THE TOMB OF CHRIST, JERUSALEM; ANALYTICAL PHOTOGRAMMETRY AND 3D COMPUTER-MODELLING FOR ARCHAEOLOGY AND RESTORATION.

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ABSTRACT

The Tomb is a complex structure with confined, highly ornamented internal spaces under almost continuous occupation by priests, pilgrims and tourists. About 170 photographs and 800 survey measurements were taken to produce a comprehensive record of the exterior and interior. Data were combined in a simultaneous multistation convergent bundle adjustment to give about 1000 camera parameters and 1000 object point coordinates with 3000 degrees of freedom. The estimated camera parameters were used in conjunction with an analytical plotter to produce 3D data. The historical background to and reasons for the survey, the site work, computations, accuracies and 3D computer-models are described and illustrated. Use of 3D photogrammetric and other data for archaeological research and restoration is described.

KEY WORDS: Accuracy. Analytical. Archaeological. CAD/CAM. Computer Graphics.

1. HISTORICAL BACKGROUND.

The structure which is known as the Tomb of Christ is situated in the middle of the Rotunda of the Church of the Holy Sepulchre in Jerusalem (Fig.1). It is the latest in a series of edicules (little houses) which have occupied the same site since Constantine's builders in 326 - 335 constructed the great church to enclose the sites of the crucifixion and resurrection. Bishop Macarius of Jerusalem in 326 had identified the latter which then was covered by Hadrian's Temple of Aphrodite, erected in 135. As the Roman Temple and soil were removed, an eyewitness, Eusebius, Bishop of Caesarea, reported that a cave came into view. It is probable that the authenticity of Macarius' identification of the site and Eusebius' description of the uncovering of the cave there will never be independently verified, but continuous occupation and recognition of that site since the time of Constantine are widely accepted.

Constantine's builders cut away the outer parts of rock surrounding the Tomb, leaving a monolith standing in the centre of an open, levelled courtyard (cf. the tomb in Fig.2). According to Eusebius, the cave was "adorned with choice columns and much ornament, sparing no art to make it beautiful". By about 390, a covered rotunda had been built with the decorated tomb at its centre. Evidence of the structure of this Constantinian edicule exists in the form of models (one is at Narbonne, apparently of the 5th century), crude representations on silver flasks and ivories bought by pilgrims (Freeman-Grenville, 1991) and in accounts and sketches made by visitors to the site, notably by Arculf in the late 7th century. Based on such evidence, Wilkinson (1972,1981) has proposed a representation of the Constantinian edicule.

It is probable that the structure of Constantine's edicule remained unaltered for 700 years, surviving the Persian sack of Jerusalem in 614 and the Arab capture of the city in 638. Some repairs and renovations were no doubt necessary, particularly to the ornamentation, but the main structural elements remained until, in 1009, the mad Fatimid Caliph al-Hakim ordered the edicule to be smashed to pieces. This was not an isolated act: " -- he treated Moslem, Jew and Christian with even-handed venom" (Freeman-Grenville, 1987). Rebuilding was carried out by the Byzantine emperor Constantine Monomachus in 1048. It was in this form that the edicule was seen by the Crusaders in 1099 and visited by pilgrims for 500 years. The temptation to take home souveniers and

Figure 1. The Edicule as it is today.

pieces of the shrine for religious and commercial advantage was not always resisted, neither was the temptation to leave behind personal inscriptions and even coats of arms carved into the stone. By 1555, the whole structure had become so dilapidated that the Custos of the Holy Land, Father Boniface of Ragusa (a Franciscan) arranged for the edicule to be rebuilt "from the first foundations" (Stefani, 1875).

The 1555 reconstruction lasted until 1808 when a fire, started in an Armenian chapel in a gallery, spread to timbers which supported the lead roof over the Rotunda. The subsequent collapse of the roof onto the edicule below meant that reconstruction was again carried out. With the permission of the Ottoman Porte, the architect Comninos of Mytilene was responsible for the design and reconstruction of the edicule according to the taste of the Greek Orthodox community. The present Edicule is that

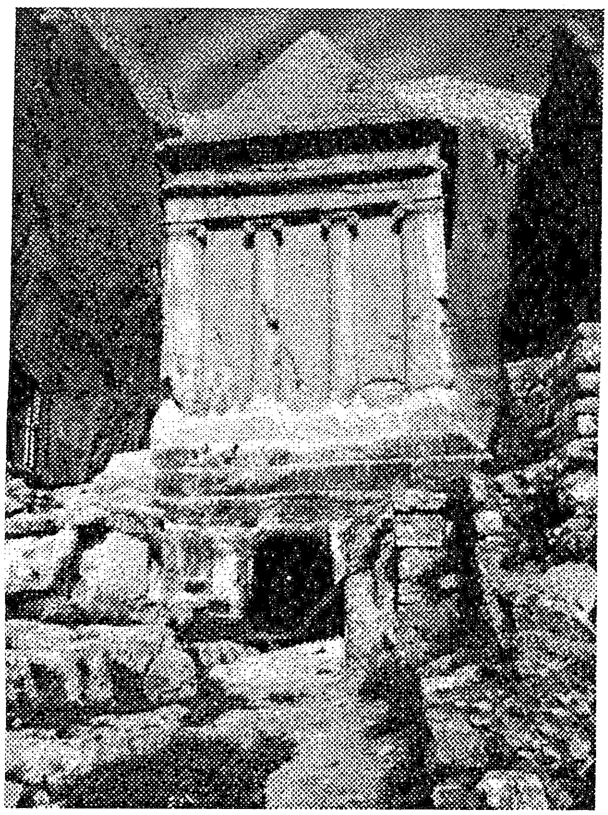

Figure 2. The rock-cut "Tomb of Zechariah" circa 100BC in the Kidron valley, Jerusalem.

of Comninos, but in 1927 it was badly damaged by an earthquake which also weakened the dome over the Rotunda and other parts of the Church. The Mandate Government of Palestine took remedial action to stop the collapse of the Edicule. A steel cradle (Fig.1) was erected around the outside. Timber wedges were inserted between the steel girders and the load-bearing stone walls of the Edicule. In the 65 years since then, it has not been possible for the Christian communities in the Church of the Holy Sepulchre to agree on what should be done to repair the damage sustained in the 1927 earthquake. The structure is in a parlous state. The temporary steel and timber shores show signs of loosening. Misalignments of important structural stonework are obvious. Despite such dilapidations, the Edicule is in almost continuous occupation by priests, pilgrims and tourists. In the 1960's the improved ecumenical atmosphere engendered hopes that action could be agreed and work put in hand to renew, restore or repair the Edicule, or at least to make it safe. A survey of the Edicule was required before any reconstruction began, not only to provide a historical record never before made in accurate detail, but also to aid reconstruction. This paper is a description of the surveys, photography and some photogrammetry undertaken as a result of the 1989 and 1990 site visits. Some descriptions and illustrations of photogrammetrically derived graphics which are being produced are also given. The overall objectives of the combination of archaeology and photogrammetry are to be found in Biddle et al (1992).

2. REASONS FOR A PHOTOGRAMMETRIC SURVEY.

Several complex and very sensitive matters must be recognised and understood before any survey can be undertaken. Some of these have been described in the previous section of this paper. Others originate in history but are part of the daily lives of those who live and work in the Church of the Holy Sepulchre. These matters are related to ownership of and responsibility for the Holy Places. They are governed by an arrangement known as the "Status Quo" which has been ratified by the Treaties of Paris (1855) and Berlin (1878), by the British during the Palestine Mandate, by the Hashemite Government of Jordan and most recently by the Government of Israel. Under the Status Quo, ownership of, access to and responsibility for the Edicule (and other places) are described in relation to the three major religious Communities (Greek, Latin and Armenian) and the three minor (Coptic, Ethiopian and Syriac) present in the Holy Sepulchre. Since these arrangements have never been formally described, but only ratified by successive international treaties and state governments, they are continually under contention. Each community seeks to maintain its own rights whilst at the same time watching others for signs of negligence in maintaining their's which might provide an opportunity to take upon itself a responsibility not hitherto assigned to it under the Status Quo.

Against this background of complex duties and responsibilities, daily enacted with fervour, the prime mover of the survey, Dr G.S.P. Freeman-Grenville, invited Professor Martin Biddle of Hertford College Oxford and Magister Birthe Kjølbye-Biddle to undertake an archaeological investigation and survey. For many years Freeman-Grenville has pointed out the need for surveys of the Tomb to be made before and during any restoration (Freeman-Grenville, 1987). Enquiries made in Jerusalem resulted in permission being granted on the understanding that the method would be discreet, non-intrusive and of short duration and would be seen to involve no risk of damage to or alteration of, the structure. The archaeological investigators had worked with the authors of this paper on the recording of the Shrine of St Alban by photogrammetry prior to its dismantlement and reconstruction. They recognised that photogrammetry was the only survey method capable of meeting the above requirements whilst providing extensive and potentially very accurate three-dimensional data of the outside and inside surfaces of the Edicule. Conventional methods of archaeological recording would take place at the same time as the photography. The two activities would seem to an observer to be little different from the note-making and photography undertaken daily by pilgrims and tourists. Even an electronic tacheometer on a survey tripod could be taken for a cine or video camera recording a visit by a group of pilgrims or tourists. It was therefore decided that an attempt should be made in April 1989 to see how much, if any, archaeological investigation and photogrammetric survey could be achieved in practice. No reconnaissance was possible prior to that visit. It was scheduled to last 10 days, including journeys between London and Jerusalem.

3. SITE CONDITIONS, CONTROL SURVEY AND PHOTOGRAPHY.

3.1. April 16-25, 1989

It was soon apparent that the control survey measurements and photographs could not be obtained either quickly or systematically. The decision was taken that analytical methods based on a multistation bundle adjustment with

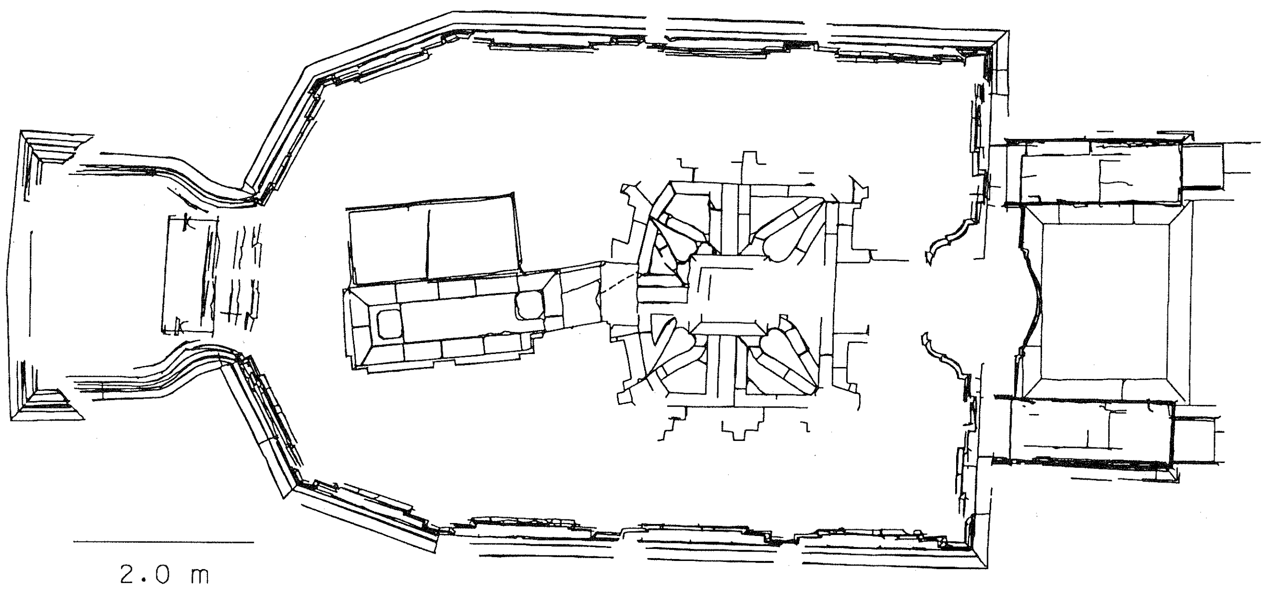

Figure 3. Plan of the Edicule (in progress) showing the two inner chambers.

survey measurements and photocoordinates as the weighted observations would be used. Therefore any photograph and any survey measurement which could be obtained would contribute to the record of the Tomb.

Permission to place small adhesive paper targets on the steel girders which supported the Edicule was given in advance, but when they were first emplaced they were viewed with great suspicion by some of the representatives of the Communities. Some targets were removed and thrown down. It was known that the right to clean, or affix things to, certain parts of the Edicule was defined by the Status Quo. Could placing a target be construed as an infringement of the Status Quo? Patience and goodwill prevailed. The presence of the small targets was finally seen as not a threat to the Status Quo. During the next few days one of the custodians of the Tomb guarded the targets from inquisitive tourists with almost as much fervour as he performed his more usual duties.

Five survey stations were defined by identifying marks on the floor of the Rotunda and three more on the floor of the gallery. These eight stations and the lines of sight between them formed a framework which enclosed the Edicule. Measurements of horizontal and zenith angles and slope distances were made using a Wild TC1600 recording tacheometer. For distance measurements to the targets on the Edicule a hand-held mini-prism was used. Had free access to stations and targets been possible, the control survey could have been done in a few hours. It took five days to complete the external control survey. Lines of sight were usually obscured by the almost continuous throng of tourists and pilgrims around the Rotunda and queuing to enter the Edicule. Similar problems have presumably always faced those who wished to survey the Tomb. Over 850 years ago, the Russian Abbot Daniel wrote "I went after my mass to the Guardian of the Keys of the Holy Sepulchre and said ' I want to retrieve my lamp!' He received me with affection and let me go alone into the Sepulchre..... Then I measured the length and the width and the height of the tomb as it is presently, an act no one can do when there are people about." (Daniel the Abbot, 1106).

Photography was equally difficult to acquire. The overall plan adopted was to take, as far as possible, converging sets of near-normal stereopairs using a Zeiss (Jena) UMK 10/1318 with Agfa Avipan 100PE glass plates. The ambient light levels in the Rotunda were very low. A little daylight filtered down from the crown of the Rotunda dome. A few tungsten light bulbs of low wattage were sometimes alight in adjacent chapels, but they added little to the light from the candles inside the Edicule and on altars around the Rotunda. Two 2kW tungsten halogen light sources had been taken to Jerusalem. The light from these was reflected off the walls of the Rotunda onto the Edicule to minimise harsh shadows, especially those cast by the steel girders. Variations of the type and reliability of the power sockets available resembled the diversities of the Communities in the Church. Once again, much patience and understanding were necessary on all sides. Often two hours and once four hours passed between taking the first and second photographs of a stereopair.

Hours spent waiting to take a photograph were nevertheless full of interest: the passing throng of pilgrims and tourists speaking many different languages and behaving in very different ways; a chant from the Copts in a language similar to that spoken by the Pharoahs; a fugue on the Franciscans' organ; a liturgical procession lead by the Armenian Patriarch; bass and tenor choral singing from the Greek Orthodox Katholikon. Events such as these, sometimes taking place simultaneously, made surveying a unique experience for all involved. It was clearly not going to be possible to make any survey measurements or take any photographs with the UMK inside the Edicule during the time the Church was open to the public. Only by joining the queue could it be entered during the day.

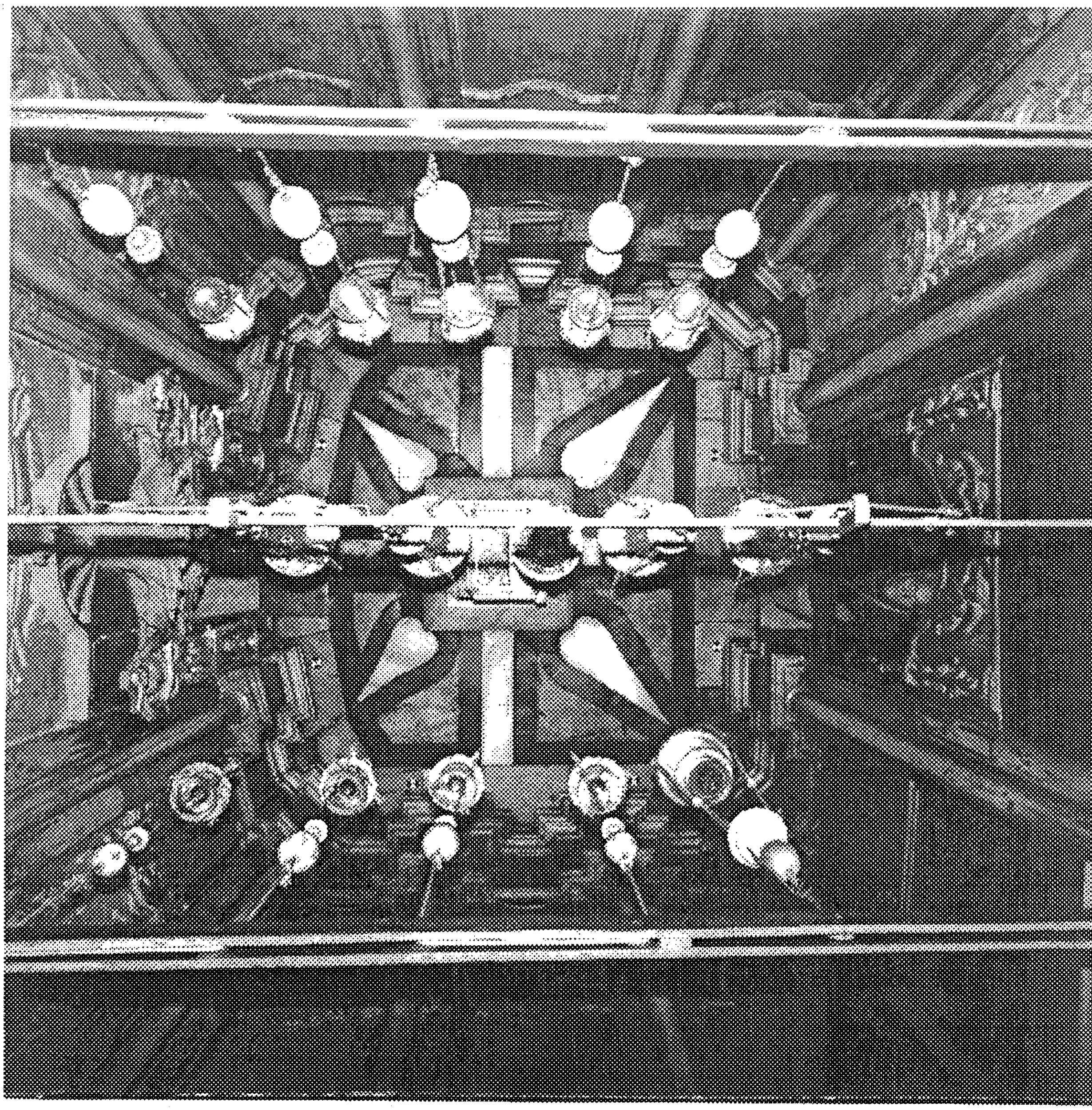

Figure 4. Chapel of the Angel ("near vertical"Hasselblad photograph). The entrance from the Rotunda is on the right; the entrance to the Tomb Chamber, on the left.

Following a series of requests, members of the team were however especially privileged on two nights to be allowed to remain in the Church after it was closed to the public at 20.00h, not to be reopened until dawn the next day. Three hours between the 20.00h closure and the start of the Communities' liturgies at around 23:00h were therefore available for undisturbed work inside the Edicule. Individual pilgrims however, had remained hidden in the Church until it was closed, only to emerge from the gloom after a while for their own private devotions at the Tomb, so the full three hours' work was not possible.

The interior of the Edicule consists of two chambers (Fig.3). The outer, the Chapel of the Angel (Fig.4), is roughly 3m square at floor level, with a 1m high pedestal at its centre. The walls are lined with highly decorated marble slabs up to a height of about 2.5m. Fifteen oil lamps are suspended in a cluster from a metal grid which can be lowered from the roof by a pulley so that they can be filled. Custodianship of and access to the lamps are governed by the Status Quo. When in position they hang down to within about 2m of the floor.

The entrance from the Chapel of the Angel to the inner chamber, the Tomb Chamber, is through a small passageway about 1.3m high, 0.6m wide and 0.8m long. The Tomb Chamber is roughly 2m square, but a horizontal marble slab, about 1.2m wide runs along one side 0.7m above the floor, so leaving an area of floor only 0.8m wide. The marble slab is believed to cover the rock-cut bench in the original burial chamber. The walls are covered by plain marble slabs with a richly carved marble ikon covering the wall above the horizontal slab. Forty three oil lamps hang in the confined space above.

The nature of the interior above the levels of the oil lamps in both chambers could only be seen when halogen lamps were brought inside. The ceilings in both chambers were then revealed as domed and caked with soot; an interior cupola, supported by columns above the top level of the marble wall coverings, was brought to light in the Tomb Chamber.

Confronted by such complex shapes and ornamentation in confined spaces, it was decided that only a superficial record of the interiors could be made in the time available. Moreover it would have been most inappropriate to leave any targets on the walls, so the control survey was quickly extended into (but not out of) both chambers by electronic tacheometry. Taped distances in many combinations between the survey stations inside and the targets were made. Photographs were taken with the UMK and then all evidence removed during one energetic two-hour spell on one of the two nights when the team was allowed to remain in the Church after the closing ceremony at 20.00h. Occupation of the Edicule was shared with the occasional pilgrim and other members of the team making archaeological records of inscriptions and ornaments and taking photographs for descriptive purposes.

All 40 Avipan plates were processed at night in a hostel bathroom using a specially prepared plate processing tank. Ilford ID11 developer was selected because it was easily transported in powder form, and its dilution could be varied for tonal control of the Agfa plates used. By processing the plates daily it was possible to design lighting, exposure and processing so that detail was adequately recorded.

Computations of some of the main elements of the control survey were carried out as the survey progressed to check that they contained no gross errors. About 450 measurements were recorded on the MEM module of the Tachymat (the least number personally recorded over several days' observations!).

3.2. 11 - 27 April 1990.

The second visit was for a longer period because of the need to do much more work inside the Edicule than outside. It was not known beforehand whether permission would be given for working at night. In the event no work took place before Easter, but for 7 days and 6 nights between 16 and 25 April work was undertaken.

All 8 external survey stations used in 1989 were re-located and found by check measurements to be in position. A site grid was set out for a hand survey of the floor of the Rotunda. This grid was in the same coordinate system as that used for the control survey. The first major task was to extend the control survey into the Edicule and out again, preferably by a different route. The Chapel of the Angel and the Tomb Chamber each had a cowled hole in the roof (Fig.1) to let out smoke from the oil lamps. It was possible to use the tacheometer on a trivet set over a floor station to sight and measure to a mini-prism vertically above through each smoke hole. A diagonal eyepiece was used. Other holes, used for passing out flames during the Greek Orthodox Ceremony of the Holy Fire on Easter Saturday, ran through the meter-thick walls of the Chapel of the Angel . It was not possible to measure with EDM through these holes because they were too long and narrow, but sightings were made through to give a third connection between internal and external stations. Five new instrument stations were used, two on the floor of the Rotunda, two inside the Edicule and one on the roof.

The intention in 1990 was to complete the photography of the exterior by a few fill-in stereopairs but most importantly to obtain as complete a record as possible of the complex and confined interior spaces, including the two internal domes above the levels of the hanging oil lamps. A Hassleblad SWC with Zeiss Biogon lens had been modified at the Engineering Surveying Research Centre by the incorporation of a 100 point reseau grid plate and by pinning the lens to give a stable lens cone for sharp images of objects from 1.2m to infinity at f/22. A T-shaped mono-pod mount for the camera/flash combination was produced. The length of the vertical stem could be varied from about 0.5m to 2.5m. The short horizontal arm had a mount for flash at its centre. The camera could be attached to either end of the horizontal arm, so that the lighting arrangement remained constant for each stereopair. The mount with camera and flash attached was poked up through the burning oil lamps so that photographs of the domes could be obtained. A series of sight holes in the vertical stem of the monopod and a small level bubble allowed approximate setting of the camera exterior orientation for each exposure. Photographs could also be

Table 1. Some statistics from the bundle adjustment.

No. of cameras	6
No. of photographs	196
No. of ext. or. parameters	1176
No. of object points	414
No. of object pt. coordinates	1242
Total no. of unknown params.	2418
No. of constraints needed	4
No. of survey measurements	996
No of measured photocoords.	5894
Total no. of measurements	6890
No. of degrees of freedom	4476
A priori std. dev. angles	0.01
A priori std. dev. distances	1 to 10 mm
A priori std. dev. photocroords.	10 to 125 μm
A posteriori rms std. dev. X	3.5mm
A posteriori rms std. dev. Y	3.6mm
A posteriori rms std. dev. Z	4.4mm
A posteriori max std dev X	19.6mm*
A posteriori max std dev. Y	19.2mm*
A posteriori max std dev. Z	33.1mm*
* For natural features which are imaged on only two photographs. Only 20 points have coordinate standard deviations greater than 10mm.	

taken with the mount inverted and held down through the smoke holes from the roof (Fig.4). All photographs were taken on Ilford FP4 film which is a consistent and tolerant emulsion. Processing was again carried out in a hostel bathroom using Ilford ID11 at 1:1.

No UMK photography was obtained in 1990, but about 160 photographs were taken with the Hasselblad. As in the previous year, about 450 survey measurements were made.

4. THE BUNDLE ADJUSTMENT.

An account of computations which were carried out following the 1989 and 1990 visits is given by Biddle et al (1992).

The primary survey data consists of photographs, archaeological descriptions, sketches and plans and the site survey measurements. From these primary data, secondary data can be derived by different techniques, in different forms and for different purposes. One of the major purposes of the survey is the accurate spatial definition of the main structural features of the Edicule. If it had been possible to take stereopairs of metric photographs, each with more than three well disposed and well defined coordinated control points, then accurate photogrammetry could have been carried out directly. Given the site problems, some photographs, particularly of the spaces above the level of the lamps inside the Edicule, included no predefined control points and some had only one or two. Thus a bundle adjustment was necessary to provide a homogeneous set of coordinated points for each stereopair and exterior orientation parameters of all the photographs.

Pass points (or tie points) were identified and marked on prints. The photocoordinates of these and of the surveyed targets were measured in an Intergraph Intermap Analytic (IMA). These measurements were used in conjunction with the site survey measurements of height differences, horizontal angles, zenith angles and slope distances in a linearised least squares process to estimate the spatial coordinates of the survey stations, the surveyed control points and the pass points and the exterior orientations of the previously calibrated cameras.

The computation was carried out using the Generalised Adjustment Program (GAP) written in C by staff and research students of the Engineering Surveying Research Centre. The program was run under UNIX on a Sun Sparcstation 1+.

Memory storage limitations (16Mb + 50 Mb swap space) meant that a simultaneous solution for all 2418 unknowns was unacceptably slow, taking about a day for one iteration; almost all the run time was used for swapping data. The dense network of photography and survey did not lend itself to automatic rigorous sequential estimation, so a quasi-sequential method was used. Two sequences of independent observations were used, but only the variances of the coordinates estimated in the first sequence were input into the second sequence; covariances were ignored. Later, a full simultaneous

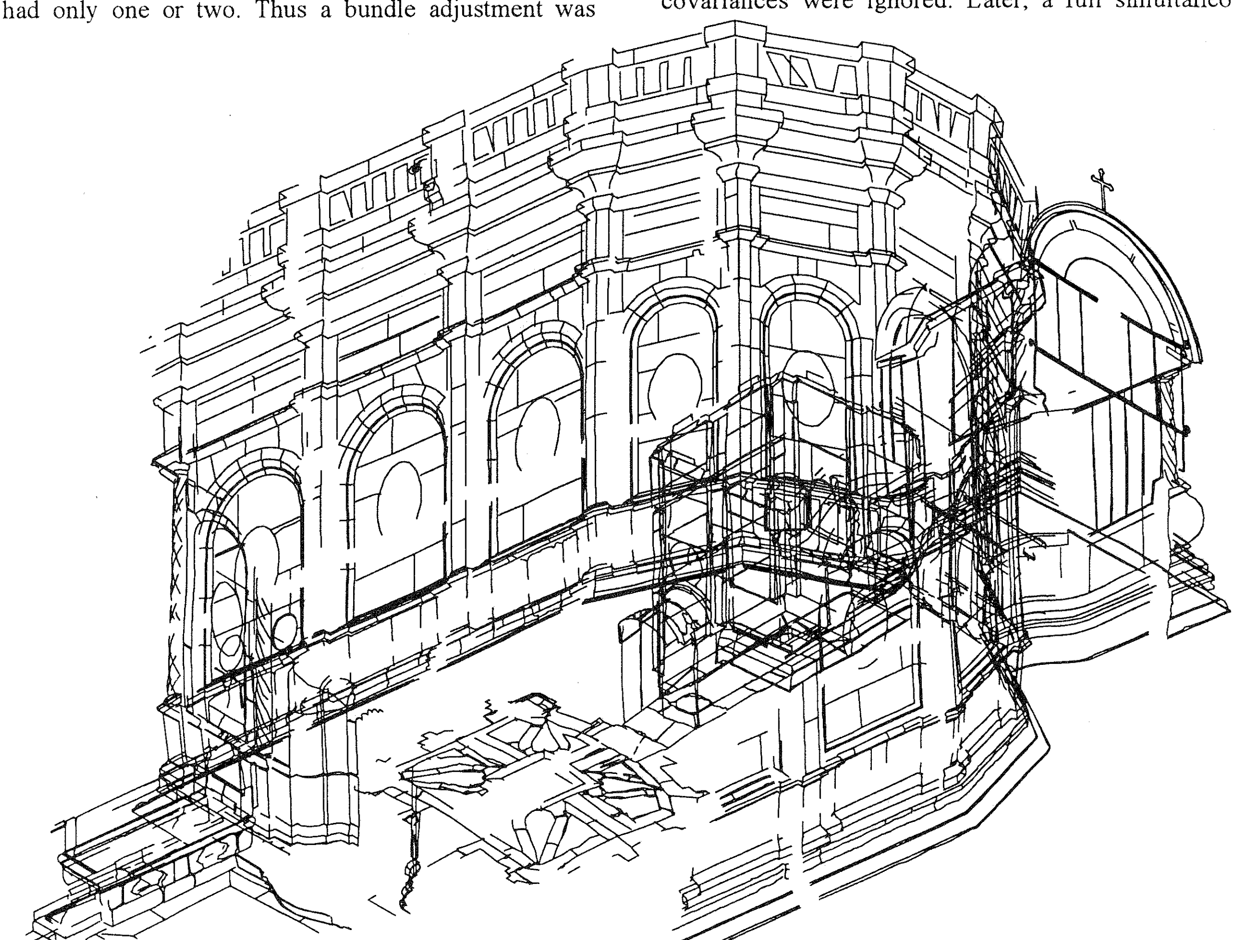

Figure 5. Cut-away linestring model of the Edicule (in progress).

estimation was made using a Silicon Graphics VGX computer with 32MB of RAM. Some statistics relating to this rigorous least squares estimation are shown in Table 1. For about 40 measurements, the least squares residuals were larger than three-times their a priori values, giving an initial a posteriori variance factor of 1.4 (significantly greater than unity). Those 40 measurements were "de-weighted" by a combination of the 'Danish' method of robustified least squares and the judgement of those who carried out the measurements (survey and photogrammetric). In all cases the measurements were to targets only 1 or 2 meters from the instrument (camera or tacheometer) so the a priori standard deviations were too low. After this process, the variance factor was insignificantly different from unity (5% significance) and the a posteriori variances shown in Table 1 indicate homogeneous precision, apart from 11 poorly-defined natural features (pass points), each of which appears on only two photographs.

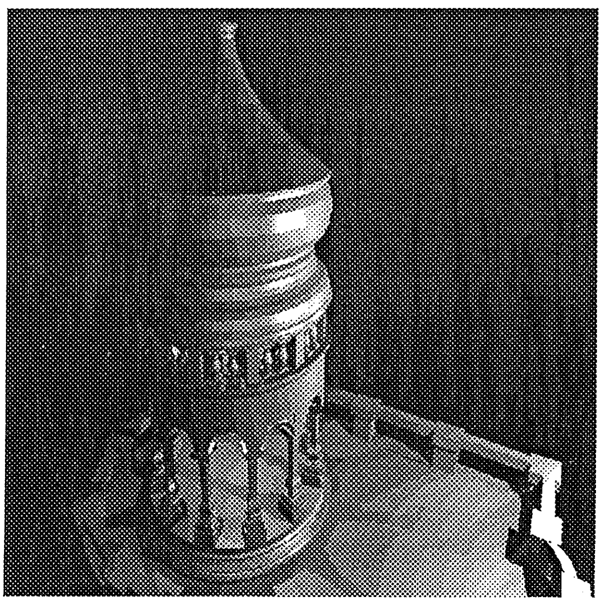

Figure 6. A ray traced image of the Edicule (cupola and roof) CAD Model.

5. STEREO-RESTITUTION, DIGITISATION AND GRAPHICS

The exterior orientation elements of all photographs were loaded into the database of the Intergraph Intermap Analytic. Results of independent camera calibrations (focal lengths, principal point displacements and radial and tangential lens distortions) had also been stored at the IMA. Stereo models were set up using the IMA Simultaneous Orientation option, with principal point displacements and lens distortions (in look-up-tables) incorporated into the real-time loop. For Hassleblad photographs, 6 images were placed on each stage so as to allow 6 stereo models to be called up and interchanged. In this way several views of the complicated 3D structure could be used during the digitisation process.

The initial digitising of features on the IMA was in the form of 3-D linestring elements, These were stored in individual design files, one for each stereo pair. These files were then merged, or referenced together, this allowed for representation within the CAD system of separate elevations, plans and cross-sections. All the data can be merged together, but with such objects as the Edicule, these unstructured, individual linestrings, whilst giving a good overall impression, cause confusion when studied in detail (Fig 5). They do however provide an accurate spatial representation of linear features which can be used to generate data which are easier to interpret and of more relevance to archaeological investigation.

To make full use of 3-D CAD models of objects (Fig. 6), the individual features must be represented by shapes that have surface characteristics. These shapes have to be derived from the original linestrings (Littleworth et al 1992). For ancient objects with their eroded and worn stonework, creating closed shapes from the original linestrings is a time-consuming practice. Assumptions must be made concerning the form of objects to enable the placement of CAD shapes and surfaces. This inevitably leads to lowering of the original photogrammetric accuracy, but the usefulness of the data is increased. The original linestrings (or the photographs themselves) can be referred to when accuracy is important, for example in checking alignments and height differences.

6. CONCLUSIONS

The secondary data from photogrammetry are conventional archaeological plans, elevations and sections and the three dimensional computer-graphics models of the Edicule. The latter are at present simplified but accurate representations of the main structural elements. The original decorative features are shown on the photography and can be plotted or digitised to give a full surface model if required. At present the main work is to combine the photogrammetrically derived computer graphics with the archaeological record in a database. The floor plans produced by archaeologists have been scanned and fitted to the photogrammetric data. Previous representations of structures on the site of and around the present Edicule are also being digitised and used in conjunction with modern data to see how the present structure might be related to earlier ones, and possibly to see to what extent remains of the original rock-cut tomb might be included in the walls of the present Edicule.

Only by photogrammetry, a non-intrusive, passive technique, could such an immense amount of accurate detail have been obtained. Use of the data will lead to hypotheses about the present structure and its development from the original Constantinian Edicule. These hypotheses will it is hoped be of value to those who will be responsible for the renovation, restoration or repair of the Edicule. Such work can not be too long delayed, given the present parlous state of the building.

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