 m. The City of Lansing is located approximately in the center of the block. Accordingly, the data set contains urban and suburban areas as well as some forest, fields and smaller lakes.

Aerial Triangulation

For the purposes of this investigation, aerial triangulation was performed with manual measurements and, for comparison, based on automatic point measurement (APM). Manual measurements were made on approximately 100 well defined 6-fold tie-points in the panchromatic backward and forward bands and the green nadir bands of adjacent strips. The APM run was made using the same image bands. It resulted in approximately 900 tie points. Manual measurements of 12 photo-identified control points were included in both triangulation adjustments.

The Leica XPro/Orima software (Hinsken et al., 2002) was used to refine exterior orientations. The triangulation constrained the GPS datum to the control and solved for the IMU misalignment by image strip.

Shear Analysis Runs

For Shear Analysis, three-dimensional offsets were computed from patches of 512 x 512 image pixels in size with a fairly dense spacing of 2000 pixels on average. This setup results in a total of 808 patches, with 48-52 patches along each of the short ADS strip overlaps in the western part of the block, 001/002-007/008, and 74-76 patches in each of the longer eastern overlaps, 008/009-013/014 (cp. also Figure 2). The automatic Shear Analysis was run on all three block configurations: Direct Georeferencing as well as triangulated orientation based on manual measurements and APM. The results are analyzed and discussed in the following chapters.

INDEPENDENT VERIFICATION OF OFFSETS

The integrated geometric/radiometric image point cloud matching approach was initially verified with synthetic data – heights and intensities assigned to predefined locations – and artificially introduced offsets. This data set is still being used as part of the acceptance testing of our Shear Analysis software.

With the goal of replacing the manual QC, the automatically computed offsets have to be compared against the interactive measurements and the derived statistics for real-world data sets such as the Lansing block. As the configuration used in North West's production is the triangulation based on manual measurements, this result has undergone the traditional QC process. A total of 51 check point pairs were manually measured, 3 in each of the shorter overlaps and 5 in each of the longer ones (Figure 2). This allows for two kinds of independent verifications of the automatic computation: the comparison of individual offsets (Table 1) and RMS values for the entire block (Table 2). Please note that manual measurements were naturally carried out in a single stereo pair – panchromatic backward and forward bands in this case –, while the automatic Shear Analysis utilizes three bands (see above) and the green nadir intensity. This might have some systematic influence on the direct comparison but the overall RMSs should not be impacted; see Gehrke (2012) for further discussion.

Comparison of Individual Offsets

Out of the 51 manually derived offsets in the Lansing block, 44 are located within or near Shear Analysis patches. For those correspondences, offset differences have been computed in X, Y and Z. Respective averages, maximums and also the standard deviation of an individual difference are shown in Table 1.

Table 1. Average and maximum values as well as standard deviations of differences between manually measured and automatically computed offsets, based on 44 corresponding locations.

Difference in …	**Average**	**Maximum**	**Std. Dev.**
X [GSD]	0.03 ± 0.07	0.92	0.44
Y [GSD]	0.05 ± 0.04	0.55	0.24
Z [GSD]	0.10 ± 0.05	0.75	0.31

It can be seen that the average planimetric and height offset differences are statistically insignificant. Maximum differences are smaller than 1.0 GSD, the standard deviations are at or below 0.5 GSD for planimetry and height, respectively. These numbers represent accumulated errors from manual measurements in two overlapping data sets on one hand, and SGM and image point cloud matching on the other hand. Assuming an accuracy in the order of a ¼ pixel or 0.25 GSD on ground for human stereo point measurement (horizontal and vertical accuracy are similar with the stereo angle used here), the derived offsets feature standard deviations of 0.35 GSD. Considering the above-mentioned difference standard deviations of 0.5 GSD (or better), the accuracy of the automatically derived patch offsets is similar to the manual ones (or better). This finding agrees with other data sets discussed by Gehrke (2012). As a result, the computed offsets can be considered suitable for Shear Analysis.

Comparison of RMSs

The planimetric and height RMS offsets are a crucial part of the QC report. Aiming for automation of this QC, Shear Analysis results must be comparable to the ones currently derived from manual measurements, even though the underlying computation is carried out in a different way. Table 2 compares the overall RMS values of both methods. The numbers are in very good agreement – with differences similar to Table 1 and, accordingly, insignificant –, which confirms the feasibility of the automated Shear Analysis for QC.

Note that the large number of Shear Analysis results (722) is a clear advantage over manual measurements (51). It allows for more detailed, overlap-based analysis as discussed in the following chapter. However, the availability of only 3 or 5 manually derived offsets per overlap is not representative for statistically meaningful comparison between manual measurements and Shear Analysis for individual overlaps.

Table 2. Comparison of relative offset RMSs, manual QC vs. automatic Shear Analysis.

	Manual QC	**Shear Analysis**
Measurements	51	722
X [GSD]	0.56	0.67
Y [GSD]	0.23	0.17
Planimetry [GSD]	**0.61**	**0.69**
Height [GSD]	**0.42**	**0.38**
Overall [GSD]	0.74	0.79

Table 3. Shear Analysis summary for the Lansing block: Comparison of patch numbers and offset RMSs for Direct Georeferencing as well as aerial triangulation based on manual measurements and APM.

	Direct Georeferencing	**Triangulation (Manual Meas.)**	**Triangulation (APM-Based)**
Total Patches	808	808	808
Valid Patches	643	722	722
Success Rate [%]	79.6	89.4	89.4
X [GSD]	0.72	0.67	0.67
Y [GSD]	0.78	0.17	0.18
Planimetry [GSD]	**1.06**	**0.69**	**0.69**
Height [GSD]	**0.25**	**0.38**	**0.24**
Overall [GSD]	1.09	0.79	0.74

AUTOMATED SHEAR ANALYSIS

The automatically computed offset results and related statistics for all patches in a block are output into a single, comprehensive report. Based on that, the user is provided excerpts of different kind, in particular: detailed tabular views of all offset parameters that enable examination of the image point cloud matching; comparison of reliable offsets against Shear Analysis thresholds; summaries per image overlap as well as for the entire block; graphical outputs of patch footprints and offset vectors with attributes assigned, which allows for further analysis in commercial mapping software such as Global Mapper or ArcGIS. Such visualization is the primary tool used in the QC process – see Figures 2 and 5 for a respective overview and close-ups of the Lansing block.

In the following, we compare the results from automatic Shear Analysis runs based on three different exterior orientations, namely Direct Georeferencing and triangulation using manual measurements and APM points.

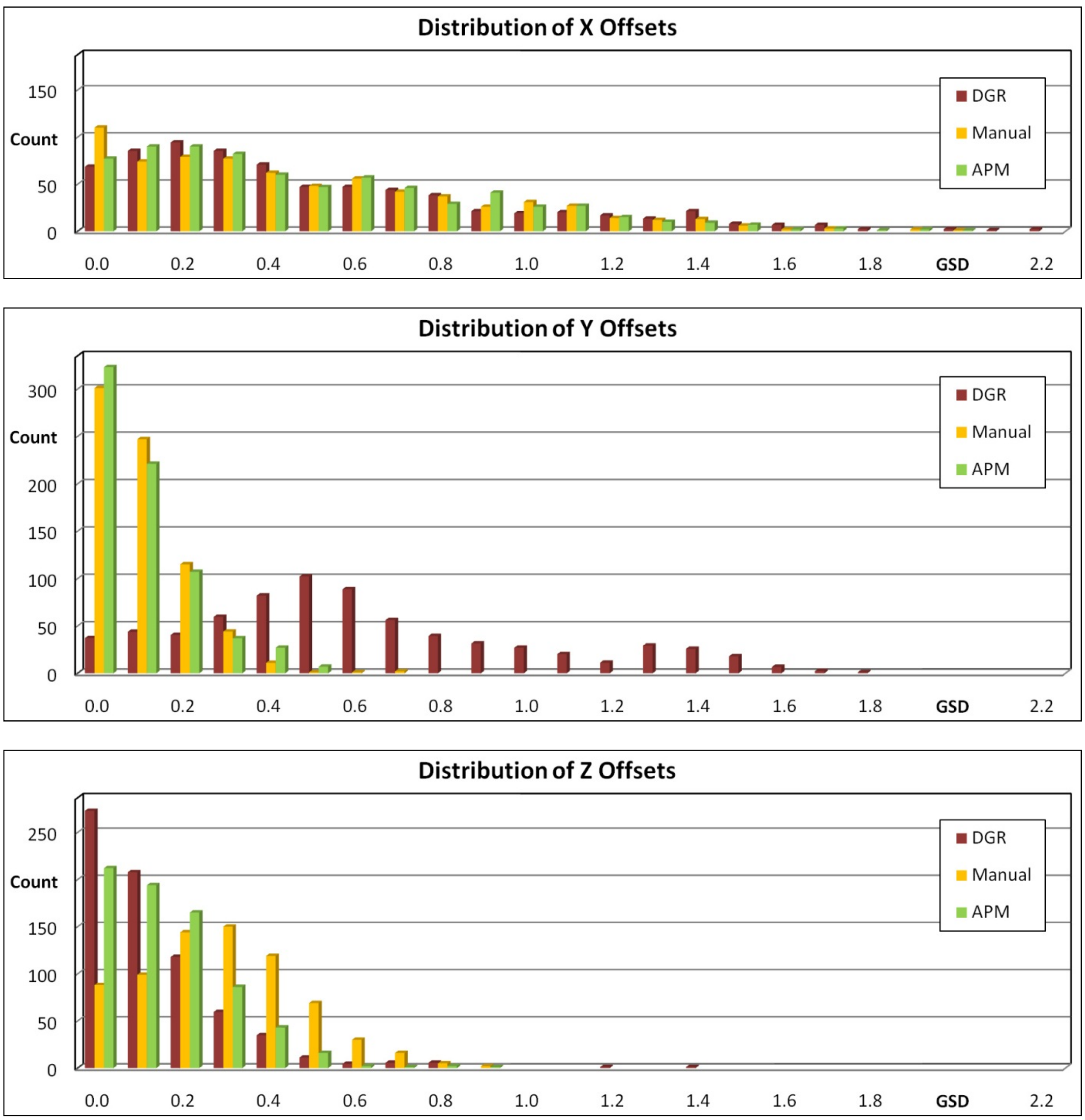

Figure 3. Offset distributions in the Lansing block; comparison for Direct Georeferencing (DGR) as well as aerial triangulation based on manual measurements and APM.

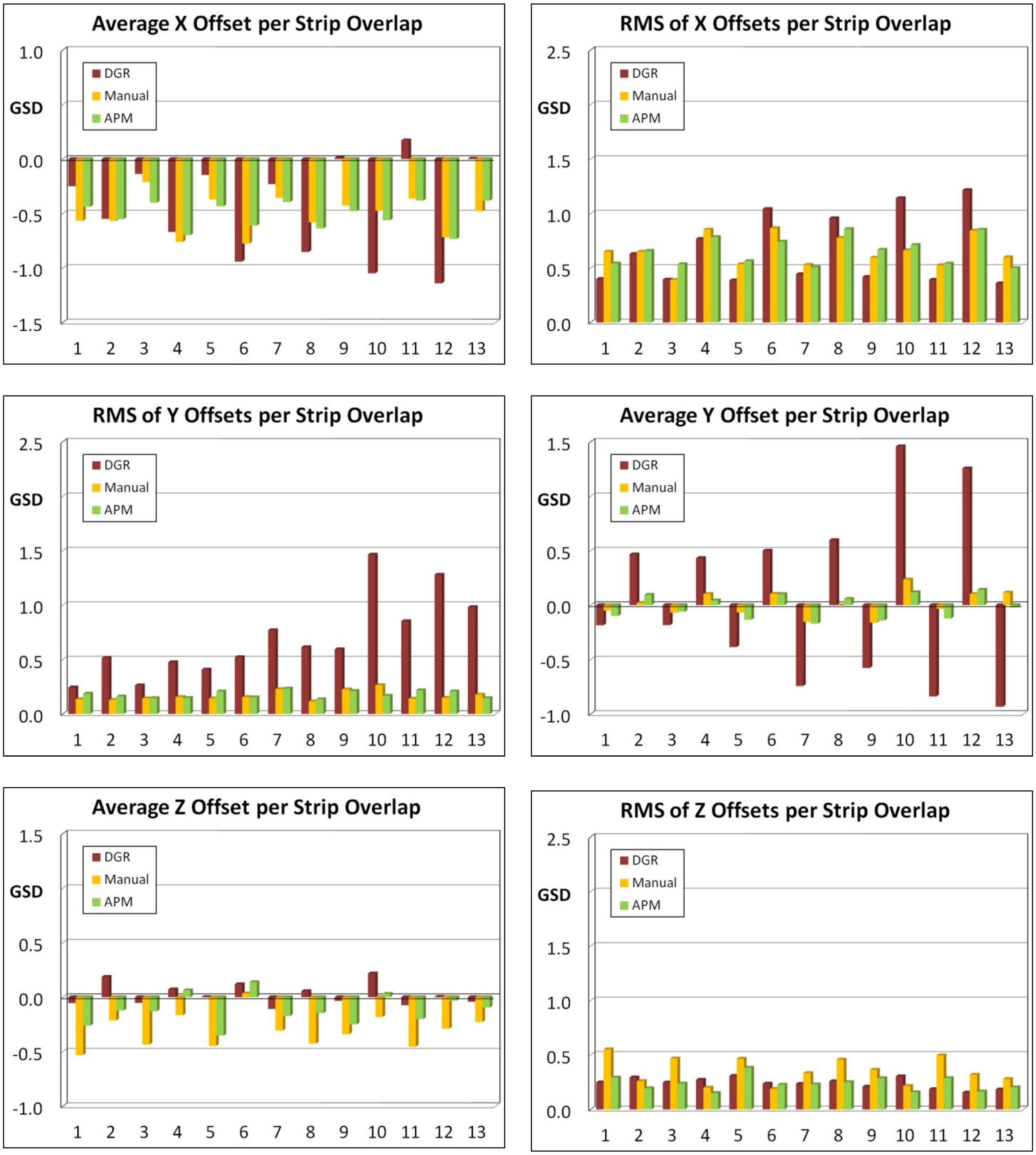

Figure 4. Comparison of average offsets and RMSs in individual strip overlaps of the Lansing block; results from Direct Georeferencing (DGR) as well as aerial triangulation based on manual measurements and APM.

Overall Block Statistics

Table 3 provides an overview of the number of patches and the resulting block RMS values as used in QC. There are two obvious differences when comparing results before and after triangulation: First, the RMSs reduce and, second, the number of valid offsets increases with triangulation.

The overall RMS reduction is a desired outcome of the triangulation and can therefore be expected. In this case, the effect is rather minor in X (approximately across flight direction) and significant in Y (approximately along flight direction), which shows the largest of all RMSs for the Direct Georeferencing case. Height RMSs are generally small and, therefore, not significantly altered. It is noteworthy that the overall accuracy from Direct Georeferencing is just over 1.0 GSD, which underlines the quality of the GPS/IMU solution. Nevertheless, it would just fail QC for this block, while the triangulation results pass; respective RMS values are significantly below 1.0 GSD. The very numbers are almost identical in planimetry, but the APM-based results show an improvement of the overall height RMS. Without aiming for a detailed analysis of the aerial triangulation in the context of this paper, it can be stated that general enhancements can be expected from the increased accuracy and amount of image points provided by APM versus human measurements as well as from the triangulation parameterization: A larger number of image points allows for more dense distribution of exterior orientation fixes, i.e. a higher degree of freedom in the line-scanner trajectory model; see Hinsken et al. (2002) for the details of the ADS adjustment approach. However, both manual and APM-based RMS values are in good agreement with the experiences from North West's ADS production work.

The overall percentage of successfully derived and validated patch offsets is large in this block; see also Figure 5 and the related discussion. The fact that the number of offsets automatically classified as valid increases after triangulation is explained by improvements in both image matching, based on the adjusted epipolar geometry, and image point cloud matching, due to smaller geometric offsets. The exact agreement of valid patches in total between triangulation results based on manual measurements and APM is coincidence. In fact, there are a few differences in the validity of individual offsets.

Figure 3 illustrates the distribution of all offsets in the block. Similar to the RMS comparison in Table 3, the major improvement of the triangulation is immediately obvious in Y direction. Furthermore, it can be seen that the maximum offsets are reduced in all directions, even for heights for which the block RMS does not improve over Direct Georeferencing. Comparing the two triangulation results, the gain of APM – in combination with the adapted triangulation approach as mentioned above – over using manual measurements is most visible in the distribution of relative height offsets.

Analysis of Individual Overlaps

The large number of valid patches provided from the automatic Shear Analysis allows for more detailed investigation, namely the evaluation of individual overlaps as shown in Figure 4. Again, the significant reduction of offsets in Y stands out. But the overlap-based analysis also reveals a pattern in the Direct Georeferencing results, predominantly due to some variation of the initial heading angle (kappa); this issue was corrected by the triangulation. Looking at the X direction, it can be seen that the triangulation levels offsets throughout the block: Larger averages, and accordingly RMSs, per overlap decrease significantly while initially smaller ones increase somewhat, going along with a slight overall reduction as discussed in the previous section. This harmonization is strongest for the APM triangulation – despite the overall block RMS in X being identical for offsets based on APM and manual measurements (cp. Table 3). The relative height offsets are essentially shifted between the two triangulation results, with APM – again, in combination with the adapted adjustment model – leading to smaller discrepancies.

This detailed analysis is expected to assist not only in the very QC process but also in the general analysis of image orientation parameters and aerial triangulation behavior. Because the required amount of measurements would turn such detailed analysis into unjustifiable effort within the traditionally manual QC process, it can only be carried out as part of the new automated Shear Analysis.

Shear Analysis Performance on Different Terrain

The success rate of the SGM-based image point cloud collection and subsequent geometric/radiometric image point cloud matching is strongly dependent on the image content – i.e., on the sensor, illumination and viewing geometry and especially terrain properties and their variation within a patch. This is influenced by a multitude of factors and the interaction of which is highly complex. However, image matching requires intensity gradients and, in addition, the image point cloud matching benefits from height gradients. Furthermore, the surface approximation by local planes must be valid. Based on those theoretical considerations as well as practical tests on real-world data, different types of terrain can be characterized regarding the Shear Analysis success.

So far, we investigated the Shear Analysis performance on a number of ADS blocks from North West's production that predominantly include mountains, urban/suburban areas and forests. Mountainous terrain inherently features significant height and intensity gradients, which leads to a high percentage of reliable offsets, with results for 80-90% of the patch locations. The success rate in urban areas can range widely, 60-90%. The same holds true for forests, where it is generally lower, in the order of 20-50%. The main issue, especially in higher vegetation such as trees, is its representation by essentially scattered points, which impacts or even invalidates the approximation by local planes. The matching can be expected to fail on water, but see below.

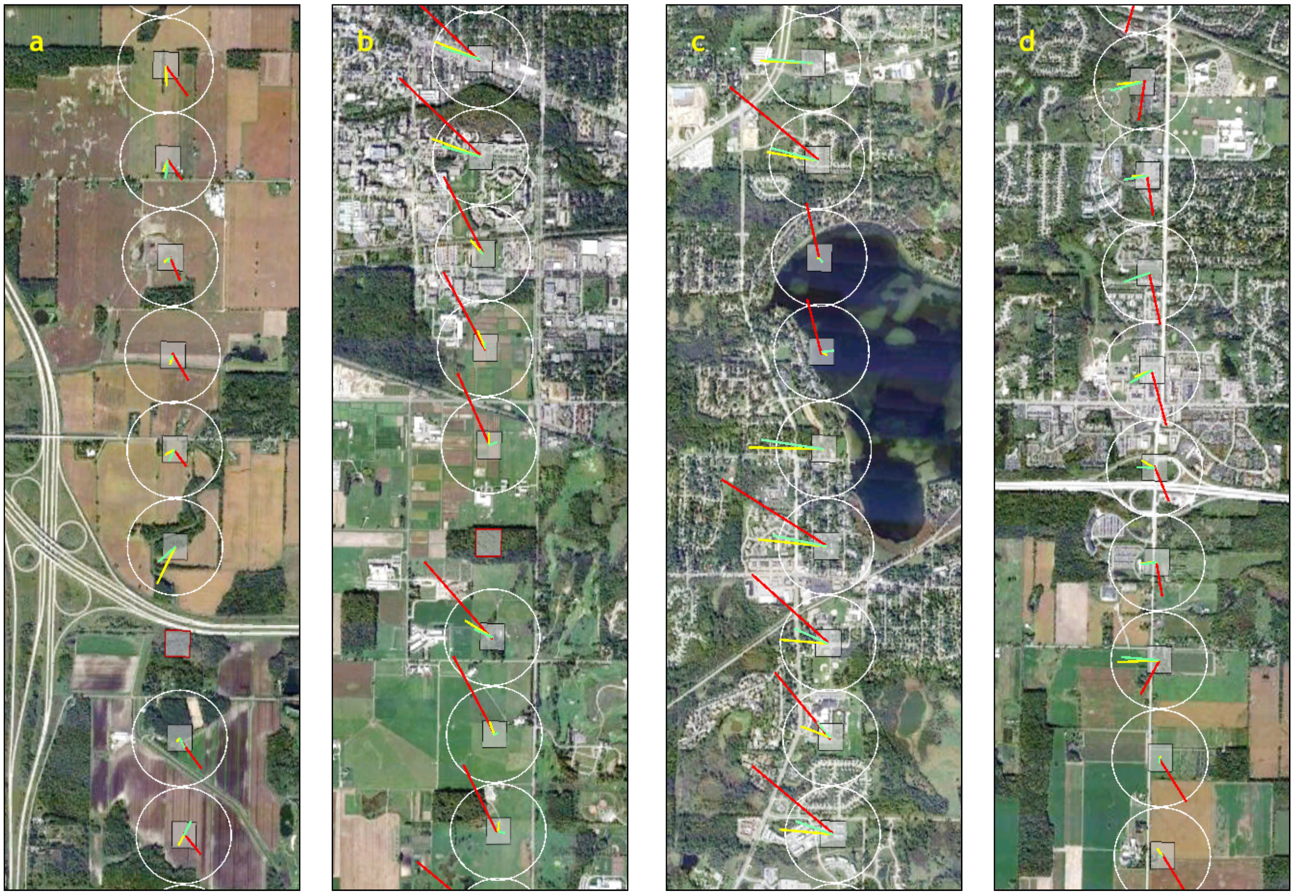

Figure 5. Shear Analysis in different terrain and overlaps, left to right: a) strips 009/010, b) strips 010/011, c) strips 012/013, d) strips 011/012; see Figure 2 for locations in the Lansing block. Planimetric offset vectors are shown for Direct Georeferencing (red) and triangulation results using manual measurements (yellow) and APM (green). Offsets are scaled with a factor of 1000; white circles indicate 1 GSD. Invalid patches are shown in red.

The Lansing block discussed in this paper achieved generally high success rates (Table 3), based on its diverse, urban landscape and small fields; it contains no larger forests or water bodies. The benefit from using radiometric information is indicated by the successful offset computation for a large amount of patches, especially visible in Figures 5.a and 5.b, in which a number of apparently flat fields, some even with little texture, provide correct results.
The same figures show two patches that are entirely made up of dense forest, where the computation failed to deliver reliable offsets. In both cases, only a slight shift of the patch location – to include a clearing, a field or the highway – would very likely improve that situation.

Finally, the two neighboring patches within Lake Lansing (Figure 5.c) require to be discussed here. Based on some ground visibility, image point cloud collection and subsequent matching were obviously successful. There are in fact not even indications of potential issues but, despite that, the resulting offsets are approximately 1.5 GSD off in X direction compared to neighboring patches – and that is the case for all three configurations. The explanation for this systematic difference is the observation of the lake ground being impacted by refraction at the water surface. Knowing the imaging configuration, we can even estimate the lake's depth at about 2 m, which is very reasonable. Nevertheless, the contribution of such offsets to Shear Analysis is wrong and they should be eliminated.

CONCLUSION AND OUTLOOK

We have presented a new approach of automating QC of the georeferencing of Leica ADS data, based on the combined geometric/radiometric matching of photogrammetrically derived, dense image point clouds. Such a Shear Analysis approach has significant advantages over the traditionally manual QC, first of all its automation. Based on that, a significantly larger number of samples can be utilized to enable a more sound and more detailed analysis – such as the evaluation of individual image overlaps. It has been shown, that the accuracy achieved by the automatic Shear Analysis is at least as good as the manual process; results are in good agreement for a number of data sets including the ADS block of Lansing, Michigan, which is discussed in detail in the context of this paper. In conclusion, the automated Shear Analysis allows for more reliable and more thorough QC and is expected to become a beneficial tool beyond (current) QC requirements. Even though it has been demonstrated with ADS line-scanner data in this paper, the principle can be applied to any stereo imagery including frame data.

The discussion of the Shear Analysis performance in different terrain suggests two improvements of our approach. First, the patch selection would benefit from using an interest operator that provides a measure of suitability for both image matching and image point cloud matching. In many cases, only slight variations of the currently fixed patch location pattern would be required so that the overall patch distribution remains even. Second, water areas should be eliminated up-front, based on water masks and/or an NDVI classification, which saves computation time and prevents from erroneous input for Shear Analysis.

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