QUANTIFICATION OF TURBULENCE FOR AIRBORNE LINE-SCANNER IMAGES

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ABSTRACT

Line-scanner sensors acquire image data during a continuous scan of the terrain. In the airborne case, this record is exposed to and, therefore, sensitive to atmospheric turbulence. Even though the corresponding observation geometry is well-known from GPS/IMU data, heavy turbulence may degrade the image quality. In order to provide high quality products, potential issues need to be reliably discovered – as early as possible.

This paper describes and illustrates parameters that quantify atmospheric turbulence and its impact on image data and products: A parameterization of the line-scan itself, the Normalized Coverage Speed (NCS), is derived from ground projections of neighboring scan-lines. With regard to image quality, potential smearing is localized from the relation between actual and desired pixel footprints, the Pixel Smear Ratio (PSR). The (perceived) Relative Pixel Error (RPE) and, based on that, the occurrence and also the dimensions of turbulence-related artifacts in rectified imagery are predictable based on the projection geometry and rectification height.

These quality parameters are computed very early in the work-flow, along with other sanity checks. They can be plotted co-located with raw or rectified imagery in the XPro Viewer and considerably assist quality control. They will be part of future releases of the Leica XPro software package.

KEYWORDS: Pushbroom, Orientation, Analysis, Accuracy, Quality

MOTIVATION

Airborne line-scanner (or push-broom) images acquired with Leica Geosystems' ADS are commonly used in the mapping industry. Such data are the result of a continuous ground scan along the flight path. Raw images consist of hundreds of thousands of individual scan-lines, all of them featuring their own exterior orientation, which continually changes according to the aircraft movement through the atmosphere. This scanning process is sensitive to atmospheric turbulence, even though the ADS is always flown with an active mount that damps most of it. The (remaining) impact will be visible in the acquired raw images. However, the exterior orientation parameters (EOP) for ADS data are well-known, based on high-frequency GPS/IMU measurements. Virtually all sensor movement is recorded in the EOP and, accordingly, the ADS sensor model provides the geometrically correct solution for any transformation between ground and image coordinates, even in cases of heavy turbulence. This means that geometric distortions perceived in the raw data can be fully corrected in the ortho-rectification process. Nevertheless, in the event the actual (local) ground scan deviates substantially from the planned ground sampling distance (GSD) or the scan is momentarily jerked backwards, products derived from such data might show radiometric degradation such as smearing or artifacts. These effects need to be discovered and also quantified as early as possible in the processing chain to save time and costs and, if necessary, to call re-flights in a timely manner.

Unfortunately the influence of atmospheric turbulence on any derived product cannot be classified based on raw images or by orientation analysis for several reasons. Firstly, position and attitude consist of altogether six parameters; the interaction of which is not immediately apparent. Secondly: the EOPs provide a record of the sensor movement but do not describe the actual ground coverage. Finally, the impact of turbulence on a certain product depends on the terrain elevation in combination with various specifications. In that regard we have researched parameters to describe the scan and, most important, the quality of derived image products. Such parameters are required to allow for a reliable discrimination of turbulence that degrades image quality, so that line-scanner data set can be automatically classified and an operator can be pointed directly to problematic areas.

The remainder of this paper starts with a review of the line-scanner principle as well as image and product properties, specifically under the influence of atmospheric turbulence. Based on that, the newly developed quality parameters and their usage for quality control are described. Example imagery and corresponding parameter plots are shown for a typical (fairly) smooth flight and for a data set that shows some – in parts exceptionally heavy – turbulence impact.

LINE-SCANNER GEOMETRY IN ATMOSPHERIC TURBULENCE

The focal plate of the ADS consists of various CCD lines with different band filters, arranged in several groups to provide stereo ability, in case of the ADS80: three panchromatic lines in nadir, forward and backward views as well as two groups of NRGB color lines in nadir and backward views; cp. Fuchs & Adigüzel (2010) for details and calibration. During the continuous scan, data for all these bands are jointly accumulated (with up to 833 single-line frames per second in the case of the ADS80) into a product referred to as a 'take'. This leads to central perspective within scan-lines and parallel projection (disturbed by turbulence) in flight direction. The in-line GSD depends on flight altitude and can be in the order of 3 cm to 1 m. The in-flight GSD is determined by the flight speed and the exposure (integration time) and is usually adapted to be consistent with the in-line GSD; however, under- or oversampling is possible. The exterior orientation parameters are computed from joint GPS/IMU processing as described by Sun et al. (2006); they can be improved by triangulation (Hinsken et al., 2002). The line-scanner geometry is well-understood and reflected in the highly-optimized ADS sensor model, which has been co-developed by the authors. See Sandau et al. (2000) and Hisken et al. (2002) for further description of the ADS geometry and scan principle.

Radiometric properties of the acquired raw data depend on the imaging configuration. Final products undergo sophisticated radiometric processing including atmospheric and BRDF corrections (Downey et al.). Geometric anomalies caused by atmospheric turbulence might degrade the image product radiometry, resulting in irreparable smearing or artifacts. This depends largely upon the type of product and its geometric specifications.

Geometric Properties of Line-Scanner Images and Derived Products

A raw level-0 (L0) line-scanner image is merely a collection of scan-lines (exposures) from a certain CCD. Due to the aircraft/sensor movement in the atmosphere and the resulting ground coverage, this kind of image appears distorted (wavy). The L0 imagery is not intended for direct viewing by an operator.

The vast majority of these raw data distortions including possible under- or oversampling is removed by the rectification to a plane at the mean terrain height, which is defined as the level-1 (L1) product. It can be thought of as the result of an ideal, turbulence-free, linear scan. Similar to a classical frame image, the remaining geometric "distortions" are parallaxes that originate from different terrain elevation and object heights. Accordingly, L1 images from different viewing angles are used for stereo-photogrammetry, including manual measurements as well as the automatic terrain extraction as described, e.g., by Gehrke et al. (2010). L1 data from different CCDs of the same group – i.e., with very similar viewing angles – can be rectified to the same band geometry and combined to generate RGB or FCIR color products.

Level-2 (L2) images are based on ortho-rectification using a Digital Elevation Model (DEM) or Digital Terrain Model (DSM). This allows not only for the combination of any bands – even though color products are typically generated from CCDs of the same group – but also for mosaicking across overlapping takes.

Turbulence Impact

Atmospheric turbulence, even though damped by the senor mount, may result in immediate changes of the sensor position and attitude, with an angular speed being the dominant cause of undesired inhomogeneous ground coverage. There are essentially two kinds of impacts on derived products: smearing and artifacts; the latter often in conjunction with the first.

Smearing can result from any fast movement of the line-scanner during an exposure, which results in an increase in the raw pixel footprints. Eventually during L1/L2 generation several (smaller) product pixels are rectified from the same or, considering the bilinear interpolation in the input data, similar input. This ambiguity will blur the derived image in the respective location.

Artifacts can be caused by the scan intermittently moving backwards, e.g. due to a fast decrease of the pitch angle. Figure 1 illustrates such an event of very heavy turbulence, resulting in triple ground coverage: The area in-between a start point S and an end point E is first covered forward ($S^1 – E^1$, often along with temporarily increasing pitch), then backward ($E^2 – S^2$, due to fast decreasing pitch), and finally forward again ($S^3 – E^3$, under increasing pitch). Since the terrain is fully covered with imagery and the sensor movement is recorded in the EOP, it is still possible to ortho-rectify and generate a geometrically correct and – depending on the severity of the turbulence event – radiometrically acceptable L2 image. Due to the implementation of the iterative computation in the ADS sensor model, the image content results from forward coverage only; at some position P the data will seamlessly switch from the first to the third raw coverage – with parts of the L0 data (including the backward movement) unused. This situation changes with any rectification to an elevation different from the surface such as the L1 plane as shown in Figure 1. In case of a rectification height above ground, the point P will appear twice (from P^1 and P^3) and the terrain is fully covered – but spatially compressed – outside these spots. The gap in-between is filled with a repetition of the neighboring, already covered surface (although from different raw data), causing an artifact either in P^1 or in P^3. A similar artifact occurs for rectification heights below ground, but coverage is missing in that case. Depending on the accuracy of the DSM/DEM used for ortho-rectification and the size of the raw data to be skipped, artifacts might also occur in L2 products but at a smaller scale.

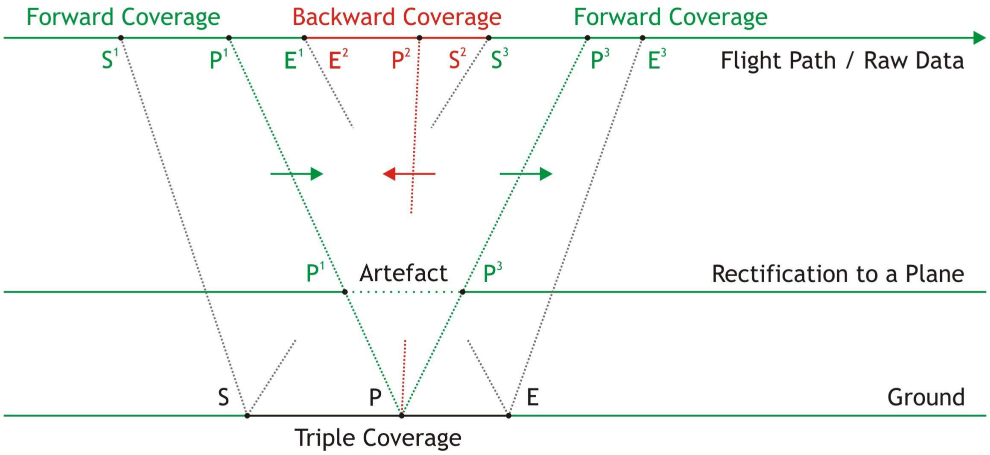

Figure 1. Line scan geometry in an event of heavy turbulence that leads to triple ground coverage.

QUANTIFICATION OF TURBULENCE

The exterior orientation reflects all atmospheric turbulence of an imaging flight. Therefore, the EOP will clearly indicate events of turbulence and potential issues in the data. As mentioned in the motivation of this paper, this indication is not straightforward, and a proper quantification of the turbulence impact needs to consider the terrain as well as product specifications. Respective parameters are obviously based on the exterior but also on the interior orientation (sensor calibration). For the flight analysis along with the EOP, the parameters are computed in the EOP frequency or the scan frequency (usually higher). If desired all parameters can be projected into a particular product coordinate system and displayed with that imagery (see following chapter on quality control).

Exterior Orientation Parameters (EOP) and Angular Speed

All sensor movements including atmospheric turbulence are recorded in the exterior orientation. An EOP set at a given location consists of six parameters: the sensor position (X, Y, Z) and attitude (roll, pitch, yaw). The predominant effects of turbulence factors are changes in attitude – so it can be discovered by analyzing the angular speed. A fast decreasing pitch might result in backward coverage; similarly a yaw rotation can cause effective backward scan on one side of the take in connection with a fast forward move on the other. Such increased ground coverage speed as well as roll rotations tend to cause smearing in products but do not quantify it, because the interaction of the three angles is not intuitive and, more important, the amount of smearing depends on product specifications. Similarly, artifacts that generally result from backward coverage might or might not actually occur in products, mainly depending on the rectification height as shown in Figure 1.

The EOP – and especially the angular speed – will show a certain correlation with the parameters described in the following. They can be surely utilized to guide a user to potential issues but they might result in false positives. The angular speed is already analyzed in XPro DataPrep to issue warnings on turbulence.

Normalized Coverage Speed (NCS)

With the goal of combining the EOP parameters and provide a single parameter that indicates actual ground coverage, each EOP set is projected onto the ground by computing object coordinates for the outermost pixels of a nadir scan-line – i.e., the edge of an image take –, where the impact of sensor movements is maximal. Based on that, the Normalized Coverage Speed (NCS) is the first derivation of the in-flight position, i.e. the distance d_{L2} between neighboring scan-line projections relative to the average in-flight distance d_{EOP} between subsequent EOP sets. Computations are carried out for the left and the right side of the image:

$$NCS^{left,right} = \frac{d_{L2}^{left,right}}{d_{EOP}}$$

A smooth flight will result in NCS ~ 1 throughout; large speeds correspond to (too) fast forward coverage and negative values to backward movement on ground, usually in connection with the fast forward coverage before and/or afterwards. A single NCS parameter per EOP set needs to reflect the extreme case, i.e. the largest deviation from a uniform coverage. However, any occurrence of backward coverage should be indicated, even if it goes along with faster forward coverage at the opposite edge, as it can be caused by fast yaw rotations. This leads to:

$$NCS = \begin{cases} \min\left\{NCS^{left}, NCS^{right}\right\} & \text{if } NCS^{left} < 0 \text{ or } NCS^{right} < 0 \\ \max\left\{\left|NCS^{left} - 1\right|, \left|NCS^{right} - 1\right|\right\} + 1 & \text{otherwise} \end{cases}$$

The NCS is a straightforward description of the flight and will reveal turbulence but, similar to the EOP, it is not suited to classify the derived imagery.

Pixel Smear Ratio (PSR)

Heavy turbulence might cause coverage changes or accelerations in any direction, both along and across take, which leads to smearing. The reason is that the footprint of a certain exposure differs from the desired area. Since the intensity of such a raw pixel contributes to all product pixels that intersect with it, a distorted and/or enlarged footprint will result in identical or similar intensities in the product and may cause smearing, depending on the local entropy of intensities. A quantification of this smearing can be derived from the fraction of a raw pixel that is not part of the expected coverage (thus not the desired radiometry). The expected coverage is determined by the product pixel, presumably the squared across-flight GSD area $A_{GSD.}$ Areas outside that product pixel, A_{Smear}, contribute to smearing (Figure 2). This is mathematically expressed by the relation of these areas, the Pixel Smear Ratio (PSR). The PSR is computed similar to the NCS, based on ground projections of neighboring scan-lines on the left and right edges, and the final parameter is retrieved from the maximum smear:

$$PSR = \max\left\{PSR^{left}, PSR^{right}\right\} = \frac{\max\left\{A_{Smear}^{left}, A_{Smear}^{right}\right\}}{A_{GSD}}$$

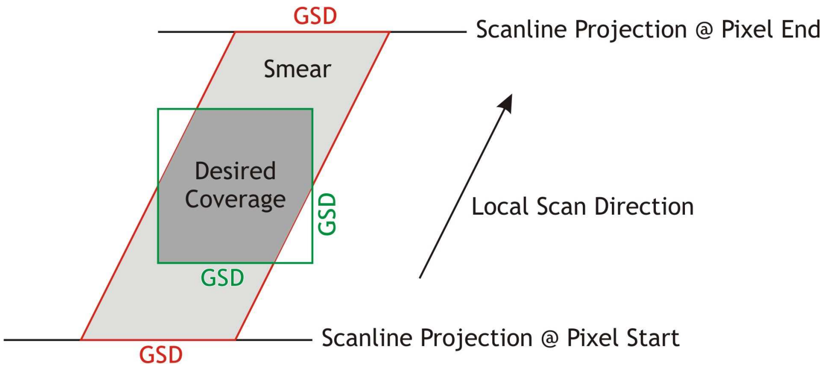

Figure 2. Visualization of the PSR: Schematic ground projections of the expected and actual pixel footprints.

The resulting values are inherently positive. PSR ~ 0 indicates no turbulence-related smearing and, in that regard, sharp image products. Increased PSRs suggest smearing issues; PSR ≥ 1 is a suitable warning threshold, since the majority of the product pixel radiometry originates from undesired coverage in that case.

Note that there is no smearing issue if the raw pixel is smaller than the final pixel, which is the case in temporary slow forward coverage or general oversampling. Vice versa, in the (rare) case of undersampling the PSR will point towards a general level of blurring. The PSR is often correlated with the NCS, essentially because the in-flight component of the PSR is identical with the NCS for perfectly smooth flights that are neither under- nor over-sampled, i.e.: PSR = NCS – 1 = 0. Practically there are distinct exceptions – especially in heavy turbulence; in particular: oversampling, where NCS > 1 does not cause smearing as long as the instantaneous in-flight GSD is below the across-flight GSD, or immediate roll moves that are not reflected in the NCS (cp., e.g., Figure 6).

The PSR as described classifies an L2 image in the resolution of the (average) across-flight GSD. It would be possible to compute the PSR for any product. However, while product GSDs other than the nominal value change desired pixel footprints/areas, it can be assumed that the impact is rather small – in terms of missing severe smearing in any product by computing a single, generalized PSR. It should be possible to judge (unusual) products of very different GSD using adapted thresholds.

Relative Pixel Error (RPE)

Heavy turbulence that causes backward coverage will result in image artifacts if the rectification elevation is off the surface, which is unavoidable in L1. Those artifacts are visible as double coverage in case the elevation is too high and missing coverage if it is too low (cp. Figure 1). A quantification of the double or missing coverage – or, more general, of relative errors in pixel or, respectively, projected scan-line positions – can be achieved from comparing the actual ground coverage to the corresponding coverage in the (plane-)rectified product. The difference indicates the relative offset in-between L1 image pixels, which originates from turbulence but also from variations in terrain elevation that result in image parallax; the latter of which influences must be excluded from the computation of the Relative Pixel Error (RPE) – the parallax is no error but desired, at least in a plane-rectified stereo product.

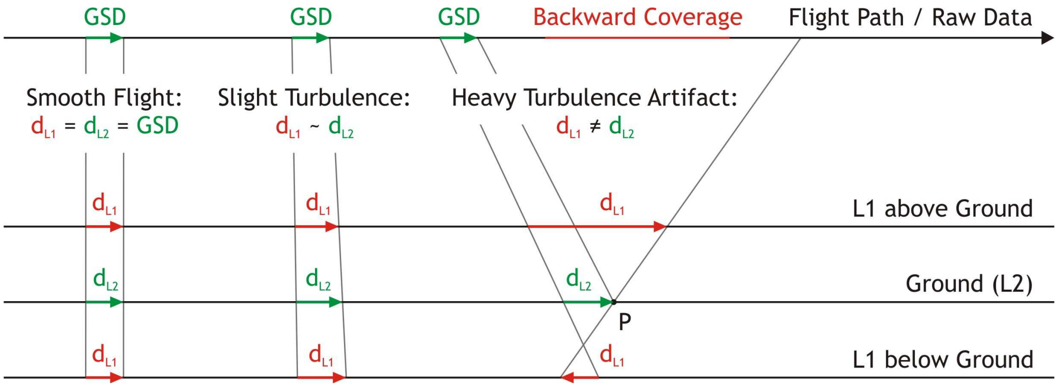

Figure 3. RPE geometry in different events of turbulence. See also Figure 1.

The RPE computation needs to resemble the rectification process, which is indirect for ADS data processing with Leica XPro, i.e. based on ground-to-image projections. Nevertheless, in order to derive an EOP-conformal parameter – including backward coverage and data next to it –, the computation is initialized from ground projections of a parallax-free, nadir scan-line in equidistant steps of the L1 GSD (= across-flight). Based on that, the rays for neighboring ground pixels (L2) are reconstructed by indirect rectification, and their intersections with the rectification surface (L1) are computed. Note that those ground-to-image rays differ from the image-to-ground initialization in and around backward coverage, starting in some position P (cp. Figure 1) as illustrated in the right part of Figure 3. The RPE is the location error of a product pixel or local scan-line projection relative to its neighbor, which corresponds to the difference between the ground distance d_{L2} and the corresponding product distance d_{L1}, normalized with the GSD. Since the RPE depends on turbulence as well as on the elevation difference between ground and rectification surface, it should be sampled at a reasonable spacing in the scan-line – e.g. every 1000 pixels, with the two edges being the minimum configuration where the turbulence impact is maximal. This results in n RPEs per scan-line:

$$RPE^{i} = \frac{d_{L1}^{i} - d_{L2}^{i}}{GSD} \quad i = 0,1,\ldots,n$$

Such location-dependent RPEs provide a two-dimensional quality map for an image product. However, the maximum per scan-line is considered as useful and is preferred as a single along-take quality measure for the analysis along with the EOP and other quality parameters:

$$RPE = RPE^{max} \quad \left|RPE^{max}\right| = \max\left\{\left|RPE^{0}\right|, \left|RPE^{1}\right|, \ldots, \left|RPE^{n}\right|\right\}$$

The RPE is generally very close to 0, even in atmospheric turbulence. Only in cases of backward coverage, it describes the size of the resulting artifact, with RPE < 0 for missing data in case of a rectification height below ground and RPE > 0 for the duplication of content in case of a rectification height above ground (Figures 1 and 3).

It should be theoretically possible to quantify an L1 stereo pair in a similar way than the RPE. Such a Relative Stereo Error (RSE) would need to regard RPEs over a certain window – that depends on the stereo viewing setup – and to combine the individual image parameters in some way. However, this potential parameter is not further discussed here. In general, it can be assumed that the stereo impression is disturbed where the PSR indicates issues in one (or both) of the images, especially in case of a larger artifact.

USAGE OF TURBULENCE MEASURES FOR QUALITY CONTROL

The ADS data processing chain goes along with quality control (QC), starting with the verification of the acquired data. This is a two-fold process: At the download and geo-referencing steps, the raw imagery and metadata are automatically checked for completeness and sanity, e.g. against turbulence thresholds (so far, based on angular speed). Once set up for viewing and further processing, all imagery is interactively checked for correct exposure, the presence of clouds or atmospheric haze and turbulence-related issues. This imagery should be as close as possible to the finals products in terms of the occurrence of potential errors. QC is therefore carried out using the XPro Viewer with L1 on-the-fly (L1 OTF) and/or so-called 'Quick L2' images, which are rectified in connection with the geo-referencing step; they are geometrically based on a coarse, worldwide DEM (gTopo) and the original (non-triangulated) orientation and use a simple radiometric correction function.

The new parameters NCS, PSR and RPE are currently integrated into the QC process. They are automatically generated along with the geo-referencing in XPro DataPrep. In addition to the already existing verification of the angular speed, warnings and error messages are now issued in case of exceeded turbulence parameter thresholds, which are still to be refined based on testing and usage in production. Obviously, any backward moving ground coverage is a warning case, indicated by NCS < 0. Errors are extreme turbulence impacts, such as larger L1 artifacts where |RPE| > 1 pixel. Based on that, ADS takes are automatically classified by turbulence issues in a traffic light manner, i.e. as (potentially) good (green), data with warnings (yellow), and the occurrence of errors (red).

The Leica XPro OrientationPlot tool has been extended by the quality parameter plots and respective numerical displays to enhance the possibilities for the detailed orientation analysis. Each EOP set is assigned with its corresponding NCS as well as PSR and RPE data, which are down-sampled to the usually lower EOP frequency by assigning their maxima within each EOP interval.

Most beneficial for the QC process is the integration of the XPro Viewer with the OrientationPlot as shown in Figure 4. Loading a recording session into the XPro Viewer, the take names will be colored based on the traffic light classification, so that warnings and error cases are immediately visible. If desired, the respective EOP and quality parameters can be plotted and, moreover, co-located with the image, e.g. L1 OTF. The display of potentially disturbed image areas can be triggered with a single mouse click instead of scrolling through hundreds of thousands of image lines, because smearing and artifacts need to be verified at full resolution. The search for clouds and such has to be carried out regardless but can be performed in a minification level, which is much faster.

EXAMPLES

For the vast majority of ADS imaging flights, the atmospheric turbulence is low, i.e. negligible in terms of its impact on the imagery and derived products. One of such examples is an ADS40 data set from the municipality of

Level: L1 Product: RGB

Apply Correction: Calibrated

- 20100124160136_30103
  - 048_103_100124_1925_
  - 049_103_100124_1717_
  - 049_103_100124_1909_
  - 050_103_100124_1650_
  - 051_103_100124_1622_
  - 117_103_100124_1900_
  - 118_103_100124_1855_
  - 119_103_100124_1849_
  - 120_103_100124_1843_
  - 121_103_100124_1837_
  - 122_103_100124_1832_
  - 123_103_100124_1826_
  - 124_103_100124_1819_
  - 125_103_100124_1813_
  - 126_103_100124_1808_
  - 127_103_100124_1802_
  - 128_103_100124_1756_
  - 129_103_100124_1750_
  - 130_103_100124_1744_
  - 131_103_100124_1738_
  - 132_103_100124_1733_

X:548684.640 metres, Y: 3250488.873 metres, Z: 171.767 metres. Sample: 6741.61, Line: 9221.67. Magnified: 1x Pixel: 771 851 749

UTM_14N

EOP: D:/testdata/L0_data/L0_data_10/10-700_TNRIS_SAN_ANTONIO/Released_to_AT/20100124160136_30103/raw/127_103_100124_1802_.eop

t: 64977.9685 s
NCS: 3.013
RPE: -0.113
PSR: 2.130

Quality

☑ Normalized Coverage Speed (NCS) ▨ (NCS exceeds predefined error limits)

☑ Relative Pixel Error (RPE) in L1 🟧 (RPE exceeds predefined error limits)

☑ Pixel Smear Ratio (PSR) 🟩 (PSR exceeds predefined error limits)

Display Scaling

☐ Automatic

Upper 4.500

Lower -3.500

GPS Time: 64977.9685s

☑ Sync with View

Figure 4. Corresponding L1 image in the XPro Viewer and quality parameters in the OrientationPlot in synchronized location (but different in-flight zoom) at the maximum of a smeared area (PSR > 2); right next to it a cluster of artifacts, caused by several backward movements (NCS < 0) and correctly indicated by the RPE.

Romanshorn, Switzerland, with a GSD of 10 cm. The parameters as plotted in Figure 5, top, are very close to their ideal values: $\mathrm{NCS} \sim 1$ ($0.8 < \mathrm{NCS} < 1.2$), $\mathrm{PSR} < 0.2$ and $|\mathrm{RPE}| < 0.05$, which confirms the smoothness. Accordingly, the corresponding imagery, which is not shown here, has no turbulence-related radiometric issues at all; it has been used as a reference data set for various investigations for more than four years.

We have no statistics about the amount of data sets that are impacted by heavy turbulence – neither in general nor for North West Geomatics' production –, which emphasizes that those flights are very rare. But they do happen, and the main driver for this investigation has been a data set acquired by North West with an ADS80 in the area of San Antonio, Texas; with imagery acquired at a GSD of 15 cm (a typical county mapping project). A number of takes has been impacted by partial heavy turbulence. A particularly bad session, for which a few re-flights had to be called, is discussed in the following. The XPro Viewer in Figure 4 provides the corresponding list of all image takes with traffic light classification; quality parameter plots for two examples with smearing and artifacts are shown in Figure 5.

Figure 5. Quality parameter plots for entire ADS takes with different atmospheric turbulence: NCS (grey), PSR (green) and RPE (orange) as functions of GPS time. Top: Romanshorn 10 cm, take 957, with very low turbulence. Middle: San Antonio 15 cm, take 050, with generally little turbulence but one event of smearing ($\mathrm{PSR} \sim 3$). Bottom: San Antonio 15 cm, take 050, with a few cases fast forward coverage ($\mathrm{NCS} > 2$) and backward moves ($\mathrm{NCS} < 0$), corresponding artifacts ($|\mathrm{RPE}| > 0$) and a little bit of smearing ($\mathrm{PSR} \sim 1.5$).

Smearing

The quality parameters for the San Antonio take 050 (Figure 5, middle) indicate fairly low turbulence for almost all of the flight but a distinct spike at GPS time 61,432 sec, where the PSR ~ 3 points to a smearing issue. The respective L0 and L1 image sections from about 500 scan-lines as well as the corresponding parameter plots are shown in Figure 6. This part of the flight can be divided into three sections: a smooth start (~ 100 pixels), the immediate roll event (~ 300 pixels) and finally a somewhat turbulent part (~ 100 pixels). Eventually the sensor rolls back, but not quite as fast as in this example.

The smooth section is confirmed by the NCS ~ 1 and negligible PSR and RPE. The L0 image shows very little geometric distortion, the L1 none at all; it appears sharp. The roll rotation causes the ground coverage to shift by more than 900 pixels leftwards (relative to the flight direction) within just 300 pixels in flight, resulting in a heavily distorted L0 and ground coverage with skewed pixel footprints. The L1 rectification removes these distortions but shows smearing, which is very strong at PSR ~ 3 and still recognizable for PSR ~ 1.5. As this issue is predominantly caused by the roll, the in-flight coverage speed is fairly regular (NCS ~ 1) and, accordingly, there are no artifacts in the L1 product (PSR ~ 0). The last part in Figure 6 shows still some turbulence impact (PSR of ~ 0.5), which causes geometric distortions in L0 but is invisible in L1.

Note that the L1 geometry is correct throughout the example; the building edge and shadow are straight lines, even for the heavily distorted areas in L0. This would be the case for an L2 product as well. However, it would also show the smearing in identical areas.

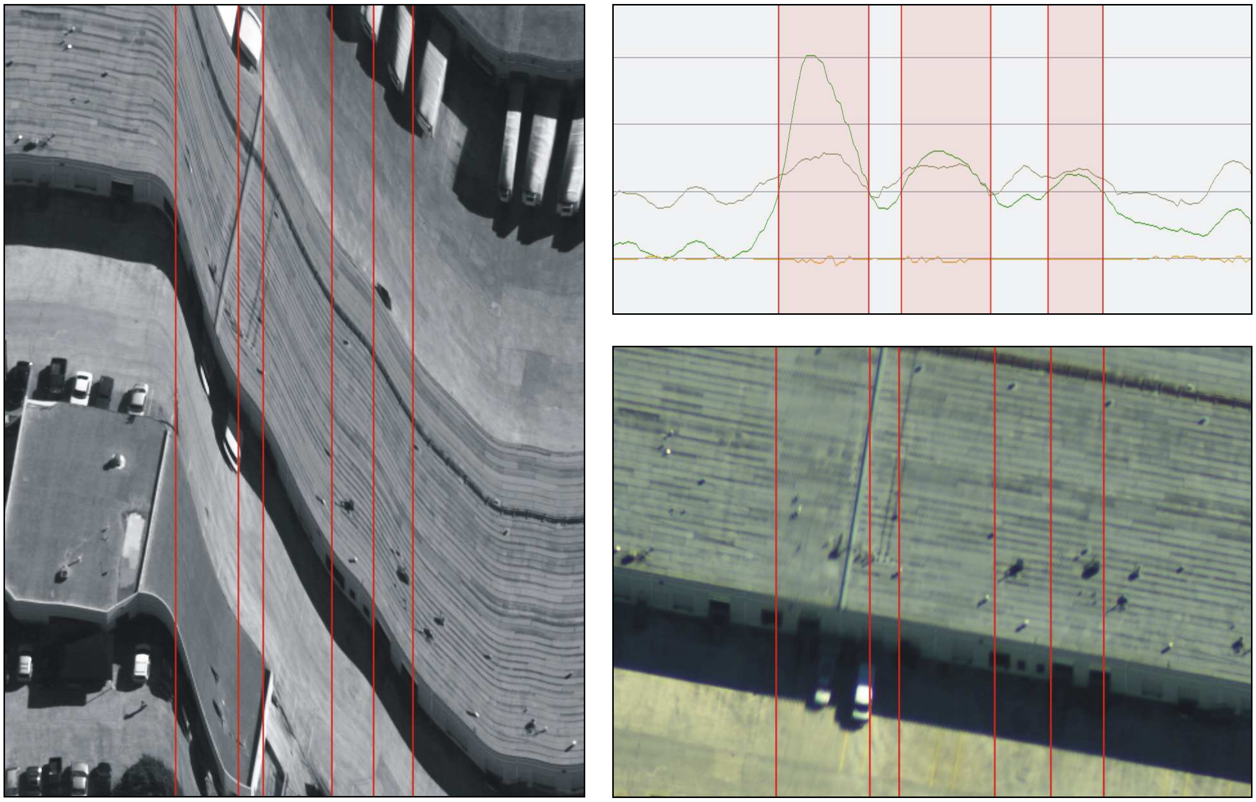

Figure 6. Left: L0 image of the green nadir band with strong distortions due to a fast roll move. Upper-right: Plots of the corresponding NCS (grey), PSR (green) and RPE (orange) parameters; potential smearing (PSR > 1) indicated in red. Lower-right: RGB L1 image, clearly showing the predicted smearing. Note there is no 1:1 relation between raw data and parameter plots on one hand and derived images such as L1 on the other hand. Images examples show almost 500 pixels in flight direction (left to right), which corresponds to ~ 150 dpi.

L1 Artifact (and Smearing)

The San Antonio take 048 has been acquired under some atmospheric turbulence, in parts very heavy so that fast pitch rotations cause backward ground coverage (Figure 5, bottom). A resultant L1 artifact in combination with a missing pixel (RPE ~ -1) occurs at GPS time 70,530 sec. The parameter plot as well as the corresponding L0 and derived L1 and L2 data are shown in Figure 7. The depicted trees show a lot of texture that enhances the visibility of turbulence-related issues. (However, note that trees are moving objects and the combination of ADS color bands, which have been acquired with an overall delay of ~ 10 msec, might introduce a certain level of smearing that is not reflected in the quality parameters.)

The turbulence has caused a fast pitch oscillation with effective backward movement (NCS < 0), surrounded by fast forward coverage (NCS ~ 2) and, next to that, slow but still forward coverage (NCS ~ 0.3 and NCS ~ 0.1, respectively). The geometric distortions are clearly visible in the L0 data, predominantly in flight direction. The triple ground coverage is underlined by (approximate) symmetries around the solid yellow lines; some distinct triple-points are visible. The slow coverage, marked by dashed yellow lines, appears similar at first glance but, in agreement with the NCS, there is no indication of backward coverage in the L0. Areas marked in red correspond to fast movement along with extended raw pixel footprints. The resulting smearing (PSR ~ 1.5) is clearly visible in the L1 and L2 products – note the stretch compared to the L0 content. In comparison, the stretched L0 areas at slow ground coverage and around the backward move are sharp in L1 and L2, which agrees with the prediction of PSR ~ 0. Finally, the L1 artifact is at the predicted location, approximately at the beginning of the triple ground coverage, and suggests the loss of about one pixel across the image (RPE ~ -1). Such artifacts are generally best visible – or, from the standpoint of product quality: worst – in color images, because the switch from the first to the third forward coverage (cp. Figure 1) happens at slightly different positions in different bands.

With the rectification to the true ground height in the L2 product, the artifact disappears but the smearing remains.

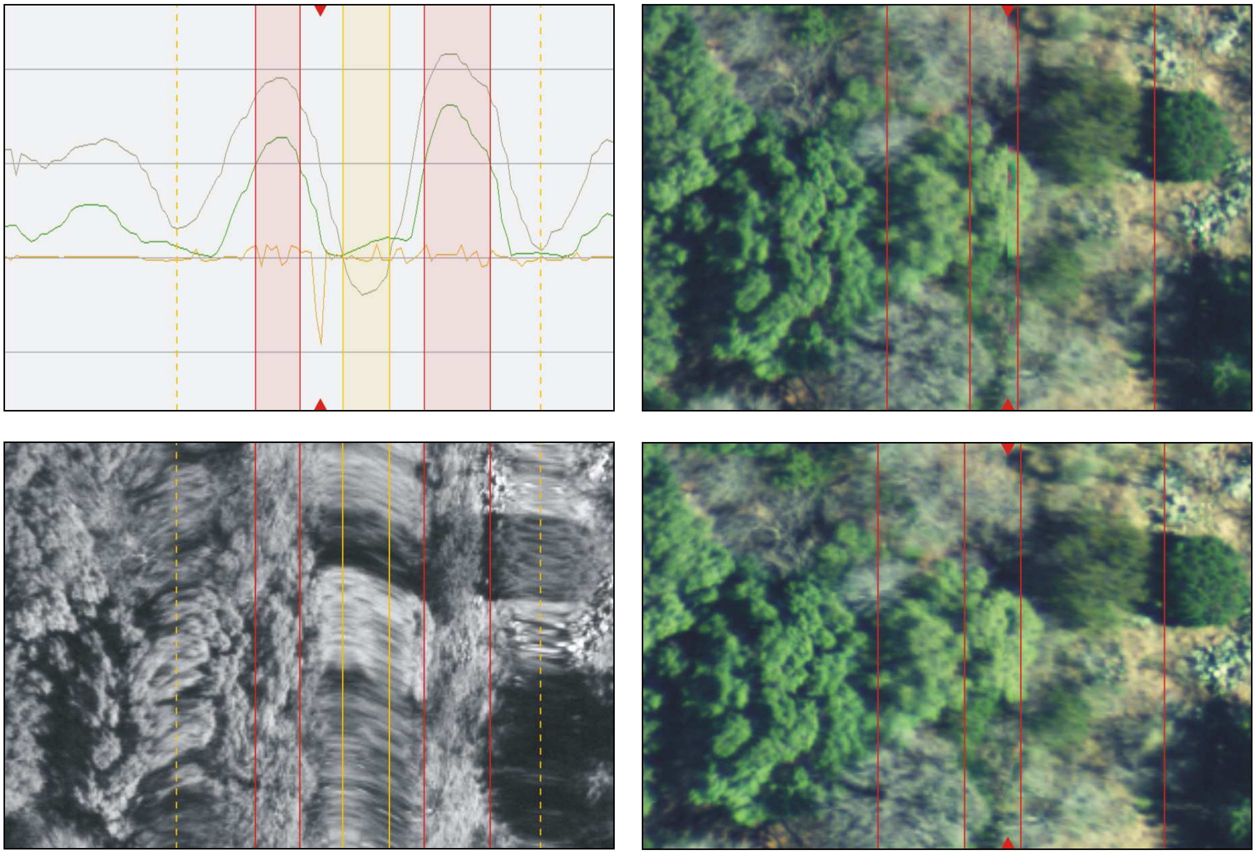

Figure 7. Upper-left: Plots of the NCS (grey), PSR (green) and RPE (orange) parameters for an event of heavy turbulence; backward ground coverage (NCS < 0) indicated in yellow with slow coverage (NCS ~ 0) around dashed lines, potential smearing (PSR > 1) in red, and the artifact of about one missing pixel (RPE ~ -1) by red arrows. Lower-left: Corresponding L0 image for the green nadir band; note the symmetries from opposing coverage directions at the solid yellow lines. Upper-right: RGB L1 image, showing smearing and the artifact as predicted. Lower-right: RGB Quick L2 image with identical smearing but no artifact. Images are rendered at high zoom level – with data from only 300 x 200 pixels (~ 90 dpi) – to emphasize the artifact in L1. Flight direction is left to right.

CONCLUSION AND OUTLOOK

This paper has presented three newly developed quality parameters for the classification of atmospheric turbulence for line-scanner images such as Leica ADS. They are based on the exterior orientation, which provides a record of all turbulence, but also consider the terrain as well as product specifications. It has been shown – both theoretically and for practical examples from ADS data – that these parameters are suited to not only point to events of turbulence but also quantify the impact in terms of smearing or artifacts on particular products. This significantly extends the possibilities for the flight and data analysis, which utilizes solely the exterior orientation so far.

Even though heavy turbulence is very rare in the sense of a significant degradation of the product quality, it has to be discovered reliably and early. That is why we have integrated the new parameters into the Leica XPro ground processing workflow, in which they are used to provide an automatic traffic light classification of ADS takes. Most beneficial for quality control is the possibility of displaying them co-located with the imagery in the XPro Viewer, so that an operator can be directly pointed to potential issues and evaluate the image content. Based on the experience in North West Geomatics' production usage and testing at Leica Geosystems, the parameters and tools will be part of upcoming Leica XPro software releases.

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