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MEASURING FLUME SURFACES FOR HYDRAULICS RESEARCH USING A KODAK DCS460

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Abstract

A critical problem in hydraulics research is accurate measurement of fluvially worked sediments, both in the field and in scaled representations of field situations in laboratory flumes. Such measurement must provide information on individual grain characteristics, and their organisation into structures referred to as bedforms. Existing measurement approaches are based upon mechanical or laser profiling devices, which are both expensive and take considerable time to acquire data, particularly where information is required at very high densities. This paper demonstrates how conventional automated terrain model extraction software, combined with image acquisition using a Kodak DCS460 digital camera, has been effective in generating digital elevation models of complex bed morphology. This has reduced time spent collecting data in the flume and has allowed data collection at much higher spatial and temporal densities. Application of the method is illustrated by research carried out at Hydraulics Research Wallingford. Issues discussed include configuration of photographs and control coordinates; appropriate camera calibration methods; stability of inner orientation of the Kodak DCS460; and accuracies obtained. Comparisons with independent check data reveal that accuracies of ±2·5 mm have been achieved using a camera-to-object distance of 4·2 m.

KEYWORDS: camera calibration, close range photogrammetry, DEM accuracy, digital photogrammetry, river channel morphology

INTRODUCTION

RESEARCH into river channel hydraulics places considerable emphasis upon the measurement of bed topography. It has long been recognised that river channel topography has a number of different spatial scales (for example Leopold et al., 1964) ranging from the grain scale, through organisations of grains into the bedform scale, to the channel scale. The morphological properties of each of these scales are central to determining river channel processes but despite this significance, measurement of river channel morphology has proved difficult and has tended to lag behind measurement of processes (Lane et al., 1998).

Current research being conducted by a number of UK universities is seeking to increase understanding of the interactions between river channel flow, sediment transport and bedform development. Part of this is based upon experimental work undertaken at Hydraulics Research (HR) Wallingford using two scaled representations of river channel reaches, one a meandering channel, the other a straight channel flume. Central to both projects is the need to measure the spatio-temporal development of grain and bedform scales of channel morphology and the effects of this upon both flow structures and sediment transport. Existing measurement methods involve both mechanical and laser profiling devices, both of which take considerable time to use. This paper seeks to evaluate whether automated close range digital photogrammetry can improve the spatial density and resolution of information acquisition, and focuses upon technical aspects of the application that are likely to be of wider interest to the photogrammetric community. It is accompanied by a parallel paper that is being published in a journal that will be of more interest to the hydraulics community (Lane et al., in press).

CURRENT MEASUREMENT METHODS

It is possible to identify two distinct groups of methods available to measure the morphology of mobile laboratory channels. The simplest methods are based upon a series of individual point measurements that are repeated sequentially over an area. This may be acceptable in controlled laboratory conditions, where the bed can be fixed during measurement, but not if the bed is actively evolving. The second group of methods allows acquisition of measurements instantaneously, or nearly so. These are preferred because they allow experimental work to continue without inducing unnecessary delays. Although final digital elevation model (DEM) data acquisition may be strictly sequential, initial data acquisition with a photogrammetric approach is nearly instantaneous and may therefore be classified as an area-based technique.

Sequential Point-based Methods

Measurement of the morphology of mobile beds has been carried out at HR Wallingford for twenty years (HR Wallingford, 2000). The traditional method employs a tool known as a "point gauge", which consists of a vertical graduated rod clamped on a horizontal bar. The rod is lowered manually to the bed surface and a simple height change is measured, assuming a horizontal datum. The rod is then moved along the bar to the next desired location and the measurement is repeated. This simple approach is very time consuming and typically limits application to a set of cross sections that are sampled at wide intervals.

Recent research at HR Wallingford (2000) has overcome some of the deficiencies through development of the "touch sensitive, incremental 2D bed profiling system", which automates the profiling process. The profiler consists of a 10 mm diameter stainless steel tube with a machined rack and a probe, which is powered up and down by a DC motor. At one end of the probe is a simple "finger" switch that detects when the probe just touches the sediment surface. The distance between the end of the finger and the top of the probe is measured using a reflected pulse of infrared light, transmitted to a sensor using optical fibre. The probe is mounted upon a carriage and a PC equipped with two proprietary interface cards is used both to control the measurement cycle and to measure the probe position. The user is able to control the start point, total distance to be traversed and number of sampling points, and once started, all operation and measurement is fully automatic. Despite these improvements data acquisition rates are still comparatively slow, with approximately five seconds required to measure each point. It is possible to measure a sequence of repeated but offset profiles to cover a small regular area and hence to create a DEM, but the instrument is used mainly for the acquisition of channel cross sections, with the beam being moved manually to successive locations.

Measurement of elevations within small areas is possible using a "laser displacement sensor" developed by Graham and White Ltd. This comprises a sensor mounted upon a motorised positioning system, which locates the laser within an assumed horizontal plane. The distance to the bed is measured at a point, the sensor is then displaced and the cycle is repeated until full coverage of the desired area is obtained. Such a system is capable of measuring very precise distances between the sensor and the bed and it has the ability to measure directly through shallow water. The narrowly defined laser beam enables high resolution DEMs to be generated but the main problem with this system is the speed of data acquisition. Even when data collection is restricted to an area of 0·25 × 0·25 m, it still requires eight hours to acquire a DEM with a resolution of 0·5 mm. This restricts data collection to areas that are often smaller than is desirable. Further, careful calibration of the system may be required and there is evidence that accuracies are dependent upon the colour of the bed material (University of Aberdeen, 1994).

Coincident Area-based Methods

Coincident area-based methods are based upon near-instantaneous recording of morphology over a wide area. This is particularly advantageous for repeated experimental work that is being carried out in an expensive research facility and includes both photogrammetry and other optical techniques.

One recent innovation involves the use of a spatial light modulator (SLM) to generate synthetic fringes recorded by a digital sensor. This approach has origins in previously reported projection moiré methods (for example Kearney and Forno, 1989), although significant developments have been made. One of the main challenges with projection moiré is to transform the recorded phase distribution, which is in the range $-\pi$ to $+\pi$, into a continuous phase distribution. Any propagation of 2π phase errors leads to large inaccuracies in the final measured object shape. A technique known as temporal phase unwrapping (Huntley and Saldner, 1997) has overcome this problem by varying the pitch of the fringes projected by the SLM. Through processing a sequence of recorded images it is possible to unwrap the resulting phase variation at each pixel, independently of all other pixels. This procedure can be carried out in near real time using a signal processor and allows near instantaneous recording of morphology over a large area.

There is considerable evidence of photogrammetry being used to measure river channel information. Lo and Wong (1973) first used 35 mm cameras to examine the development of rills and gullies on a small section of weathered granite in Hong Kong. Collins and Moon (1979) measured stream bank erosion photogrammetrically and their approach was further developed by Welch and Jordan (1983), whereby non-metric 35 mm imagery was acquired at a height of 8·2 m above a dynamic meander bend. Analytical methods were used to measure both profiles and three dimensional terrain models. This study emphasised the need to record a large number of points to represent three dimensional topography accurately (Welch and Jordan, 1983). Kirby (1991) demonstrated the value of photogrammetry for measuring at the grain scale, although the application was not strictly applied to streambed morphology. He studied the micro-relief of desert surfaces, using vertical photographs obtained with a metric camera supported by a gantry. Analytical methods of photogrammetry were used to extract transects or profiles through the terrain surface. Manual measurement methods were used, achieving a precision of 1 mm.

Lane et al. (1994) combined analytical photogrammetry with tacheometric methods to quantify change occurring in rapidly evolving braided proglacial channels in the Alps. A Wild P32 camera was used to acquire highly oblique terrestrial images and the study demonstrated how improved topographic monitoring could assist fluvial research (Lane et al., 1996), even if the obliqueness of the imagery meant that manual measurement had to be used.

Advances in digital photogrammetry, particularly automated DEM extraction, are significant for geomorphologists interested in the measurement of dynamic natural surfaces. Such surfaces are well suited to automatic DEM measurement because active processes prevent colonisation by vegetation and are avoided by human construction. The surface extracted automatically is typically the desired surface, which is rarely true when such tools are applied to aerial photography of urban environments (Smith et al., 1997). Automated DEM extraction therefore offers the possibility of broadening the use of photogrammetry within both geomorphology and river channel research. Other significant factors include the reduced dependence upon expensive hardware and the speed with which information may now be generated.

Pyle et al. (1997) have used digital photogrammetry to monitor rapidly eroding stream banks. In this project imagery was acquired using a semi-metric Hasselblad camera, from which the imagery was then scanned. To allow automated extraction, the cameras were set up as an aerial analogue, with the control coordinate system rotated parallel to the eroding bank face (Chandler, 1999). This allowed the extraction of high density DEMs and hence the unexpected identification of small areas of change when none was thought to have occurred. Conversely, during a subsequent period of intense erosion in which catastrophic bank failure occurred, small areas of zero morphological change were identified.

Butler et al. (1998) applied automated DEM extraction to vertical close range photography acquired for small areas of a dry streambed. The aim of this project was to measure bed roughness, which is critical to improved understanding of both flow processes and sediment transport. Measures of bed roughness were derived from the automatically generated DEMs and compared with external estimates of streambed roughness. The main problem was the difficulty in assessing the quality of the acquired information with reference to independent data at a much lower density (Butler et al., 1998; Lane et al., 2000).

The results presented in this paper are based upon two projects that were specifically formulated to allow comparison of digital photogrammetric data with high-density data, independently acquired using sequential point-based methods.

DIGITAL PHOTOGRAMMETRY USING ORTHOMAX AND THE KODAK DCS460

Various software packages are available to extract DEMs automatically, but the ERDAS IMAGINE OrthoMAX package is popular within the UK research community because of the cost effective CHEST (Combined Higher Education Software Team) licensing arrangement. The software package was available at both Loughborough and Cambridge Universities and had been used successfully on a variety of related projects (Brunsden and Chandler, 1996; Pyle et al., 1997; Stojic et al., 1998; Butler et al., 1998; Chandler, 1999; Lane et al., 2000). An EPSRC research contract provided the funding required for two Kodak digital cameras, a DCS460 and a DCS420. These were purchased primarily because examination of the photogrammetric literature suggested that the DCS460, the DCS420 and their predecessor, the DCS200, had demonstrated considerable potential for digital photogrammetry (Fraser, 1997; Ganci and Shortis, 1996; Fraser and Shortis, 1995; Peipe and Schneider, 1995).

This section describes how digital imagery was acquired from two laboratory flumes at HR Wallingford, using a Kodak DCS460, and how this was used in combination with the OrthoMAX software to extract DEMs of the flume channel surfaces.

Image Acquisition

The geometry of the meandering channel of the Flood Channel Facility (FCF), along with site constraints, presented several difficulties when designing the photogrammetric configuration. The final data required was a DEM representing one full wavelength of the sinuous channel bed, between the crosses marked A and B on Fig. 1. The required area of coverage was 15 × 8 m and the channel width within this area was 1·6 m. The desired vertical precision of points in the final DEM was not specified but a precision of 1 to 2 mm was agreed as desirable. The focal length of the lens of the DCS460 camera was 28 mm and with a camera-to-object distance of 4·2 m (image scale 1:150), each pixel represented an area of 1·4 mm square on the object. A movable gantry platform was available and adapted to support the camera using a simple scaffold plank, with a 60 mm diameter drilled hole for the camera lens.

With an object distance of 4·2 m the footprint of each image was 4·1 × 2·8 m, too small to provide full coverage of the meandering channel using one conventional strip. The difficult sinusoidal shape of the meander suggested that the most efficient and reliable means of providing stereoscopic coverage was to acquire a sequence of overlapping stereopairs. A design consisting of 10 overlapping pairs was selected, each consisting of two photos displaced laterally by 0·4 m (Fig. 1). This design

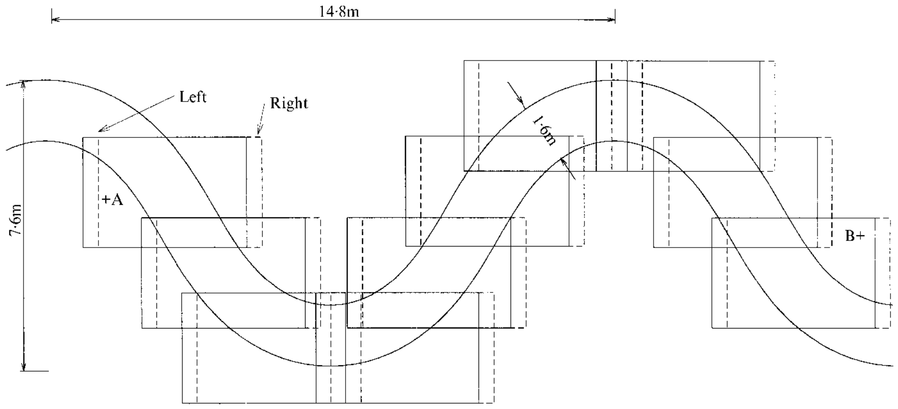

FIG. 1. Photographic coverage for the Flood Channel Facility.

provided several advantages. The gantry crane could translate in the *X* and *Y* ground directions, which allowed the 0·4 m base to be achieved easily, and provided a base to height ratio of 1:10 with an endlap of 90%. This highly redundant coverage combined with generous overlaps between pairs ensured that full coverage would be obtained, even if cameras were not placed in exactly the intended positions.

With both analogue and digital photography it is important to obtain adequately exposed images with, in the latter case, the desired object represented using a wide range of pixel radiance values (that is, good contrast). The provision of adequate illumination and selection of appropriate camera exposure settings is therefore critical. The FCF is located within a building similar to an aircraft hangar, with no natural light. The existing lighting was poor and had to be supplemented by four portable arc lamps, each with an output of 5 kW. The lamps were oriented to provide two lighting approaches. Firstly, reflected light was generated through bouncing light from the ceiling 6 m above the channel. The alternative involved illuminating the streambed directly by shining the lamps obliquely at the channel bed. The latter produced images of high contrast but included small areas of deep shadows, while the bounced illumination removed the harsh shadows but produced flatter images with less contrast. Both lighting scenarios were successfully used to extract DEMs automatically, although the bounced illumination was found to be slightly more successful.

One of the major advantages of using a digital camera for image acquisition is that exposure settings can be checked on site by downloading images onto a portable PC. This was found to be invaluable and removed traditional concerns over the suitability of chosen exposure settings. The camera was operated in "aperture priority" mode, with an overexposure setting of +0·3, which ensured that illumination was adequate for the slightly darker sand grains occupying the flume bed. The typical exposure setting was an aperture of f8 with a shutter speed of 1 s. "On-the-job" (Clarke and Fryer, 1998) or *in situ* self-calibration methods were to be used to calibrate the camera and, to prevent variation of the focal length during image acquisition, the auto-focus ability of the camera was switched off and the lens taped at infinity focus.

Image acquisition for the smaller Tilting Flume project was more straightforward. The channel width was only 0·6 m, extending to 1·0 m to take into account the need to locate photogrammetric control on the fixed channel banks. Thus, it was easy to gain stereo coverage with a single pair of photographs taken from an object distance of 2·0 m and with a scale of 1:71. A standard photobase of 0·25 m was chosen, providing a base to height ratio of 1:8. A small movable frame was constructed to support both the cameras and a Perspex sheet, necessary for two-media through-water photogrammetry (Butler et al., in review). The frame design again utilised a small movable board, with a 60 mm diameter drilled hole, to support the camera at the desired elevation. The focusing distance of the lens was set to 2·0 m.

Photogrammetric Control

Use of proprietary software often constrains photogrammetric design because certain requirements are assumed. One such requirement with OrthoMAX is the need for conventional photogrammetric control points, typically in the form of visible coordinated points.

In the FCF project, the designed block of photographs consisted of stereopairs that needed to be combined using the aerial triangulation software module. To ensure that the project was successful it was decided to establish excessive redundant control points, with approximately eight per stereomodel (Fig. 1 and Fig. 3). These only needed to be visible during image acquisition and so 60 × 40 mm control markers were secured along the edge of the channel using silicon bathroom sealant. These points all lay upon the flat floodplain of the constructed channel and, because on-the-job calibration methods were to be applied, it was felt important to place markers at other lower elevations. It was undesirable to place markers on the sediment surface, but it was feasible to stick targets on the sloping sides of the concrete channel, just above the channel bed.

Horizontal and vertical angles were measured to these markers from four survey stations, each point being visible from at least three different stations. A Leica 1610 digital tacheometer was used to measure all angles, with 570 measurements recorded on a data logger; these were supplemented by distances measured between stations and targets using a steel band. Height differences between a selection of points were also included, measured using a Leica NA3000 digital level. All measurements were combined in a least squares variation of coordinates program and error ellipses generated from this network suggested that the rms precision of these control points was homogeneous and approximately 0·4 mm.

The photogrammetric control requirements for the Tilting Flume project were different. Stable marker points were required for successive repeat tests held over a period of a year. The scale of the photography was also much larger (1:78). Thus, ten small permanent markers were created using the heads of crosshead screws, permanently fixed flush into the concrete lining of the Tilting Flume, and at three levels. Final coordinates representing these points were established using combined theodolite and distance measurements, which were subjected to least squares adjustment.

Photogrammetric Measurement

Measuring digital images acquired by the Kodak DCS460 in the OrthoMAX software was straightforward, although the inner orientation procedure had to be slightly modified because no fiducial marks were available. The four corners of the frame provide appropriate reference marks, with initial values created using the known dimensions of the CCD array, 27·6 × 18·6 mm.

The measurement of the image locations of the photogrammetric control points was entirely conventional, the "auto-place" functionality helping to automate the measurement of corresponding points appearing upon multiple frames. This tool uses the normalised cross-correlation coefficient (ERDAS, 1995) to locate optimum conjugate point matches appearing upon two or three images, the same approach used for auto-extraction of DEMs. Eight additional tie points were measured per stereopair, mainly through selection of points located upon the streambed. The auto-place feature was again found to be of value and provided early confidence that the imagery would be capable of auto-extraction of DEMs.

Photo frames were added and measured in stereopairs and the block triangulation tool executed repeatedly to construct a valid block, free of gross errors. Photo-coordinate residuals were initially high, but a poor result was expected due to the inaccurate lens model that had been entered initially. It was only following subsequent calibration procedures that this could be revised and improved upon.

Camera Calibration

It is well established that accurate data can be only extracted if the parameters used to describe the internal geometry of the camera are known accurately (Wolf, 1983; Slama, 1980; Fraser, 1997; Shortis et al., 1998). Use of an uncalibrated Kodak DCS460 digital camera, based upon standard 35 mm SLR components and designed for photojournalism, clearly requires calibration parameters to be established to an appropriate level of accuracy. Once calibrated, high accuracies are achievable using the DCS460 and studies have suggested that accuracies can even surpass 1:100 000 (Fraser, 1997; Shortis et al., 1998).

A self-calibrating bundle adjustment provides the obvious method available to derive appropriate inner orientation (IO) parameters and, as Fraser (1997) reports, the familiar eight parameter physical model advocated by Kenefick et al. (1972) may be used. This model comprises various elements to represent the principal distance, principal point offset and correction terms to model both radial and tangential lens distortion. These have been appropriate for conventional analogue cameras and Fraser (1997) and Patias and Streilein (1996) simply advocate the inclusion of two additional parameters for use with digital cameras. One parameter is used to model differences in scale between the x and y image axes, with a second term to compensate for potential non-orthogonality between the image axes.

Loughborough University has access to the self-calibrating bundle adjustment program, originally developed by J. Clark at City University (Chandler and Clark, 1992). This program, called GAP, was modified to include the camera model recommended by Patias and Streilein (1996) and Fraser (1997). This program would provide the basic capability to derive appropriate camera models for the project, although different data processing options were available and other issues needed to be resolved.

The OrthoMAX software was selected for final DEM acquisition, but it is not designed for use with imagery obtained using a Kodak DCS460 digital camera. Any IO parameters recovered during self-calibration had to be either implemented within the OrthoMAX software or would have to be dropped. This software supports only six of the eight Kenefick parameters, namely the principal distance, principal point offsets and three terms to model radial lens distortion. Tangential distortion is ignored by the software. Experience gained from other self-calibration studies suggested that for medium accuracy work using stereo restitution these simple parameters would probably be sufficient, a view shared by Fraser (1997). However, it was considered necessary to implement differential image scale, primarily because of the arbitrary photo-coordinate values used to define the four corner reference marks, and a means of doing this within OrthoMAX had to be developed.

A secondary concern was the unstable inner geometry of the DCS series of digital cameras, reported initially by Shortis and Beyer (1996) and more recently by Shortis et al. (1998). The instability is primarily related to the non-rigid attachment of the CCD array to the camera body, a deliberate design feature that increases camera durability. This apparent instability not only suggests that the validity of recovered camera parameters is time-dependent, but also causes a dilemma when acquiring imagery appropriate for self-calibration. It is normal practice to obtain convergent oblique imagery and include frames with a 90° roll angle to minimise parameter correlation and hence recover reliable principal point offsets (Kenefick et al., 1972; Granshaw, 1980). It can be envisaged that applying such orthogonal rolls during image acquisition is likely to induce a physical displacement of the CCD array, particularly with oblique imagery. The photo-variant self-calibration approach may then become more appropriate (Shortis et al., 1998).

The user is therefore faced with two choices, both problematical. Firstly, a convergent set of imagery may be acquired of a retro-reflective test field. Measurement and subsequent self-calibration using a free net adjustment (Granshaw, 1980) would yield precise estimates of the camera IO for that instant, but application of these parameters using subsequent imagery may be inaccurate due to the instability. Secondly, an *in situ* or "on-the-job" calibration approach may be adopted (Abdel Aziz and Karara, 1971; Clarke and Fryer, 1998), in which imagery used for actual DEM extraction is measured and combined with object coordinates to calibrate the camera. Such an approach will yield less precise estimates but the parameters may prove to be more accurate. The obvious solution to this dilemma was to adopt both methods and assess the impact of different calibration approaches upon the accuracy of data finally generated.

Eleven convergent and oblique images were obtained of a three dimensional testfield equipped with 30 retro-reflective targets. At four of the camera stations, four additional frames were obtained with the camera rotated through 90 degrees. Photo coordinates were measured automatically using the "Visilog" general purpose image processing program, which had been used successfully earlier (Chandler and Padfield, 1996). These data were combined in GAP, with additional parameters including principal distance, principal point offsets, two radial distortion parameters and differential scale recovered initially. The recovered differential scale parameter was 1·0023 and a way had to be found to implement this within the

OrthoMAX software. This was achieved through rescaling the original *y* photo-coordinate values used to define the four corner reference marks. The photo coordinates for each frame were recomputed using revised affine parameters derived using the rescaled reference marks and reprocessed in GAP with an identical set of additional parameters. This was carried out to ensure that the modified locations representing the fiducial marks were appropriate, verified by an estimated differential scale factor of unity. The differential scale factor was then removed and a final set of additional parameters was recovered. These values were then entered into the OrthoMAX software along with radial lens distortions at 10 radial distances, to allow computation of the OrthoMAX radial lens coefficients. These parameters represent the "Testfield" set listed in Table I.

Table I. Calibration parameters for DCS460 used on FCF project (infinity focus).

Calibration method	*Focal length (mm)*	*x shift (mm)*	*y shift (mm)*	k_1 *(m^{-2})*	k_2 *(m^{-4})*	k_3 *(m^{-6})*
Testfield	28·676	0·309	−0·022	−140·8	187 332	0
	±0·010	±0·004	±0·004	±2·2	±7970	fixed
In situ **with** principal point offset	28·487	0·268	−0·090	−141·2	183 740	0
	±0·110	±0·039	±0·04	±1·7	±5580	fixed
In situ **without** principal point offset	28·619	0·000	0·000	−141·0	182 354	0
	±0·100	fixed	fixed	±1·7	±5537	fixed

The alternative strategy involved carrying out an *in situ* calibration using the imagery covering the FCF. The image locations of all targets and pass points had been measured within OrthoMAX but were stored within the OrthoMAX database in a binary and inaccessible format. Fortunately, it is possible to create an ASCII file containing all data used in the OrthoMAX triangulation. A simple program was developed which allows this data to be extracted and restructured to the format required for GAP. Initially, the same set of additional parameters was included in the self-calibration and used to generate the "*in situ* with principal point offset" parameters in Table I. Removing the principal point offset also generated a third set of parameters. This was carried out in order to investigate the significance of the principal point offset for the DCS460 used in a standard stereo configuration.

An appropriate set of camera parameters had to be established for the Tilting Flume project, primarily because the camera was focused at a different focal distance (2 m). The same dual calibration processing strategy originally used for the FCF was adopted. A smaller testfield consisting of 70 retro-reflective planar targets was used for the self-calibration method and the *in situ* calibration was established using photographs of the Tilting Flume itself. The two sets of calibration values derived for the smaller Tilting Flume project are listed in Table II.

Generation of DEMs and Orthophotographs

Once appropriate camera models had been established the OrthoMAX software was used to generate DEMs and to produce orthophotographs. This was

TABLE II. Calibration parameters for DCS460 used on Tilting Flume project (2 m focus).

Calibration method	*Focal length (mm)*	*x shift (mm)*	*y shift (mm)*	k_1 *(m^{-2})*	k_2 *(m^{-4})*	k_3 *(m^{-6})*
Testfield	28·874 ±0·010	0·230 ±0·009	0·063 ±0·006	−141·8 ±1·0	194 172 ±3539	0 fixed
In situ **without** principal point offset	28·677 ±0·890	0·000 fixed	0·000 fixed	−128·7 ±17·2	173 573 ±14985	0 fixed

a routine procedure and standard tools within OrthoMAX and IMAGINE allow the user to generate this data.

For the FCF project, DEMs were generated from each stereopair at an initial resolution, or post spacing, of 10 mm. Internal estimates provided by the software suggested that the automated DEM correlation procedure was successful, with 80% to 85% of all points registering a successful match. Apparent failures were located in areas towards the edge of the overlap, and typically on the textureless surface of the flat floodplain. The large overlaps provided by the conservative design of the camera stations allowed failure regions to be rapidly replaced from an adjacent stereopair. These eight DEMs were then mosaicked together to create a composite DEM representing one full wavelength. A slope-shaded representation of this DEM (Fig. 2) demonstrates how successfully the automatic DEM extraction has qualitatively represented the streambed surface. It is worth emphasising that this DEM is unedited. Certainly all macro-topographical features are represented with bed waves and sediment bars clearly visible. It was also encouraging that the algorithm appeared to be successful on the steep banks of the channel, a region where failure was expected. Initially, this was merely attributed to linear interpolation providing appropriate elevations for these sloping surfaces of constant gradient. However, more detailed analysis of the distribution of acceptably matched points showed that approximately 70% of points within these sloping areas had indeed matched successfully.

The DEM consisted of over 600 000 points sampled every 10 mm. This proved to be too detailed and unmanageable for subsequent work, and so a lower resolution of 25 mm was finally adopted. It is planned to use this morphological data in two ways. Firstly, it will be used within a three dimensional Computational Fluid Dynamic (CFD) model, to validate the conveyance prediction of two-stage meandering channel flow. Secondly, the DEM will be used in spatial and spectral analysis to calculate the flow resistance associated with bedforms, one of the main sources of energy dissipation in a meandering channel. It has been found useful to generate orthophotos (Fig. 3) which assist greatly in the identification and interpretation of features visible within the DEM.

Similar data extraction procedures were adopted for the Tilting Flume project, with a DEM generated at a resolution of 3 mm (Fig. 4) over the full test area (0·4 × 0·3 m) and an orthophoto created (Fig. 5). As with the FCF study, a high percentage of points were successfully matched (75% to 80%) and the locations of points which failed to match appeared to be distributed randomly over the full area.

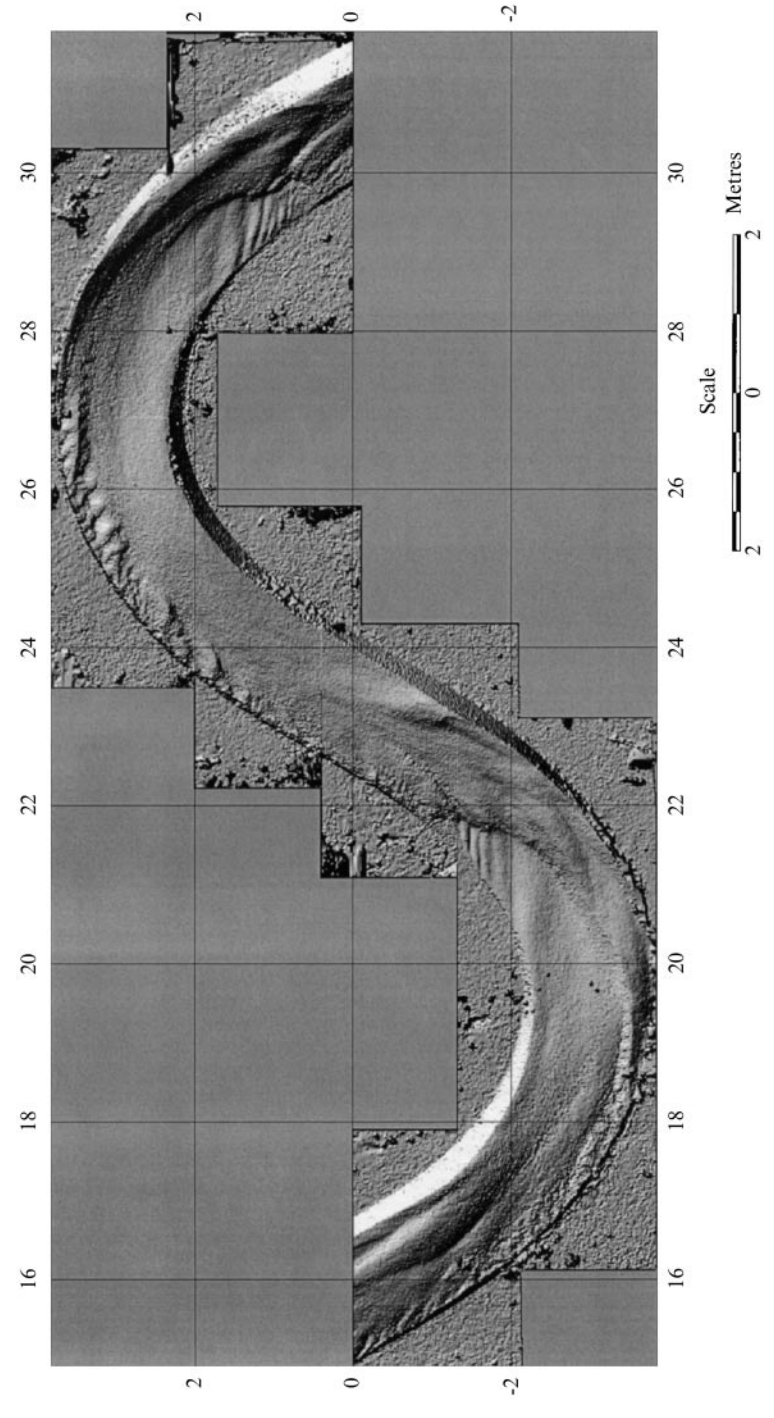

FIG. 2. Slope shaded representation of digital elevation model, Flood Channel Facility.

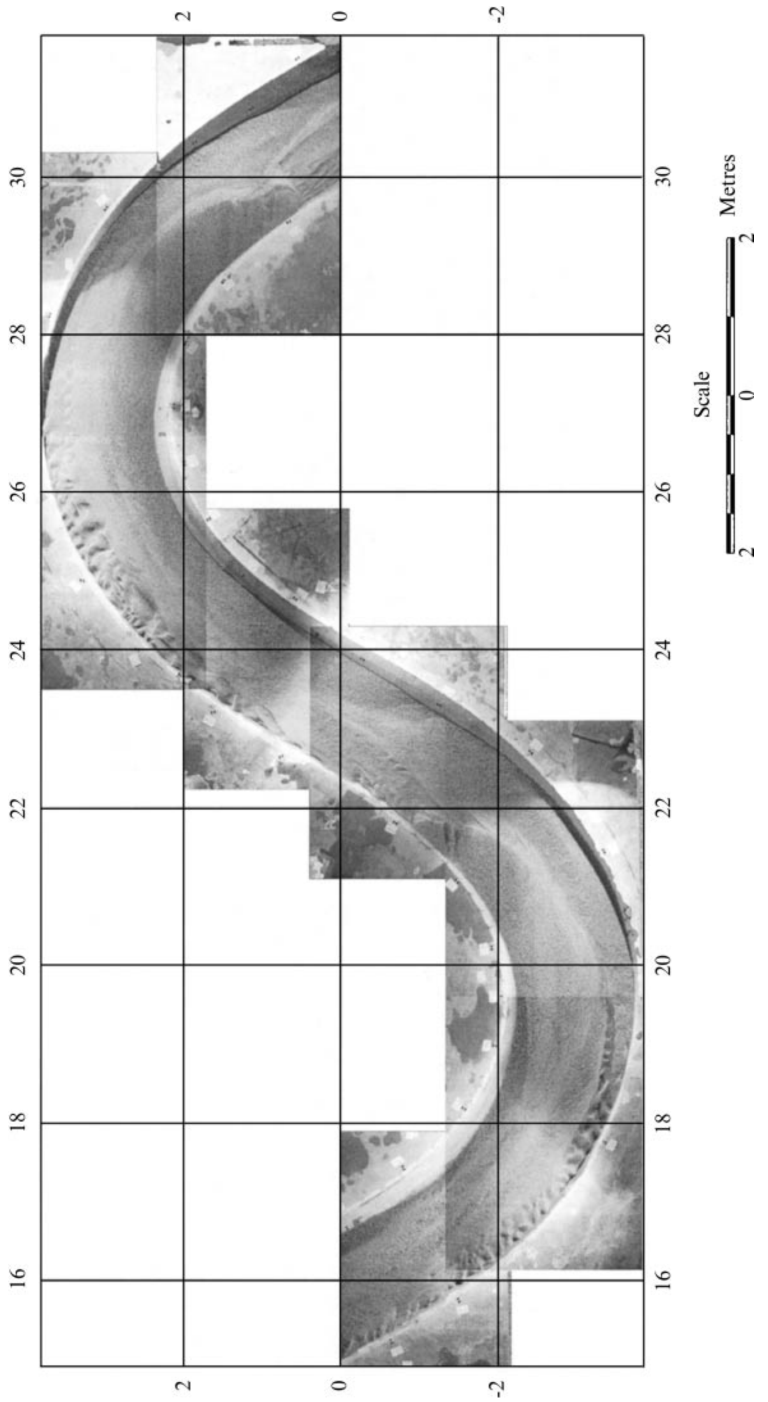

Fig. 3. Orthophoto of Flood Channel Facility.

Accuracy of OrthoMAX and DCS460 for Streambed DEMs

Although the DEMs represented by Fig. 2 and Fig. 4 give the appearance that morphology has been recorded successfully, it is always important to carry out independent checks to assess and quantify true accuracies. This should be achieved by comparing estimated DEM elevations with heights derived using an independent and accepted technique. For the FCF project, a series of cross-sectional profiles had been measured using the automated touch-sensitive, incremental 2D bed profiling system that was described earlier. For the Tilting Flume project, it was possible to carry out an area-based accuracy assessment because a DEM had been generated using a Keyence (LC2450) laser displacement sensor. The accuracy assessments were important, both to provide users of the data with information concerning quality of the DEM, and also to explore photogrammetric issues, notably appropriate self-calibration procedures.

FCF Accuracy Assessments

Fig. 6 is a cross section through the channel bed derived by the touch-sensitive profiler and automated digital photogrammetry, using the convergent testfield camera model. The horizontal sampling density was 25 mm for the profiler and 10 mm for the photogrammetry, although this latter density could have been increased to 5 mm. The correspondence is good, with an overall rms error of ±2·6 mm, if grossly inaccurate elevations are ignored. Particularly close agreement

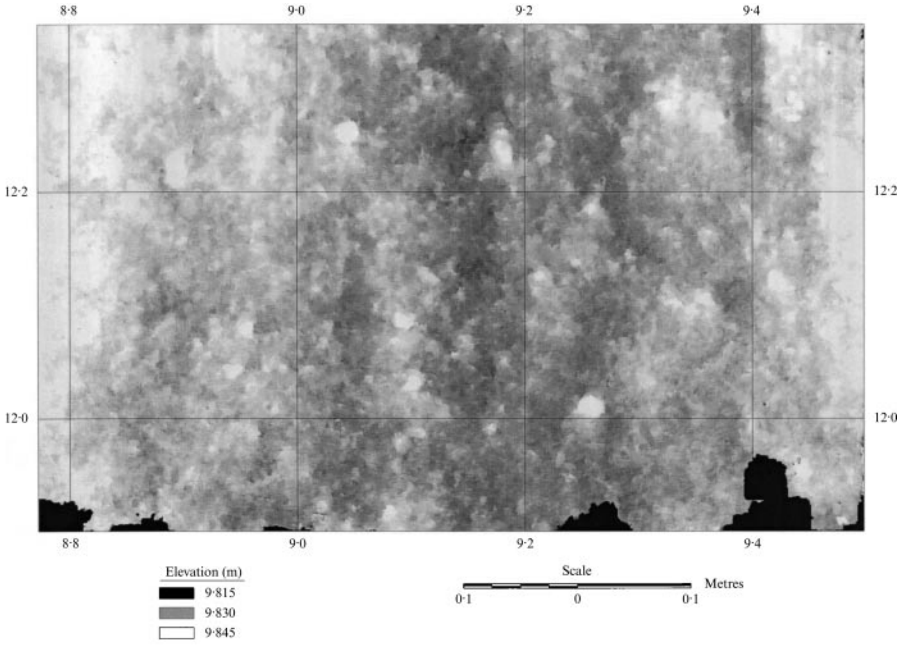

Fig. 4. Digital elevation model, Tilting Flume.

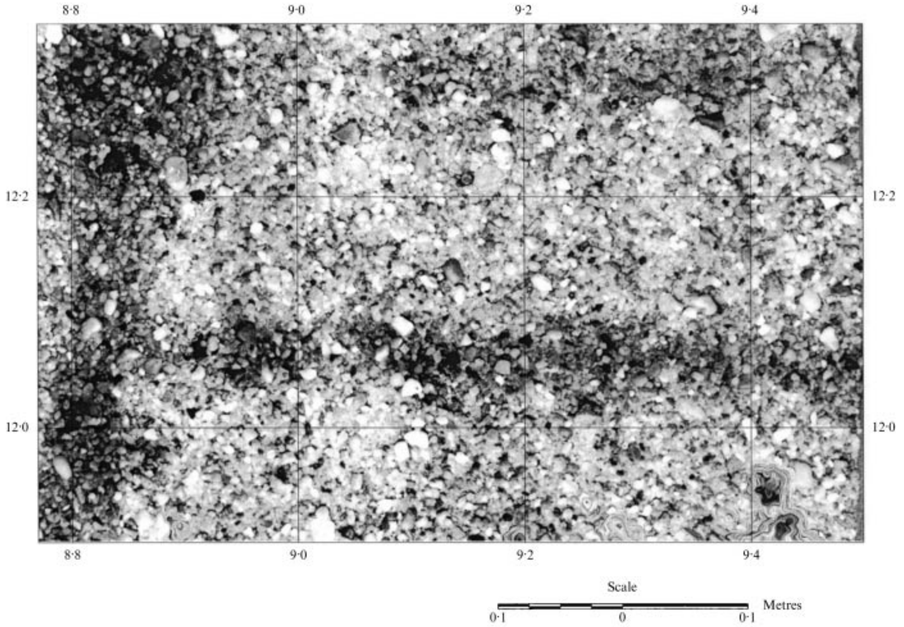

FIG. 5. Orthophoto, Tilting Flume.

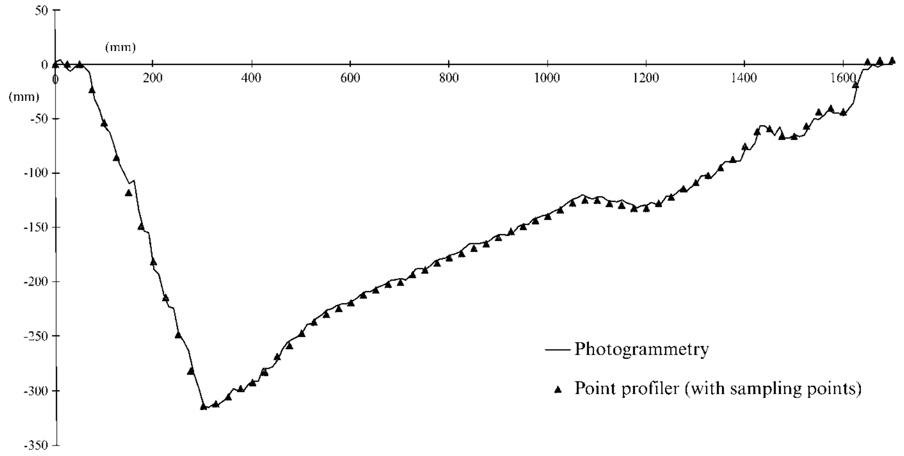

FIG. 6. Accuracy assessment: photogrammetry and point profiler, Flood Channel Facility.

can be identified within the steep channel sides, a region where the correlation algorithm was expected to fail.

Differences between DEMs generated using the convergent self-calibration model and the two adopted *in situ* calibration methods produced only minor changes in the generated surfaces. These differences are difficult to identify at the unexaggerated scale of the cross section. An alternative method involved determining rms errors by comparing the profiler point elevations with the photogrammetric estimates derived using the three differing camera models. These errors are presented in Table III.

TABLE III. Impact of calibration method upon accuracy (FCF).

Calibration method	*Rms error (mm)*
Testfield	±2·6
In situ **with** principal point offset	±2·7
In situ **without** principal point offset	±2·5

Tilting Flume Accuracy Assessments

A unique characteristic of the Tilting Flume project was the availability of a very dense DEM generated by the Keyence (LC2450) laser displacement sensor, which could be used to quantify the accuracies of the photogrammetry directly. The area-based nature of this data also allowed accuracy assessments to be based upon the entire surface, rather than restricted to cross sections. For this scale of application, the laser profiler provided a higher horizontal resolution (0·5 mm) DEM than the photogrammetry (3 mm), and so the laser profiler had to be sampled to the same grid resolution as the photogrammetric DEM using bilinear interpolation. Two DEMs were generated by photogrammetry, derived using either the testfield or *in situ* calibration model, and these were then compared with the sampled laser DEM. Fig. 7 shows the elevation differences between a laser-profiled surface and the photogrammetrically acquired DEM using the testfield calibration model. It demonstrates that differences are mainly within the 2 mm range, although there are notable exceptions at individual points. It also suggests that accuracies do not vary spatially, implying that the camera model is of an appropriate accuracy. To quantify and compare the two camera calibration models further, the rms error was again derived. This was achieved by comparing both photogrammetric DEMs with the laser surface at all 5589 locations. These results are presented in Table IV.

TABLE IV. Impact of calibration method upon accuracy (Tilting Flume).

Calibration method	*Rms error (mm)*
Testfield	±1·72
In situ **without** principal point offset	±1·69

DISCUSSION

Assuming that the "preferred" camera model used for both projects was derived using the full testfield calibration approach, it is apparent that the rms errors derived for each project, and represented in Tables III and IV, are very similar. The image scale for the FCF project was 1:150 and therefore approximately half that of the smaller Tilting Flume project (1:71). The accuracies achieved in

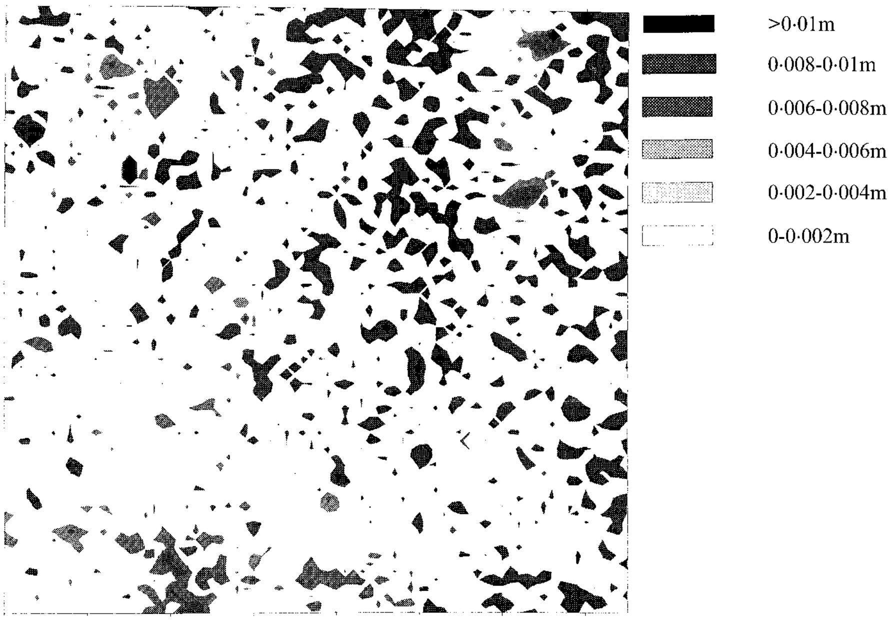

FIG. 7. Differences between laser profiled surface and photogrammetry, Tilting Flume.

the FCF project are lower, but certainly not in the same proportion as the difference in image scale would suggest. This inconsistency can be explained easily by considering the relative size and nature of the stream bed materials in the two projects and reassessing the DEM generation procedure itself.

Impact of Surface Roughness upon Area-based Algorithms

The median grain size of material adopted for the FCF project was only 0·9 mm whilst the rough gravel surface used in for the Tilting Flume project was approximately 24 mm. Simple examination of the two sets of imagery reveals that individual grain particles clearly dominate the large scale imagery of the Tilting Flume (Fig. 5), but are only just visible for the FCF (Fig. 3). The larger particles inevitably create a more topographically varied, or "rougher", surface and it is suggested that surfaces with high relief, relative to the object distance, are far less suited to an area-based heighting algorithm. It should be remembered that the height estimate assigned to a single pixel location has been established using an image patch which is generally 5 to 10 times the pixel size on the object. The single height estimate is effectively the average height within such a small image patch. The dimensions of these patches for the Tilting Flume project are between 7 and 14 mm and so crevices which are visible in the orthophoto (Fig. 5) are not fully represented in the DEM (Fig. 4). Conversely, in the FCF imagery (Fig. 3) the particles are small and the consequent surface smooth, so the averaging effect within patch sizes of just 3 to 6 mm is, in most circumstances, perfectly appropriate.

The deep crevices between sediment clasts in the Tilting Flume can also cause significant "dead ground" between the left and right images, which could also account for the lower than expected accuracy estimates. Indeed, for a randomly selected sample of points, there was a significant association (at the 95% confidence level) between match success or failure and whether or not the pixel was on the edge of a clast or in the middle, with more failures on clast edges. This is also supported by reliability estimates of the DEM (Chandler, 1999) which were generated by comparing photogrammetrically derived elevations within the same area obtained using two different image pairs. Subtracting the two DEMs (Fig. 8) produces a mean error of 2·1 mm, a standard deviation of 1·1 mm and an elevation difference range of 14·4 mm. Fig. 8 suggests that the errors are spatially localised, with a small number of points displaying exceptionally large differences (> 10 mm), but with most differences being less than 2 mm. This suggests that changes in camera position are having a localised effect on surface representation that is of a significant magnitude when compared to the individual grains being studied. The observation that crevices are problematic is important, as a first reaction to the low DEM resolution problem is to decrease the camera-to-object distance and so increase the scale of the imagery. However, this will only increase the magnitude of the crevice effect due to the increased relative relief of the surface at lower object distances.

An obvious question is whether or not surface quality can be improved by using multiple image pairs, where one image pair might be more capable of seeing into a crevice than another. One of the best indicators of this might be matching success where a failed match could be due to the two images seeing different views of the same point.

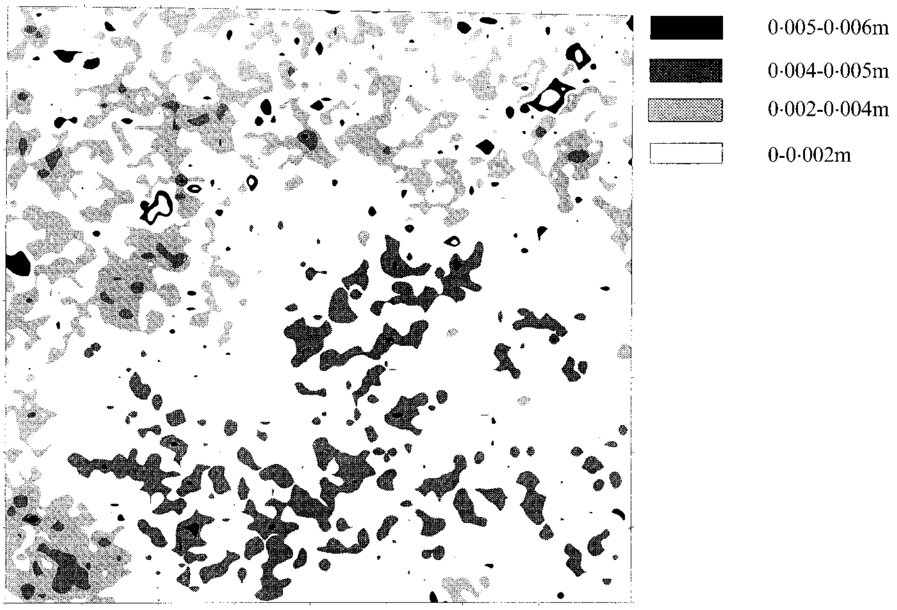

Fig. 8. Differences between photogrammetric DEMs acquired using different imagery, Tilting Flume.

One possible way to counteract this problem is to take DEMs acquired using two (or more) image pairs and to combine them, according to matching success. Where one DEM has a point with a matching failure, but the other has a success, the elevation of the failed point is replaced by the elevation of the successful point from the second DEM. This procedure was carried out, but when judged with respect to the laser profiler data, the standard deviation of error increased to 1·7 mm. It is clear that this simple approach was ineffective and perhaps not capable of counteracting the crack problem. The method could however, be valid for counteracting other potential error sources and therefore improving the quality of generated DEMs.

Impact of Calibration on Achievable Accuracy

An issue of interest to photogrammetrists is the performance of the Kodak DCS460 digital camera, in particular the validity of the differing calibration methods used. A comparison of accuracies achieved using the three calibration methods adopted for the FCF (Table III) suggests that the *in situ* calibration method with a principal point offset of zero was the most accurate, with an overall rms error of ±2·5 mm. However, the difference between this and the other two methods remains small and suggests that the calibration method, and indeed inclusion of a principal point offset, is not so critical. This finding was repeated for the Tilting Flume project (Table IV), where the difference between the two calibration methods did not reveal a significant difference in accuracy. These results perhaps confirm the suggestion made by Fraser (1997) that, for medium accuracy work using digital cameras and stereo restitution, the important inner orientation parameters are simply an appropriate lens model together with the focal length. Indeed, in situations where relief variation is low, even this requirement can be relaxed further, as an accurate focal length is not strictly required (Fraser, 2000). Correlation between principal point offsets and exterior orientation is particularly high for vertical imagery of a comparatively flat object (Granshaw, 1980). It is therefore likely that some of the systematic errors associated with stability of the CCD arrays are being absorbed by the exterior orientation parameters through a process of projective compensation (Granshaw, 1980).

Since *in situ* calibration requires measurement of imagery used for data extraction only, this calibration approach is perhaps to be preferred. The only caveat to this recommendation would be the need to obtain an appropriate number of measurements, of both photogrammetric control and additional tie points, distributed across the entire image format, which would enable reliable lens parameters to be recovered. There is always a danger of estimating inaccurate additional parameters, typically through over-parameterisation (Granshaw, 1980; Chandler et al., 1989). Although the classical method used to identify such cases involves comparing estimates with their standard errors, comparing parameters with values derived from prior and comparable work provides a more direct indicator of validity.

CONCLUSIONS

Automated digital photogrammetric software and a Kodak DCS460 digital camera have been successfully employed to generate dense, accurate DEMs of two river channel beds, at two scales. Important factors that affect efficiency include image acquisition, control distribution and camera calibration, and recommendations have been both presented and discussed. Independent accuracy assessments should always be carried out and have revealed findings in two distinct areas.

Firstly, the accuracy tests have enabled the effectiveness of the technique to be established and reveal that an area-based terrain extraction algorithm is best suited to measuring surfaces composed of small particles that tend to create a smooth and continuous morphological surface. In situations where larger particles are visible, an area-based approach is only capable of measuring macro relief and detecting clast organisation and is not suited to measuring microstructures created by adjacent clasts. Alternative technologies such as the high-resolution laser profiler may be more appropriate in such situations because this device can penetrate into crevices. Despite this advantage, the laser profiler is not ideal because it can only measure within a restricted area and is very slow.

Secondly, the accuracy assessments have also confirmed that the camera calibration procedure used to derive inner orientation parameters is not critical for terrain model extraction using a Kodak DCS460 digital camera in a stereo configuration. The recommended approach would involve determining focal length and a radial lens model using an *in situ* self-calibrating bundle adjustment. It is essential, of course, to derive accurate parameters and great care is necessary to ensure this. Comparing estimated parameters with both their standard errors and prior determined values is recommended. There is, however, no substitute for independent accuracy tests using points within the DEM and these should always be included.

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Résumé

La détermination précise de la façon dont les sédiments sont travaillés par les fleuves est un problème critique dans les recherches en hydraulique, que ce soit sur le terrain ou en laboratoire, sur les maquettes à échelle réduite simulant les situations du terrain. Une telle détermination doit fournir des informations sur les comportements propres aux grains des sédiments et comment s'organisent leurs structures selon la forme du lit des rivières. Les méthodes de mesures actuelles sont basées sur des systèmes de profilage mécaniques ou à laser, avec lesquels l'acquisition des données est à la fois longue et onéreuse, notamment lorsque l'on a besoin de très grandes densités d'informations. On montre dans cet article que la combinaison d'une caméra numérique Kodak DCS460 pour la saisie d'images, et d'un logiciel classique d'extraction automatique du modèle de terrain, s'est révélée efficace pour l'établissement de modèles numériques des altitudes dans le cas de lits à morphologie complexe. On a pu réduire ainsi les temps de saisie des données tout en augmentant considérablement leurs densités spatiale et temporelle. Une illustration de cette méthode est constituée par les applications menées au Centre de Recherches Hydrauliques de Wallingford. On y a abordé les problèmes relatifs à la configuration des photographies, aux coordonnées des points d'appui, aux méthodes d'étalonnage de la caméra, à la stabilité de l'orientation interne de la caméra Kodak DCS460, et aux précisions obtenues. Des comparaisons avec des données de vérification indépendantes ont montré que l'on était arrivé à des précisions de ±2,5 mm avec un éloignement de la caméra à l'objet de 4,2 m.

Zusammenfassung

Ein kritisches Problem bei hydraulischen Forschungen ist die genaue Vermessung fluvial geformter Sedimente, und zwar sowohl im Gelände als auch bei maßstäblich nachgebildeten Situationen in Laborkanälen. Solche Messungen müssen Informationen über einzelne Korncharakteristika und ihre Organisation in Strukturen bezogen auf die Bettformen liefern. Bestehende Messanordnungen basieren auf mechanischen oder Laser-Profilmessern, die beide teuer und sehr zeitaufwendig bei der Datengewinnung sind, vor allem wenn die Informationen in großer Dichte gefordert sind. Im Beitrag wird gezeigt, wie konventionelle Software zur automatischen Herleitung von Geländemodellen in Verbindung mit der

Bildgewinnung mittels einer Digitalkamera DCS460 von Kodak effektiv bei der Erzeugung digitaler Höhenmodelle einer komplexen Bettmorphologie sein kann. Dadurch wurde die Zeit zur Datenerfassung im Kanal reduziert und die Datengewinnung konnte mit viel größerer räumlicher und zeitlicher Dichte erfolgen. Eine Anwendung der Methode wird durch die am Hydraulic Research in Wallingford durchgeführte Forschung vorgeführt. Die diskutierten Fragen betreffen die Anordnung der Photos und der Paßpunkte, geeignete Methoden zur Kammerkalibrierung, die Stabilität der inneren Orientierung der Kamera DCS460 von Kodak und die erreichten Genauigkeiten. Vergleiche mit unabhängigen Kontrolldaten zeigten, dass bei einer Aufnahmeentfernung von 4,2 m Genauigkeiten von ±2,5 mm erreicht wurden.