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ESEX Commentary

High spatial resolution data acquisition for the geosciences: kite aerial photography

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: This paper highlights the requirement for very high resolution (<0·25 m) elevation data for quantitative and qualitative morphometric analyses. Traditional techniques for high resolution data capture (e.g. airborne, heliborne) are prohibitively expensive for small studies and therefore a kite-based platform was developed, in conjunction with a consumer non-metric digital camera, for data capture. The combination of kite and digital camera is more generally termed kite aerial photography (KAP). The accuracy of data derived by digital photogrammetry and imagery acquired using a kite based non-metric camera is assessed by three experiments: one on smooth terrain, one on tor terrain and one on a glaciofluvial esker. Ground control targets were surveyed at all three sites, with the imagery subsequently processed using the Leica Photogrammetry Suite. The results demonstrate that the method can extract a high number of sampling points at high accuracy, provided that there is suitable image texture across the site. However, final judgment concerning the suitability of derived data is dependent upon an understanding of measurement variability and user quantification of acceptable accuracy. Copyright © 2008 John Wiley & Sons, Ltd.

KEYWORDS: Kite; aerial; digital; photogrammetry; DEM; mapping

Introduction

Digital elevation models (DEMs) form important sources of input data for environmental monitoring and modelling. For example, they have been used for geomorphological mapping (Clark and Meehan, 2001), the age-discrimination of landslides (McKean and Roering, 2004), crater classification (Bue and Stepinski, 2006) and the quantification of volumetric changes of glaciers (Etzellmuller, 2000). When using DEMs in such applications it is important that they are 'fit-for-purpose', providing the necessary spatial resolution and horizontal and vertical accuracies. Initial drivers for the use of DEMs were regionally based because only relatively coarse spatial resolution data were available, traditionally being derived from photogrammetrically produced contour data. Regional-scale DEMs have also been produced using imagery from *spaceborne* sensors such as the Shuttle Radar Topography Mission (Rabus *et al*., 2003). More recently, the collection of *airborne* imagery, and production of DEMs, using digital photogrammetry, LiDAR and interferometric SAR have led to the availability of higher spatial resolution data. This has been coupled with increased interest in close-range, non-metric, digital photogrammetry (e.g. Butler *et al*., 1998).

It is therefore now more common to produce DEMs at spatial resolutions of several millimetres, several metres or tens of metres, but there remains a lack of data collection at resolutions of centimetres to tens of centimetres. The simplest method used to increase the spatial resolution of a DEM is to move the sensor closer to the target of interest. Centimetre-scale spatial resolutions usually require altitudes of up to ~200 m. Such low flying heights are impracticable in most cases, as aircraft and helicopter hire is prohibitively expensive and may be limited by flying height restrictions. Low cost alternatives utilize remote controlled, unmanned, platforms and include balloons (e.g. Vozikis, 1983; Marks, 1989), model aircraft (e.g. Green *et al*., 1998) and kites (e.g. Boike and Yoshikawa, 2003). These can fly consumer grade (non-metric) digital cameras in order to derive stereophotography suitable for automated DEM generation (Chandler *et al*., 2005).

This paper outlines an experiment to collect high spatial resolution stereo-imagery for the photogrammetric generation of DEMs as input to geomorphological process-based studies. For this research we used a kite platform as it remains comparatively inexpensive, is extremely portable and can operate in a variety of environments. The research outputs

Figure 1 Remote controlled rig and camera used for the acquisition of aerial imagery. The rig allows full rotate, pan and tilting movements of the camera in addition to remote shutter release (Haefner, 2005). This figure is available in colour online at www.interscience.wiley.com/journal/espl

are used to test the effectiveness of the methodology for providing low cost, high resolution data.

Methodology

In order to develop a methodology for the collection of aerial data from a kite platform, two test flights were undertaken prior to deployment at a field-site in Scotland. A site consisting of smooth morphology was selected for the first flight, which allowed distribution of 30 marker points necessary to test the feasibility of the technique in a simplified terrain configuration. More rugged morphology was captured subsequently, in a full test flight. The digital camera used for all image acquisition was a Nikon D70 (incorporating a 6 megapixel sensor) with a fixed 24 mm wide-angle lens (Digital Photography Review, 2007). The camera is robust and is equipped with a high quality wide-angle lens to provide extensive ground coverage. A rig was specially designed to allow full rotation, panning and tilting movements, as well as remote shutter release (Figure 1). The rig weighed 0·45 kg and the camera 1 kg. An unframed kite of parafoil design, with a surface area of 6·7 m^2, was used as it is very stable and has a large lifting capacity, ideally suited to aerial photography in a variety of wind speeds (Figure 2).

The photogrammetric use of aerial imagery requires sharp definition and this is controlled on the camera by focus, shutter speed, aperture and ISO settings. With flying heights in excess of 50 m, a focus setting of infinity is used. The focus ring is normally taped and auto-focus setting switched off, this eradicates changes to the focal length during the flight. As the kite is usually moving during image capture, fast shutter speeds are needed. Field tests suggest speeds in excess of 1/500 s are required. In addition an aperture of at least F8 (for a wide angle DSLR) is preferable, to allow sufficient light to enter the camera system whilst minimizing lens distortions. In most field situations an ISO setting of at least 400 is necessary for normal UK daylight conditions. With automatic digital cameras, these stipulations mean that the ISO is set prior to image capture with the camera in 'aperture priority' mode. Prior testing may be required in order to ensure shutter speeds are fast enough.

The first test flight, in November 2005, involved the collection of imagery acquired from a flying height of ~60 m over a flat (planar), grass covered playing field in Loughborough, UK. In order to calibrate the full photogrammetric system and assess accuracies, 30 ground control points (GCPs) were distributed evenly over an area 40 × 50 m. The GCPs consisted of targets 20 cm square, created by laminating A4 paper printed with a simple black and white target design. The positions of these targets were determined using a Leica TPS1200 Total Station. To ensure accuracy, angle and distance measurements were acquired from two ends of a baseline and coordinates derived using a least-squares 'variation of coordinates' estimation program, within a local coordinate system. This same basic survey technique was used for the subsequent DEM generation test and the field-site in Scotland.

The second test flight, in January 2006, involved the collection of a single stereo-pair over Beacon Hill, Leicestershire (National Grid Reference SK 509 148), from a flying height ~50 m. The summit of Beacon Hill comprises several emergent tors producing short vertical exposures interspersed with areas of smooth grass. A test area 20 × 20 m

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Figure 2 Unframed (parafoil) kite used for lifting the rig and camera payload. This figure is available in colour online at www.interscience.wiley.com/journal/espl

was selected to include both types of terrain with changes in relief of ~10 cm. A Leica TPS1200 Total Station was used to establish the coordinates of seven targeted ground control points, necessary for photogrammetric restitution and subsequent DEM generation to represent the ground surface. In addition, a motorized total station (Leica TCA1105) and detail pole was used to measure 399 independent XYZ co-ordinates. The sampling strategy involved capturing points in a semi-regular grid initially, which was then locally intensified in the rockier and topographically rougher areas.

Photogrammetric data processing was performed using Leica Photogrammetry Suite v9.1 (LPS) and involved the input of the ground control points and overlapping (stereo) photographs. Both the original colour photographs and greyscale equivalents were entered into LPS. The control points were measured and processed using the triangulation software within LPS. In order to derive accurate spatial data using consumer-grade digital cameras, it is necessary to determine the inner geometry of the sensor to an appropriate level of accuracy (Chandler *et al.*, 2005). Parameters to consider include the focal length, principal point offset, and parameters of a polynomial used to model radial lens distortion (Chandler *et al.*, 2005). A self-calibrating bundle adjustment is often used for this purpose and LPS provides the capability. In this study, use was also made of an independent self-calibrating bundle adjustment 'GAP', which has been used successfully for many years (Chandler and Clark, 1992).

Processing of the Beacon Hill flight data involved the use of the same photogrammetric process, with the *same* GAP inner geometry derived for the previous stereo-imagery and incorporated seven ground control points. Subsequent processing involved the generation of orthophotographs and DEMs.

The third site involved fieldwork over two days in June 2006 near Gartocharn, south of Loch Lomond, western central Scotland (NS 45 85,) in order to acquire aerial imagery of an esker. Ground control was surveyed using a Kern E1 theodolite with electronic distance measurement. The esker is *c*. 100 m wide and the kite was flown at a height of ~150 m in order to capture as much of the landform as possible. This allowed the collection of imagery with a ground resolution of ~0·04 m pixels. During the two day period the weather was generally patchy cloud, with strong sunshine and light winds, allowing the successful acquisition of over 150 individual frames.

Results

The first test flight involved ascertaining the feasibility of a kite platform and non-metric camera for the acquisition of high spatial resolution imagery and DEM generation. Initial processing used a self-calibrating bundle adjustment with eight photographs and 11 ground control points to derive the inner camera geometry and a further 18 checkpoints to assess the accuracy of the restitution independently. Of the three inner geometries tested, the first involved no calibration, the second involved the LPS self-calibration and the third combined the LPS self-calibration with the GAP model parameters (Table I). The combined approach produced the best results, with a significantly reduced root mean square error (RMSE; X = 0·009 m, Y = 0·008 m and Z = 0·038 m) derived from the 18 checkpoints, which exceeded our expectations for the technique.

The second test flight utilized the same methodology and GAP derived inner geometry as the first test flight. Photogrammetric processing yielded RMSE values fit to the ground control points of 0·003 m (X), 0·004 m (Y) and 0·003 m (Z). These results are comparable to those derived from the first test flight, demonstrating suitability of the inner geometry which had been determined prior and implying some geometric stability of the camera, particularly the lens model. The LPS was used to generate a surface model using 3900 points measured automatically (point locations marked on Figure 3). The LPS 'Automated Terrain Extraction' (ATE) algorithm derives surface measurements automatically by initially identifying high contrast 'interest points' appearing on each photograph. Small image patches surrounding each are then image-matched using the well established 'normalized cross-correlation' technique (Leica, 2005). If the optimum matched position generates a cross-correlation

Table I RMSE accuracy of the photogrammetric model for the first test flight, November 2005. Note the significant improvement in results through the use of the combined GAP/LPS calibration model (Chandler and Clark, 1992)

	RMSE derived from ground control check points (m)		
Calibration Model	X	Y	Z
LPS – no calibration	0·070	0·080	0·231
LPS – Self-calibration	0·069	0·116	0·106
Combined GAP and LPS calibration	0·009	0·008	0·038

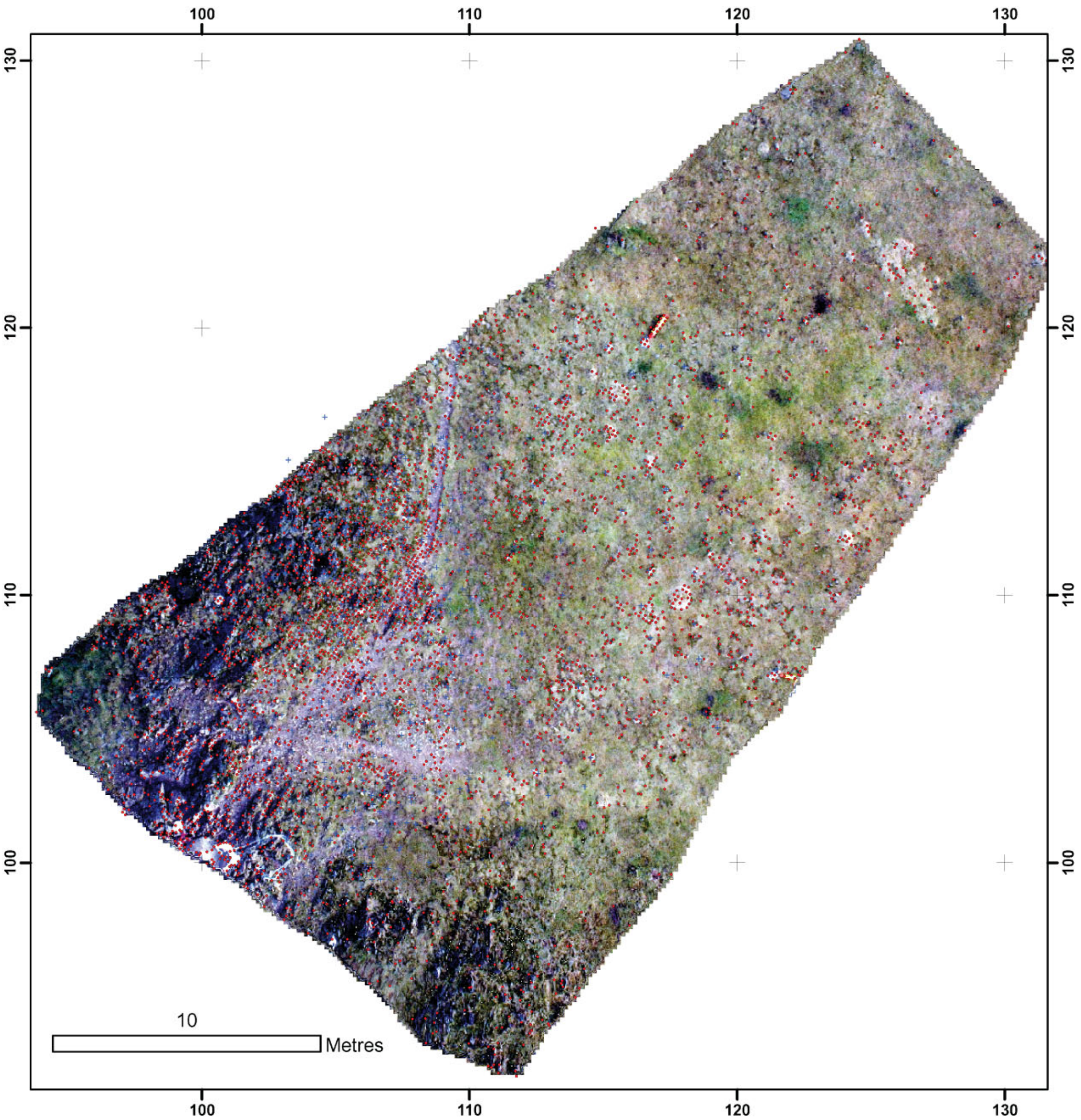

Figure 3 Orthophotograph of Site 2 (Beacon Hill) overlaid with extracted elevation points (red) and independent total station elevation points (blue). Photogrammetric processing is in metres using a local co-ordinate system.

Table II Surface accuracy based upon comparing photogrammetric and total station DEM data for four different correlation coefficients

Correlation coefficient	Mean error (m)	Standard deviation of error (m)	Number of points collected	Approximate density (points per metre)
0·6	0·010	0·072	16 236	25
0·7	–0·008	0·071	9 314	14
0·8 (adopted)	**–0·012**	**0·065**	**3 891**	**6**
0·9	–0·010	0·179	643	1

coefficient that is greater than a user defined threshold, the point is accepted and three-dimensional position determined. The user can then optionally create a regular grid-based DEM through an interpolation process and/or generate an orthophotograph (Figure 3).

The fieldwork conducted for the second test flight also involved the measurement of 399 independent elevation points using the Total Station. These measurements were used to assess the quality of the photogrammetrically acquired surface using a single interpolation procedure (Table II). The elevation of each measured total station data point was compared with a computed elevation for the same location, interpolated from Delaunay triangulation of the photogrammetrically acquired data points. Two key

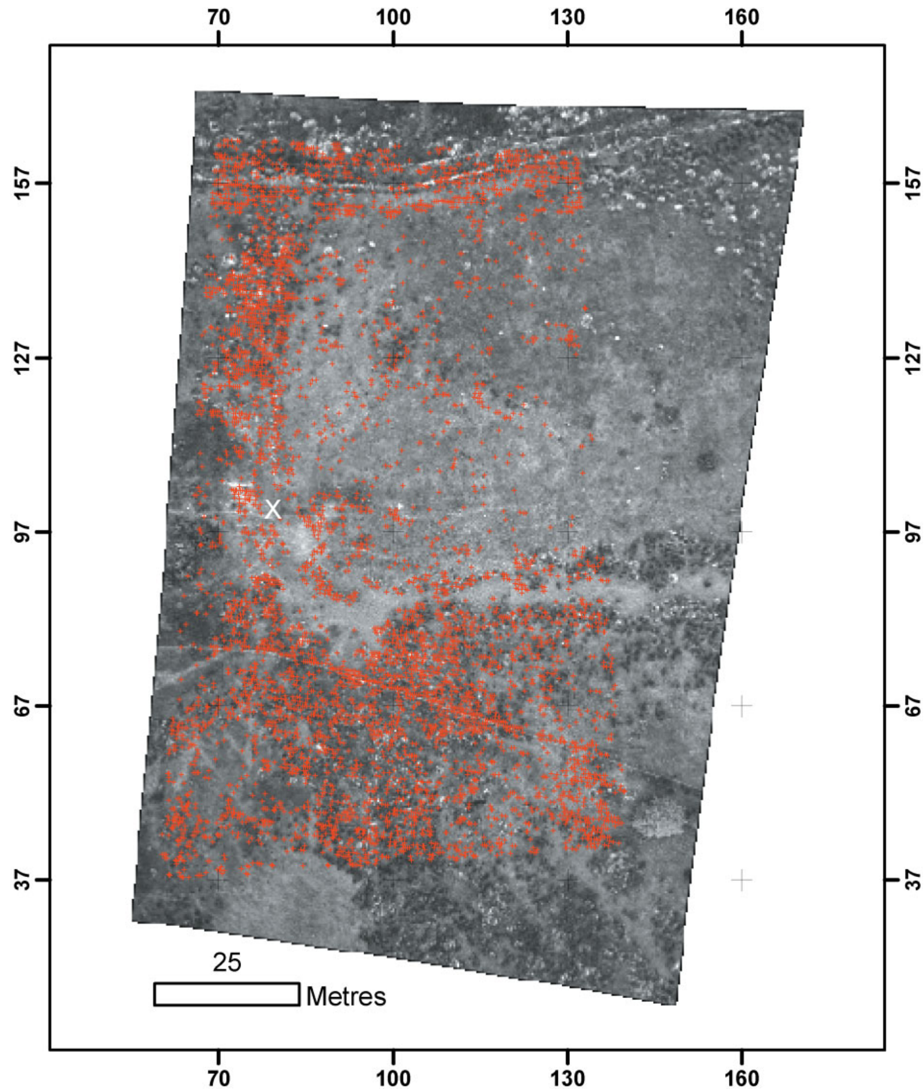

Figure 4 Orthophotograph of the esker at Gartocharn, south of Loch Lomond, Scotland, produced by Leica Photogrammetry Suite 9.1 and overlaid with elevation points used for DEM raster generation. Photogrammetric processing is in metres using a local co-ordinate system. The esker crosses the image from left to right in the central third of the frame, with the small depression marked by a white cross.

summative statistics were generated for a series of surfaces, each extracted using a range of different cross-correlation statistics (0·6–0·9), a critical parameter used to control the ATE module within LPS. The mean error (ME) indicates the presence of bias or systematic errors; whereas the standard deviation of error (SDE) provides a measure of surface variability or precision. Past research (Li, 1988; Lane *et al*., 2000; Chandler *et al*., 2005) has demonstrated that these two statistics are more informative for surface comparison than the RMSE more traditionally used in surveying.

Primary data output for the esker study yielded aerial photography, derivative DEMs and orthophotographs from stereo-pairs. The aerial photography (Figure 4) depicts the esker running across the central third of the photograph as a ridge covered by grass and patches of small bushes. The bushes cover ~20 per cent of the area imaged and are not considered representative of the fine-resolution morphology. Detail of a small depression is clearly visible and marked, on the DEM (Figure 5).

Given the stability in the configuration of data acquisition and processing during the two test flights, the same configuration was used for field work in Gartocharn. Initial photogrammetric processing of a single stereo-pair yielded RMSE fit to the ground control points of 0·010 m (X), 0·009 m (Y) and 0·001 m (Z). This model was then used for the extraction of over 5000 elevation points (correlation coefficient: 0·8) from the imagery. Figure 4 is an orthophotograph overlaid with automatically extracted elevation points used for raster DEM generation. The DEM was subsequently overlaid with the orthophotograph and 1 m interval contours (Figure 5) and viewed obliquely to depict the terrain.

Evaluation

In order to evaluate the success of the project output, it is necessary to review the acquisition of imagery, accuracy of the photogrammetry and validity of the DEM output. These three attributes are required in order to produce data that can be used for quantitative and qualitative geomorphological studies.

The kite platform proved remarkably stable and able to fly in light winds. Although not every photograph was acquired vertically, or necessarily in the desired location, the ability to capture large numbers of photographs, remotely, meant that a number of images suitable for photogrammetric processing were available.

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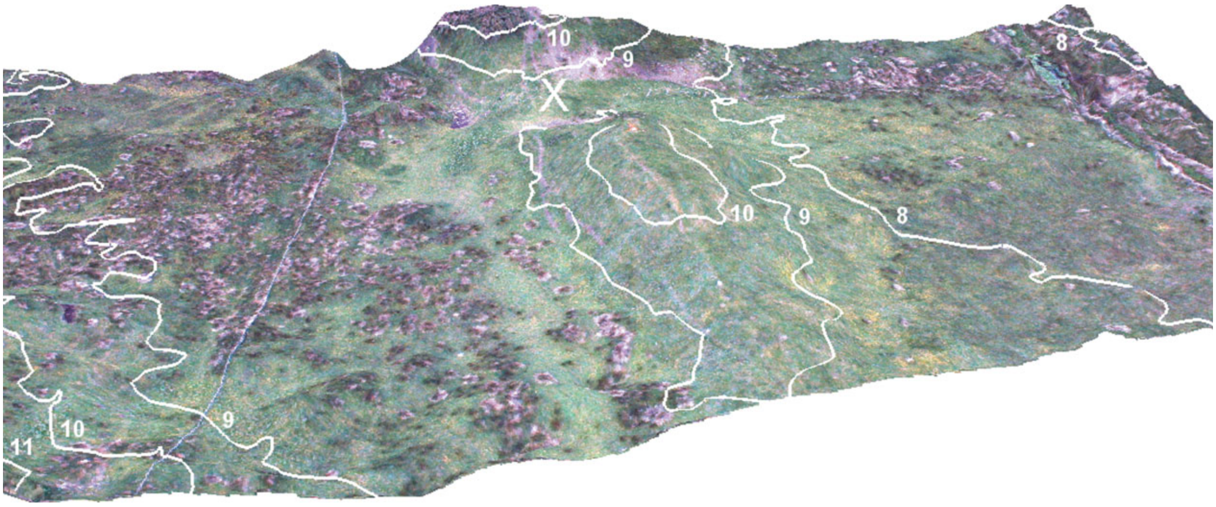

Figure 5 Oblique view of the esker using the orthophotograph draped over the DEM. Contour lines, shown as white lines, are in metres. The small depression is marked with a white cross. This figure is available in colour online at www.interscience.wiley.com/journal/espl

The accuracy of the photogrammetric data exceeded expectations. Initially, it was feared that the combination of the non-metric digital camera, flown from a dynamic platform may degrade overall performance. This was simply not the case. The accuracies of measured checkpoints (for the two initial trials) acquired using the combined GAP and LPS calibration approach were excellent, even in the weaker Z direction. For all three sites, the RMSE error fit to the control was very low also, implying potential for high accuracy data acquisition in all cases.

Estimates of surface accuracy derived by comparing photogrammetrically acquired data with the 399 points measured using the total station are also excellent, but demand further explanation (Table II). In all instances, the ME is very low (–0·010 to +0·010) implying that there is no significant bias in any of the photogrammetrically extracted datasets. This is particularly gratifying and implies that the method used to calibrate the camera is sufficiently accurate for the task. The SDE is typically around 0·07 m and only increases significantly when a correlation coefficient of 0·9 was used. This can be explained by reviewing the number of points collected and average point density, subsequently used to create a surface by Delaunay triangulation (643 points, 1 point m^{-2}). In this instance, the distances between photogrammetric data points and the total station checkpoints can exceed 1 m, increasing the chance of larger height discrepancies due to interpolation effects. It is striking how the density of points increases with a reduction of the correlation coefficient. However, a lower coefficient increases the chance of 'false matches' and potential inclusion of erroneous data points. This effect is well known (Gooch *et al*., 1999; Lane *et al*., 2000) and some judgment is required in selecting the optimum correlation coefficient. It is comforting that a range of coefficients (0·7–0·8) appear to have produced a surface which is of an acceptable accuracy, despite some variation in point density. Final coefficient selection should always be based upon visual surface appraisal (Wood and Fisher, 1993) and following quantitative assessment using independent checkpoint data, as recommended when conducting any photogrammetric survey (Chandler, 1999).

It has to be remembered that final DEMs are derived from a semi-random set of high contrast points of known XYZ coordinates, which are individually accurate. The DEMs are generated from this set of points, being interpolated to a regular raster grid. The quality of the DEM is therefore directly related to the location and density of extracted points and although over 5000 points were extracted for the esker field-site, the point density is not as high as we would have liked. The distribution of measured points is particularly critical. In high-contrast regions exhibiting good image texture, extracted points are regularly as close as ~0·25 m, whereas in low-contrast regions with poor texture, this can increase to ~7 m. This is demonstrated at the esker site, where the fence line and low bushes form regions of high contrast and therefore have large numbers of points, whereas regions consisting of homogeneous areas of grass have far fewer points (Figure 4).

Table II demonstrates that decreasing the correlation coefficient for the image-matching algorithm can significantly increase the point density. Ideally, we would want to use a single channel for the elevation point extraction that maximizes reflectance and therefore increases heterogeneity. In this instance it is intuitive to use the green channel to maximize the response of vegetation. Three other methods can be used to increase image contrast, either solely or in combination. The simplest method is to reduce the flying height; contrast is maximized through an increase in spatial resolution. Unfortunately this reduces the areal coverage of photographs requiring the collection of further stereo-pairs. The second method involves imaging a site during periods with low solar elevation, while maintaining enough brightness to produce sharp images. This has been used as a method for introducing contrast for geomorphological mapping (Slaney, 1981). The third method utilizes the fact that ATE in LPS uses a single band, often generated as a simple greyscale from the RGB channels of a digital colour photograph. The green and red channels could potentially be utilized to produce a simple ratio image (i.e. a vegetation index). With an additional camera, a ratio of the near infrared (Milton, 2002) and red channels should yield better results. This last method is currently the focus of ongoing research.

Although it has been possible to generate high accuracy point data, the problem of generating only a relatively low number of points at critical positions such as the homogeneous parts of the esker ridge, can mean that a DEM does not have the precision required for the research topic under investigation. It is therefore important to recognize that derived DEMs must be generated at a resolution and

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level of accuracy that is appropriate for the research questions being posed (Chandler *et al.*, 2000). The perfect measurement, and by implication the perfect surface representation, never exists and some appreciation of this reality is important when assessing the quality of surfaces and derived DEMs.

Conclusions

This paper is a response to the lack of low-cost methods for the acquisition of aerial imagery from altitudes of up to ~200 m and is designed to demonstrate the potential for a kite-borne, non-metric camera to provide such imagery. Kite-borne aerial photography was used to capture imagery at three study sites, testing whether such imagery was suitable for photogrammetric processing. The KAP proved time-efficient and very cost effective, yielding successful photogrammetric imagery with ground control point RMSE of ~10 mm in planform. Verification of extracted elevation values against independently surveyed ground control confirms that high accuracy photogrammetric surveying is achievable.

The three study sites comprised a mixture of rocks, grass and small bushes. Surface homogeneity of grass meant that the default image-matching algorithm used for the automated extraction of elevation values produced a low density of points in such regions. The quality of DEMs interpolated from such low density data would therefore not be suitable for use in some applications. Reducing the cross-correlation coefficient offers the potential to yield a significantly higher point density but at the risk of introducing gross errors, demonstrating the importance of check data. The DEMs must always be generated at a resolution that is appropriate for the intended application and ideally this should be quantified prior to the data collection exercise. It may be possible to increase the contrast of the original aerial imagery, without reducing the cross-correlation coefficient, through a combination of lower flying altitudes, imaging with lower sun angles to introduce shadow and therefore contrast, or the use of the green channel of the image. Alternatively, with an additional camera, a ratio of the near infra-red and red channels (i.e. a vegetation index) may be effective and there is a need for further experimentation.

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