IMPROVING THE ACCURACY OF PHOTOGRAMMETRIC ABSOLUTE ORIENTATION USING SURFACE MATCHING

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ABSTRACT:

Research was conducted into improving the accuracy of photogrammetric absolute orientation, using a least squares surface matching algorithm rather than conventional ground control points (GCPs). To ascertain the success of the developed algorithm, a comparison between the two methods was carried out. Targets were laid at a test site, and near-vertical stereopairs of small format imagery were captured using a Kodak DCS 660 camera and microlight platform, from three flying heights. Stereomodels for each height were orientated using six GCPs as control, after which DEMs were extracted using automatic routines and compared with the remaining targets. For the surface matching orientation a kinematic GPS DEM of the test area was collected, and image stereomodels recreated – this time processed only to the relative orientation stage. DEMs were again extracted but were not yet in the desired reference system, requiring development of the matching algorithm. As an alternative means of performing the orientation, GCPs were bypassed and the GPS surface was used to register the unorientated DEMs. The matched surfaces were then compared with the checkpoints, showing a higher correspondence to the checkpoints for all three flying heights. This suggests that higher orientation precisions can be achieved with DEMs than using traditional GCPs, an especially important result for small format photogrammetry where more images and more GCPs are required. Although this study focused on small format imagery of a single area, implications on the wider discipline of photogrammetry are readily apparent.

1. INTRODUCTION

The conventional photogrammetric processing approach required a minimum of three height and two plan ground control points (GCPs) per stereopair to allow successful absolute orientation to be carried out (Rosenholm and Torlegård, 1988). Modern developments in digital photogrammetric workstations (DPWs) employ aerial triangulation and simultaneous bundle adjustment to combine the relative and absolute orientation stages into a single process, requiring fewer ground control points, with automatically measured tie points providing an efficient substitute to link adjacent stereomodels. Despite this, for some terrain areas the identification of hard features to be used as ground control may be difficult, requiring logistically inefficient and expensive pre-marking, or complex direct inertial systems as an alternative. Examples of such terrain areas are coastlines, landslides, glaciers and deserts, where the often dynamic nature of occurring processes, and few natural or man-made hard features make the collection of photocontrol the most inefficient and least automated part of the processing chain (Schenk, 1999). This stage also constitutes a significant monetary cost – between 10% and 50% of a project's expense (Warner et al., 1996; Wolf and Dewitt, 2000).

It is becoming increasingly common for digital elevation models (DEMs – defined here as regular or irregularly distributed point sets) to be the main end product of a survey project, from photogrammetry, airborne laser scanning (ALS), terrestrial laser scanning and airborne Synthetic Aperture Radar (SAR) Interferometry (InSAR). These surfaces may have use in many disciplines and applications, for geomorphological change detection, coastal erosion monitoring, flood prediction and architecture to name but a few. Consequently, in these projects it is the final DEM that is important, and this provides an alternative processing strategy for photogrammetric DEMs.

Instead of using costly GCPs to provide registration to the desired reference system, a photogrammetric DEM may be orientated using an existing DEM and a surface matching algorithm – in effect using a control surface to perform the registration. This paper focuses on the accuracy of the ensuing absolute orientation, by comparing the performance of conventional orientations using GCPs and orientations using surface matching, for DEMs produced from digital small format photography captured from varying flying heights.

2. SURFACE MATCHING

Surface matching provides a common and fundamental problem in computer vision (Zhang and Hebert, 1999); however, its use in the spatial information discipline is intrinsically linked. The general problem, given two free-form shapes or point sets, one of which may be in a reference coordinate system and the other of which may be in a model coordinate system, is to find the

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rigid transformation relating the two surfaces, to establish correspondence (Besl and McKay, 1992). This relates to finding the "optimal rotation and translation that aligns, or registers, the model shape and the data shape minimising the distance between the shapes" (Besl and McKay, 1992). It is apparent that a similar problem exists in this research, where an unorientated photogrammetric DEM is to be registered using a reference DEM.

A popular choice in the computer vision field is the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992), designed to match not only surfaces but also other geometric primitives such as line segments and curves. Within the spatial information field, matching algorithms have tended towards least squares adjustments, minimising quantities between surfaces. Indeed, Mitchell and Chadwick (1999) argue that such methods, applied to the relatively simple 2½D DEMs found most often in surveying, provide a more suitable implementation, without loss of accuracy, than the ICP-style algorithms. For this reason, development of a least squares method that minimises the vertical differences between DEMs was carried out in this research.

The surface matching approach adopted is based on the standard seven-parameter 3D conformal transformation, commonly used in photogrammetry and surveying, that relates the coordinates of control points in different coordinate systems (Wolf and Dewitt, 2000). With the use of surfaces, the procedure is complicated by the fact that no control points may be identifiable to carry out the transformation, for reasons relating to the distinct point distributions; quantities; data collection techniques used, with associated accuracies; and temporal changes that may have occurred between the acquisition of each dataset. Instead of control points being used, the aim of the method is to find conjugate surface patches that may then be used to carry out the transformation. Vertical separations between the points of the unorientated surface and a triangulated reference DEM are therefore computed, which are minimised in the iterative least squares procedure, resulting in transformation parameter estimates. Complications to the matching implementation, relating to the use of irregular and disparate data, the non-linearity of the solution, and the need for patch gradients to exist in multiple directions (e.g. Rosenholm and Torlegård, 1988), are evident and are discussed further in Mitchell and Chadwick (1999) and Mills et al. (2003). In spite of these difficulties, this surface matching algorithm offers significant advantages from the high level of redundancy, the potential for automation and, importantly, by having an independent reference surface that allows the accuracy of the unorientated DEM to be validated.

3. EXPERIMENTATION

The surface matching method formed the critical orientation stage in a coastal zone monitoring study, allowing DEMs extracted from a strip of digital small format digital photography (SFAP) to be effectively registered to a global reference system. As part of this study, it was necessary to determine the success of the algorithm and its implementation. Consequently, testing was conducted to compare the DEM accuracy achievable using both the conventional orientation approach using GCPs, and the surface matching technique. The following sections therefore detail the data collection, processing and DEM extraction for both methods, as well as results and discussion.

3.1 Digital Small Format Aerial Photogrammetry

Digital SFAP was chosen as the primary photogrammetric acquisition technique because of its cost effectiveness and speed of processing, especially for the single image strip required for coastline coverage. To further speed up data collection, the digital camera was mounted on a microlight platform, allowing rapid scrambling and a larger weather window than possible with a standard survey aircraft (Warner et al., 1996). A significant limitation associated with SFAP is the smaller ground coverage in each image, caused by the film size or dimensions of the charge-coupled device (CCD) in a digital camera. Combined with a focal length far shorter than that of standard large format cameras makes for an exorbitant increase in the amount of images needed to provide stereocoverage (Warner et al., 1996). With the increase in images comes the requirement for an increase in GCPs to provide an accurate absolute orientation, making SFAP seem impractical for anything other than the smallest areas. Hence the value of the surface matching as an alternative orientation technique is demonstrated.

3.2 Test Area and Data Collection

The area chosen for this study was the coastline of Filey Bay, North Yorkshire, UK, a sensitive environmental area with ongoing coastal erosion. For this experiment, a small section of the bay was chosen, comprising a flat beach, gently sloping cliff (rising to around 40 m), and grassed cliff top car park (Figure 1).

Figure 1. Orthophoto of Filey Bay test site, taken using DCS 660. Area is approximately 200 x 200 m

Near-vertical stereo aerial photography of this test site was acquired on 10 August, 2001, using a Kodak DCS 660 single lens reflex (SLR) digital camera. This camera is one in a line of high-resolution (6 megapixel) cameras already used successfully by the photogrammetric community (e.g. Maas and Kersten, 1997; Chandler et al., 2001). The camera was mounted on a Thruster T600 Sprint microlight platform, the lens fixed on the infinity setting and the aperture priority mode set, ensuring an average shutter speed of 1/800 s at ISO200. To investigate the heighting precision of this photogrammetric configuration, imagery of the test area was captured from varying flying heights: 270 m (900 ft; 1:9600 scale), 450 m (1500 ft; 1:16,000 scale) and 600 m (2000 ft; 1:22,000 scale).

Prior to the aerial survey being carried out, fifty-four one-metre diameter white targets were laid, distributed to ensure that an adequate number would be visible within the image overlap. These were coordinated using a Leica TCR307 total station, providing data with 7" angle measurement precision and 2 mm + 2 ppm. Two control markers were monumented and observed in a static Global Positioning System (GPS) network, allowing the various acquisition techniques to be registered to the UTM coordinate system, a plane projection of WGS-84. These control points formed the total station set-ups for observing the ground targets. Convergent imagery of the targets was captured during the aerial sortie, and used to calibrate the DCS 660 camera in a self-calibrating bundle adjustment, resulting in a root mean square (RMS) error of 0.35 µm and a relative network precision of 1:42,000.

3.3 Conventional Orientation

Imagery was processed in Leica Geosystems' SOCET SET version 4.3.1 (now owned wholly by BAE Systems), a digital photogrammetric workstation allowing image orientation and DEM extraction. A model was conventionally orientated in SOCET SET using a stereopair of images captured from 600 m and six of the targets as GCPs; these were distributed throughout the stereocoverage to attain a strong adjustment solution – less than 0.01 m coordinate residuals and an image residual of 0.38 pixels. At 1:22,000 and with a 60% overlap, this configuration provided a *B/H* ratio of 0.4 resulting in an expected heighting precision of 0.35 m (Light, 2001). Following orientation, a DEM was created using the automatic terrain extraction (ATE) facility of the DPW. Least squares correlation is used for this task, and the adaptive parameter strategy was chosen for extracting the DEMs. This is a more sophisticated algorithm than the non-adaptive methods, parameter strategies of which are determined according to user-specified terrain types. Instead of requiring a single parameter strategy for each DEM, regardless of terrain type, the adaptive ATE performs epipolar resampling and *Y*-parallax removal, as well as examining image and terrain content to modify matching parameters on-the-fly. Using this strategy, a triangular irregular network (TIN) DEM of the test area was created, with progressive sampling based on a 2 m grid.

Identical methodology was carried out for the imagery captured from 270 m and 450 m, the only difference being that, because the lower flying reduced the ground coverage of the images, fewer check targets were visible in an image stereopair – detrimental for the later accuracy comparisons. This was resolved by using a strip of three images for the 450 m model, containing 24 targets, and four images for the 270 m model, containing 14 targets (excluding those targets used as GCPs).

Following photogrammetric processing, a DEM of the cliff test area existed for each of the three flying heights where imagery was acquired. These conventionally controlled DEMs were then compared with the remaining ground check targets to give an estimate of the precision of the photogrammetric surfaces. Measures defining DEM accuracy are essential, but have not yet reached a point where a standard method exists to determine the correspondence between a digital terrain representation and the 'true' surface. Consequently, there are few guidelines for practitioners (Flotron and Koelbl, 2000). A common means to define accuracy has traditionally been descriptive statistics based on the difference in height between the DEM surface and *n* check measurements. Because the check data is usually point or surface based, it is unlikely that conjugate points will be available, and the DEM height value is therefore interpolated at the planimetric positions of the validating data. The mean, standard deviation and range of the extreme *Z* differences can then be determined (e.g. Shearer, 1990). *Z* differences were interpolated between the photogrammetric DEMs and the checkpoints contained within the extents of each surface. Standard deviations of these were calculated, with results presented in Table 1 and Figure 2.

Flying height	270 m	450 m	600 m
Expected σ(m)	0.153	0.255	0.350
Conventional σ(m)	0.401	0.438	0.496

Table 1. Expected and conventionally controlled heighting precisions for various flying heights

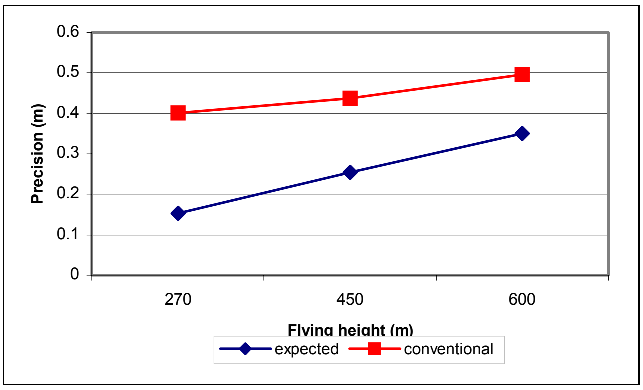

Figure 2. Effect of flying height on DEM precision

Examination of these reveals that worse than expected precisions resulted for all three flying heights used, implying that such a formula is too optimistic for the format or configuration of the photography. However, for the three heights used, the expected precision increases linearly with height whereas the observed precision line has a lower gradient, suggesting that the formulae may represent higher altitude data better.

4. SURFACE MATCHING ORIENTATION

The second stage of this research involved the use of surface matching to perform the critical registration of the small format photogrammetric DEMs to the desired coordinate system, instead of using ground control points. For this stage a second, independent surface was required, and this was achieved using kinematic GPS.

4.1 Kinematic GPS

Since its inauguration in 1994, GPS has been used primarily in the observation and monitoring of static point networks. However, with advances in technology and processing techniques, it is now possible to reliably achieve a high measurement precision without the long occupation of single points. Kinematic GPS has become an efficient means of processing individual data observations relative to a base station sited over a known point. Because of the highly accurate point data, often quoted to around the 0.010 m level (e.g. Hofmann-Wellenhof et al., 2001), kinematic GPS has become popular for recording the trajectory of a moving receiver. A critical component of processing involves resolving the ambiguities between dual frequency carrier phase measurements of the reference and roving receivers. Much research has been conducted in this area, and now the process has been simplified by the introduction of sophisticated algorithms that determine ambiguities "on-the-fly" (OTF).

A wireframe DEM of the Filey Bay test area was collected using kinematic GPS, by tracking the position of a roving receiver as it traversed breaks in slope and terrain profiles (Figure 3). To facilitate data collection, and to attempt to minimise changes in the antenna heights, the GPSycle – a standard detail pole with a mountain bike wheel attached – was used (Buckley and Mills, 2000). This data was processed using kinematic OTF phase processing. The resulting DEM was a relatively coarse, but highly accurate, representation of the coastline test site, comprising strings of data points. Repeatability testing of the kinematic GPS configuration, using a baseline at the University of Newcastle upon Tyne, indicated a value of 0.014 m was a more realistic indicator of DEM height precision than the 0.010 m reported in the literature for individual points – taking no account of factors such as terrain undulations, vegetation or point distribution.

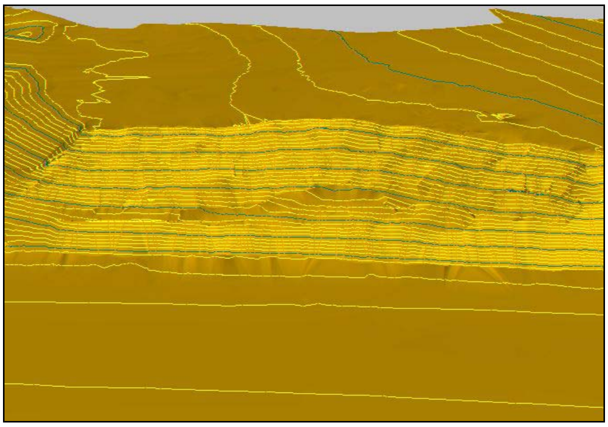

Figure 3. Perspective view of GPS DEM (200 x 200 m area)

4.2 Registration Using Matching

Digital SFAP of the Filey test area was reprocessed in the DPW, for each of the three flying heights. The procedure followed a similar route as for the conventional data but with one exception: none of the ground targets were used as GCPs. SOCET SET uses a single bundle adjustment to perform relative and absolute orientation simultaneously. This presented a problem for the proposed methodology of controlling photogrammetric DEMs to the reference system using surface matching rather than GCPs, as the bundle block adjustment required a minimum of three control points in the adjustment to obtain a solution for relative orientation. Consequently, three 'pseudo' GCPs were measured in the stereopair (and first stereopair of the image strip for the 270 m and 450 m flying heights), roughly scaled from existing mapping. Obviously, the accuracy of the mapping was detrimental to the quality of this control. A number of manual tie points were measured before automatic matching was employed to increase redundancy.

Once the simultaneous bundle adjustment had been carried out, DEMs of the same area as used for the conventional orientation were extracted using the ATE. Following DEM processing, surface models were created, but were not yet registered to the UTM coordinate system of the GPS surface. Therefore matching was required to recover the transformation parameters necessary to register the two models.

Pre-match processing of the GPS DEM was carried out to ensure that the extents of the surface roughly corresponded with, and were slightly larger than, the photogrammetric DEMs. Only points where the ambiguity resolution was fixed were incorporated into the DEM, creating the best possible surface. A feature of the kinematic OTF phase processing is the high data capture rate needed for successful ambiguity resolution; however, this creates problems with the distribution of points in the final DEM, with many points in the profile direction but few between profiles, resulting in long, thin triangles and mass point clusters in the TIN surface. The data were thinned to reduce the observation rate and, additionally, the distance between points was examined to ensure the existence of mass points, such as where the roving GPS receiver was stationary for multiple epochs, was eliminated. This helped give a more even triangulation with more equilateral triangles – useful during the search for conjugate surface patches in the least squares matching algorithm.

Because the imagery from the different flying heights were controlled using the 'pseudo' control points, it was expected that initial approximations of one for scale and zero for each of the rotations and translations would be suitable as initial parameter approximations for the least squares solution. Indeed, this was true of the 600 m and 450 m DEMs, with only reasonably small parameters found – suggesting that the 'pseudo' control points used were close to their true coordinate values (Table 2). However, the large parameter corrections seen in the 270 m match show that for this model a poor initial absolute orientation was calculated in the DPW, resolved using surface matching.

Match result	600 m	450 m	270 m
Outlier tol.	1 m	1 m	1 m
Translation (X, Y, Z) m	1.407 ±0.315 -0.913 ±0.233 0.863 ±0.107	0.713 ±0.267 -4.206 ±0.157 -0.756 ±0.100	21.170 ±0.557 -1.896 ±0.296 4.035 ±0.175
Scale	0.996 ±0.001	1.000 ±0.001	0.939 ±0.002
Rotation (ω, ϕ, κ) °	0.357 ±0.009 0.153 ±0.010 0.154 ±0.030	-0.131 ±0.008 -0.110 ±0.010 0.535 ±0.019	0.064 ±0.011 -0.173 ±0.015 0.349 ±0.041
RMS (m)	0.456	0.456	0.403

Table 2. Surface matching solutions for different heights

Flying height	270 m	450 m	600 m
σ (conventional)	0.401	0.438	0.496
Mean (conventional)	0.054	-0.062	-0.104
RMS (conventional)	0.391	0.433	0.496
σ (matching)	0.331	0.404	0.414
Mean (matching)	0.015	-0.007	0.011
RMS (matching)	0.319	0.396	0.405
Number of targets	14	24	22

Table 3. Z difference statistics between conventional and surface matching orientations (m)

Once the three DEMs were matched, the original surfaces were transformed by the matching parameters, resulting in the DEMs being in the same coordinate system as the GPS models. Comparison with the ground check targets was again possible, in the same manner as for the conventionally orientated DEMs. Although additional checkpoints were available – those points that were used as GCPs in the conventional orientation – the configuration was not changed, meaning that the same assessment was made. *Z* differences were again taken between the DEMs and the checkpoints (Table 3), allowing the heighting precision graph to be revised (Figure 4).

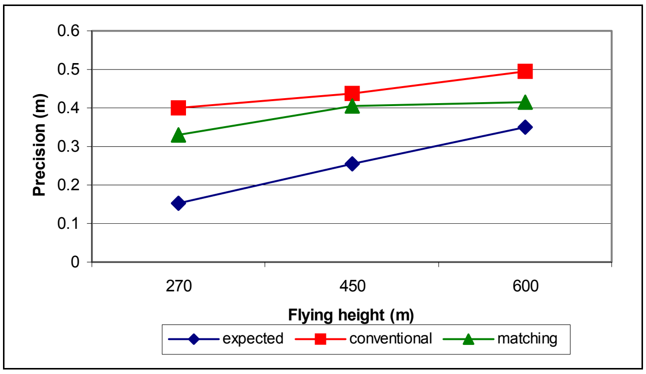

Figure 4. Effect of flying height on DEM precision

5. DISCUSSION

It is interesting and useful to note that employing surface matching to the orientation problem had a positive influence on the precision of the resulting DEMs, the matching removing systematic errors present across the whole of the surface models. This suggests that for small area DEMs the method is more advantageous and efficient than using conventional photocontrol, especially if a reference DEM already exists, as is becoming increasingly common in an age of digital terrain modelling. Examining the resulting precisions of both the conventionally controlled and match-controlled DEMs suggests that the expected precisions of the aerial photography are optimistic for such low flying heights. However, the fact that a less steep line gradient exists for both test datasets means that intersection with the linear expected values may occur at some greater height; further data and testing would be required to confirm this.

It is apparent from Table 3 that the conventionally controlled DEMs have systematic error affecting them (as indicated by the higher mean of differences), to a greater extent than the match-controlled surfaces. The cause of this is unclear but could be related to a host of factors such as the image configuration, poor bundle adjustment results, or an imperfect GCP distribution. Similar factors may affect the match-controlled surfaces, but the effect of surface matching is to minimise the height differences, removing bias

It is noted that the surfaces extracted from the digital SFAP were more sensitive to small errors in the aerial triangulation stage. An example was seen during conventional processing: despite low image and control residuals, after adjustment and comparison with ground points a systematic offset of 0.5 m was present in the coordinate differences. When the triangulation was checked and modified by a slight adjustment to the tie point configuration, this error was reduced. The problem reinforces an important advantage of the surface matching approach – that of having an independent surface model that as well as being used in the critical registration procedure, also allows validation of the photogrammetric DEM. Additionally, the DEMs created from lower scale imagery contained more noise than from the higher 600 m data, having connotations on the accuracy of the surfaces created. Consequently, more tests with conventional imagery at lower scales are required to determine whether the results are true for all scales. If so, the technique would be most valuable for photogrammetry, having the potential to reduce expenses incurred in collected ground control considerably, where a DEM already exists or can be easily acquired.

The surface matching algorithm is not the superlative solution to the problem of DEM registration, as issues affecting the success of the technique remain. Because the two matched DEMs were collected using different terrain modelling techniques – GPS and digital photogrammetry – each model is in effect a wholly different representation of the same real-world surface. The DEMs have different structures, different point configurations, differing accuracies. Each of these introduces disparities, not only with each other but with the 'true' surface. In addition, each of the measurement techniques records the terrain in a different manner. For example, kinematic GPS measures to the true ground height, as the detail pole is in contact with the terrain surface at all times, while photogrammetry images all vegetation and surface objects. Because of this, discrepancies are again introduced. Although not a problem in this research, the matching of DEMs collected at different epochs may again introduce change between the surfaces, causing further differences. All of these effects mean that in the least squares minimisation of height differences, it is not the same true surface that is being compared; rather, it is two similar models which therefore leaves the solution open to absorbing error into the output parameters, resulting in an imperfect solution. This may not be apparent from the output statistics, as the absorbed interpolation error will appear to result in a good minimisation of differences; however, parameter standard deviations may be optimistic (Maas, 2000).

The most likely outcome of discrepancies influencing the end solution is that transformation parameters may contain error. In a similar way, because of the ill-posed nature of the matching problem, multiple solutions may be attainable, with the only change between matches being the choice of initial parameter estimates or outlier exclusion threshold. Multiple solutions may result in multiple parameter sets, and a significant problem is to determine how these affect the position in space of the transformed DEM. Small (or reasonably large) parameter changes may have little or no effect on the final position of the matched DEM. However, any change will mean that the position of the model will be moved and, though height precision may be higher, the planimetric position may suffer. Difficulties with assessing the planimetric accuracy of an essentially 'featureless' terrain representation occur, requiring ancillary data such as intensity values with airborne laser scanning DEMs (e.g. Maas, 2000), to ensure true conjugate surface patches are compared. Despite this pessimism, the effect of differing absolute orientations, with alternate configurations of GCPs, has not been fully investigated, leaving the registration to be, at best, an approximation of reality.

6. CONCLUSIONS

This paper has addressed the subject of photogrammetric DEM absolute orientation, and the attempt to improve the efficiency of this notoriously expensive and manual process. A surface matching algorithm was developed and used to minimise height differences between a reference surface and a photogrammetric DEM in a model coordinate system. To assess the effectiveness of the procedure, a comparison was made between a conventional orientation using GCPs and surface matching, using digital SFAP models. DEMs were produced from imagery captured from three flying heights. Following extraction and orientation of the DEMs, a comparison with checkpoints was made to determine the heighting precision of each method. These results showed that the matching orientated improved the heighting precision of all three of the DEMs, while the conventionally orientated surfaces suffered a larger systematic error.

These results are encouraging, and have the potential to offer photogrammetry a real benefit. In addition to the reduction of systematic error, the surface matching algorithm offers an increase in automation, the existence of additional verification data in the form of the reference DEM, and increased versatility, as data from many sources may be used. However, further research may yet be carried out, to improve the robustness of the algorithm and determine the effect of differing solutions on the absolute position of the transformed DEMs. In addition, the use of digital SFAP introduced significant errors due to the scale and inherent instabilities of the image configuration when compared with conventional large format photography. Testing on more orthodox datasets would therefore be of great value.

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