

A PC-Based System for Computer Assisted Archaeological Interpretation of Aerial Photographs

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Abstract

Medium altitude aerial survey photographs are a useful source of information for archaeologists, particularly in the identification, measurement and classification of monuments. However these photographs contain far more information than can be extracted by the human eye. Measurements of shape and size can be crudely ascertained by manually studying aerial photographs. Digital image processing on a computer can be used to extract more accurate measurements. Digital Elevation Models (DEMs) are becoming an essential data product for computer literate landscape archaeologists. Using DEMs, measures of location can also be computed for monuments identified in aerial photographs. However the generation of DEMs continues to be an expensive and labour-intensive process, requiring either ground survey, interpolation from existing contour maps, or the application of expensive photogrammetric equipment. This paper describes how a standard desktop personal computer has been used to:

1. Analyse stereo pairs of aerial photographs and automatically generate DEMs for their overlapping region, by measuring the parallax values of the points visible in both photographs.
2. Accurately trace the boundaries of circular and sub-circular monuments visible in the photographs.
3. Generate integrated and accurate measurements of shape, size, and location for these monuments. These measurements are then used to produce monument classification.
4. Export the DEMs and monument information to a Geographical Information System (GIS), for integration with other spatial data.

1 Introduction

Aerial photography is often used for preliminary archaeological survey, which is a traditional discovery-oriented remote sensing application. It is also used for inventory-level recording of large areas, mapping, and topographic analysis of smaller areas, prior to excavation (Ebert and Lyons, 1983; or Palmer, 1989). As a remote sensing technique, aerial photography is non-destructive, and therefore has value as part of the set of tools used in modern non-destructive archaeology and cultural resources management. Its importance today is greater than ever, as a significant proportion of archaeological assessment is geared towards prioritising the importance of sites for preservation (Hampton, 1983).

Digital image processing has been demonstrated as a useful technology for assisting the study of low contrast archaeological material in aerial photographs (e.g. Scollar 1990; or Forte 1993). Through interactive adjustment and re-mapping of contrast or

colour reproduction, the limitations of the human ability to perceive subtle changes in tone or colour can be overcome. These digital techniques can be thought of as flexible and rapid equivalents to traditional dark room re-processing techniques. Computers have also been used to assist in the generation of plans of archaeological sites - particularly crop mark and soil mark sites - from oblique aerial photographs (e.g. Scollar 1975, 1990; or Haigh 1983; or Haigh *et al* 1983).

While many general purpose image processing software packages, as well as GIS packages, can be used to carry out image enhancement, the functionality has not yet become part of an integrated air-photo analysis toolset. Ideally, a system for computer assisted archaeological analysis of aerial photographs would provide interactive image processing during the photo investigation and computer-assisted feature mapping process. As highlighted by Lemmens, Stancic and Verwaal, it is essential that such a piece of software would integrate fully into the modern GIS toolset by providing

automatic co-ordinate based mapping and data export facilities. Lemmens *et. al.* also recognise the potential of a system that would not only map and export archaeological features, but would also automatically identify them in the first place (Lemmens *et. al.* 1993).

This paper describes the *Aerial Archaeology System* (AAS) which is a software package that has been developed by the author in an attempt to meet the requirements of computer-assisted aerial photograph analysis.

In addition to the requirements identified above, the AAS also takes automatic measurements of shape, size, and topographic context of archaeological features. A set of 120 Irish monuments have been measured, and the data has been subjected to cluster analyses. The AAS will automatically apply a classification system, based on the results of the cluster analyses, to the measurements taken on newly identified Irish monuments, in order to assist the user in their interpretative tasks.

2 The aerial archaeology system

The Aerial Archaeology System (AAS) software package has been written for Windows 95 using Visual Basic for its front end, Dynamic Linked Library (DLL) export functions written in Visual C++ for its intensive calculations, and hook-up to an Access (.mdb) database for its data management requirements. The aim of the AAS is to assist archaeologists in studying stereo pairs of vertical aerial photographs and to generate information regarding the monuments visible in them. The main features are:

1. Calculation of scale, location, and orientation of photographs based on user-supplied control points.
2. Assisted discovery and accurate tracing of archaeological features in the photographs.
3. Automatic morphological measurement of these features, and calculation of their location in the user's co-ordinate system.
4. Creation of Digital Elevation Models (DEMs) of monuments and their immediate localities through analysis of overlapping stereo pairs of photographs.
5. Integrated database management of all primary and derived data in the system.
6. Export of data products in common formats (typically xyz files for DEMs and dxf files for monument traces).

7. Automated classification system (using a neural network simulation), to assist initial interpretation of new monuments as they are discovered.

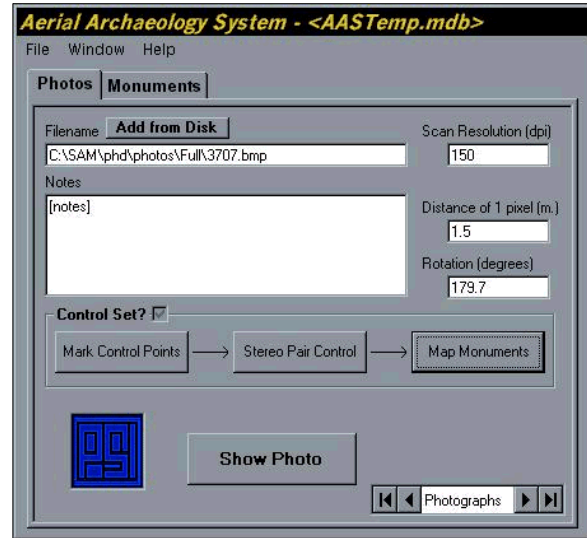


Figure 1. The AAS Window (Photos tab).

The main window of the AAS (see figure 1 and figure 2) is used to browse the primary data objects in the system - photographs and monuments - and to initiate processing upon these objects. When working with photographs (figure 1), the *Show Photo* button displays the current photograph in a separate window, in which various low-level image processing functions can be applied directly, for early photographic analysis and to search for areas of interest. The primary work on each photograph follows 3 steps:

1. *Mark Control Points*. This button displays the photograph and allows the user to define 2-dimensional control points and the photo's principal point. The scale and orientation of the photograph are worked out automatically.
2. *Stereo Pair Control*. For any 2 photos that share at least 3 control points, the user identifies their conjugate principal points. The system then calculates the distance flown by the plane between the 2 exposures, and the rotation required to apply to each photograph to make their horizontal axes correspond to the flight path of the plane between the 2 exposures. This information is required for the DEM generation system.
3. *Map Monuments*. This button is used to initiate the computer-assisted identification and mapping of monuments in photos that have full control

(including stereo partners) defined. As each monument is mapped, a variety of morphological measurements are automatically carried out. Monument mapping is further described in section 3, below.

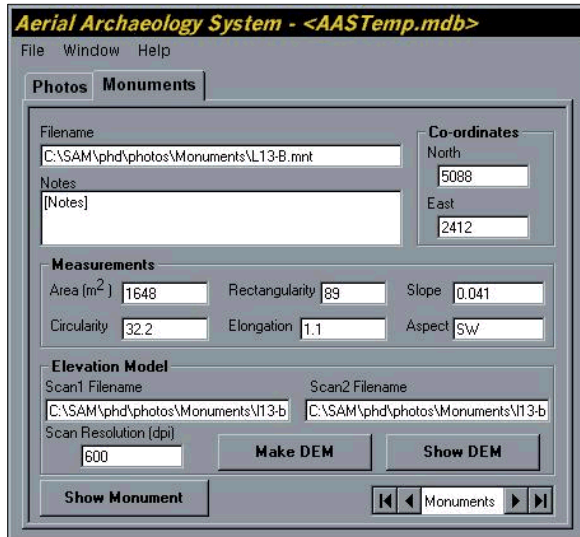


Figure 2. The AAS Window (Monuments tab).

When working with monuments (figure 2), the *Show Monument* button displays the edge-tracing of the current monument in a separate window. Exportation of the monument to a dxf file is facilitated from this window. The *Make DEM* button brings up the DEM generation window (described in section 4, below). The slope and aspect (facing) of a monument are automatically calculated from its DEM. The *Show DEM* button displays the DEM in a separate window. In this window, exportation and importation to/from xyz files can be carried out, and resolution resampling on the x/y and z axes can be applied.

3 Monument mapping

An important task of the AAS is to assist the user in identifying, mapping, and measuring archaeological monuments in aerial photographs. The initial intention was to create a system that would automatically identify monuments, rather than merely assist in their discovery. Experiments were therefore carried out using traditional "scene understanding" techniques.

The first step in automatic scene understanding is normally the application of an edge-enhancement filter, which determines how different pixels are from their neighbours: abrupt changes in brightness are interpreted as the edges of objects. The aim is to

automatically recognise objects in the scene, which are assumed to be characterised by their edges (Boyle and Thomas, 1988). This technique works well in industrial applications where objects are typically of very high contrast with their backgrounds, but the edges of archaeological features tend to be of very low contrast, indeed lower contrast than many of the modern features visible in the photographs.

A number of strategies for working with imperfectly extracted edges were attempted, including:

1. Relaxation techniques, which extrapolate partial lines until they meet other lines (e.g. Boyle and Thomas 1988; or Yoon and Park 1996);
2. Skeletonising, which reduces the thickness of lines to their single pixel width "skeleton" (e.g. Boyle and Thomas 1988);
3. Directional edge-detection filters, which yield information regarding the direction of an edge in one of the 8 cardinal directions of the bitmap (e.g. Davies 1990; or Gonzalez and Woods 1992);
4. Other problem-specific approaches, which build up evidence for the existence of a predefined shape (e.g. a circle) at each point in the image (e.g. Durham *et. al.* 1993; or Lemmens *et. al.* 1993).

The main conclusions from this work were that studying only eight edge directions is too simplistic, that low contrast objects are extremely difficult to find automatically unless their shapes are very well known, and that archaeological features are not generically characterisable as perfect circles or any other shape.

The solution that was developed and implemented in the AAS searches not for entire circular objects, but rather for many small arcs of varying centre point and radius (see figure 3). These arcs are determined through a truly directional edge detection approach, which uses bilinear interpolation to estimate pixel values on an arc, and tests these against the interpolated pixel values on an arc with the same centre but with a radius of 1 pixel less (see Redfern, 1997).

The procedure for mapping monuments in the AAS begins with a study of the photograph, and the interactive use of histogram equalisation to assist the identification of low contrast features (see figure 4). The area containing a monument is identified by the user, and the computer traces its circumference. This tracing can be touched up by the user where required

-- in figure 3, for example, the oblique lighting of the ringfort causes its computer-derived edges to tend towards the outside of the earthen banks which are perpendicular to the light, but towards the inside of the banks which are parallel to the light, with the result that the extracted shape is distorted. The automatic shape extraction and manual touch-up (if required) only takes a few seconds and is almost fully automated, which means that the extracted shape is as objective as possible.

A number of accurate and objective measurements of size and shape are automatically derived from the extracted monument, and its location in the user's coordinate system is calculated. The 4 measurements currently made are: circularity, rectangularity, elongation, and total area (Redfern 1997). Measurements of slope and aspect (facing) are also made: these are derived from DEMs, which are discussed below in section 4. Since the monuments cover only very small areas in their overall photographs, the distortion of their shapes due to variations in elevation are negligible (Lillesand and Kiefer 1987). See for example Castleman (1979) for a discussion of relevant image processing techniques for the morphological measurement of extracted objects.

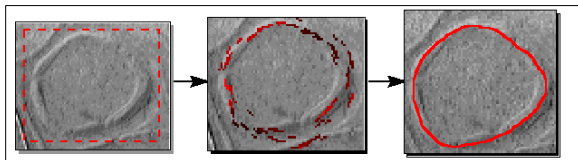


Figure 3. Semi-automatic edge tracing. The user identifies the area containing the feature of interest; the computer then extracts arcs of varying strength, centre, and radius, rejects outliers, and smoothes the remaining arcs together using weighted moving averages into a coherent shape which is approximated at weak areas.

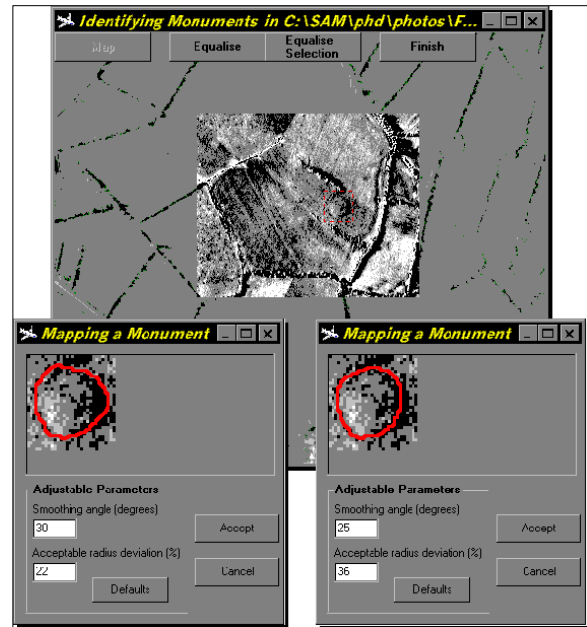


Figure 4. The AAS monument mapping procedure. The user studies the photograph and makes use of local or global histogram equalisation, which attempts to maximise the overall contrast, and therefore visual interpretability, of the image. The operator then identifies the approximate area containing a monument, and the computer presents a suggested tracing of that monument (lower left). The user can "touch up" the suggested shape by modifying arcs with mouse clicks or adjusting parameters (lower right). The entire process takes a few seconds.

4 DEM generation

Given a stereo pair of photos, measurements can be made between corresponding points in the overlapping region, to determine the approximate height of these points. The measurements made are of the parallax apparent in the direction of flight of the plane - and can be made between any clearly distinguishable points in the photo overlap (Slama *et. Al.* 1980).

This manual technique has been automated in the AAS. The software generates DEMs of small regions around individual monuments. It does not process the entire overlap between photographs because low-frequency distortions render these larger DEMs inaccurate. Severe distortions towards the edges of photographs also mean that monuments cannot be modelled if either image is close to the edge of its photograph.

The bulk of the computational work is carried out during the cross-correlation stage, where each of the pixels in the first image is matched to a corresponding pixel in the second image. Cross-correlation is a process which analyses the differences between local regions around a search pixel and candidate matching pixels (see e.g. Castleman 1979). The AAS user manually identifies 3 or more corresponding points between the images, which are displayed side by side (see figure 5). This allows the software to cut down the search region, for each pixel being matched in the second image, which not only speeds up the process but also dramatically cuts down the number of erroneous matches.

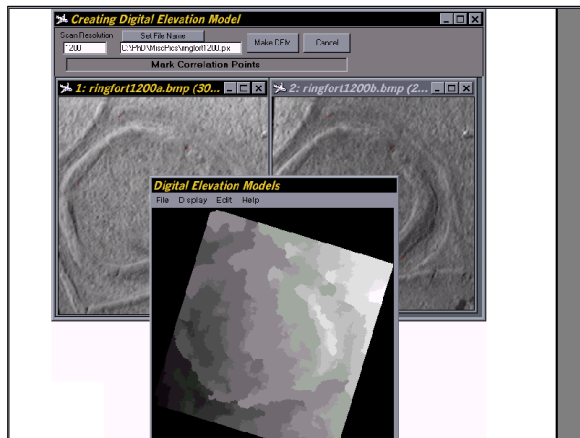


Figure 5. Digital Elevation Modelling in the AAS. The stereo images are displayed, and the user identifies a few corresponding points. The software then produces a DEM. This 90,000 pixel example took about 10 minutes on a Pentium 166. The artificial "double-contour" effect is a result of scanning beyond the resolution of the photograph

The steps carried out by the AAS are:

1. Calculate the relative search region, based on the user-identified control points, that potentially holds the match for each pixel.
2. Process both images, to turn them into maps of local difference rather than absolute brightness. An edge-enhancement filter, such as the Laplacian, which is an isotropic measure of the second spatial differential (Marr 1982), is used for this. This increases the accuracy of cross-correlation, since low-frequency differences such as overall exposure or moving cloud-cover are negated, and also because small high-frequency features which are visible in both images, such as grass tussocks, are emphasised.
3. Pass twice through the first image, and for each pixel:

4. - Reduce the search region if a number of its neighbours have identical parallax values.
5. - Cross-correlate to find the best matching position in the search region in the second image.
6. Rectify distortion due to the flight patch not being parallel to x -axis of photos, since parallax must be measured parallel to the flight path (Lillesand and Kiefer 1987).
7. Reject small contours (with areas of typically less than 50 pixels) resulting from errors in the cross-correlation stage or from modern features such as walls and bushes. The areas of contours are calculated by application of a recursive "flood-fill" function. Resulting gaps are then filled in from neighbouring pixels.
8. Orient the DEM so that North is parallel to the y axis. This involves rotating around the principal point of the parent photograph.
9. Calculate the units of height, i.e. the meaning of 1 unit of parallax (see below).
10. Calculate ground slope and aspect (facing) by submitting the DEM points to a 3D linear regression (after Robinson, 1981), which yields a best-fit plane.

Due to low-frequency distortions in the photographs, the AAS does not calculate the height scale of its DEMs empirically. With all units of measurement expressed in terms of metres, the height in metres that is represented by 1 unit of parallax can be calculated from the airbase (distance travelled between exposures) and flying height (see figure 6).

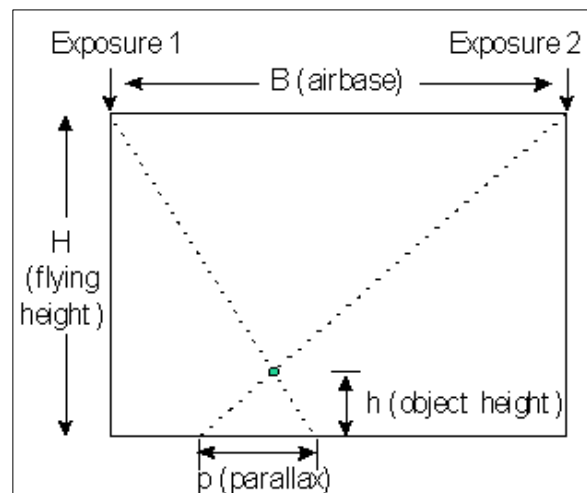


Figure 6. Calculation of units of parallax.

By similar triangles, $B/p = (H-h)/h$

$$\Rightarrow hB = pH - ph$$

$$\Rightarrow h[B+p] = pH$$

$$\Rightarrow h = (pH)/(B+p)$$

Therefore, if $D_p = 1$ pixel

Then $D_h = (\text{pixdist} \cdot H)/(B + \text{pixdist})$ where pixdist is the ground distance represented by one pixel in the image

The accuracy of the small-area DEMs generated by the AAS has been tested against a number of monuments that have been topographically surveyed using electronic distance measure (EDM). As long as neither monument image from the stereo pair comes from the edge of its photograph, the accuracy proves to be very good (see figure 7). In addition to visual comparison, rows of corresponding height values from the EDM data and the computer data were exported to a spreadsheet, and the average correlation coefficient between these rows was calculated to be 0.96.

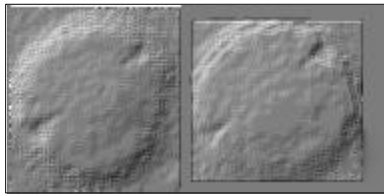


Figure 7. A visual comparison between EDM-generated data (left) and computer-generated data (right). The x/y scale of the computer data, and the z scale of the EDM data, have been reduced.

5 Potential classification

The AAS has been used to take measurements on 120 circular and sub-circular monuments in the region of Bruff, Co. Limerick. The data has been submitted to cluster analysis using Ward's method (described in Everitt 1980), which suggests 4 main monument types, 2 of which have sub-types evident. A back-propagation Artificial Neural Network (ANN) simulator (algorithm after Chan and Fallside 1987), which has been integrated into the overall AAS package, will be used to assist the initial interpretation of monuments as they are discovered, by suggesting their classification.

It is recognised that without proof of statistical significance, any numerical classification scheme lies on shaky ground (e.g. Adams and Adams 1991). Therefore a simple coefficient that measures "goodness of clustering" was defined; it measures the average ratio of distance to objects in the same cluster to distance to objects in other clusters (similar to Faúndez-Abans *et al* 1996). Monte-Carlo simulation was then used to verify the statistical significance of the clusters. One hundred sets of test measurements were generated, where each set comprised 120 "fake" monuments, whose 6 measurements were selected randomly from correctly distributed data. The distribution of measurements for each variable was taken from the real data. Each set was submitted to a cluster analysis, and the "goodness of cluster" coefficient calculated. In 97 of the 100 cases, the clustering was less well defined than in the case of the real data. This provides evidence that there is statistical significance to support the clusters derived, that is, they are unlikely (3% probability) to be the result of random fluctuations. It is obvious that there is a difference between statistical significance and archaeological significance. Statistical significance allows observations such as "the most circular monuments tend to be on relatively flat ground" to be made with some conviction; however, that is not to say that the factors causing this observation are necessarily archaeological -- "statistical significance is a necessary but not a sufficient condition for type designation." (Adams and Adams 1991, p.177).

It is now widely believed that morphological studies cannot progress beyond a certain point without the support of dating evidence (e.g. Palmer 1989; or Walker 1997). Systematic excavation of selected representatives of morphological types is required, in order to test the categories that have been developed (Whimster 1989; or Walker 1997). Site typologies should rarely be regarded as definitive: each is merely part of a procedure designed to create hypotheses about the function of the material being studied. Further, classifications should be iteratively refined rather than be accepted as final (Whimster 1989). Therefore, though the classifications created from the data generated by the AAS may have little archaeological "meaning" at present, it is hoped that they may prove to be a useful first step in the iterative process of monument typology in the Irish context.

The work on the classification aspect of the system is still ongoing. Measurements are currently being made on well preserved monuments of known or obvious type (ringforts, henges, ringbarrows and enclosures),

in an attempt to ascertain whether the differences between types are characterised by recognisable patterns in the 6 measurements of morphology and location made by the AAS. If this is the case, then it will be possible for the system to classify poorly preserved monuments, many of which are visible as no more than faint marks in their photographs. This will be of more immediate value than the hypothetical and initially meaningless classifications developed from cluster analysis.

6 Conclusions

A number of aspects of the AAS represent useful developments for archaeological aerial photograph analysis. The true value of the AAS, however, lies in the fact that it has been developed to form an integral part of the GIS toolset: this is essential for any mapping application in which large amounts of data are generated and manipulated; and is also the "strong opinion" of Lemmens *et al* (1993 p.50).

Four aspects of the system may prove to be of particular use to further developments in the area:

1. The simple but effective technique for small-area DEM generation from stereo pairs.
2. The development of a knowledge-based approach to recognising low-contrast sub-circular archaeological features in digitised photographs, and the definition of these features through their constituent primitives (in this case, arcs) rather than attempting to define them through some idealised but impossible shape (e.g. the circle).

3. The automatic and accurate morphological and locational measurements of features.
4. The approach to *fully integrated* data management and photograph analysis facilities in a single, user-friendly application.

There are at least two areas in which further research could immediately benefit descendants of the AAS. Further attempts to fully automate monument detection is perhaps the primary issue. This may only be possible in regions where monuments are of higher contrast than in the studies described in this paper. It may be possible to search exhaustively for sub-circular shapes at least 50% (say) of whose arcs have higher than a pre-defined edge strength. This would involve massive amounts of computer time; however a batch system which could steadily work through archives of aerial photographs during the night should be feasible.

The modelling of the low-frequency distortions in aerial survey photographs would also be a useful area of further development, as it would enable full-photo DEMs to be created using the algorithm used by the AAS. The need for this development is less urgent, as reasonably priced solutions are very recently available in commercial software products (e.g. EASI/PACE or TNTmips).

A final area that requires further research is in the use of existing geographical information to assist the knowledge-based detection and interpretation of monuments; again, this would ideally be based on full integration with GIS (this point has previously been made by Lemmens 1990 and Lemmens *et al* 1993).

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