8

Some techniques for cost-effective three-dimensional mapping of underwater sites

Nick Rule

(Survey Consultant, Emsworth, UK)

8.1. The problems of working underwater

In order to understand the merit of the techniques presented in this paper, it is worth briefly recounting some of the problems of working underwater. These include poor visibility, lack of time, physiological and psychological effects, and corrosion of equipment.

8.1.1. Visibility

Underwater visibility varies widely from site to site. For example, muddy estuaries can be so turbid that visibility is zero, and it is pitch black. At the other extreme, clean rocky coasts can have excellent visibility. There are all stages in between and many exceptions. The importance of visibility to this paper lies firstly in its degree of impairment of everyday work, and secondly because it determines whether photogrammetric methods are feasible. Examples personally experienced include the *Mary Rose*, buried in Solent mud, where visibility rarely exceeded 2m (Rule 1982). On this site photogrammetry was hardly ever used, and it was noticeable that when visibility dropped below 0.5m all work was significantly impeded. By contrast the *Sea Venture* in Bermuda lies in a coral gully (Adams 1985; Adams and Rule 1991), and normally has visibility in excess of 15m. Extensive use was made of photomosaics at this site.

8.1.2. Time / physiological effects

It is well known that divers can spend less time in deep water sites than in shallow water sites for fear of "the bends" (decompression sickness). For example, divers on the *Mary Rose*, at an average depth of 12m, rarely totalled more than three hours per day underwater and averaged much less. This does not compare favourably with land archaeology and is a major factor in the cost of underwater excavations, which is often measured in dollars per hour of "bottom time".

8.1.3. Psychological effects

Although I am yet to find conclusive published research, I am convinced that as soon as I submerge my intelligence significantly drops. This idea is enshrined in the well-known "Martini law", which states that every 10m of depth has the same effect as drinking a double Martini.

8.1.4. Corrosion

The sea is a harsh environment, where sensitive equipment can easily get dropped or otherwise broken, where one grain of sand in a seal can cause a leak, and where almost everything corrodes rapidly. In short, any technique to be used for underwater mapping must use extremely robust equipment. It is not purely for financial reasons that the tape measure is the preferred tool of many underwater archaeologists.

8.1.5. Impact of the above upon accuracy

A professional diver has been jokingly defined as someone who, when put naked into a padded cell and given two ball bearings, will rapidly manage to break one and lose the other. Given the real life problems described above, it is not difficult to see how the joke has arisen and how it applies to all underwater workers. The important thing is that all of the above problems contribute to a high error rate underwater. I have studied the rate of blunders recorded during the mapping of various sites (blunders are here defined after Bomford (1971) as non-systematic errors). These blunders were detected as inconsistencies in sets of tape measurements where each set had a high degree of redundancy; in many cases a blunder was actually re-measured for final confirmation.

In a database of 3731 tape measurements (maximum value 43.41m, average value 6.58m) from 12 surveys on 11 sites, 151 measurements (4%) were rejected as blunders whilst drawing up the plans (a more detailed study of the differences between sites is planned for a future paper). My experience, backed by informal experiments with students, suggests that 4% is an interesting number. When hand plotting a set of data with 2% errors it is relatively easy to isolate and reject the blunders. By contrast, when hand plotting with 10% blunders, it is almost impossible. So our observed value of approximately 5% lies somewhere on the frontier of what is humanly possible to plot with ruler and compass. It is no wonder that such plots for large sites can take weeks or months.

8.1.6. Keep it simple, stupid (KISS)

The term "cost effective techniques" in the title of this paper is a euphemism for quick and simple techniques, using simple equipment which amateur or low-budget professional projects can afford. For the reasons discussed above, we will focus on speed and simplicity underwater and the desire to quantify the error processes involved.

8.2. A KISS technique for photogrammetry — the Morrison Cube

If the site has sufficient visibility, quick and simple photogrammetry is clearly the technique of choice. A pho-

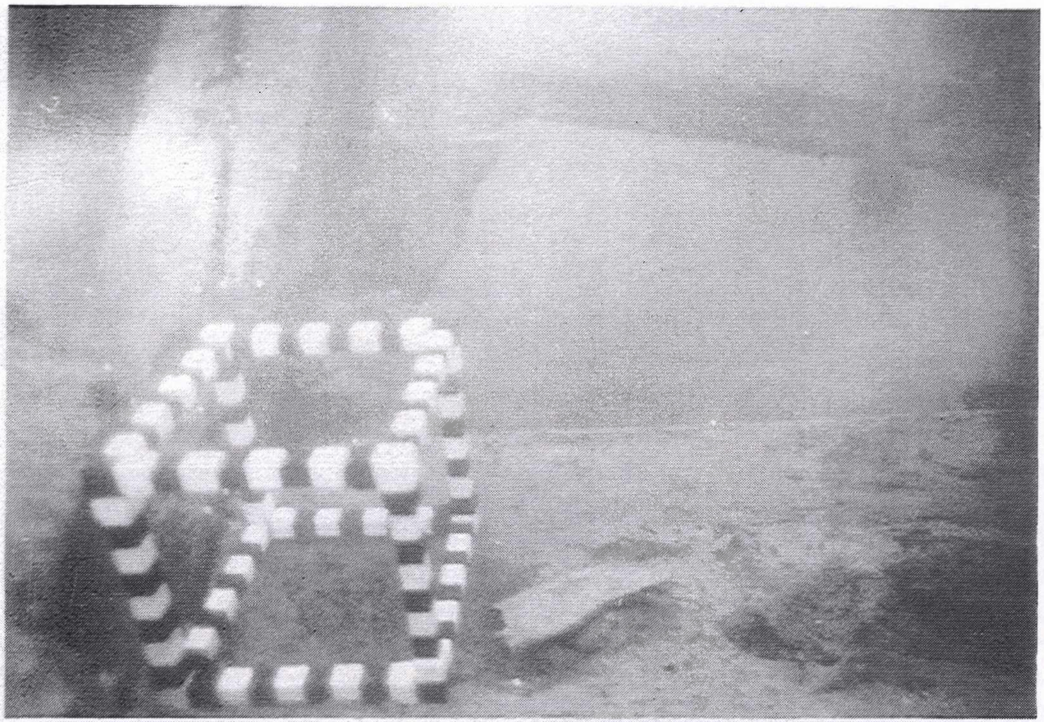


Figure 8.1: Photograph of area of the stern castle of the Mary Rose, *with a 20cm skeleton cube used as a scale. The white dots are map pins.*

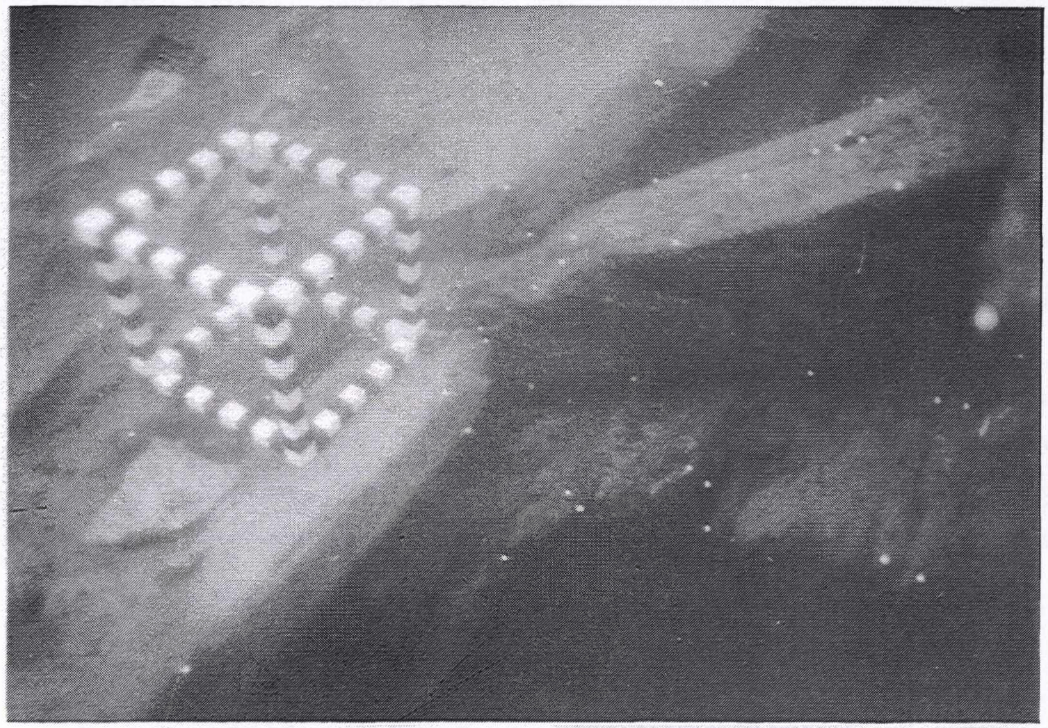


Figure 8.2: Photograph of the same scene as Fig. 8.1, but viewed from a different direction.

tograph can be taken in a few seconds, yet store information on a thousand relationships between points in a site. If at least five points in a photograph are of known co-ordinates, then it is possible (Bogart 1991) to calculate the location, gaze direction, focal length, and other parameters for that camera, by applying a least squares fit to formulae from ray-tracing geometry, as illustrated in Figs. 8.1–8.3. If an unknown point can be identified in at least two such photographs, it is then possible to calculate the three dimensional co-ordinates of that point (Fig. 8.4).

The five known points can be established by tape survey (as described below), or by placing a reference frame such as a skeleton cube in each photograph (Morrison 1969). This latter technique was used to map part of the stern castle of the *Mary Rose* in 1981; due to the poor visibility a 20cm cube was used, and areas of about 1m^2 were mapped in each set of photographs (see Fig. 8.5).

A least squares best fit is used at two stages when processing such photographs — firstly to determine the camera parameters if more than five known points can be

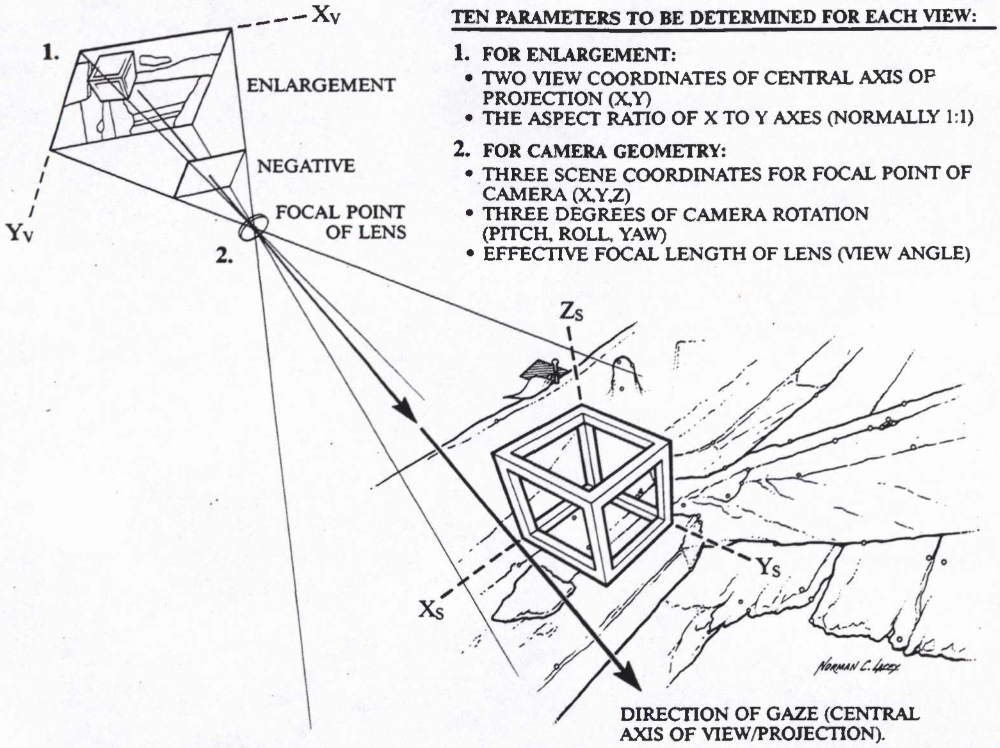


Figure 8.3: Diagram indicating the ten parameters that determine the geometry of a photograph.

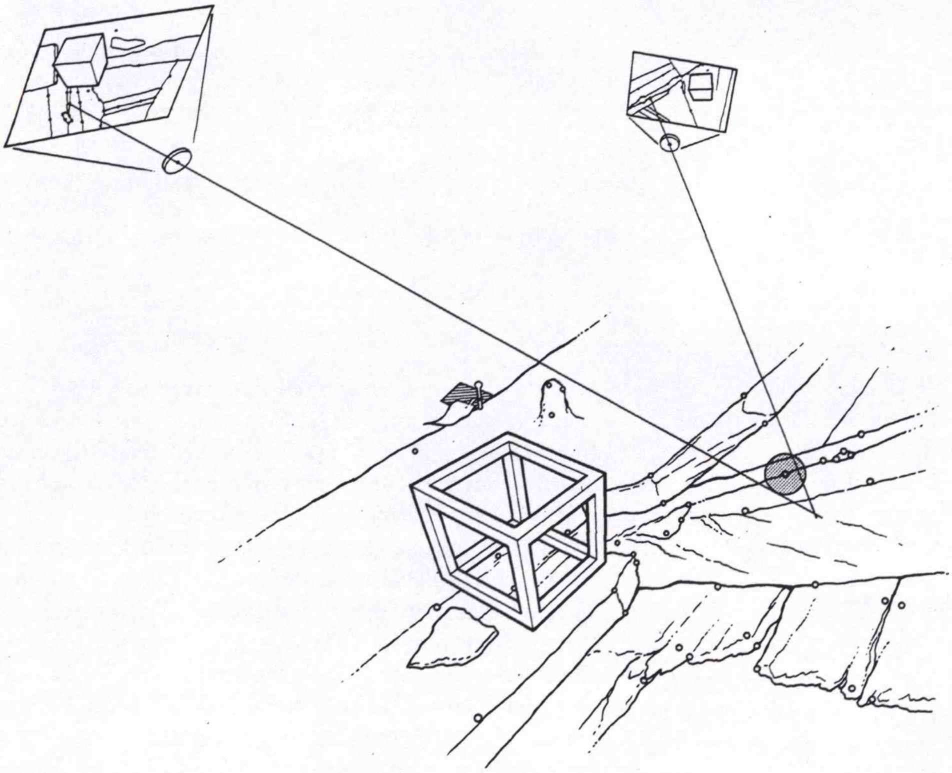


Figure 8.4: Diagram showing the intersection of rays from two photographs being used to define the "best fit" sphere of confidence.

found, and secondly to determine the co-ordinates of the unknown points from the rays defined by each photograph (see Fig. 8.4). The average of the absolute values of the residual errors in the fit of points to rays is used as a measure of confidence in the resulting plan.

8.3. A KISS technique for tape survey

As has been mentioned earlier, the predominant survey tool is often the tape measure. Here divers have one advantage over land archaeologists — they can move easily in three dimensions, and take measurements in the most awkward situations (e.g. upside down). The quick and simple tape survey technique starts with the siting of datum points suitable for tape measurement. In the case of the *Mary Rose* these were initially strong nails hammered into the major timbers; these were replaced in 1981 with plastic hooks. The datum points are sited so as to have line of sight to each other, and to the areas to be surveyed. In the case of the *Mary Rose* this was typically high up on each side of the main deck beams.

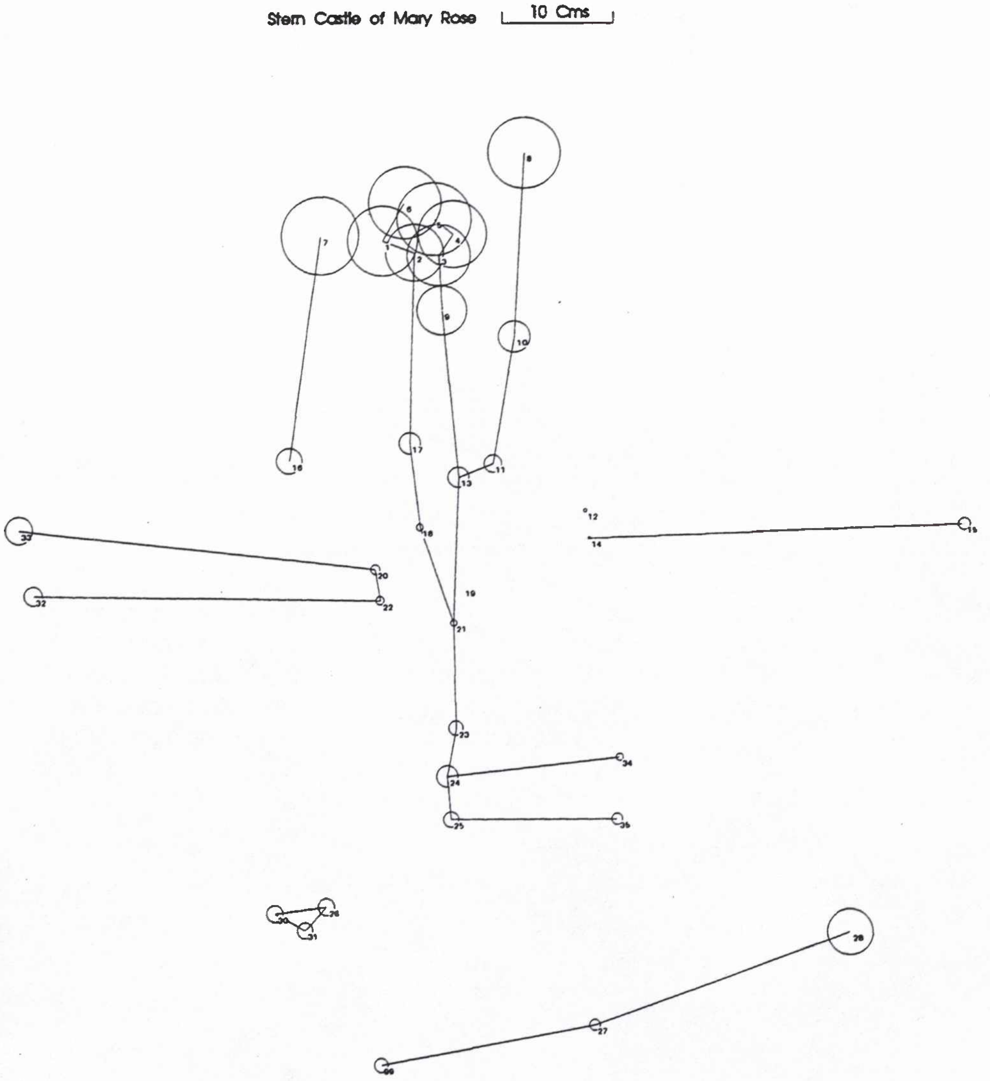


Figure 8.5: Plan derived from Figs. 8.1 and 8.2, plotting X against Y axes as defined by the skeleton cube, and showing circles of confidence. The average absolute residual error for the fit of rays to points is 1.3cm.

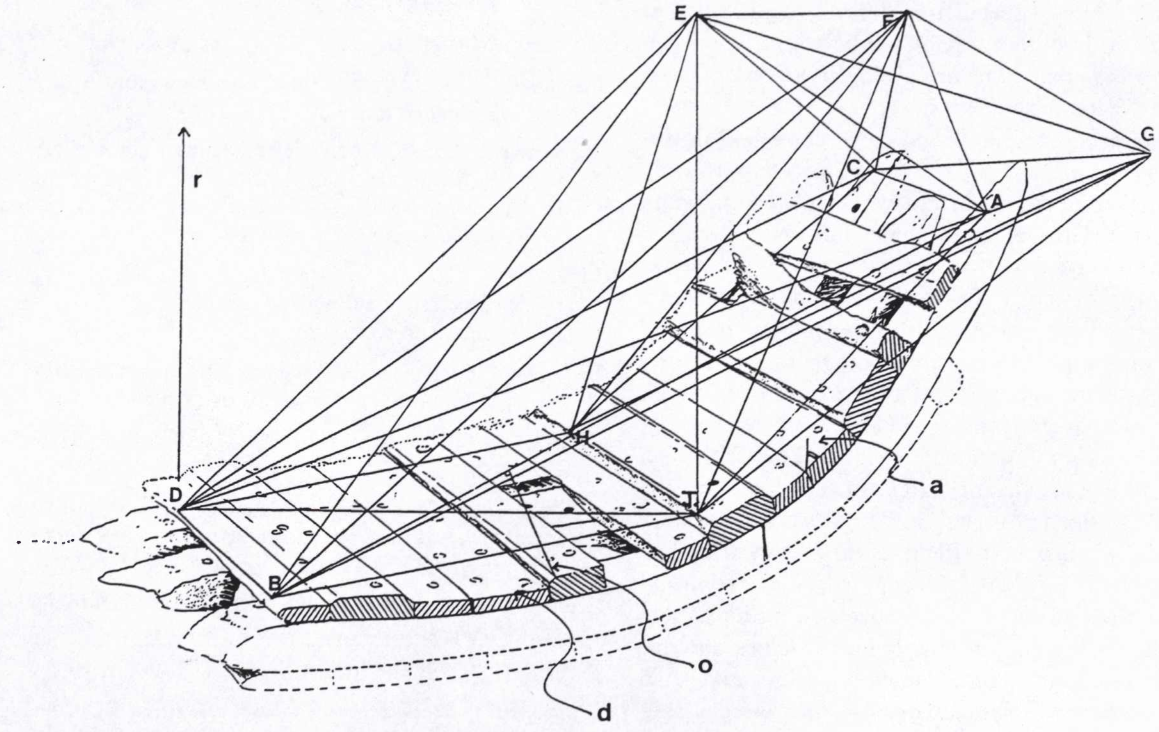
We next measure the direct distance (not the horizontal distance) between each datum point and all its neighbours (typically 5 to 10 measurements). The result of this is a complex three dimensional web of measurements between points, all of whom at this stage are of unknown position, although it should be possible to draw a sketch plan.

8.3.1. Determination of best fit

The problem, then, is how to adjust the X, Y, and Z co-ordinates of the datum points so as to best fit the measurements between them. In order to do this we need a definition of best fit, and this will again be the average absolute residual error. For each measurement the residual is defined as the difference between the actual measurement observed underwater and the distance as currently plotted on the plan. The average of the absolute value of the residuals for all the measurements is a measure of how well the plan fits the measurements. In this way the problem is reduced to a multidimensional function which is to be minimised, with three co-ordinate dimensions X, Y, and Z for every unknown datum point. Whilst there are no known mathematical techniques for completely solving any other than the simplest cases, there are numerous families of iterative techniques for adjusting the X, Y, and Z co-ordinates of each point in order to obtain a near optimal fit. I have successfully used Least Squares (Cross 1981, Bomford 1971), the Downhill Simplex Algorithm (Press 1986), and Multidimensional Scaling (Spencer 1986, Schiffman et al. 1981). The latter will be used to illustrate the technique.

All the techniques take a guess, perform an operation, and (hopefully) obtain a better guess. This is repeated over and over again until the guess produces a "sufficiently good" fit (what constitutes "sufficient" must be defined). Multidimensional scaling takes each measurement, and calculates the vectors that will move the datum points at each end so as to reduce the residual for that measurement to zero. For each datum point, the vectors arising from each measurement using that point are averaged and at each iteration the points are adjusted by these averages. Usually this gives rise to a better overall fit. A useful mental analogy is to think of all the measurements as springs, some pushing and some pulling on the datum points at each end. When these springs have all pushed and pulled, the resulting balance is the best fit, or close to it.

If the minimum number of measurements is taken, this technique will find a fit. If a few redundant measurements (i.e. check measurements) are taken, calculation of the average residual for the plan will give a good and useful meas-



©Tom Adams & Nick Rule

Figure 8.6: A profile of the wreck of the Warwick *used a combination of measurement types, including direct distances (a), relative depths (r), slopes (a), and offsets (o).*

ure of confidence. If sufficient redundant measurements are taken, it becomes possible to isolate and reject most of the blunders. This is done by careful visualisation of the data, in particular by drawing a plan of the points and the measurements between them with various codes including:

- colour coding of each measurement according to the sign of its residual;
- coding the thickness of lines according to the absolute magnitude of each residual;
- drawing circles around each datum point according to the average of the absolute values of the residuals for each measurement involving that datum point.

The result of this technique is a plan of the primary datum points for the site, with a known confidence in each datum point, and in the overall plan. The technique is then extended to the survey of secondary points such as uncovered artefacts and ship structure by taking a few measurements between primary datum points and object; in the case of direct distance measurements three are needed, so four are normally taken so as to provide redundancy (this is the technique termed Direct Survey Measurement, or DSM, Rule 1989).

8.3.2. Use of other measurements: slopes, offsets, bearings, relative depths

Multidimensional scaling lends itself well to many types of measurement, including:

- Direct Distances, measured with tape measure or ultrasonic range meter (or EDM on land);
- Relative Depths, measured with the depth gauge in a diver's dive computer, by aqua-level (Wilkes 1971), depth-meter (Maarleveld & Botma 1987), or using calibrated line to a buoy on the surface (or a surveyor's level on land);
- Bearings, measured with compass (or theodolite on land);
- Slopes, measured with clinometer (or theodolite);
- Sextant bearings;
- Offsets measured with tapes and set square.

Each can be used to calculate a vector acting on its appropriate datum points, and I have written programs that have successfully mixed all these types (except the sextant, for which there was no demand). For example, the wreck of the *Warwick*, an English merchantman wrecked by a hurricane in Bermuda in 1619, was visited by Jon Adams and myself in 1988; a section across the ship was mapped using a combination of 14 distances, 10 slopes, and 17 offsets between 22 datum points (Fig. 8.6). Multidimensional scaling was used to fit these points to the measurements.

It should also be noted that measurements can be weighted, for example to reflect the different accuracies inherent in a mixture of EDM and taped distances.

8.4. Conclusions

A brief discussion of the problems faced when working underwater has suggested that underwater techniques must be quick and simple to use, and that even then a high error rate must be expected and planned for. The two techniques presented here have successfully traded complexity of processing in air in order to gain simplicity and speed underwater, and have then gone on to simplify the work in air by means of computer programs.

With one exception all of the work described in this paper has been processed (or recently re-processed) using programs running under the Microsoft Windows operating system, with the clarity of data visualisation and ease of use that one would expect from such programs. With one exception all the programs have been written by myself, as a hobby interest in the evenings and at weekends, so it should not be difficult for professional archaeologists to write their own versions (all the necessary references have been cited).

The ability to quantify error, and isolate and reject blunders, is of paramount importance when working with such a high error rate. This quantification is needed to allow the archaeologist to sleep at night, knowing that the plans are not rubbish. Also it is cost-effective; the survey team can take measurements, fit plans, isolate blunders, and re-measure until the required accuracy (as specified in the project plan) has been achieved. At this point resources can immediately be re-deployed onto something else, rather than continue to waste time and much money doing unnecessary work.

Bibliography

ADAMS, J. 1985. "Sea Venture, a second interim report, part 1", *The International Journal of Nautical Archaeology*, 14(4): 279–299.

ADAMS, J. & N. RULE 1991. "A comparison of the application of a three dimensional survey system on three underwater archaeological sites". In *Scheepsarcheologie: prioriteiten en lopend onderzoek; inleidingen gehouden tijdens de glavimans symposia in 1986 en 1988, Flevobericht* nr 322, pp. 145–154. Ministerie van Verkeer en Waterstaat, Holland.

BOGART, R. 1991. "View correlation", *in* Arvo, J. (ed.), *Graphics Gems II*, pp. 181–190. Academic Press, Boston.

BOMFORD, G. 1971. *Geodesy*. Clarendon press, Oxford.

CROSS, P. 1981. "The computation of position at sea", *The Hydrographic Journal* 20: pp. 7–16.

MAARLEVELD & H. C. BOTMA 1987. "Underwater heightmeter: a new handheld precision instrument for elevation measuring in underwater surveying", *The International Journal of Nautical Archaeology* 16(2): pp. 87-94.

MORRISON, I. 1969. "An inexpensive photogrammetric approach to the reduction of survey diving time", *Underwater Association of Malta Reports.*

PRESS, W. 1986. *Numerical Recipes — The art of Scientific Computing.* Cambridge University Press, Cambridge.

RULE, M. 1982. *The Mary Rose*, pp. 218–220. Conway Maritime Press.

RULE, N. 1989. "The Direct Survey Method (DSM) of underwater survey, and its application underwater", *The International Journal of Nautical Archaeology* 18(2): 157-162.

SCHIFFMAN, M. L. REYNOLDS & F. L. YOUNG 1981. *Introduction to Multidimensional Scaling.* Academic Press.

SPENCER 1986. "Similarity mapping", *Byte* August 1986

WILKES 1971. *Nautical Archaeology.* David and Charles, Newton Abbott.

Nick Rule,
Mill House,
Westbourne,
Emsworth,
Hants,
GB-PO10 8TG