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SHORT COMMUNICATION

ON THE ACCURACY OF HEIGHTING FROM AERIAL PHOTOGRAPHS AND MAPS: IMPLICATIONS TO PROCESS MODELLERS

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ABSTRACT

A concern to all scientists engaged in modelling landform must be the accuracy with which heights can be obtained from aerial photographs and their derivatives, conventional topographic maps. Morphological information is of importance for terrain description and analysis and increasingly as a critical boundary condition for models of geomorphological processes. This paper offers some cautionary advice in the use of aerial photographs and maps to provide morphological information.

Current mapping specifications are reviewed and the prospects for improved accuracy in heighting, given new equipment such as cameras equipped with forward motion compensation, are analysed in the light of recent published material. An analysis is presented of the manner in which random errors in photogrammetric observations can be propagated through a block of aerial photographs. A further analysis is made with the addition of a small systematic error of a type and magnitude occasionally encountered in practice. These analyses show that the use of published map data (digital or not) for producing landform models should be made only after careful assessment of the accuracy of those data and that some of the claims currently being made for height accuracy obtained with new photogrammetric equipment are valid only in special cases.

KEY WORDS Photogrammetry DEMs Variance propagation Data quality

INTRODUCTION

Earth and water scientists involved with the development of computational models to monitor and predict landscape evolution often rely on the integrity of digital elevation models (DEMs) (Moore and Grayson, 1991; Lane *et al.*, 1994; Moore *et al.*, 1991). The most common source for DEM modelling is the contour derived from existing topographic maps (Moore *et al.*, 1991). Even published DEMs are predominantly derived from this source, with few examples of DEMs being produced directly from measured three-dimensional coordinates. This source of height data obtained from government mapping agencies is often one of the cheaper and more readily accessible forms of such information, but how accurate is it?

Another concern is whether or not earth scientists are fully aware of the limitations of DEMs as sources of spatial information. There are some warnings in the geographical literature (Rhind and Clark, 1988; Moore *et al.*, 1991), but with widespread access to computers to process such data, warnings need to be reiterated.

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On this occasion the warning is made by providers of spatial data: surveyors and photogrammetrists. The main problem arises once a DEM is in a computerized DEM system because there is little control on how that information is used. A rich variety of parameters can be derived from a DEM, such as slope angle, aspect, profile and plan curvature, even 'Yin Yang' (Dana Tomlin, 1990). However, the authors have seen no examples in the literature of the use of propagation of variance necessary to estimate the precision of derived parameters as a function of the precision of original source data. Another potential problem is associated with scale of application. Typically, the applied researcher will be restricted to a comparatively small area within which critical environmental parameters can be measured practicably. The spatial context can be provided by an existing DEM covering a much larger region, and it is far cheaper to extract the relevant area from this dataset than to commission a new survey. There are few restraints on manipulating and processing these data and a real danger exists of deriving a series of parameters for a small specific area which are inaccurate because they are based on data originally derived for more general use over a much wider area.

Perhaps more seriously, DEMs are required increasingly as direct input to distributed models of landform process (Bates *et al.*, 1992; Dietrich *et al.*, 1993; Sharp *et al.*, 1993; Lane *et al.*, 1994). In such models, distributed elevation information is a key controlling factor and errors in morphological description will result in poor model performance. This is most critical in applications involving low relief such as the floodplain environment, where small topographical highs and lows control the exact spatial patterns of floodplain inundation and sedimentation. If this height information is taken from a source that already contains substantial error, then this error may be propagated through to model predictions.

In order to examine existing contour plans as sources of spatial information, accuracies claimed by various authors are presented and reviewed. A simulation of a typical mapping project follows, in which variances of photogrammetric measurements are propagated through the photogrammetric least squares estimation procedure and enable the precision of derived height points to be examined. A further analysis is made with the addition of a small systematic error of a type and magnitude occasionally encountered in practice. This is followed by an examination of how the accuracy of data acquired by photogrammetry is downgraded further by conversion to the final mapping product often used as the primary source of spatial data.

AERIAL PHOTOGRAMMETRY AND ACHIEVABLE ACCURACIES

A flying height of 1500 m and a camera focal length of 150 mm are typical for aerial mapping; these produce a photographic scale of 1 : 10 000. From such a scale it is usual practice to produce maps at scales as large as 1 : 1000 to 1 : 2500. Such maps variously show contours with a vertical interval of 1, 2, 5 or 10 m, depending on the nature of the terrain and the purpose for which the maps were intended.

Textbooks on photogrammetry (e.g. Wolf, 1983; Burnside, 1979; Slama, 1980) indicate that heights of well-defined points can, conventionally, be obtained with a precision of 1/10 000 of the flying height (e.g. Wolf, 1983). For the typical flying height of 1500 m, this corresponds to a vertical precision of $\pm 0{\cdot}15$ m. Such a precision is apparently suitable for contouring at 1 m intervals or greater, but how reliable is the critical parameter of 1/10 000 of the flying height? Table I indicates that other organizations and authors quote considerable variation in this value, partly because of recent developments in camera technology.

A knowledge of the blurring of the image which takes place on aerial photographs has been fundamental to the design of aerial survey film for many years. This systematic effect is due to the movement of the aircraft while the lens shutter is open during exposure. The development and commercial availability in the last few years of aerial cameras that actually move the image plane at the time of exposure to compensate for the forward motion of the aircraft, has enabled a breakthrough in image quality and resolution. These cameras are called forward motion compensation (FMC) cameras and a unit that can be fitted to existing cameras is now on the market. A new aerial camera with FMC and lenses that provide for higher resolution may cost of the order of US$1 000 000, so there is an understandable reluctance on the part of the traditional mapping agencies to acquire this technology. The purchase of a new FMC camera would be difficult to justify on the basis of any improvements to standard map series.

Table I. Accuracies quoted in the literature

Source	Spot heights*	Notes
Cooper (1982)	1·1	Block of 76 photographs, various adjustment techniques
Methley *et al.* (1982)	1·2	Block of 35 photographs, variation of 0·9–3·0, generally 1·2
Cox (1992)	0·7	Forward motion compensation (FMC) camera used
Newby (1992)	1·5	Ordnance Survey (U.K.), general mapping specification
Stevens *et al.* (1992)	0·25	Targeted points only, FMC cameras used
Neill (1993)	0·8	61 test points, analytical plotter, FMC cameras used

* Accuracies of spot heights standardized to parts per 10 000 of flying height

Examining Table I, the accuracies claimed by Stevens *et al.* (1992) would be difficult, if not nearly impossible, to obtain using standard map production procedures. It must be understood that there is a distinct difference between the accuracies that can be obtained by photogrammetry when targeted points, rather than natural features, are used. Most experienced photogrammetric operators believe they can produce heights of targeted points twice as accurately as heights of natural features. Placing a contour line across topography is generally thought to be half as accurate as spot heighting of natural features. Thus, while Stevens *et al.* (1992) claim 0·25/10 000 of the flying height using the latest technology, this probably only represents 1/10 000 for the accuracy of contouring. Nevertheless, it still represents a possible three-fold improvement on present practice (Newby, 1992). The future for landscape modellers who can obtain access to heights derived from photography using the latest equipment does seem increasingly promising, if expensive.

THE INFLUENCE OF RANDOM ERRORS IN THE HEIGHTING PROCESS

The precision with which a photogrammetrist can measure, on an aerial photograph, the position of the image of a targeted point is somewhere in the region of 2 or 3 μm, given the very best of clear photography and modern instrumentation in good order. Assuming that this is not always the case (and certainly many points chosen for aerial triangulation and other photogrammetric tasks will be neither pre-marked nor visible with such clarity), a value of 5 μm is used here as the standard deviation of a photogrammetric measurement for a study of the propagation of random errors which could be expected in an aerial triangulation.

A small block of 15 photographs, arranged in three strips of five photographs each, covering a flat area of approximately 5 km by 5 km, was simulated in a computer study. A flying height of 1500 m and a camera equipped with a focal length of 150 mm was assumed. Each strip had the conventional 60 per cent forward overlap and 20 per cent sidelap. A 'perfect' set of observations for up to 15 ground points per stereomodel was computed. Numbers generated at random from a normal distribution with zero expectation and a variance of 25 were added to the 'perfect' data to simulate random measurement errors having a standard deviation of ± 5 μm.

Twenty ground control points were dispersed throughout the model in the manner that would be applied in practice. The results of least squares estimation showed that the heights of the ground points had standard deviations (root-mean-square (r.m.s.) value) of $\pm 0{\cdot}08$ m, with a maximum discrepancy from known height of 0·24 m. While such a value seems large, it falls within the bounds of three standard deviations, a limit which most surveyors and photogrammetrists regard as acceptable. It must be remembered that only random errors are present in this simulation and that in real situations, systematic errors of magnitude greater than 5 μm may arise through factors which include film unflatness, film stretch, instrument errors and operator fatigue.

When the number of control points was reduced to eight, situated in 'ideal' locations around the edges of the block, the r.m.s. standard deviations of the estimated heights increased to $\pm 0{\cdot}14$ m with the maximum difference from 'true' being 0·37 m. Again, this maximum value would be regarded by most photogrammestrists as statistically insignificant.

The implications of this simulation are relevant to earth scientists involved with the development of computational models to monitor and predict landscape evolution. It must be realized that the results of the aerial triangulation phase provide control values for the spot heighting and contouring of each stereo model in the subsequent mapping process. Therefore, if some control points are already in error in height by approximately 0·3 m from random errors alone, how large could one expect the uncertainty in heighting to rise? The 1 : 10 000 photography used in this example could conceivably be used to produce maps at 1 : 1000 scale and with a contour interval as small as 1 m!

The precision of taking observations to the natural surface for spot heights or surface contours would be, on average, worse than $\pm 5\,\mu$m. If a reasonable conservative value of $\pm 10\,\mu$m is chosen (discussions with operators of photogrammetric instruments indicate that ± 15 to ± 20 may be more likely), then further heighting errors of up to $\pm 0{\cdot}6$ m could reasonably be expected. The summation of random errors follows the law of the propagation of variances, so a standard deviation of the order of $\pm 0{\cdot}7$ m could be present in the contours of the map sheet, from random errors alone.

Consider the premise that the area being mapped incorporated a large floodplain. A typical river gradient in such an area might be 0·5 per cent, so the positioning of contour lines (if any were to be attempted in such an area) could be about 140 m in error in planimetric position. Spot height values would be similarly displaced.

THE ADDITION OF A SYSTEMATIC ERROR

Another study undertaken by the authors has been the inclusion of a systematic error of 40 μm to the observation of one of the fiducial, or reference, marks which are imaged in the corners of each aerial photograph. The interior orientation (or initial phase of photogrammetry which occurs before measuring the images of ground points) involved taking readings on all fiducial marks. A least squares fit (usually using an affine transformation) is made to these observations, and the residuals of this fit of instrument coordinates to the camera's fiducial coordinates are displayed as a r.m.s. value.

Errors in the positions of fiducial marks are known to occur from time to time in aerial photography, usually as a result of the vacuum system for holding the film flat in the image plane not working properly in one corner and the film subsequently lifting off the image plane at that point. Since the fiducial marks are sometimes back-projected onto the film or exposed by internal illumination, the separation of the film from the image plane can easily cause a systematic error of 40 μm in the position of a fiducial mark.

If the only fiducial error were one of 40 μm in a radial direction, it would be redistributed equally amongst residuals at the four fiducial marks in that photograph by the affine transformation, resulting in a displayed r.m.s. value of only 7 μm for each residual (for a full study of the effect of fiducial errors, readers are referred to Fryer *et al.*, 1993). Fiducial residuals under 10 μm are usually accepted without question by map-makers, so a distortion, in the form of an affinely sheared set of image coordinates, would be input from this particular photograph to the process of establishing height control points throughout the block of photographs.

The effect of such an (apparently) acceptable error and its propagation through the block of simulated photographs described above has been studied. The estimated ground heights corresponding to the photograph location at which the assumed fiducial error occurred, may not reflect this error at all. Rather, at a considerable distance from where the error occurred, a 0·45 m difference in height from the previous values generated by random errors alone, was found. The height values were distorted in areas of the photogrammetric block where its geometric strength is weak. These areas occur around the periphery of a block where a ground point is imaged on fewer photographs than a point nearer to the centre of the block. Points in these areas have standard deviations of about 0·18 m in height. Again, a discrepancy of 0·45 m would not raise suspicions because it is within three standard deviations of the precision at that point.

Therefore, the addition of a significant, but not uncommon, systematic error to the random errors previously discussed could make any heighting from this simulated study accurate to only the 1 m level in certain areas of any set of maps which were produced. Given that the flying height for this study was 1500 m, a realistic figure for expressing the worst heighting accuracy of spot heights that could be expected on the map would be 6/10 000 of the flying height. In other regions on the map, the figure would be more like 2 or 3 per 10 000, a figure which agrees with the conservative approach taken by the Ordnance Survey of Great Britain (Newby, 1992).

The maximum errors from the simulated study are an order of magnitude larger than the accuracies claimed by the other references cited earlier. These other studies used targeted points and considerable field control (ground truth), and presumably were not beset by occurrences such as the vacuum on the camera partially failing. It must be further recognized that there is a tendency for many researchers to publish results that are especially good, rather than those likely to be routine in nature and possibly suffering from minor sources of error.

MAP SPECIFICATIONS AND ACCURACIES

Height accuracy on a map is often defined as the r.m.s. error in elevation relative to the map's elevation datum for well-defined points only (ASPRS, 1989). For the highest accuracy classification of maps, the limiting r.m.s. error in elevation by contour interpolation is set by the specifications at one-third the indicated contour interval for well-defined points only. The term 'well-defined points' pertains to features that can be clearly identified as discrete points on the ground. Spot heights (which should be of more value to researchers in flat areas) have a specification of a limiting r.m.s. error of one-sixth of the contour interval.

Although the source of spatial information used to produce a map is derived using rigorous photogrammetric methods, certain inaccuracies are introduced when transforming a photogrammetric plot into a paper map sheet.

Cartographic generalization (simplification/exaggeration/displacement) necessary during map compilation can compromise the spatial accuracy of plotted detail. Such routine procedures are necessary when a map is compiled at a reduced scale compared with the original photogrammetric plots. This source of degradation is primarily associated with planimetric information, but contour lines and spot heights can be displaced for aesthetic reasons. The lithographic process associated with printing maps will cause a further degradation of accuracy. Scribing and copy procedures will never be as accurate as the original plot. Printing plates will deform with temperature and the paper upon which the map is printed will be deformed by changes in temperature and humidity.

A review of the literature suggests that there is comparatively little evidence for a systematic evaluation and quantification of these sources of errors, probably because of the difficulty in isolating these variables. It would be reasonable to suggest that these may, in total, be of equal magnitude to those uncorrected systematic errors associated with the photogrammetry, perhaps 2 or 3 per 10 000 of the flying height.

The standard manner of checking the accuracy of heights shown on a map includes degradations caused by both photogrammetric and cartographic/printing inaccuracies. The procedure involves selecting a minimum of 20 points from the final printed map, which meet the 'well-defined' criterion. The map heights are compared with their ground survey values, which in turn must have been measured to an accuracy of at least one-twentieth of the contour interval. Further, most mapping organizations will only 'guarantee' that a contour line has been placed in the correct horizontal position to within half the horizontal (planimetric) interval for that contour line for 90 per cent of the time.

Testing by national mapping agencies for compliance to these 'standards' is optional. Not all agencies are prepared to give details, but some do. Only 3 per cent of the topographic maps in the U.S.A. are rigorously checked in this way, and the figure for Australia is 1 per cent (Manning, 1983). In Great Britain the percentage is similar to these figures (Newby, 1993).

MORE ACCURATE DIGITAL ELEVATION MODELS?

If an accurate representation of morphology is required then a map should not be regarded automatically as the preferred source of spatial information. A more accurate DEM will always be generated by direct field survey (total station/tacheometer) or terrestrial/aerial photogrammetry. Breaks of slope can be delineated directly and density of data points varied according to the extent of topographic variation. Such a flexible sampling strategy will derive a more accurate representation of topography than deriving a DEM from contours or even measuring a grid-based DEM (Chandler, 1989). Modern 'triangular' based DEM processing software can make effective use of such irregularly spaced height information to produce an accurate and efficient description of morphology. It should be remembered that there are accuracy limitations to all spatial data sources, including DEMs measured directly. The precision of measured data points can vary considerably and the accuracy of the final surface depends also upon how well the sampling locations were selected from all possible terrain points.

The cost of deriving DEMs directly by photogrammetry may be lower than many earth scientists suspect. Photogrammetric surveys carried out using ground-based or terrestrial photographs are suitable for many projects and avoid expensive aerial sorties. Automated DEM data acquisition, using image correlation of scanned photographic images, also provides hope for reduced measurement costs.

CONCLUSIONS

Caveat emptor is applicable to the use of map data for landform modelling. This paper has attempted to demonstrate that despite modern equipment, height accuracies which have been achieved in special surveys using targeted points cannot be equated to the accuracy one can expect from standard map series, even when all reasonable care has been taken. Earth scientists wishing to extract heights from published maps should appreciate the simple sources of random error which can propagate through the photogrammetry and be aware of errors sources involved in map compilation and production.

The incidence of systematic errors in the mapping process has also been briefly examined. It has been shown that as a consequence of the way that least squares estimation processes distribute errors, the detection of systematic errors, which would seem to be large in comparison with the random errors of observation, can become indistinguishable from random errors in even a relatively small block of photographs.

Values of ± 1 and ± 3 parts per 10 000 of the flying height seem to be the best that can be expected for the standard deviations of spot heights and contours, respectively, in standard mapping. Simulated studies reported here and actual results indicate their validity. Undetected systematic errors can also occur, which would lead to values about five times larger in some areas of the map than in other areas. Even lower accuracies will occur when ground control is sparse and when the random errors in the photogrammetry are larger than the $\pm 5\,\mu m$ value that has been assumed here. In such cases, the figures could easily be as high as ± 10 and ± 30 parts per 10 000 of the flying height for spot height and contour height accuracy, respectively. The determining factor is not the map scale, but the relationship between the terrain and the camera during the aerial photography from which the map was derived.

The future may hold some hope for an increase in height accuracy as modern FMC cameras gradually replace the more conventional ones in use by many mapping agencies for standard topographic mapping. This new technology will generate higher quality and larger scale photography, but this must be accompanied by a higher precision of measurement and adequate ground control if significant improvements in the accuracy of heights are to be achieved.

Providers of spatial data have warned scientists involved with modelling processes that there are limitations to the quality of sources of spatial data. The significance of these errors compared with the effects of other simplifications necessary when modelling natural processes is not a matter which surveyors and photogrammetrists can assess, but it would be valuable for such an assessment to be undertaken.

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