THEORETICAL AND PRACTICAL ASPECTS OF ARCHAEOLOGICAL ORTHOIMAGING

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ABSTRACT

Orthophotos are a standard requirement in archaeological documentation; yet they differ in several respects from aerial orthoimaging. The required large scales of end-products call for close-range photography, usually taken from low altitude or with raised cameras for horizontal recording. Special camera platforms need to be devised to this effect, such as the flexible low-cost devices (small balloon; adapted fishing-rod) used here. With such 'unstable' platforms image tilt, recording distances and overlap are not easily controlled, hence irregular strip geometries are expected. Besides, the non-metric cameras used have unknown inner orientation and often large lens distortion. Our experiences with such bundle adjustments are discussed. Precise surface description is a further issue, more than often involving modeling of rough surfaces with abrupt changes, discontinuities and protruding parts. Examples from different projects illustrate the authors' experience as regards data collection allowing generation of 'vertical triangles', indispensable for creating 'true orthophotos' with commercial software. A final aspect addressed in this contribution concerns the exploitation of the numerous existing line drawings of sites. This graphical information, mostly planar, might be extensively used as exclusive ground control to produce orthomosaics for innumerable sites, at least as basic archival documentation. Rather than performing purely planimetric strip adjustment, an approach is tested here which additionally makes use of suitably weighted model elevations of such planar 'control points' derived from the maps. The presented results show an increase in accuracy, thus indicating that in several cases existing 2D information may help minimise, or even eliminate, the need for control surveys. The discussed aspects of archaeological orthophotography are illustrated with examples from various Greek sites, namely the parodoi of the ancient theatre of Sparta, the ancient castle of Aigosthena, the ancient theatre of Zea in Piraeus and an archaic site of Zeus in Athens.

1. INTRODUCTION

Orthomosaics, based on reliable elevation information, are now perhaps *the* standard photogrammetric products for archaeological documentation. Indeed, among the deliverables asked for by archaeological services, conventional line drawings tend to be replaced by raster products, notably orthophotography (but also digital developments, other projections and drapings or phototextured models). This is true not only for ordinary documentation but also for restoration purposes of ancient theatres, retaining walls etc. Although line drawings may also be produced on top of the orthomosaic, the latter constitutes a powerful textured representation combining geometric accuracy with a wealth of detail (e.g. regarding damages and decay), thus providing a suitable basis for conservation and restoration planning.

However, compared to conventional aerial orthoimaging, its archaeological counterpart displays a number of peculiarities. To start with, the required large scales of the end-products call for close-range photography. But most archaeological sites need to be recorded either from above (as in the instance of excavations or theatres) or using a raised camera with horizontal axis dictated by object height (as in the case of castles or retaining walls). This poses serious questions concerning image planning and acquisition. Hence, special camera platforms need to be devised to meet the variety of requirements, as archaeological sites may be in densely built areas or, at the other end, in isolated regions accessible only on foot. Besides, possible solutions are also limited by available financial resources which, regrettably, are often poor. In such instances flexible low-cost devices – such as small balloons and adapted fishing-rods – have been used for vertical and horizontal recording (Karras et al., 1999; Petsa, 2001).

Being inherently 'unstable', such camera elevators involve two major questions. First, the image tilts cannot be fully controlled. Even if monitors adapted to the raised camera are employed (as in one of the projects referred to later), irregular strip and block geometries are generally expected to emerge. Imaging distances are also not totally controllable, eventually resulting in large variations in image scale. This aggravates the expected problem of scale variations due to the often large depth extension of objects compared to the imaging distance.

The second question is related to the fact that mainly low-cost, small and medium format, non-metric cameras are used in most archaeological surveys; besides, only such light-weight cameras may be raised by the simple camera platforms mentioned above. Of course, these cameras are characterised by unknown interior orientation, a problem enhanced by the presence of considerable distortion in the wide-angle lenses usually used in such cases. The points made above underline the typical difficulties facing phototriangulation in archaeological projects.

A further important aspect of archaeological orthoimaging concerns the precise surface modeling of the site or monument, to ensure end-products of both geometric accuracy and high visual quality. Furthermore, accurate surface modeling is not only the prerequisite for orthoprojection but also provides invaluable information regarding morphology and deformation, constituting a tool in itself for the evaluation and restoration processes. In archaeological applications, object shape is often characterised by abrupt changes in depth and successive 'falls' or 'breaks' on a surface which, as a rule, cannot be regarded as 'regular'. Even in areas which initially had a regular shape, damage often produces more complex shapes. Hence, no simple CAD modeling is generally possible (unlike most architectural items which can be modeled as a combination of basic regular shapes; cf. Wiedemann, 1996). For instance, this often entails the modeling of 'irregular' surface patches perpendicular to the main object plane and 'ridges' or strongly protruding structures. In archaeological documentation, surface modeling and triangulation still remain a very crucial issue (Baratin et al., 2000).

Finally, a further aspect addressed in this contribution concerns the exploitation of pre-existing graphical plans and line drawings. Indeed, numerous archaeological sites have been mapped at one time or another, mostly with field surveys commissioned by the Ministry of Culture which has thus amassed a wealth of planar data with no, or sparse, elevation data. Graphical data of this type can be well exploited at an extended scale as exclusive control information to generate orthomosaics for innumerable sites, at least as a basic archival documentation. One may proceed by simply deriving planar control points from such 2D information and perform a purely planimetric adjustment. The resulting inaccuracy in absolute orientation, however, could be diminished by exploiting the 3D model elevations with a suitable weighting. The results presented here indicate that, in fact, this pre-existing information may prove useful in several cases for cost-effective approaches of orthophotography by limiting, or even eliminating, the need for new field surveys. The aspects of archaeological orthoimaging referred to above are discussed and illustrated with examples from four different Greek sites.

2. PHOTOTRIANGULATION

This is a key issue in archaeological surveys since, for a number of reasons already referred to, the questions of performing the bundle adjustment and recovering reliable values for the image exterior orientation parameters may well not be trivial. Starting with interior orientation, it must be pointed out that a full self-calibrating bundle adjustment may often be infeasible. This may be due to a combination of the limited extension in depth of the object, the inaccuracy and low 'identifiability' of control points (which, more than often, need to be simple natural detail points) and the unfavourable strip geometry. Full pre-calibration is one way to tackle this problem. However, this is not always practicable. For instance, in each of the four projects which serve here as examples a different non-metric camera has been employed (all belong to the Department of Surveying & Photogrammetry of the Greek Ministry of Culture).

In case of relatively limited relief, Karras and Mavromati (2001) have demonstrated that the use of 'nominal' interior orientation values (the principal point in an analogue camera is ignored; the nominal focal length is used as camera constant) does not affect accuracy to a considerable extent. Contrary to this, the effects of radial lens distortion may be decisive, particularly in the case of wide-angle photography. The correction of this error is capable of trebling accuracy. Lens distortion could be modeled through bundle adjustment, but may also be estimated separately by employing simple techniques of partial pre-calibration, for instance using images of straight linear features. This approach has been adopted in all examples used here, which form parts of wider projects. These are the following:

- *Sparta* (parodoi walls of the ancient theatre in Sparta). The strip used here consisted of 6 images of mean scale 1:250, taken with a medium format Mamiya camera with wide-angle 45 mm lens. Recording has been performed with horizontal camera axis using a fishing-rod to raise the camera. For the 44 control points used, the RMS_{XYZ} error of bundle adjustment was 1.6 cm.
- *Aigosthena* (eastern façade of the ancient castle in Aigosthena). Here again a total of 6 images acquired with horizontal axis were used. The medium format Fuji camera (45 mm wide-angle lens) was raised with a small meteorological balloon to give a mean image scale of 1:300. The RMS_{XYZ} error for the 68 control points used was 1.3 cm.
- *Zea* (small ancient theatre in Piraeus). The 4 images used in this instance had been acquired vertically, employing the same means, with a small format Cannon camera (28 mm wide-angle lens). For a mean image scale of 1:1200, the RMS_{XYZ} error for 82 control points was 2.8 cm.
- *Ag. Marina* (archaic site in Athens, dedicated to Zeus). The 7 images selected here had a mean scale of 1:1100 and had been acquired vertically as above with a small format Nikon camera (28 mm wide-angle lens). The RMS_{XYZ} error for the 100 control points was 3.7 cm. [This project has been fully documented in Karras et al., 1999.]

To a considerable extent, the satisfactory RMS errors referred to above are attributed to the correction of radial distortion. However, further aspects of a successful adjustment have also to be mentioned. With the means for raising the camera used, 'flight' planning cannot be fully adhered to, which may result in rather unfavourable imaging geometry. In vertical photography, image tilt does exist but apparently can be limited below 5°. The problem here are mainly the differences $\Delta\kappa$ in rotations about the vertical camera axis, which may even exceed 15°. Contrary to this, horizontal photography suffers mainly from ϕ-tilts about the vertical image axis (which in the case of *Aigosthena* exceeded 15°). To confront this problem, relatively small stereo-bases are required to secure adequate overlap, along with liberal control information of sufficient accuracy and tie points determined by as many rays as possible. Control and tie points, which often are not signalised (as in the examples discussed here), must be measured carefully on the image, particularly if significant perspective distortion is present as a consequence of surface relief and image tilt. Actually, it is this need for ample ground control which has led to investigations, presented in Section 4, regarding the possibility to exploit pre-existing plans as a source for ground control. Finally, the differences in imaging distances are also to be kept within certain tolerances (if image resizing and processing, for instance, with different camera constants or strip segmentation in smaller parts is to be avoided).

3. SURFACE MODELING

As mentioned already, accurate surface modeling is a key issue in the generation of orthoimages both geometrically reliable and visually correct. Locally inaccurate description of very demanding surfaces leads here to geometric inaccuracies and 'stretched' or 'melted' orthoimage areas. The commercially available software commonly used represents object surfaces as a DTM with a single value Z for each planimetric XY location (more complex surfaces not representable in this way call for special treatment; e.g. Knyaz & Zheltov, 2000). All photogrammetrically collected elevation points and breaklines are typically integrated by Delaunay triangulation into a surface mesh defined by triangles. In fact, manual stereoscopic measurement is still the main mode of collection. Automatic DTM generation in archaeological orthoimaging remains an open question (Baratin et al., 2000). Laser scanning collection, on the other hand, faces problems of post-processing for the creation of triangulated meshes suitable for the existing orthophoto software (Böhler et al., 2001). Besides, not every archaeological site is accessible to laser scanners as it may be to photography.

Obviously, attention must be paid in the collection phase to the inclusion of all significant surface breaks and discontinuities (a process which also requires certain amounts of experience). But one must also a priori have a clear idea of the type of algorithm which will be used to generate the surface model for orthophoto production (as pointed out by Baratin et al., 2000). In the experience of the authors, perhaps the most usual problem in orthoimaging archaeological objects is modeling surfaces orthogonal to each other, i.e. the formation of 'vertical' triangles, a task encountered in all projects outlined above. In such cases, the software needs to be 'assisted' by suitable collection.

Generally, data for vertical faces are sampled as a combination of breaklines on top with spot heights at the bottom. This, however, does not necessarily protect from a 'random' triangulation which will later cause a deformation during image resampling. Attempting to create orthoimages possibly equivalent to the importance of the monuments, the following collection scheme has been adopted. The top of a 'vertical' surface patch is described by a polyline. For each polyline segment (d), three points were collected at the bottom, as shown in Fig. 1: two corresponding to its endpoints (A,C) and one (B) approximately to its middle.

This scheme, though somewhat tedious, allows to constrain the formation of triangles by 'forcing' it to follow the surface form and, thus, secures a possibly faithful modeling (within the scale tolerance). It is needless to say that only certain 'difficult' parts, not a whole surface, have to be described in this manner. On the other hand it is clear that good surface description is necessary but not sufficient: suitable images must also be available as the result of careful planning.

In Fig. 2 an example is shown from the *Aigosthena* project. It is clearly seen that all surface breaks have been faithfully modeled which helps produce a geometrically correct orthoprojection.

A second example given in Fig. 3 is drawn from the *Sparta* project. There, a view of the western parodos is shown, along with

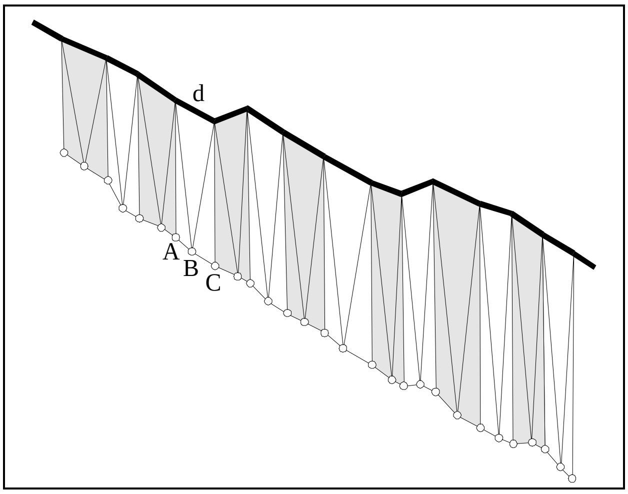

Figure 1. Breakline and points forming 'vertical' triangles.

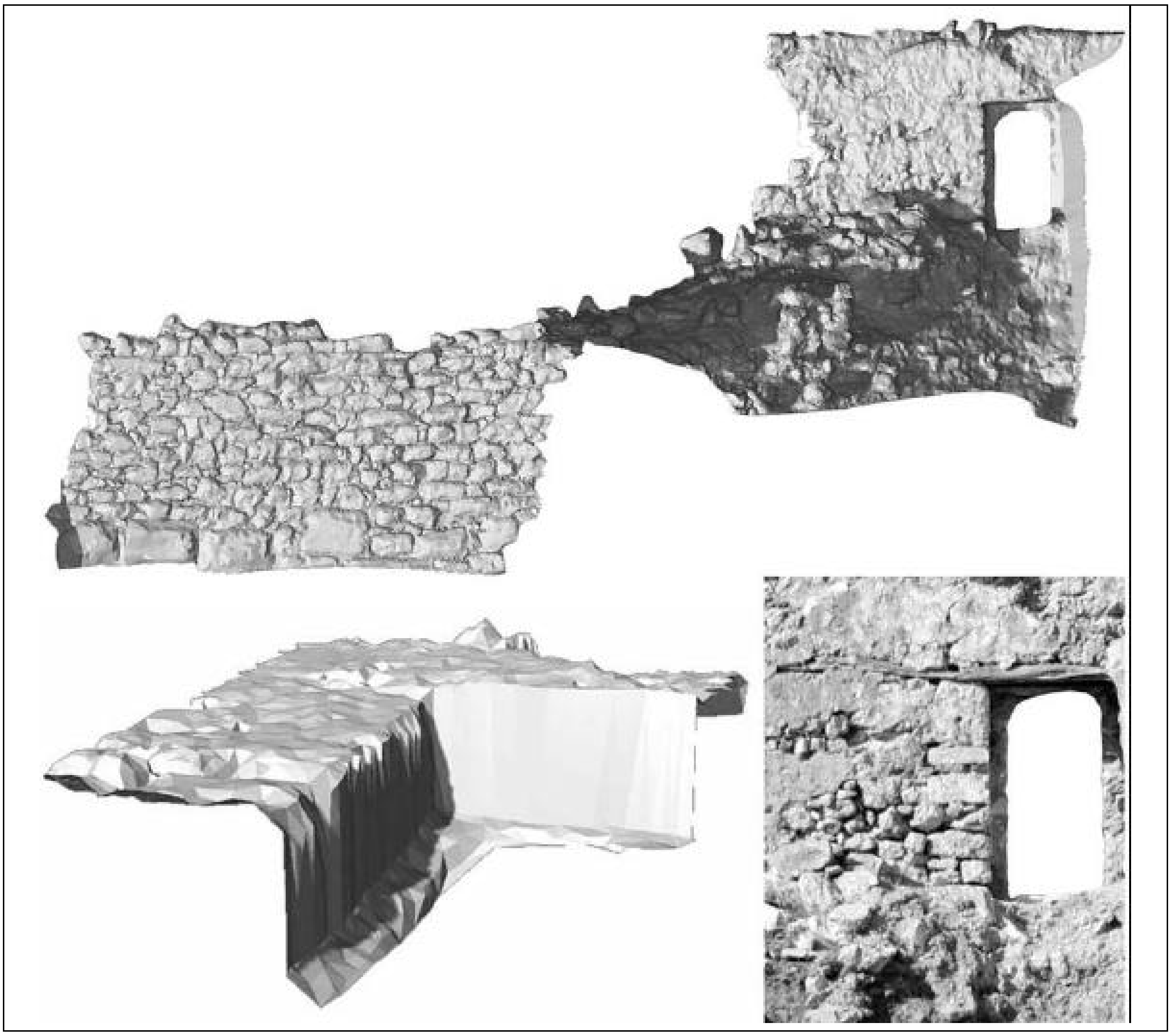

Figure 2. Shaded surface model of a part of the Aigosthena Castle (top). Below are also are seen a detail of the surface model by the window, showing the 'vertical' hang, and the corresponding area of the orthomosaic.

the shaded model of a detail area, whose orthoimage is also to be seen. The full orthomosaics of the two parodoi are presented in Fig. 4, whereas in Fig. 5 a further example of surface modeling from the eastern parodos is given. Finally, the products of the *Zea* project are illustrated in Fig. 6.

4. USE OF EXISTING PLANS AS CONTROL

As already mentioned, an aspect regarding cost efficiency in the production of digital orthomosaics concerns the exploitation of pre-existing line drawings, plans or elevations of a site. Indeed,

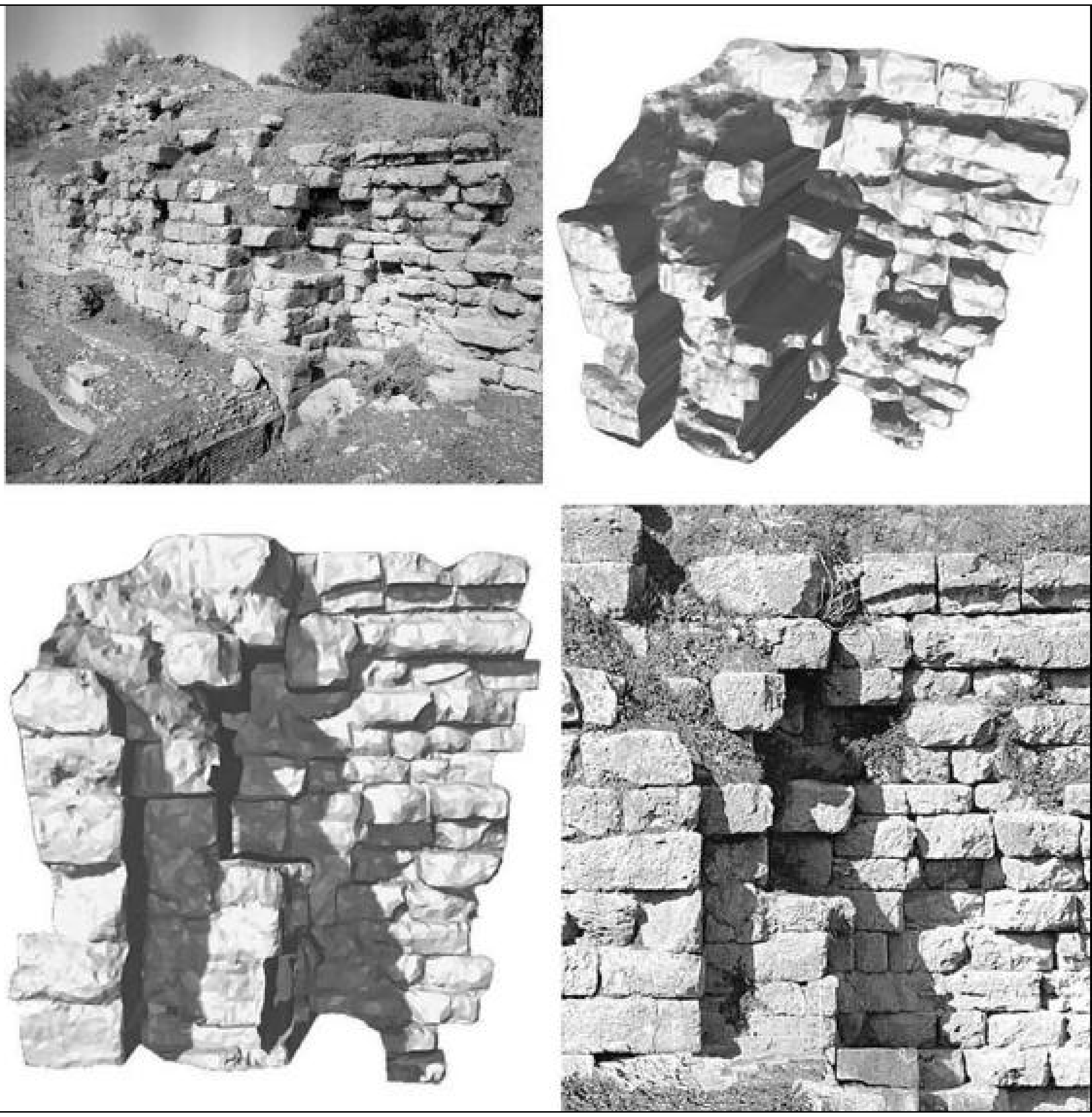

Figure 3. Sparta: View of the western parodos, shaded models of a detail area and the corresponding area of the orthomosaic.

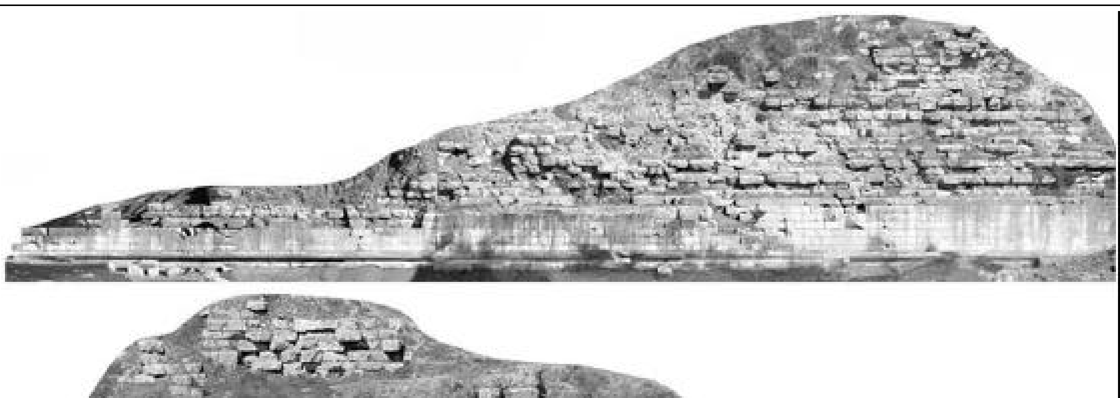

Figure 4. The final orthomosaics of the eastern and. western parodoi of the ancient theatre of Sparta.

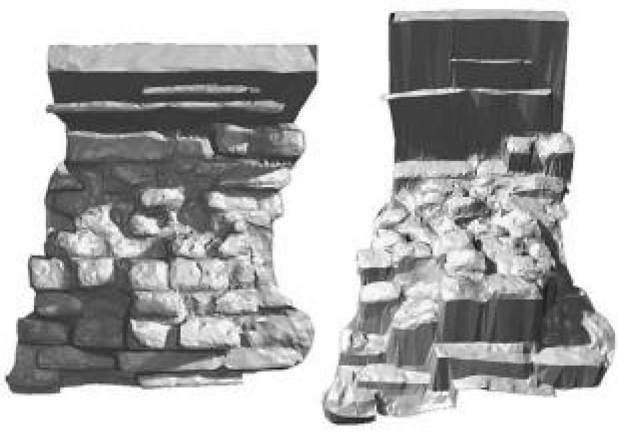

Figure 5. Sparta: shaded details of a surface patch.

Figure 6. Shaded model and orthomosaic of the Zea theatre.

numerous archaeological sites have been mapped at one time or another, usually with geodetic surveys on behalf of the Ministry of Culture, which has produced an amassed wealth of available data, mostly planar. Depending, of course, on their accuracy and quality, one might well take advantage of such graphical data at an extended scale as exclusive control information to produce orthomosaics for innumerable sites, at least as basic archival documentation.

One could proceed by simply deriving planar control points XY from such 2D information and execute a 'purely planimetric' adjustment. As, however, solution is impossible without some elevations, the procedure in a digital photogrammetric workstation could be as follows. First, a 'relative' phototriangulation is performed, i.e. the strip model is formed (in the system of the first image), providing for all control points their model coordinates xyz, which can be correctly scaled. These elevations z, referring to a tilted model system of arbitrary z-origin, are then used with very small weight in control point triplets XYz for a new bundle adjustment. Outcome of such essentially planar adjustments will be the exterior orientation of the images, related to the arbitrary model z-origin.

Experimentation has indicated that the resulting inaccuracies in elevation, due to small uncorrected model tilt, may be diminished by using more realistic weighting. After the first solution, the ω, ϕ, κ values for the reference image are used to determine a maximum value for the model displacement in z, at the control point remotest from the nadir N of the image. This value is used in a new bundle adjustment as better approximation for weighting model elevations. to provide new ω, ϕ, κ values. From these a final weight for each z is calculated as its expected uncertainty due to model tilt. The XY coordinates are first rotated by κ, and their absolute ΔX and ΔY differences from N are then combined with the absolute ω, ϕ values to give the error estimation

$$s_z = \Delta X\phi + \Delta Y\omega$$

used for weighting elevations in the final phototriangulation. In this sense, object relief is also taken into account.

Both the described approach and 'planimetric' adjustment have been applied to the data of all four projects. Table 7 presents the RMS differences of the resulting control point coordinates from those estimated by bundle adjustment using full 3D control. Of course, all Z-values thus obtained have been first shifted to refer to the mean elevation of the control points.

Table 7. RMS differences between full bundle adjustment and adjustments using only 2D ground information

	planimetric adjustment			with weighted elevations		
	X(cm)	Y(cm)	Z(cm)	X(cm)	Y(cm)	Z(cm)
Zea	0.5	1.1	16.1	0.3	0.5	7.0
Ag. Marina	1.3	1.2	23.4	0.6	0.6	4.6
Aigosthena	0.4	0.4	1.9	0.4	0.4	1.8
Sparti	0.6	0.3	3.3	0.6	0.3	3.4

It is seen that in the last two cases both approaches provide very good results. This is apparently due to the strong configurations, as the extension in depth was significant compared to the short imaging distances, and most object points were intersected with several rays. The tilt of the reference image is expected to play a role, too, and so does the form of the strip (which in *Ag. Marina* is long and narrow). In the first two cases, improvement is clear. Evidently – as also witnessed by the larger discrepancies in Z – small uncorrected tilts are still present in all cases. The distribution of Z-differences, seen in Figs. 8 and 9, illustrate this effect.

Even if elevations are ignored, however, planimetric orientation appears as sufficient for the projection on the horizontal plane. Indeed, no significant differences were detected between orthoimages produced with the results from the different adjustments. Nevertheless, surface description is also an important information in itself, indispensable for the documentation of the site or the monument. In this sense, approaches for improving absolute orientation are useful.

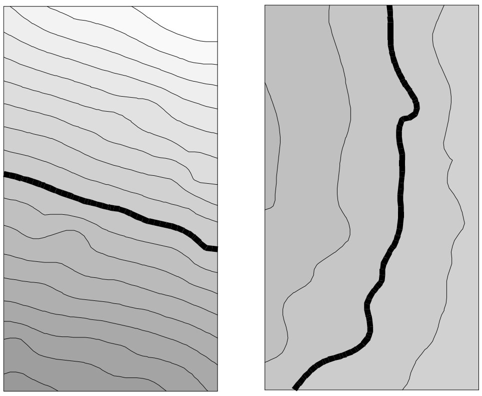

Figure 8. *Ag. Marina*: Distribution of ΔZ errors from planimetric adjustment (left) and using weighted model elevations (right); spacing: 5 cm; dark line: ΔZ = 0.

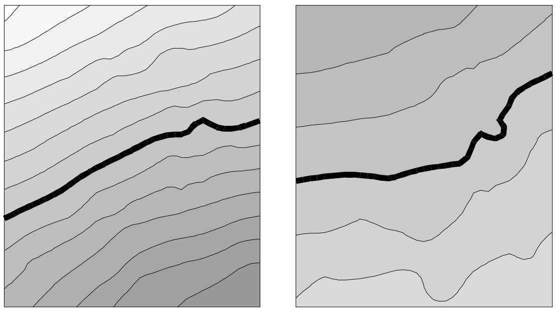

Figure 9. *Zea*: As in Fig. 8.

5. CONCLUDING REMARKS

This contribution has dealt with aspects of archaeological orthoimaging. Issues related to phototriangulation have been briefly discussed, mainly as regards the implications of employing non-metric cameras on unstable platforms (see also Karras & Mavromati, 2001). Further, the question of object modeling in the case of the 'broken' surfaces so often encountered in archaeological surveys has been addressed, and the authors' experiences in this field have been reported and illustrated with examples. Also, the possibility of using the numerous existing plots and maps as 2D control information has been discussed and evaluated. Being the standard requirement in today's archaeological documentation, the production of orthoimages still poses questions concerning the intersection of simplicity and cost-efficiency with geometric accuracy and high visual quality.

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REFERENCES

Baratin, L., Bitelli, G., Unguendoli, M., Zanutta, A., 2000. Digital orthophoto as a tool for the restoration of monuments. *Int. Arch. Phot. Rem. & Sens.*, 33(5), pp. 62-69

Böhler, W., Heinz, G., Marbs, A., 2001. The potential of non-contact close range laser scanners for cultural heritage recording. *XVIII CIPA International Symposium*, Potsdam, Germany, September 18-22 (in print).

Karras, G., Mavromati, D., Madani, M., Mavrellis, G., Lympe-ropoulos, E., Kambourakis, A., Gesafidis, S., 1999. Digital orthophotography in archaeology with low-altitude non-metric images. *Int. Arch. Phot. & Rem. Sens.*, 32(5W11), pp. 8-11.

Karras, G., Mavromati, D., 2001. Simple calibration techniques for non-metric cameras. *XVIII CIPA International Symposium*, Potsdam, Germany, September 18-22 (in print).

Knyaz, V., Zheltov, S., 2000. Approach to accurate photorealistic model generation for complex 3D objects *Int. Arch. Phot. & Rem. Sens*., 33(5), pp. 428-433

Petsa, E., 2001. *Photogrammetric Survey of the Parodos Walls of the Ancient Theatre of Sparta*. Technical Report, Technological Educational Institute of Athens, pp. 10.

Wiedemann, A., 1996. Digital orthoimages in architectural photogrammetry using digital surface models. *Int. Arch. Phot. & Rem. Sens.*, 31(5), pp. 601-609.