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EFFECTIVE APPLICATION OF AUTOMATED DIGITAL PHOTOGRAMMETRY FOR GEOMORPHOLOGICAL RESEARCH

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ABSTRACT

Developments in digital photogrammetry have provided geomorphologists with an automated tool to generate digital elevation models (DEMs) at exceedingly high densities. Although such software tools are available at low cost and run on far cheaper hardware than previous generations of photogrammetric instrumentation, some expertise is still required to derive accurate data.

Various recommendations are provided that should enable the inexperienced user to make effective use of digital photogrammetry. Key issues discussed include the role of photo-control, the significance of checkpoints in the object space, and the importance of camera calibration data. An overview of self-calibration methods is provided, which is valuable in situations when a non-photogrammetric camera has been used. Accurate camera modelling also affects DEM quality and this issue is examined through assessing the impact of DEM inaccuracies upon derived data used for geomorphological enquiry.

Although the automated software packages are designed primarily for use with satellite imagery or vertical aerial photography, it is explained how such software can be used for both close range and oblique imagery. The procedure requires rotating the object coordinate system defined by the photo-control points and the mathematics required to achieve this is provided. The procedure is used to derive the morphology of a soil surface using oblique, close-range imagery and demonstrates the effectiveness of this particular approach. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS DEMs; photo-control; surveying; coordinates; three-dimensional transformations; three-dimensional rotations; change detection; automated digital photogrammetry.

INTRODUCTION

The theme of the 1995 BGRG annual conference was 'landform monitoring, modelling and analysis' in which it was apparent that developments in the surveying and mapping technologies had advanced rapidly in recent years (Lane *et al.*, 1998). Such technologies are important to geomorphologists because they provide the primary data necessary for morphological representation at all scales, using the digital elevation model (DEM) (Petrie and Kennie, 1990; Goudie, 1990; McCullagh, 1998; Lane, 1998). Secondary sources such as the digitized contour can cause various problems, including artefacts within the model (McCullagh, 1998). Lane (1998) has demonstrated that spatial distribution of data points is important but distribution is probably more significant than source in situations where the sample size is small.

Advances in digital photogrammetry have been particularly significant in the recent past (Walker, 1996) and now allow very large samples to be generated. Applications were both presented at the 1995 BGRG conference (e.g. Raper *et al.*, 1995; Chandler and Brunsden, 1995) and have been published recently, (Brunsden and Chandler, 1996; Stojic *et al.*, 1998). Although photogrammetry provides one efficient means of deriving DEMs, it should be remembered that other technologies exist. One recent development significant for meso-scale studies is airborne laser scanning (Lohr, 1998). This technique combines differential global position system (GPS) with an inertial navigation system in an aircraft

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flying at an altitude of approximately 1000m. Distances to the ground surface are determined using a pulse modulated laser and can be used to derive DEMs automatically within swaths or strips approximately 250m wide (Lohr, 1998). At macro-scales, synthetic aperture radar suggests potential (Hogg *et al*., 1993; Vencatasawamy *et al*., 1998) although practicable problems still remain, including uncertainties introduced through the phase unwrapping process (Polidori and Armand, 1995), shadowing and speckle (Vencatasawamy *et al*., 1998). DEMs derived from a new generation of planned satellite sensors will have a significant impact. The IKONOS 1 satellite, due for launch in the middle of 1998, is one example. This will be able to generate a 1m resolution panchromatic and a 4m resolution multi-spectral image, each covering an area of 10000 km^2 (van der Lei, 1998).

Photogrammetry is applicable for landform representation and detecting morphological change in the micro-, meso- and macro-scales. Significantly, automated digital photogrammetry now offers several huge advantages compared with other surveying technologies and traditional photogrammetic methods. Primarily, the technique allows the production of DEMs using fully automated image-processing algorithms. This automation is most significant. It allows regular grid-based DEMs of consistent precision to be derived at rates exceeding 100 times those provided by earlier manual photogrammetric methods. Compared to using a modern total station or digital tacheometer in the field, this increase is even more remarkable, with an increased sampling rate of over 1000-fold. This huge increase in sampling rate therefore allows very dense DEMs to be generated which can accurately record detailed morphology, without the need to measure topographic break-lines directly. Secondly, software to carry out the photogrammetric processing is now available commercially at competitive rates, particularly for academic usage (e.g. Erdas Imagine/OrthoMax, PCI/EASI-PACE, R-WEL/Desktop Mapping System, VirtuoZo). This type of software has been developed for a wide market, including non-photogrammetrists, and guides the novice through the various photogrammetric procedures using dialogue boxes and on-line help. Finally, it is now unnecessary to invest in a specialized and expensive photogrammetric plotter to carry out digital photogrammetry because such software runs on Unix workstations. Although specialized, these platforms are comparatively cheap and if not available already, can perhaps be justified by the functionality of other software applications. Interestingly, there is a growing trend towards mounting these photogrammetric packages on even cheaper PCs using the NT operating system, (Schenk and Toth, 1997).

These positive factors have generated an upsurge in interest in photogrammetric methods amongst the geomorphological research community, although examination of the literature suggests that little has been published to date (e.g. Pyle *et al*., 1997; Brunsden and Chandler, 1996). This interest in photogrammetry is encouraging but this author has become increasingly aware of various problems that the more inexperienced users are beginning to encounter. It would be most undesirable if problems that are really due to inexperience and over-expectation are confused with the science of photogrammetry itself. The aim of this paper is to highlight potential problems and to provide some recommendations on how best to use digital photogrammetry. This advice is developed further in the final section where it is explained how such software may be applied in the case of oblique and close-range imagery. Application at this scale and configuration is more difficult than the conventional 'normal' case, but success using oblique imagery will enable the user to take full advantage of one of the more flexible and cost-effective applications of this particular technology.

RECOMMENDATIONS FOR EFFECTIVE APPLICATION OF AUTOMATED DIGITAL PHOTOGRAMMETRY

Common sense provides a valuable guiding precept when using digital photogrammetry. One of the problems with many computerized technologies is the confusing interwoven mesh of buttons/functions and graphical displays. These tend to mask what is often a comparatively simple sequence of established procedures.

Start simple, start small

A recommendation that is not specific to digital photogrammetry but appropriate when introduced to any new technology is to start with simple and small applications. Only when the small project has been tackled successfully is it prudent to start working on larger and more ambitious schemes. This is particularly true when applying photogrammetry for the first time, and especially when an application is combined with using new and unfamiliar software. It is suggested that an initial project should consist of just three frames of vertical aerial photographs acquired with a photogrammetric camera, with an appropriate camera calibration certificate. Typically, these three frames will occupy a small section of a 'strip' of aerial imagery that can be used to produce two independent but overlapping stereo-pairs and DEMs. The reliability of the DEM generation procedure can be assessed rapidly by comparing elevations within the common area. Contact diapositives produced from the original photographic negatives should be scanned using a photogrammetic quality scanner, perhaps at the comparatively low resolution of 40 μm and with 256 levels of grey. Even this specification generates a single image occupying 31 Mb of space. When all three images and the overheads of their 'reduced resolution datasets' (RRDS) are combined, this requires a working storage capacity of 120 Mb. Efficient management of large files, and their derivatives, is one skill that needs to be developed when carrying out digital photogrammetry.

Don't forget the photo-control

Photo-control points are well defined features which appear on the photographs and whose positions are known in relation to the desired coordinate reference system. Although it is desirable occasionally to avoid using photo-control completely in photogrammetry (Granshaw, 1980; Cooper, 1987), use of photo-control points is recommended, particularly for traditional applications (Wolf, 1983). Abundant photo-control is particularly desirable when using proprietary software packages, where it is often impossible to proceed unless a minimal amount of control is measured. These software packages use an algorithm known as a 'bundle adjustment' which is implemented using the criteria of least squares. The bundle adjustment program determines the best estimates for the six parameters used to specify the position and orientation of the camera frame at the instant of each exposure (known as the Exterior Orientation or EO parameters). A theoretical minimum of three photo-control points with known ordinates in three dimensions are required to determine the EO parameters for each frame, but use of this minimum is never desirable. One of the fundamental principles conveyed in basic surveying teaching is the importance of including independent checks to the measurement and subsequent calculations. Measurements taken to additional control points provide appropriate checks and such redundancy allows the important EO parameters to be estimated with increased reliability and with a precision that can be determined.

Photo-control points can be represented by either pre-marked or natural features, the latter being sometimes known as post-marked points. Pre-marked points are preferable from the measurement perspective but as the area of coverage increases, the logistical problems of installing and maintaining them prior to photo-acquisition become more severe. In most areas, the use of well defined natural features provides a valuable compromise, although their existence and suitability is highly site-specific. Natural photo-control chosen after the aerial photography has been acquired provides additional benefits. Points can be selected which are located in the ideal photogrammetric positions relative to the frame format and at points which tie frames and strips together (Wolf, 1983). Such photo-control can be selected so that it surrounds the area of interest, both in plan and in elevation. If historical photography is to be measured, then use of natural features often becomes essential.

There are varying surveying techniques that can be used to determine the three-dimensional coordinates of these photo-control points. Choice depends upon size of the area, type of photographs acquired, availability of equipment and the experience of those carrying out the survey. Some of the important factors are tabulated in Table I.

Table I. Appropriate surveying methods for establishing photo-control

Dimensions of area	Photo-type and photo-scale	Recommended equipment/technique
>1 km × 1 km (macro-scale)	Verticals (1:4000–1:50 000)	Differential GPS
<1 km × 1 km (meso-scale)	Verticals (1:2000–1:5000)	GPS or total station using bearing/distance methods
<1 km × 1 km (meso-scale)	Obliques (scale varies)	GPS or total station using bearing/distance methods
Close range or laboratory-based work (micro-scale)	Verticals/obliques/terrestrial (1:5–1:10 000)	Total station using intersection method

For small-scale vertical aerial photography, use of differential GPS is most efficient. GPS offers several significant advantages over traditional methods. Direct line of sight between the known and unknown location is not required. A precision of ± 10mm + 1 ppm over distances of up to 15km and a global capability allows GPS to establish three-dimensional photo-control with maximum efficiency over large and open areas. Although GPS is expensive to purchase, either equipment can be hired or a bureau service used. In smaller areas and in situations in which vertical/oblique or ground-base imagery is acquired, a more conventional total station or digital tacheometer is perhaps more efficient. This versatile instrument can be used in two ways. The conventional 'bearing and distance' observation can be effective for vertical imagery but an 'intersection' approach is highly recommended for all other situations. The intersection method provides the additional comfort of a single redundant measurement, which provides a check on the accuracy of the measured data.

Check point data to assess the accuracy of generated data?

It is useful to withhold a sample of the photo-control points for use as 'check-points'. Comparing the photogrammetric coordinates with the accepted survey-derived values provides the only indicator of accuracy of photogrammetric restitution. Use of such redundant data is particularly important if a DEM is to be derived using automated DEM extraction software. There is perhaps a dangerous presumption that accurate data are being generated simply because sophisticated and automated techniques are being used. Automated DEM extraction software relies upon the establishment of image correspondences defined by small patches of image data within a pair of overlapping photographs. This 'image correlation' procedure compares variations in image density and is highly dependent upon the quality of the imagery, which can vary immensely. To allow the wide applicability of software, manufacturers provide users with a series of parameters to control this procedure. The number and nature of these varies with different packages but can include as many as 12, as in the case of the Erdas Imagine/Orthomax software. Specification of these values is non-trivial and widely differing results can be obtained (Smith and Smith, 1996, 1997). Fortunately, recent studies by Lane *et al.,* (submitted) and Gooch *et al.* (in press) suggest that only a few of these parameters are critical and techniques are being developed to assist in parameter specification (Gooch *et al.*, in press). Merging and viewing the automatically extracted data within a stereo-model provides an estimate of quality, although this can be time-consuming to quantify. Comparing elevation estimates from overlapping regions of DEMs derived from adjacent stereo-pairs gives a valuable indication of internal reliability (Chandler and Brunsden, 1995). The only truly independent and quantitative means of accessing whether the DEM generation process has been accurate is to use some form of ground truth. Comparing the extracted elevations with the accepted heights at the checkpoint locations provides such data and is normally summarized by a single parameter known as the root mean square error (r.m.s.e.) (Li, 1988). It is also important to realize that automated DEM generation procedures will generate a DEM that represents the visible surface, which may not characterize the desired surface. For example, if trees or bushes are present in the imagery then the elevation estimates within the DEM will represent the top of the vegetative canopy, not the underlying terrain. If the true ground surface is desired then vegetation heights need to be estimated or measured and appropriate corrections applied.

Camera calibration

The science of photogrammetry is based upon the simple assumption that light travels in a straight line, known as a collinear line, in three-dimensional space. More significantly, it is assumed that once a light ray has left an object, it passes directly through the camera lens to create an image point on the film located in the focal plane of the camera. The light ray is represented by a single vector and the relationship between the original object point, lens and image is expressed using a special case of the perspective transformation (Wolf, 1983). This is appropriate because the transformation is from the three-dimensional object to the two-dimensional image plane. By including the focal length of the camera in this transformation, it is possible to derive the two collinearity equations, which provide the basic functional model used in photogrammetry (e.g. Wolf, 1983; Cooper, 1987).

The functional model defined by the collinearity equations is only appropriate if the bundle of light rays, which generated the image, did indeed pass directly through the lens without deviation. In addition, it is normally assumed that the film lies perfectly flat, does not distort between image acquisition and measurement, and the focal length is accurately defined. Photogrammetric or 'metric' cameras are a specialized class of camera designed for photogrammetric measurement. They are equipped with specialized lenses that have been designed to fulfil the condition of collinearity. They have also been 'calibrated' to determine parameters such as the focal length and the locations of fiducial marks. If a calibrated photogrammetric camera is used, the internal geometry can be specified, recovered during measurement and accurate data should be generated. If any of the internal parameters are inappropriately specified or if lens distortion is present, then the functional model will be inadequate and inaccurate results will inevitably be obtained. Most non-photogrammetric imaging systems may be classed as 'non-metric' and although photogrammetric measurement is feasible, this should not be considered routine, particularly for the inexperienced.

If access to the photogrammetric class of camera cannot be obtained, then use of a good quality large format camera (60×60mm) and a procedure known as self-calibration may be considered. The objective of self-calibration is to determine the critical parameters necessary to model and characterize the interior geometry of the camera during exposure. These parameters can be determined by measuring the photo-coordinates of at least 40 photo-control and pass points, appearing on a minimum of four frames and processing using an established technique known as a 'self-calibrating bundle adjustment' (SCBA) (Kenefick *et al.*, 1972; Granshaw, 1980; Chandler and Cooper, 1989). The standard bundle adjustment uses at least-squares estimation procedure to derive the best estimates for the positions and orientations of each frame and the positions of pass points. In the self-calibrating version, these unknowns are augmented by additional parameters (APs) which represent the focal length, principal point offset and parameters to model lens distortion. If the configuration and number of measurements are appropriate, then reliable APs can be derived and used for the subsequent phase of data acquisition. The SCBA has been an important tool for analytical photogrammetry for many years and the same APs and camera models have been found appropriate for even the latest generation of digital camera technology (Fraser, 1997). One implementation of the program is freely available at City University, London (http://cesgi1.city.ac.uk/cuba/), provided the acknowledgement is duly made. It should be realized that some experience is required to use a SCBA effectively. Correlation between parameters, over-parameterization, datum deficiencies, insufficient measurements and weak configurations can all have significant impacts upon the quality of the derived calibration data. If the camera modelling is inappropriate, then inaccurate data will be generated and so the presence of check data in the object assumes even greater significance.

The quality of generated DEMs required for geomorphological enquiry

Geomorphologists should have an understanding of the quality of the data generated by photogrammetry. It is instructive to adopt the convention used in surveying and photogrammetry in which overall data quality may be described by quantifying three components: precision, accuracy and reliability (Cooper and Cross, 1991; Lane *et al.*, 1998). The precision of the derived data is purely a function of the precision of the photo measurements and the scale and geometry of the photographs. Numerical estimates of precision can easily be obtained through examination of the variance propagation output from the bundle adjustment. The accuracy of data used to represent a terrain surface is dependent upon the accuracy of the photo-control and knowledge of the internal geometry of the camera. Independent checkpoints are essential to quantify the accuracy of a DEM, by comparing the positions of checkpoints with their estimated coordinates and computing the r.m.s.e. Reliability relates to the value of independent checks and generating overlapping DEMs from adjacent images provides a useful measure of (internal) reliability.

Before carrying out any photogrammetric measurement it is important to establish the required quality of any measured data, particularly the accuracy of the DEM. This is often difficult to quantify because the accuracy really depends upon how the spatial data are to be used and further processed. The accuracy of a DEM used to generate a simple contour plot for qualitative purposes can be far lower than a DEM used for process-based simulation modelling (Richards *et al.*, 1995) or determining the hydrological characteristics of drainage basins (Hogg *et al.*, 1993). To examine this further, it is useful to borrow and extend the notion of 'external reliability' used in surveying (Cooper and Cross, 1991) which measures the impact of an error upon derived data, typically coordinates. If this concept is developed, it is possible to assess the sensitivity of parameters derived from terrain models by perturbing the elevations of a sample of points and monitoring the change upon the derived data. A simple example of this procedure provides an appropriate illustration. Consider determining the distribution of slope angles for a particular site from a measured DEM (Brunsden and Chandler, 1996). A second slope angle distribution could be created using the same DEM but with elevations modified randomly according to the normal or Gaussian distribution, with a variance equivalent to the r.m.s.e. This new slope angle distribution could be compared with the first, which would indicate the sensitivity of slope angle distribution to uncertainty within the original DEM. This approach is equivalent to numerical variance propagation and can be easily applied to a variety of other geomorphological applications.

OBLIQUES AND CLOSE RANGE IMAGERY

The digital photogrammetry software that is widely available to the research community has been developed primarily for remotely sensed imagery and vertical aerial photography. This small image scale will always remain important, but research work has demonstrated that the software can function at much larger photo-scales (Stojic *et al.*, 1998) and even using oblique imagery (Pyle *et al.*, 1997). Another positive factor encouraging usage of digital photogrammetry for micro-scale applications is the development in digital camera technology. Although currently expensive, the latest generation of high-resolution digital cameras (e.g. the Kodak DCS camera series: http://www.kodak.com/global/en/professional/products/cameras/DCSIndex.shtml) provide an efficient method of deriving digital imagery directly without the need for scanning. These are not of a sufficiently high resolution to be cost-effective for aerial applications (Maas and Kersten, 1997). However, the resolution is appropriate for many close-range measurement problems, particularly change detection quantifying the impact of micro-scale geomorphological processes covering areas of 1–400 m^2.

The simplest way of using automated digital photogrammetry for such problems is to design the photography so that 'normal' vertical coverage is obtained, only at very large scale. If the camera can be positioned vertically above the object of interest, then the normal processing sequence can be adopted and DEMs generated automatically. Some form of camera support is required but this can be achieved readily using nothing more sophisticated than a plank of wood with a hole for the lens, supported by two trestles. 'Flying heights' of up to 3 m can be easily accommodated using such a simple approach.

Unfortunately, constraints often prevent the camera being positioned in the traditional and preferred 'normal' attitude and only oblique photographs can be obtained. This creates two problems during data processing. Due to the non-linear nature of the collinearity equations, a bundle adjustment requires an

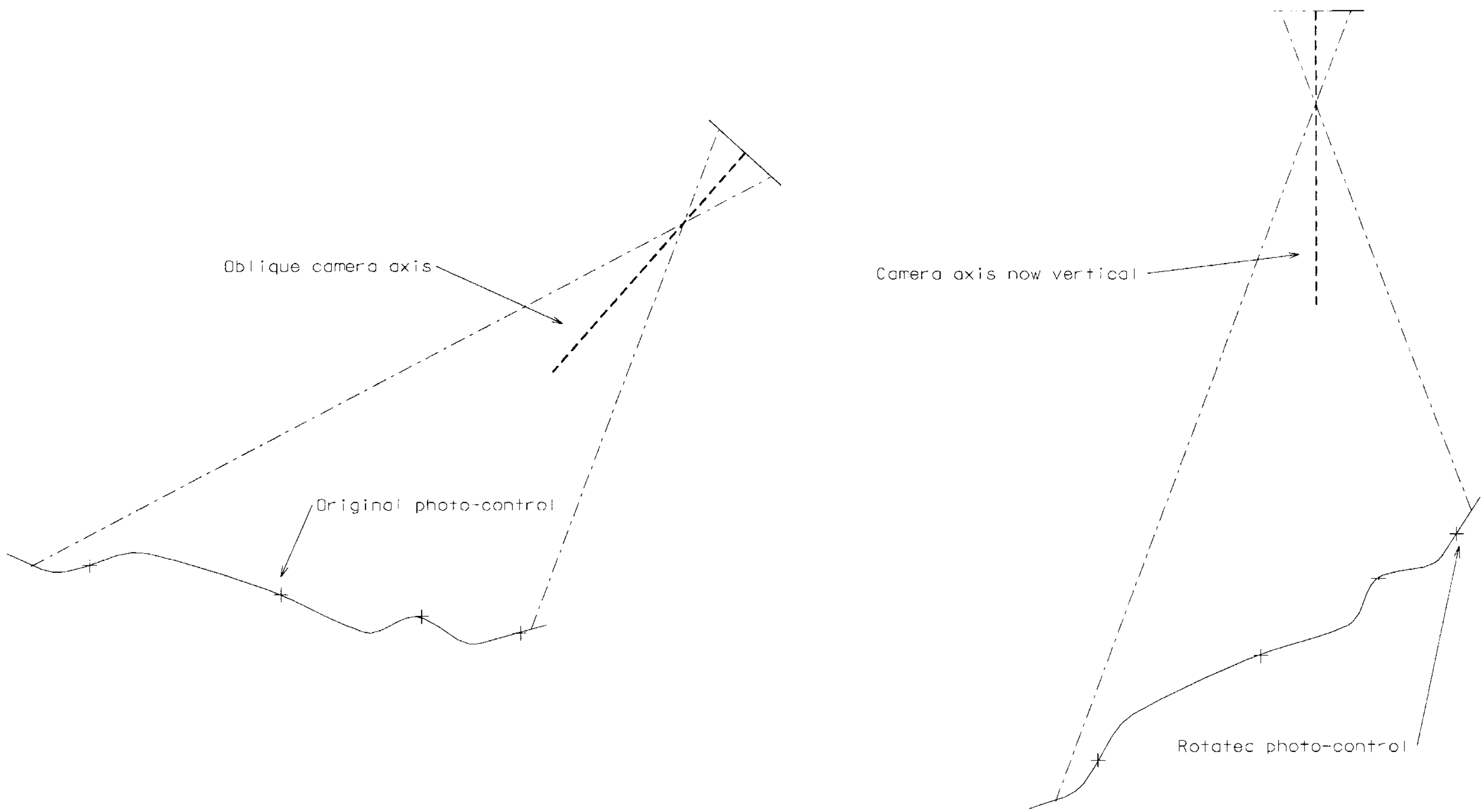

Figure 1. Rotation of photo-control to obtain 'vertical' photographs

iterative estimation procedure. Initial values are therefore required for all estimated parameters and if these are of insufficient quality, then the solution either fails to converge or produces inaccurate results. Many proprietary bundle adjustment software packages use a simple algorithm to generate these initial estimates, which assumes that two of the photo rotations are close to zero. Such an approach is adequate for vertical imagery but fails in the case of oblique imagery. The problem can be overcome by entering accurate initial estimates, but these can be difficult to ascertain, particularly values for the three independent photo-rotations.

The second problem is more critical and arises when it is hoped to generate a DEM automatically. The correlation procedure assumes that near-vertical photographs were acquired and fails if the three photo-rotations exceed angles of approximately 5–10 degrees. Internally the algorithm assumes that the depth perception or x parallax is aligned to the Z-axis of the object coordinate system, which is not the case for oblique imagery. Realization of this fact provides the basis for a simple solution. The strategy involves rotating the object coordinate system so that the mean camera axis for the selected pair of photographs is vertical and then deriving the DEM automatically in this new rotated system. The required rotation is implemented by rotating the photo-control points to derive new values, which are then entered and used by the bundle adjustment and DEM generation software. The strategy is conveyed and simplified in just two dimensions in Figure 1. The steps and associated equations required to achieve both the required direct and reverse rotations are as follows.

Step 1. Identify pair of photographs to be used for generating DEM automatically and establish average rotations using the known exterior-orientation parameters:

$$\omega = \frac{(\omega L + \omega R)}{2};\ \phi = \frac{(\phi L + \phi R)}{2};\ \kappa = \frac{(\kappa L + \kappa R)}{2}$$

where ω, ϕ, κ refer to the three independent rotations: omega, phi and kappa for the left (L) and right (R) hand photographs.

Step 2. Create a three-dimensional rotation matrix:

$r_{11} = \cos\phi.\cos\ \kappa$
$r_{12} = \sin\omega.\sin\phi.\cos\kappa + \cos\omega.\sin\kappa$
$r_{13} = -\cos\omega.\sin\phi.\cos.\kappa + \sin\omega.\sin\kappa$
$r_{21} = -\cos\phi.\sin\kappa$
$r_{22} = -\sin\omega.\sin\phi.\sin\kappa + \cos\omega.\cos.\kappa$
$r_{23} = \cos\omega.\sin\phi.\sin\kappa + \sin\omega.\cos\kappa$
$r_{31} = \sin\phi$
$r_{32} = -\sin\omega.\cos\phi$
$r_{33} = \cos\omega.\cos\phi$

Step 3. Apply rotation to each original control coordinate:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

where $[X\ \ Y\ \ Z]^T$ is a vector representing the original XYZ coordinate of each photo-control point, and $[X'\ Y'\ Z']^T$ is vector representing the rotated XYZ coordinate of each photo-control point.

Step 4. It is useful to determine and record both the applied rotation and reverse rotations, so that the final extracted DEM can be transformed back to the original coordinate system after the DEM generation process. These rotations can be determined from the three-dimensional rotation matrix using:

Figure 2. Test plot showing rainfall simulator and two Hasselblad cameras

Reverse rotation	*Applied direct rotation*
$\omega = \tan^{-1}\left(\frac{-r_{23}}{r_{33}}\right)$	$\omega = \tan^{-1}\left(\frac{-r_{32}}{r_{33}}\right)$
$\phi = \sin^{-1}(r_{13})$	$\phi = \sin^{-1}(r_{31})$
$\kappa = \tan^{-1}\left(\frac{-r_{12}}{r_{11}}\right)$	$\kappa = \tan^{-1}\left(\frac{-r_{21}}{r_{11}}\right)$

Note: To maintain precision, these angles should be recorded to at least five decimal places.

To demonstrate the effectiveness of this approach to generate a DEM automatically using oblique imagery, a simple test was performed. Stereo imagery had been obtained using a pair of Hasselblad cameras in order to monitor the evolution of a soil surface (Guerra *et al.*, in prep.). The position of the rainfall simulator (Figure 2) prevented positioning the cameras centrally over and vertically above the small $0{\cdot}8 \times 0{\cdot}4$m test area. These physical constraints ensured that the cameras had to be offset slightly, so producing slightly oblique imagery, (Figure 2).

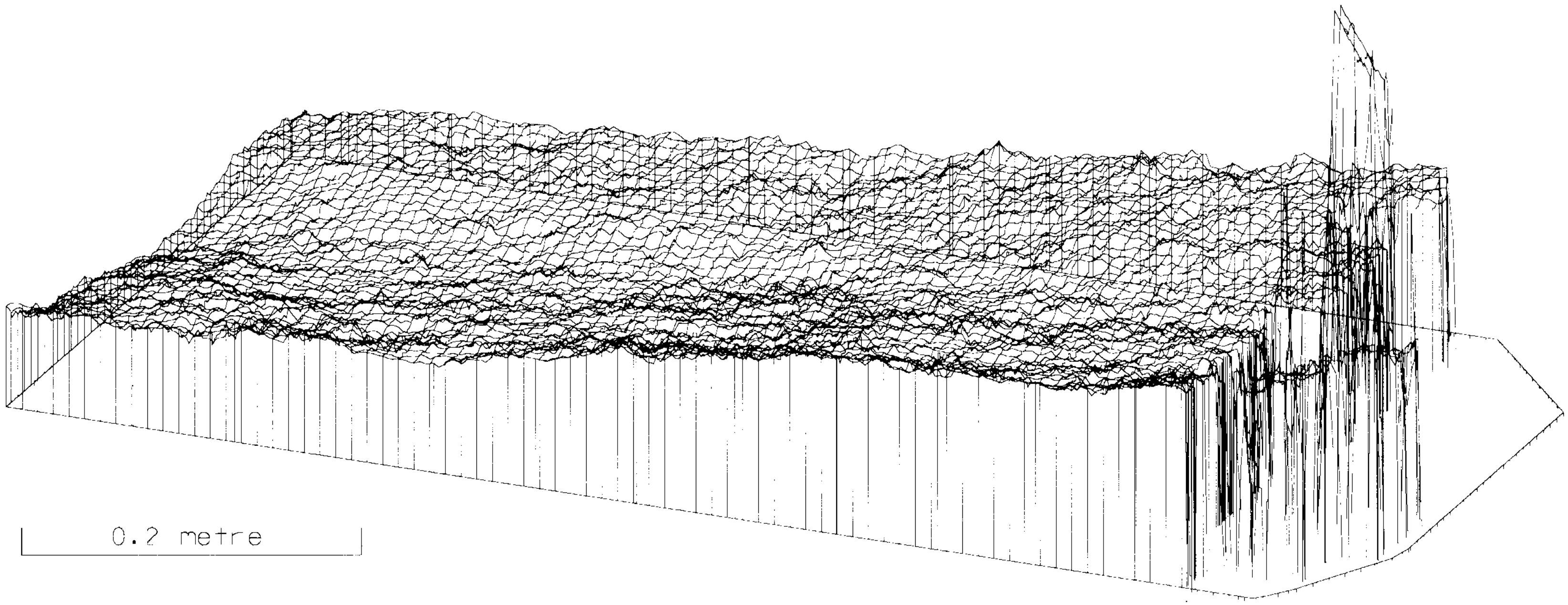

Figure 3. DEM generated using original control coordinates

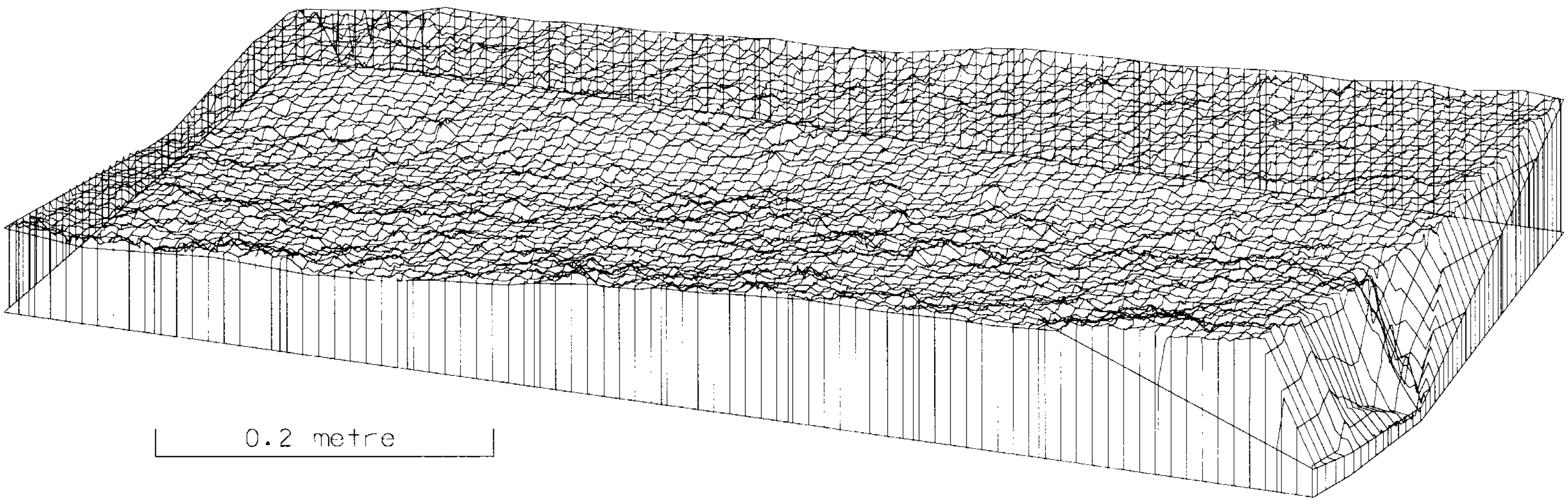

Figure 4. DEM generated using rotated control coordinates

Figure 3 is a gridded representation of the soil surface that was generated using the original unrotated photo-control. The large mountainous artefact visible at the upstream end of the DEM is a region in which the automated DEM procedure failed to correlate points. This failure occurred in the area furthest from the two cameras, where the angle between the vertical object space axis and the image ray was at a maximum. By contrast, Figure 4 represents a DEM of the same area derived using the same imagery, except that the photo-control was rotated by approximately $0°$, $22°$ and $11°$ about the three independent axes. Once the DEM had been generated automatically, it was rotated back into the original system using the required reverse rotations. Examination of the final rotated DEM reveals that a more realistic soil surface has indeed been generated. In addition, there is marked improvement in the percentage of successfully correlated points, and independent checks suggest that the correlation process was more successful.

CONCLUSION

The generation of DEMs using automated digital photogrammetry represents an important advance to representing and quantifying detailed landform morphology. The science of geomorphology, which attempts to understand the evolution of landforms, now has available a technique which can measure and quantify landform change at an appropriate density. The density is so high that factors such as the distribution of points and the role of the break-line are less important than previously. Significantly, the digital photogrammetry software required to generate such DEMs is widely available, reduces the photogrammetric expertise traditionally required and allows photogrammetry to be carried out on far cheaper Unix workstations and PCs. Although this trend is welcomed amongst the photogrammetric community, there is now a danger that the photogrammetric process will become over-trivialized. The main concern is that inexperienced users may become disillusioned with photogrammetric science, when an overly ambitious project fails to achieve expected results. To reduce the chances of this happening, recommendations have been presented which should allow the inexperienced photogrammetrist to avoid many typical problems.

It has also been demonstrated that with some expertise and initiative it is possible to use proprietary software for applications beyond the conventional vertical cases of aerial photography and satellite imagery. This allows photogrammetric methods to be applied to a far wider set of measurement problems, which includes the more cost-effective close-range and oblique cases.

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REFERENCES

Brunsden, D. and Chandler, J. H. 1996. 'The continuing evolution of the Black Ven mudslide, 1946–95. Theories put to the test', in Brooks, S. and Anderson, M. (Eds), *Advances in Hillslope Processes*, Wiley, Chichester, 869–898.

Chandler, J. H. and Brunsden, D. 1995. 'Photogrammetry, historical photography and the evolution of the Black Ven mudslide, 1946–1988. Evidence of dynamic equilibrium?' *British Geomorphological Research Group* annual conference, Cambridge, September 1995.

Chandler, J. H. and Cooper, M. A. R. 1989. 'The extraction of positional data from historical photographs and their application in geomorphology', *Photogrammetric Record,* **13**(73), 69–78.

Cooper, M. A. R. 1987. *Control Surveys in Civil Engineering*, Nichols, New York. 381 pp.

Cooper, M. A. R. and Cross, P. A. 1991. 'Statistical concepts and their application in photogrammetry and surveying', *Photogrammetric Record,* **13**(77), 645–678.

Fraser, C. S. 1997. 'Digital camera self-calibration', *ISPRS Journal of Photogrammetry and Remote Sensing,* **52**, 149–159.

Gooch, M. J. and Chandler, J. H. (in press). 'Accuracy assessment of digital elevation models generated using the ERDAS

Imagine OrthoMAX digital photogrammetric system', *Photogrammetric Record.*
Goudie, A. (Ed.) 1990. *Geomorphological Techniques*, British Geomorphological Research Group, 570 pp.
Granshaw, S. I. 1980. 'Bundle adjustment methods in engineering photogrammetry', *Photogrammetric Record,* **10**(56), 181–207.
Guerra, A. J. T., Favis-Mortlock, D., Chandler, J. H., Boardman, J. and Todd, M. (in preparation). 'An investigation of runoff, rill initiation and soil loss, using a field rainfall simulator and digital photogrammetry', *Catena.*
Hogg, J., McCormack, J. E., Roberts, S. A. and Gahegan, M. N. 1993. 'Automated derivation of stream channel networks and selected catchment characteristics from digital elevation models', in Mather, P. M. (Ed.), *Geographical Information Handling – Research and Applications*, 207–235.
Kenefick, J. F., Gyer, M. S. and Harp, B. F. 1972. 'Analytical self-calibration', *Photogrammetric Engineering,* **38**, 1117–1126.
Lane, S. N. 1998. 'The use of digital terrain modelling in the understanding of dynamic river channel systems', in Lane, S. N., Richards, K. S. and Chandler J. H. (Eds), *Landform Monitoring, Modelling and Analysis*, Wiley, Chichester, 311–342.
Lane, S. N., James, T. D. and Crowell, M. D. (submitted). 'The application of digital photogrammetry to complex topography for geomorphological research', *Photogrammetric Record.*
Lane, S. N., Chandler, J. H. and Richards, K. S. 1998. 'Landform monitoring, modelling and analysis; land form in geomorphological research', in Lane, S. N., Richards, K. S. and Chandler J. H. (Eds), *Landform Monitoring, Modelling and Analysis*, Wiley, Chichester, 1–18.
Li, Z. 1988. 'On the measure of digital terrain model accuracy', *Photogrammetric Record,* **12**(72), 873–877.
Lohr, U. 1998. 'Digital elevation models by laser scanning', *Photogrammetric Record,* **16**(91), 105–109.
Maas. H. -G. and Kersten, T. 1997. 'Aerotriangulation and DEM/Orthophoto generation from high-resolution still-video imagery. On the potential of digital cameras onboard an aircraft', *Photogrammetric Engineering and Remote Sensing,* **63**(9), 1079–1084.
McCullagh, M. J. 1998. 'Quality, use and visualisation in terrain modelling', in Lane, S. N., Richards, K. S. and Chandler J. H. (Eds), *Landform Monitoring, Modelling and Analysis*, Wiley, Chichester, 95–117.
Petrie, G. and Kennie, T. J. M. (Eds) 1990. *Terrain Modelling in Surveying and Civil Engineering*, Whittles Publishing, Latheronwheel, Caithness, 351 pp.
Polidori, L. and Armand, P. 1995. 'On the use of SAR image simulation for the validation of topographic mapping techniques', *EARSeL Advances in Remote Sensing,* **4**(2X), 40–48.
Pyle, C. J., Richards, K. S. and Chandler, J. H. 1997. 'Digital photogrammetric monitoring of river bank erosion', *Photogrammetric Record,* **15**(89), 753–763.
Raper, J. D., Livingstone, D. L., McCarthy, T. and Bristow, C. 1995. 'Evolution of the active spit complex on Scolt Head Island, N. Norfolk: Assessment of change from ground survey and aerial videography', *British Geomorphological Research Group* annual conference, Cambridge, September 1995.
Richards, K. S., Arnold, N., Lane, S., Chandra, S., El-Hames, A., Mattikalli, N. and Chandler, J. H. 1995. 'Numerical landscapes: static, kinematic and dynamic process-form relations', *Zeitschrift fur Geomorphologie*, Supplementband, **101**, 201–220.
Schenk, T. and Toth, C. 1997. 'Conceptual framework for a generalised roaming scheme', *Photogrammetric Engineering and Remote Sensing,* **63**(8), 959–964.
Smith, M. J. and Smith, D. G. 1996. 'Operational experiences of digital photogrammetric systems', *International Archives of Photogrammetry and Remote Sensing,* **31**(2), 357–362.
Smith, M. J. and Smith, D. G. 1997. 'DEMs and ortho-images from aerial photographs', *Photogrammetric Record,* **15**(90), 945–950.
Stojic, M., Chandler, J. H., Ashmore, P. and Luce, J. 1998. 'The assessment of sediment transport rates by automated digital photogrammetry', *Photogrammetric Engineering and Remote Sensing,* **64**(5), 387–395.
Van der Lei, K. 1998. 'One-stop shop for remote sensing needs', *GeoInformatics,* **1**(June), 10–13.
Vencataswamy, C. P., Clark, C. D. and Martin, R. J. 1998. 'Landform and lineament mapping using radar remote sensing', in Lane, S. N., Richards, K. S. and Chandler J. H. (Eds), *Landform Monitoring, Modelling and Analysis*, Wiley, Chichester, 165–194.
Walker, S. 1996. 'Digital photogrammetric workstations 1992–1996', *International Archives of Photogrammetry and Remote Sensing,* **31**(2), 384–395.
Wolf, P. R. 1983. *Elements of Photogrammetry*, McGraw-Hill, Singapore, 628 pp.

