ANALYSIS AND PERFORMANCE OF THE ADAPTIVE MULTI-IMAGE MATCHING ALGORITHM FOR AIRBORNE DIGITAL SENSOR ADS40

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ABSTRACT

ADS40 is the first commercial airborne pushbroom sensor system produced by LH Systems, which offers on a single camera system the possibility to acquire both 3-line panchromatic and multispectral images in up to 10 channels. The geometric configuration and characteristics of the sensor enable the development of a matching algorithm, based on a multi-image philosophy, incorporating novel strategies, primarily aiming at producing reliable DSMs/DTMs. Existing algorithms are geared towards frame imagery and do not make explicit use of the special characteristics of the sensor; thus, most of them show a low success rate, requiring additional manual editing. Multi-image constraints make use of quasi-epipolar lines, since each line has its own position and attitude, to restrict search space. A multi-patch approach, utilized in the algorithm, strengthens the identification of mismatches and can be justified since larger patches aim at reliability of a coarse solution and the smaller ones at accuracy. Additional quality measures, computed at run time, are combined in the stage of the quality control in order to assign each matched point to a possible pre-defined error class (e.g. occlusion, multiple solutions). The evaluation of the matching performance is done through a qualitative and quantitative analysis using manually measured mass points from a block of frame aerial images with the same ground sampling distance (0.22 m) as ADS40 data.

KEY WORDS: ADS40, airborne digital sensor, DSM, matching, quality control

INTRODUCTION

Single- and multi-line CCDs are employed as research tools in satellite- and airborne- based sensors and are used to acquire panchromatic and multispectral imagery in pushbroom mode for photogrammetric and remote sensing applications. Regarding airborne sensors a few systems have been developed and among them fewer commercial ones, e.g. ADS40 (LH Systems), HRSC (DLR), etc., see Table 1. The development of the photogrammetric airborne digital sensors signifies a revolutionary change after decades in aerial image acquisition and the possibility of fully digital processing from image acquisition to generation of value-added products for various applications. It can lead to shorter production times, more flexibility and lower costs. An additional advantage of ADS40 is that it was designed such that it fills a gap between the current aerial film cameras and high-resolution satellite data, serving applications that need stereo and multispectral image data with a resolution of 15 to 100 cm. New methods, compared to the existing ones for processing of scanned aerial films, are necessary for these sensors because they have significant differences to the existing film-based cameras, e.g. several (up to 9) CCD-lines with 100% overlap, a non-perspective geometry in flight direction, different radiometric characteristics, simultaneous multispectral imaging capabilities, more complicated imaging geometry and integration of GPS/INS systems for determination of the position and orientation of each line. Investigations regarding airborne linear-CCDs have been already performed in camera architecture, direct georeferencing, sensor modeling, ground processing, aerial triangulation for ADS40 (Fricker, 2001; Hinsken et al., 2002; Sandau et al., 2000; Tempelmann et al., 2000) and for other systems (Fritsch, 1997; Haala et al., 2000; Hoffmann et al., 2000; Tianen et al., 2003; Wewel et al., 1998). Less is published though on matching methods and DSM generation using airborne linear CCDs and even less details are given on the algorithms employed (Gwinner et al., 1999; Neukum, 1999, Scholten, 2000).

CCD Sensor	**No. lines**		**Linear array (pixels)**
	PAN	**MS**	
ADS40	3	4 - 6	12000 / 24000
TLS	-	3 x 3	10200
DPA	3	4	12000
HRSC	3 / 5	2/4	5184 / 12000
WAAC	3	-	5184

Table 1. List of airborne CCD line sensors. Number of panchromatic and multispectral lines for each sensor and number of pixels on each line is given.

The work presented in this paper, focuses on automated DSM generation using an image matching algorithm, adapted to the special geometric and radiometric characteristics of airborne linear CCDs, and more specifically ADS40.

ADS40 CHARACTERISTICS

ADS40 incorporates latest GPS and INS technology (Applanix) for sensor orientation and new developments in sensor technology, optics, electronics, data transfer and storage. The camera system consists of seven parallel sensor lines in the focal plane of a single lens system – three panchromatic (forward, nadir, backward), red, green, and blue lines placed next to each other and one infrared (Fig. 1). The focal plane has space for two additional lines, but these are not currently used. Each panchromatic channel consists of two lines, each with 12000 pixels, staggered (shifted with respect to each other) by 0.5 pixels. In the test data that has been processed, only one staggered line for each panchromatic channel was used. The color and near-infrared channels can support a better interpretation of imagery, classification of vegetation and man-made objects and their use can assist and make automatic object extraction more robust. Apart from the above, the near- infrared channel can further support multi-temporal analysis of land cover and vegetation, hazard prediction and disaster management due to its wavelength (835-885 μm). Their use in the extraction of homologous features is of advantage from both a radiometric and geometric point of view and later is discussed in more detail. A thorough description of the camera system and architecture of ADS40 already exists in the literature (Reulke et al., 2000; Sandau et al., 2000, Tempelmann et al., 2000), therefore only an overview of the sensor characteristics is given (Table 2).

Focal length	62.5 mm
Pixel size	6.5 μm
Read out time of arrays	800 Hz
FOV (across track)	64° deg
PAN (staggered)	2*12000 pixels
RGB – NIR	12000 pixels
No. of bits from the ADC	14

Table 2. ADS40 characteristics.

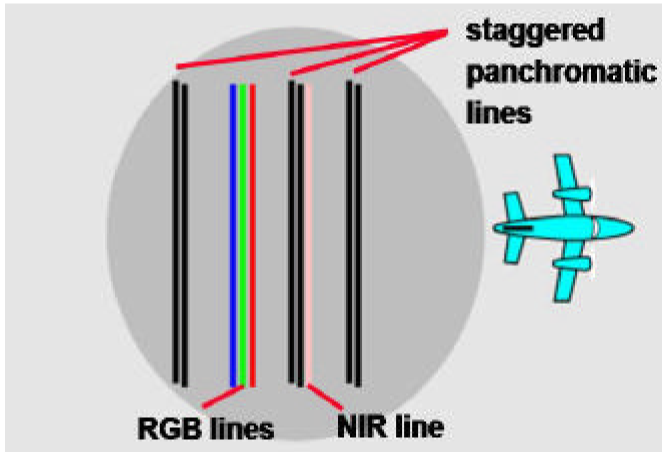

Figure 1. Configuration of channels on ADS40

Geometric characteristics

In general, with line-CCDs the images overlap 100% (with frame imagery typically only 60%), while the perspective distortions in the flight direction are small due to the quasi parallel projection. In vertical aerial photographs, tops of objects appear to lean away from the principal point of the photograph and the difference in apparent location is due to the height (relief) of the object and forms an important source of positional error. This problem is thus decreased for ADS40 (see example Fig. 2).

The problem of different image scales in flight direction, is reduced when processing rectified ADS40 images. ADS40 channels are rectified onto a height plane (Lev1 images) and therefore differences of scale, but also rotation ans shear that might exist in raw images (Lev 0 images) are removed to a large extent. Rectified images are used for stereo viewing and also in the matching process for tie point extraction and DSM/DTM generation.

Figure 2. Comparison of nadir aerial photograph (left) of 0.22 m GSD and rectified (Lev1) nadir view of ADS40 of 0.21 m GSD: Waldkirch region (CH).

All CCD lines on the focal plane, panchromatic and multispectral, at an instant of time *t* have their own position and attitude, and different viewing angles (Fig. 3) and calibration, which leads to a more complicated imaging geometry, compared to frame imagery. Geometric transformations can be more complex, thus a better accuracy can be achieved due to direct georeferencing, using GPS/INS system, and subsequent improvement of orientation and calibration using GCPs. Therefore, accuracy is not totally dependent on the definition and establishment of GCPs as in traditional photogrammetric processes.

The use of multiple channels can increase reliability and accuracy of matching results and the different viewing angles help to disambiguate difficult matching cases in automated processes (e.g. tie point extraction for aerial triangulation, DSM/DTM generation, etc.) and thus generate reliable photogrammetric products, reducing manual post processing. The combination of channels in the proposed algorithm is discussed in the next section on the algorithmic approach.

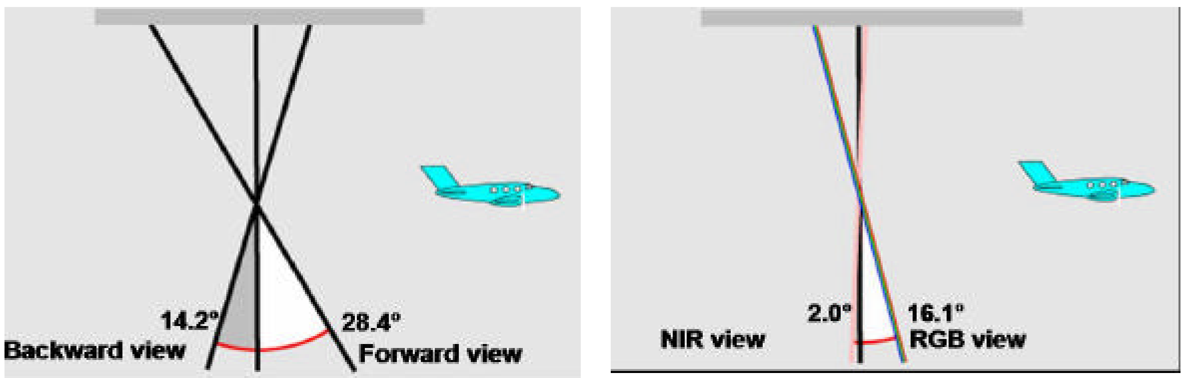

Figure 3. Viewing angles of panchromatic (left) and multispectral (right) channels. All relative to nadir.

Radiometric characteristics

ADS40 data have a dynamic range of up to 14bits (versus the usual 8bit of frame imagery) and exhibit a very good signal to noise ratio. The effective number of bits is less in the red, green and blue channels. Histograms of raw (Lev 0) images show a strong peak towards the darker grey values (about 310-340 in the panchromatic channels). The effective grey level range was 13-14 bits for the panchromatic channels and 12-13 for the multispectral, excluding grey values at the histogram ends with frequency less than ca. 0.0012% (5 times less the frequency occurring if all 14-bit values were equally occupied). The radiometric characteristics were analysed for 4 ADS40 datasets over 2 different regions (Japan, Switzerland), acquired at different time of year (winter and spring) and a noise analysis has been performed, based on the algorithm described in Baltsavias et al., 2001. Results from these datasets (Pateraki et al., 2002) and newly processed datasets were similar. The standard deviations indicate that noise is generally low and even more for the rectified (Lev1) images, due to the resampling of pixels during rectification. The multispectral channels exhibit slightly less noise than the panchromatic. Noise is increasing with increasing grey values. These results are consistent with the noise analysis that has been performed by DLR (Börner et al., 2000), stating that the standard deviation is about 2 grey values.

ALGORITHMIC APPROACH

General

As mentioned before, all existing matching algorithms are geared towards frame aerial imagery, with a usual overlap of 60% per stereopair, while in matching only two images are used. The ADS40 thus, enables the development of new matching algorithms based on a philosophy, which makes explicit use of the special characteristics of the sensor. A multi-image matching approach is followed, leading to substantial reduction of problems caused by occlusions, multiple solutions, image noise, and surface discontinuities and higher measurement accuracy through the intersection of more than two image rays. The known interior and exterior orientation are used to enforce geometric constraints, restricting the search space along quasi-epipolar lines. The sensor model developed by LH Systems is used in all transformations between image and ground coordinates. The main aim of the developed methods is to derive a DSM/DTM from rectified (Lev1) images, and a secondary one is to measure tie points or derive a coarse DSM (using raw -Lev0- or rectified -Lev1- images), results which can be used in the bundle adjustment for aerial triangulation.

Rectified (Lev1) images generally exhibit small scale and rotation differences, especially in the upper pyramid levels, and thus the use of only shifts in matching, without additional shaping parameters, is justified, leading to faster processing than other time consuming matching methods like least squares matching. Apart from normalized zero-mean cross correlation, the sum of squared differences or of the absolute differences can be used and thus further decrease processing time. Although investigations have reported that these difference measures are inferior to normalized zero-mean cross correlation, e.g. sensitive to radiometric differences, after the preprocessing and radiometric equalization that is applied (Pateraki et al., 2002), first tests show that these measures perform equally well. Matching is performed at pixels of extracted features and approximations are derived by a modified image pyramid concept using single or multi-template strategy, as described below.

In matching, different type of image information can be used: original grey value images, binary images by thresholding the edge magnitude, images where edge magnitude is kept and non-edges are set equal to 0, variations of the two previous image types, by encoding through appropriate values information on the edge pixel orientation or sign. The rationale behind using image types other than the original grey values, and especially binary ones, was a possible matching speed-up, especially in the upper pyramid levels, where not the outmost accuracy is sought for. Initial tests showed that coarse matching with binary images was slightly faster and the accuracy was similar compared to the points matched using gray level images. Therefore, binary images may be used in the upper pyramid levels without significant loss in accuracy but not in the finer pyramid levels.

Feature Extraction

Extraction of features is applied after preprocessing of the images to detect match points. Match features are extracted as densely as possible, thus making the blunder detection and correction easier and consequently reducing propagation of mismatches to the lower pyramid levels. A number of algorithms regarding feature extraction already exist in the literature and therefore our aim was to improve those algorithms in such a way that we would gain in speed and robustness. Several operators have been tested and their performance has been evaluated in terms of completeness and feature localization (e.g. Harris, Foerstner, Canny, SuSan). Edge extractors, and more specifically Canny operator, extracted one-pixel wide edge points with a denser distribution and a faster processing (50% faster vs. Foerstner operator) than point extractors. Additionally, a feature extractor has been developed aiming at derivation of more than one-pixel wide edge pixels, in order to achieve a better modeling of discontinuities (Fig. 4).

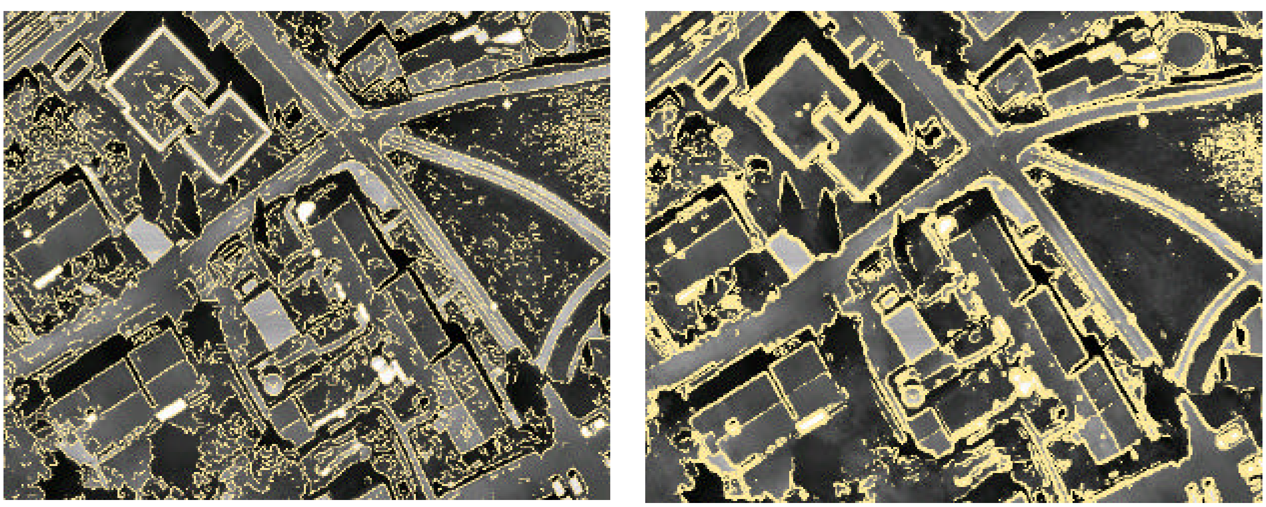

Figure 4. Left: extracted points with Canny operator. Right: Extracted edges with in-house operator.

The developed edge extractor performs a radiometric analysis of the image content, calculates statistical measures and thresholds depending on a user defined value. Compared to Canny, the in-house method needs one third of the processing time and not only extracted edges are more than one pixel wide but also no significant points, sensitive to noise are discarded. During edge extraction, additional information on edges, like orientation and sign, are derived and can be employed in further matching stages. All algorithms are adapted to 14-bit data, so that the full image information is used during processing. Feature extraction is either performed in all channels used in matching or only in the template images.

Quasi – epipolar geometry

Quasi-epipolar constraints may be applied in matching. Epipolar lines do not really exist since each line composes an image with its own position and attitude therefore, geometrical constraints are applied along a quasi-epipolar line which can be approximated either by a curve (Lev0 images) or a line (Lev1 images). A feature is defined in the so-called template image and the corresponding features are searched for in the remaining images, called patch images. By projecting a point of the template image to different height planes and back projecting onto the patch image the trajectory of the corresponding point and the epipolar curve may be defined (see Fig. 5). For rectified images the epipolar curve, if it is not very long, can be approximated by a line.

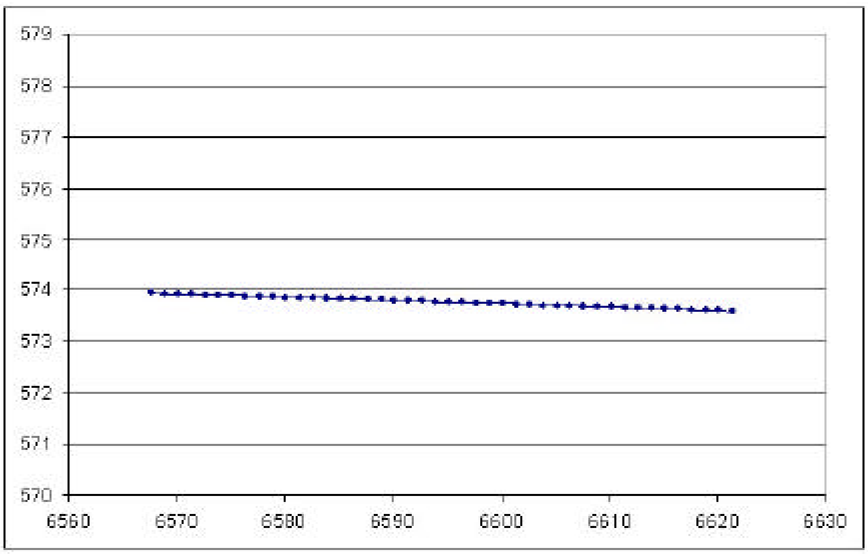

Figure 5. Epipolar line of rectified images (Lev1). The trajectory of the points (bullets) that are back projected on patch image is shown. The step in height is 1 m. x- and y- pixel coordinates are shown on the X and Y axis. The scales of X and Y-axis are not equal.

Two different approaches have been adopted for geometrically constrained matching. The first method intersects the template image ray with two height planes 5 meters below and above an approximate height, backprojects these object point to each patch image and calculates the line parameters from coordinates of these points. The second method finds an approximate height by an initial forward intersection (pairwise, using the template and each patch image), the search range in image space is transformed to height search range on the ray of the template and the points that are selected for matching are back projections of 3D points along this ray, within the height search range, and with a height step that corresponds to one pixel step in image space. Both methods give similar results for the matched points (in Lev1 images), but the first method is faster than the second one. However, the second method may be applied also for raw (Lev0) images were epipolar geometry is approximated with a curve and not with a line due to perturbations of the aircraft.

Multi-patch approach

In the first matching stages, cross-correlation or other similarity or difference measures are used delivering pixel accurate results, which can be improved by subsequent sub-pixel matching methods, e.g. least squares matching. Those measures are extracted during a multi-patch approach, where at each match point 3 passes of matching are performed with different parameters (e.g. search range, patch dimensions). The use of multi-patch approach can be justified since the larger patches aim at reliability of a coarse solution and the smaller ones at accuracy. The large patch is less sensitive to noise, occlusions, multiple solutions etc. while the small one is more accurate and better preserves height discontinuities. Matching results for each of the 3 passes are compared and used in the quality control for blunder detection.

Strategies

Most matching methods employ a time consuming interpolation to pass coarse matching results to the lower levels. To avoid this, the doublet strategy can be utilized with the aim to reduce processing time and interpolation of match results from one pyramid level to the other, but also restrict propagation of match errors to lower levels. Doublets are consisting of 2 consecutive pyramid levels. Extraction of features is performed in the lower level of doublets and these features are transferred one level up, and kept only if on this level an extracted feature (e.g. edge) also exists. Then, matching in all 2 levels from top to bottom is performed. Thus, interpolation and propagation of errors to neighboring points is avoided. For example, when 6 pyramid levels are used, instead of interpolating 5 times between the different levels, interpolation is applied between the three defined doublets, performing in total 2 interpolations. Therefore, sub-pixel accurate results are required only before each interpolation in order to obtain object space information with better accuracy.

Combined with the above strategy, the single- or multi-template strategy may be used. In single template strategy only one template is utilized and all remaining images are used as patches (most common to use nadir channel as template). The matching is performed simultaneously for all patch images and poor rays are excluded in the stage of the quality control. Finally, object coordinates are derived from the intersection of successful rays. The multi template strategy is justified since one template may not suffice to detect and avoid problems occurring in matching, especially occlusions. ADS40 thus permits with the given configuration of channels to use more than one template and facilitates identification of errors. The following combinations of channels have different role in matching. If best accuracy in Z is sought, then matching should be performed between backward and forward channels, thus is considered to be the most difficult case due to large geometric differences. Combination of backward and nadir channel is optimal for least left occlusions; red or green and forward channel best for least right occlusions. Red or green can be included in matching, due to low noise level and spectral similarity to the panchromatic ones, in contrast with near-infrared, for which radiometric differences to the panchromatic channels are large (Fig. 6). In case where three channels are used (backward, nadir and forward), the ones at the left and right most are set as templates and matching is performed pairwise starting from one template and matching to all other patch images. If the matched point is not successful, the template is changed and matching is repeated using the second template.

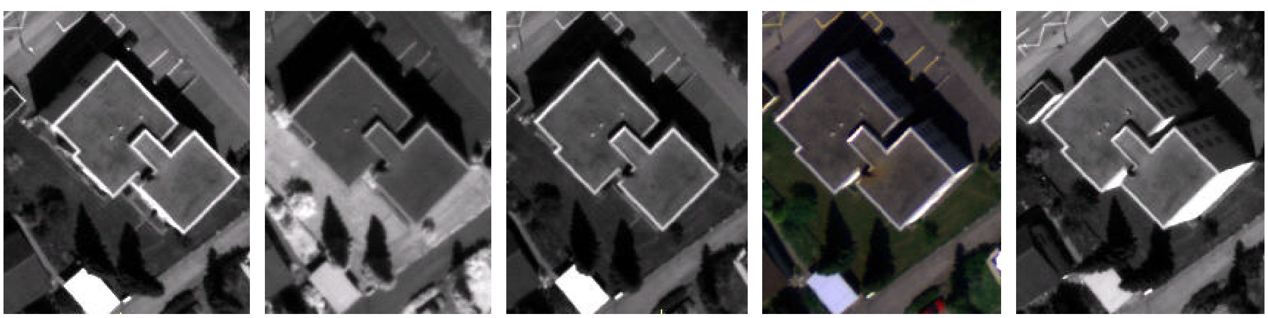

Figure 6. From left to right channel sequence: Backward, Near-infrared, Nadir, RGB, Forward. Geometric differences larger for backward and forward. Radiometric differences are large for near-infrared compared to other channels.

Blunder detection

During run time, several quality measures are calculated and used for elimination of blunders and false matches (e.g. similarity measure, the 2nd best similarity score, the change of similarity measure between the 3 patch sizes, the angle of dominant edge direction with the epipolar line at vicinity of selected match point, etc.). The quality criteria are combined according to possible occurring errors. E.g. in case of an occlusion, the cross-correlation coefficient would be small and the change of the similarity measure would be generally decreasing from the largest to the smallest patch, or the coefficient of the second patch would deviate from the other two and would be smaller. In case of a multiple solution, the second best similarity score would be probably close to the found solution and would be similar to the highest similarity score. Thresholds for the quality criteria are derived by a statistical analysis of their values in each processed pyramid level. We will investigate a fuzzy approach for threshold calculation, and relative weights when combining together multiple quality criteria to derive a single quality measure. All quality criteria are used for each image ray individually, to detect problems occurring in individual images, e.g. occlusions. Weak rays are excluded and final 3D intersection is computed using only the good rays. Regarding multiple solutions, along the epipolar lines, the multi-patch approach may not detect such problems. Thus, additionally the consistency of height in the local neighborhood is checked to detect and eliminate spike errors by a median-type filter. Least squares matching is used after blunder elimination with the above quality crieria. Successful matches are rechecked with stricter quality criteria resulting from the least squares approach.

DATASETS

In order to evaluate the algorithmic performance for DSM generation, ADS40 and aerial frame imagery have been acquired over the same region. Reference data have been classified to (i) bare ground, (ii) bare ground and man-made objects and (iii) bare ground and man-made objects and trees, and an analysis has been performed for the 3 separate classes. DSMs have been extracted in 3 regions of different land cover and vegetation: (a) bare ground, (b) bare ground and forest, (c) bare ground and man-made objects.

ADS40 imagery

The processed dataset was acquired over the region of Waldkirch in Switzerland in May 2002 and included panchromatic and multispectral imagery. A block of images has been delivered including 4 parallel- and 2 cross-strips (Fig. 7). Only rectified (Lev1) images from one strip have been used till now, with a ground sampling distance of 0.21 m. The coordinates were defined in WGS84.

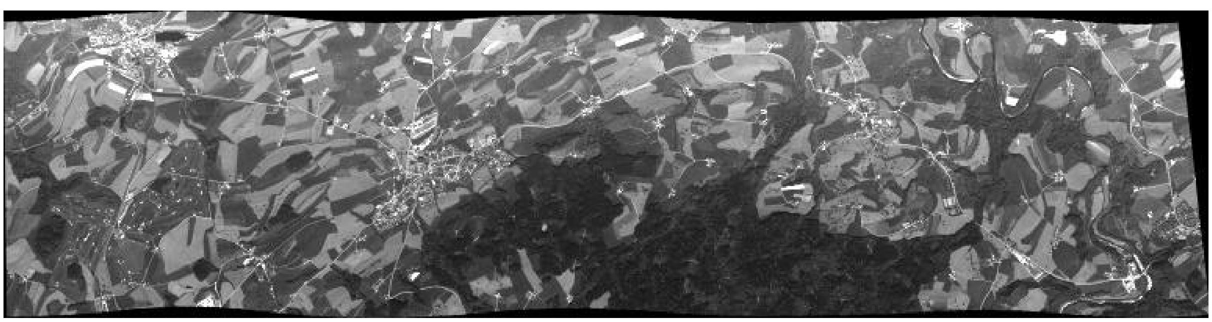

Figure 7. Nadir channel of processed strip of ADS40 imagery over Waldkirch region (CH). Areas of varying land cover (villages, sparse houses, forests, lakes).

Frame imagery

Color aerial images of 1:9300 image scale, acquired with a film camera of 15cm focal length, scanned with 25 microns pixel size and with ground sampling distance of 0.22m, have been used for manual collection of reference data on Socet Set Digital Photogrammetric Workstation. The height accuracy of manual measurements was approximately 0.30 m assuming that the operator could measure with maximum half-pixel accuracy. The coordinates were defined in the Swiss national coordinate system. The manually measured points have been separated into 3 classes: 1. bare ground, 2. class 1 plus man made objects , 3. class 2 plus trees.

Results

The 3 test regions are shown in Fig. 8a-c. Quantitative analysis has been performed with respect to terrain cover, selection and number of CCD lines for matching, and single versus multiple template strategy. The expected accuracy to be derived from ADS40 is 40 -50 cm assuming sub-pixel accuracy. The analysis of results could be influenced by additional error sources such as multitemporal differences between frame imagery and ADS40 imagery, orientation errors and conversion from Swiss national coordinate system to WGS84.

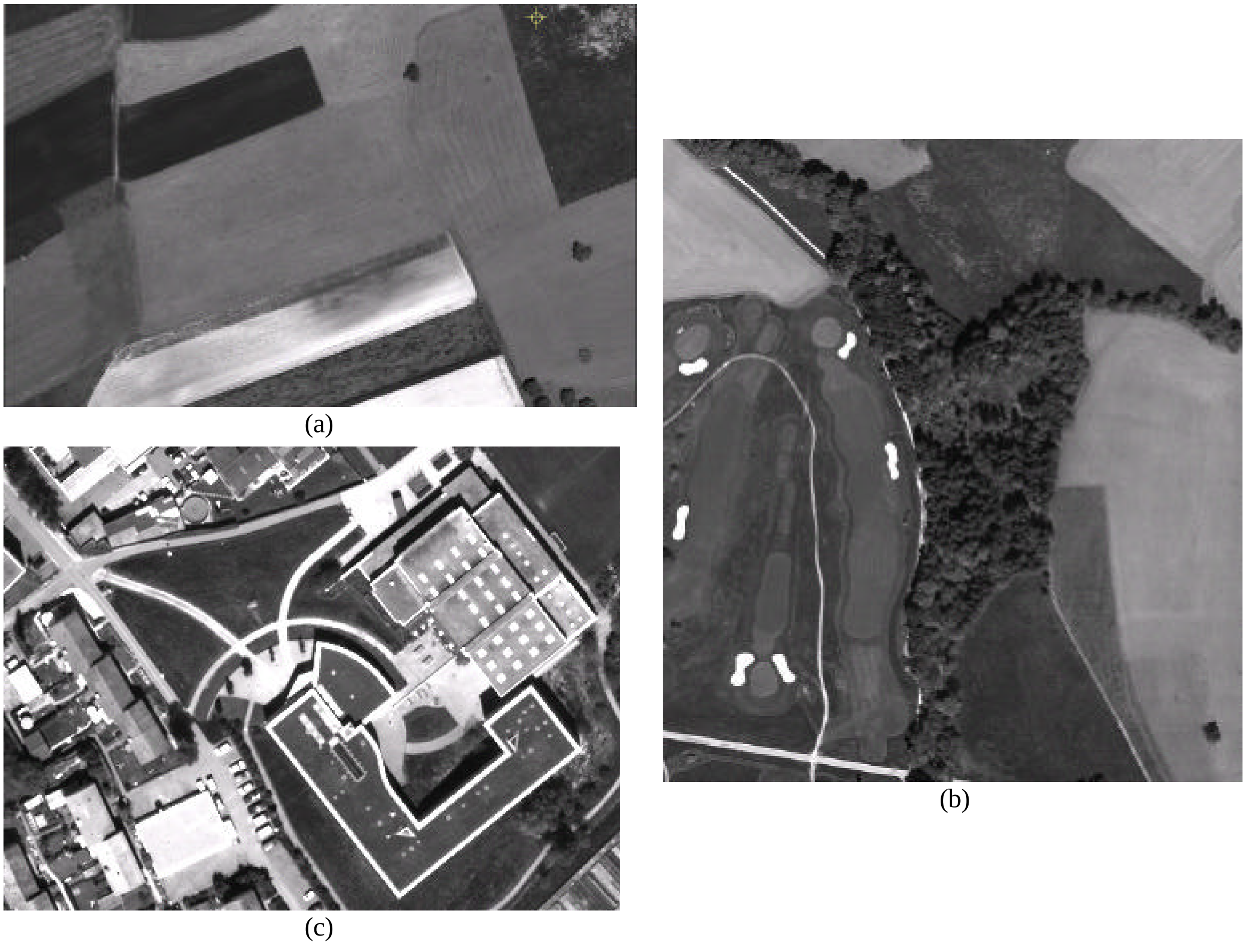

Figure 8. Region (a) of only bare ground. Sparse trees have been excluded from computations. Region (b) of forest and bare ground. Region (c) of bare ground and man-made objects.

With respect to terrain cover. In all three areas, one common strategy has been selected in order to evaluate the algorithm on different terrain. We employed single template strategy in combination with doublets and geometrical constraints, performing least squares matching in the lower doublet and using the Nadir channel as the template image. Backward and Forward have been selected as search images. In Table 3 results from the comparison of automated DSM generation from the 3 regions with the 3 classes of reference data. Region (a) has been evaluated only with BE (Bare Earth) class, region (b) only with BE and BE+ T (Bare Earth + Trees) class and region (c) with BE and BE+MMO.

Reference Data	**Region**								
	(a)			**(b)**			**(c)**		
	mean Z diff	**RMS**	**St. Dev**	**mean Z diff**	**RMS**	**St. Dev**	**mean Z diff**	**RMS**	**St. Dev**
BE	0.090	0.282	0.268	-0.043	0.293	0.290	-0.172	0.351	0.310
BE+ MMO							-0.187	0.888	0.873
BE+ T				0.010	1.936	1.938			

Table 3. Quantitative analysis of matching accuracy with respect to terrain cover. All results in meters.

With respect to terrain cover, accurate results can be derived for bare earth. Trees can be very difficult to be matched, since their surface is highly discontinuous and differs according to the viewing angle. Therefore, in region (b) when trees are included in the analysis the expected accuracy becomes worse. An additional factor is that manually measured trees, may refer to other points than those measured by matching.

With respect to selection of CCD lines. In region (c), a single template strategy (Nadir as template) has been selected with varying number of search images (from 1 up to 3). Independently of the selection of CCD lines, doublets, geometrical constraints and least squares matching in the lower doublet were applied. In Table 4, results are shown from the comparison of automated DSM generation with the 2 classes of reference data. In italics the template image is shown.

Reference Data	**Region (c)**								
	***Nad*-Bwd**			***Nad*-Bwd-Fwd**			***Nad*-Bwd-Green-Fwd**		
	mean Z diff	**RMS**	**St. Dev**	**mean Z diff**	**RMS**	**St. Dev**	**mean Z diff**	**RMS**	**St. Dev**
BE	-0.124	0.463	0.453	-0.172	0.351	0.310	-0.063	0.306	0.304
BE+ MMO	-0.199	-0.946	0.930	-0.187	0.888	0.873	-0.065	0.696	0.696

Table 4. Quantitative analysis of matching accuracy with respect to selection of CCD lines. All results in meters.

As it can be seen by increasing number of search images, accuracy also increases due to inclusion of more than two rays, with better intersection geometry. A further accuracy increase is observed, especially for MMO where occlusions occur when the fourth (G) channel is added.

With respect to single vs. multiple templates. In region (c), a single and multi-template strategy has been applied using Nadir, Backward and Forward. In Table 5, results are shown from the comparison of automated DSM with the 2 classes of reference data.

Reference Data	**Region (c)**					
	***Nad*-Bwd-Fwd (single)**			***Bwd*-Nad-*Fwd* (mult)**		
	mean Z diff	**RMS**	**Std**	**mean Z diff**	**RMS**	**Std**
BE	-0.172	0.351	0.310	-0.160	0.301	0.291
BE+ MMO	-0.187	0.888	0.873	-0.170	0.802	0.801

Table 5. Quantitative analysis of matching accuracy with respect to selection of CCD lines. All results in meters.

Using multiple templates, only small improvements occur in terms of accuracy. Especially regarding occlusions, there is no significant difference to the single template strategy.

CONCLUSIONS AND FUTURE WORK

ADS40 imagery enables the use of a multi-image approach with quasi-epipolar constraints in matching. In addition to this, the promising concept of multiple templates makes use of the special characteristics of the sensor. The quality control procedure, probably the most critical aspect of matching, will be further developed and tested, in order to support weaker features and thus robust surface modeling. More tests will be done comparing results of automatic derivation of DSM with manually measured data on ADS40 images (check internal matching accuracy) and with available laser scanner data. Further work will also include reduction of DSM to DTM using also NIR information for the elimination of trees.

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