

The Direct Survey Method (DSM) of underwater survey, and its application underwater

Nick Rule

139 Grosvenor Drive, Loughton, Essex IG10 2LB, UK

This paper describes an approach to underwater survey that has been used to advantage on the *Mary Rose*, *Sea Venture*, *Amsterdam*, and other underwater archaeological projects (Rule, 1982; Adams, 1985a; Adams, 1985b). The features that characterize the technique are: the use of direct (i.e. not necessarily horizontal) tape measurement from datum points of known three-dimensional cartesian co-ordinates; the use of redundant data to identify and quantify errors; and the use of computer programs to process the data and find best-fit solutions for the points being surveyed. The direct survey method was developed in order to provide a fast, simple, and accurate technique with quantifiable error, particularly for underwater sites with limited visibility, and those with extremely complex three-dimensional architecture (such as inside the wreck of the *Mary Rose*).

The development of the technique

Throughout the *Mary Rose* project the tape measure has always been the main surveying tool, as photographs were often unobtainable due to poor visibility, and angles were considered difficult to read accurately (for example, an error of 5° over 3 m gives an error in position of 26 cm). Between 1971 and 1980 tape trilateration was used extensively [i.e. horizontal distances are taken from at least two known points, and then plotted in the time-honoured fashion with a ruler and compass; this is sometimes described (e.g. Wilkes, 1971) as 'Triangulation'; however the term 'trilateration' was used on the *Mary Rose* (in accordance with Bomford, 1971) to distinguish this method using distances from methods using angles]. Nails were hammered into the tops of the major timbers to hold identi-

fication tags, and these nails were firm enough to be used for the attachment of tapes. On the *Mary Rose* every effort was made to take measurements from three datum points, so as to get a triangle of error when plotting.

As the excavation progressed deep trenches were dug. Objects and structure revealed by the trenches were surveyed by trilateration with the addition of a plumb line to obtain the depth below the datum points, which were roughly coplanar (Fig. 1). This work required a diver to either cling to the diver support grid or hover in mid-water, whilst juggling with a tape, graduated plumb line, and writing slate. By 1980 this work was becoming difficult, not least because many trenches were now so deep that a diver hovering at the level of the datum points could not see if his plumb was on the point being surveyed. The survey of objects and structure was becoming extremely slow (the ship could have been destroyed before the survey was finished) and extremely inaccurate (in the mid 1970s it had been decided that all objects found on the wreck would be located to within a cubic decimeter; this criteria was no longer being satisfied). The team began to experiment with alternative techniques. These problems were solved in July 1980 by the introduction of a method which we called the Direct Survey Method (DSM), and which used measurements taken directly from the datums down to the object to be surveyed (Fig. 2). This eliminated the use of a plumb line, and the trigonometry treated the distances obtained as a three-dimensional rather than a two-dimensional problem. Although no-one really liked the name DSM, it had the important advantage of being distinctive, allowing us to avoid confusion with the data obtained by trilateration.

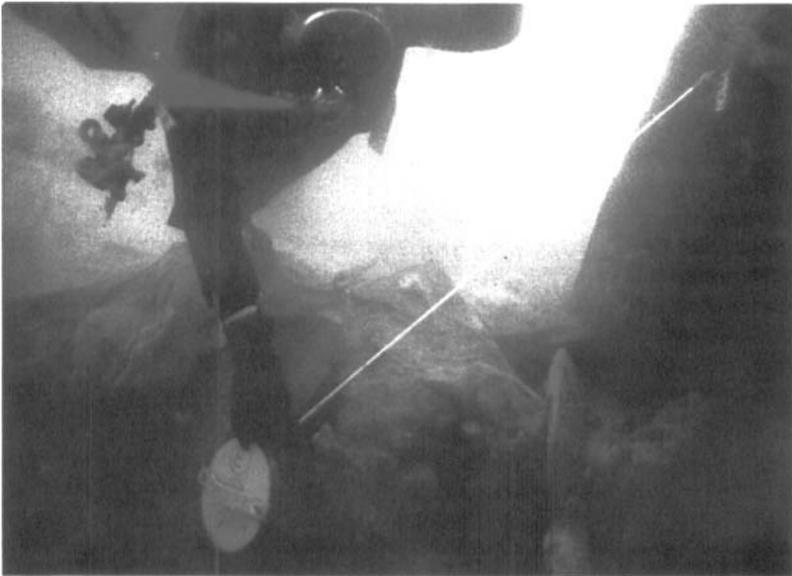


Figure 1. Direct measurement (DSM).



Figure 2. Survey in low visibility on the *Mary Rose* by conventional trilateration using a horizontal tape and plumb bob.

Over the next two years computer programs of increasing sophistication were written to perform the trigonometric and statistical calculations necessary for the processing of the direct measurements.

The technique today

The use of DSM today centres on two suites of computer programs written by the author. These programs have proven themselves sufficiently flexible to be adapted to a wide range of sites and environments. This section describes a typical hypothetical use of the programs, together with some discussion of alternative variations on the technique. My hypothetical site is a buried wreck, similar to the *Mary Rose* or *Amsterdam*, in mid-excavation. Two stages are distinguished here (corresponding to the two suites of programs): firstly the primary survey, where datum points are sited and surveyed, resulting in the three-dimensional co-ordinates of each datum point, and secondly the mapping of individual site points (objects or ship structure revealed during the excavation).

The primary survey

Nails, or preferably hooks, are attached to the wreck structure. They are sited wherever seems most suitable for future use as datum points (quite often there is little choice). They are more or less co-planar, but it is very unusual for them to be exactly so.

The distance is measured from every datum to every other for which there is line-of-sight (this web of measurements is known in DSM circles as the 'interdistances', and is drawn up as a sparse triangular matrix). Accuracy fiends do this at least twice (i.e. from A to B, and later from B to

A). Cautious workers repeat this at the start of every season to see if the datums have moved. The end result is the rapid accumulation of large amounts of redundant data and a good chance of spotting any errors.

Next the topography of the datums has to be classified into one of three types: roughly co-planar datums, not co-planar but possible to determine the relative depths, and not co-planar and not possible to determine the relative depths.

Roughly co-planar

In this situation the problem can be treated as two-dimensional and a plan can be drawn up using ruler and compasses. One problem with this is the time and skill required, another is the possibility of propagating errors as one moves out from the first few points in the plan towards the edges of the site. On the *Amsterdam* and *Sea Venture* we introduced a modification of the technique: the site plan was drawn up very roughly with ruler and compasses, at a scale of 100 : 1, using only a few of the measurements. From this plan was obtained a rough guess of the co-ordinates of each datum point. These were fed, together with all the interdistances, into one of the DSM programs (written for the *Mary Rose*, but too late to be used other than retrospectively), which performed a least-squares fit of datum co-ordinates to interdistances using an algorithm known to land surveyors as the 'variation of co-ordinates' (Bomford, 1971; Cross, 1981; Milne, 1982). This algorithm progressively refines the guess until an acceptable solution is reached. (An alternative iterative algorithm is sometimes used which takes longer to reach the optimal solution, but is less influenced by erroneous data.) This provided us with best-fit

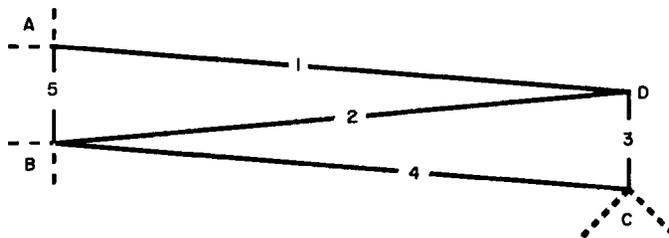


Figure 3. Plan view of measurements ('interdistances') taken between four datums. Dotted lines indicate measurements to other datums outside the diagram.

co-ordinates for each datum, plus: estimates of error in the co-ordinates of each datum; an estimate of error for the general practice of underwater measurement under the conditions of that site; an estimate of any scale error in the measuring process (i.e. stretching or bowing of tapes), with an estimate of error in that estimate; an estimate of error for each measurement (very useful for correcting mistakes, and sometimes for evaluating an individual diver's suitability for such work); an estimate of importance for each measurement. For example, in Fig. 3, measurement 3 is very important in fixing the datum D. Important measurements are usually checked because error in them will not become apparent.

It should be noted that few workers seem to realize just how non-coplanar a site has to be before significant errors result from treating it as co-planar. Take two datums 3 m apart horizontally (a typical case on the *Mary Rose*). One datum has to be 25 cm above the other before the direct distance increases by 1 cm. It is important to decide in advance on the level of accuracy required. Only then can one objectively evaluate whether the datums can be regarded as co-planar.

It is possible to weight the measurements when using the variation of co-ordinates algorithm. This is useful, for example, when mixing two techniques of different accuracy such as tape measurement and ultrasonic ranging.

Not co-planar, but possible to determine the relative depths (by means of various underwater levels etc.)

The relative depths are used, together with the application of Pythagoras' theorem, to reduce all the direct interdistances to horizontal ones; then the problem becomes that of the co-planar site above.

Not co-planar, and not able to determine relative depths

This unusual situation can be dealt with by using the three-dimensional version of the above-mentioned least-squares interdistance-fitting program. However, great skill and patience is required to establish the initial guesses. The technique here is normally to start with a few datums, and then work out adding less reliable data. The errors do not propagate when doing this because each attempt merely provides a better guess; it is

the final fit with all the datums that counts, and all are treated equally.

The survey of site points

The diver who wishes to survey a site point simply measures the distances from the site point to the nearest convenient datum point. A minimum of three datum points are needed (the present program will accept up to 25), but typically four are used. The choice of how many datum points to use is a trade-off: three will not give any indication of error, four will indicate that an error has occurred but will not indicate where, while larger numbers will progressively pin-point and quantify any errors. Using an increased number of datum points will give increased accuracy, but will also take longer.

On the surface the name of the site point is entered into one of the DSM computer programs along with the name and distance of each datum point used. The program looks up the co-ordinates of each datum point in a simple database, and then calculates a rough position for the site point, using one of three algorithms (selected by the user according to the topography of the site). This position is then used as the initial guess for an iterative adjustment using the variation of co-ordinates algorithm. The solution is printed, together with an estimate of error in the solution and an estimate of error in each of the measurements.

Results

In general, DSM has been adopted on sites that would otherwise have used trilateration. On flat sides, DSM is trilateration; the only difference is the use of the computer rather than hand plotting. On three-dimensional sites, where trilateration would have to be supplemented by plumb lines or other indications of depth, DSM has been shown to have an advantage in terms of speed, accuracy, and the treatment of errors.

Speed

To date, no direct comparison of DSM and 'trilateration + plumb line' has been made. A subjective estimate, based on experience of the change from trilateration to DSM on the *Mary Rose* (which was a 'worst case' example for trilateration), is that DSM takes roughly half the time. Certainly DSM never takes longer.

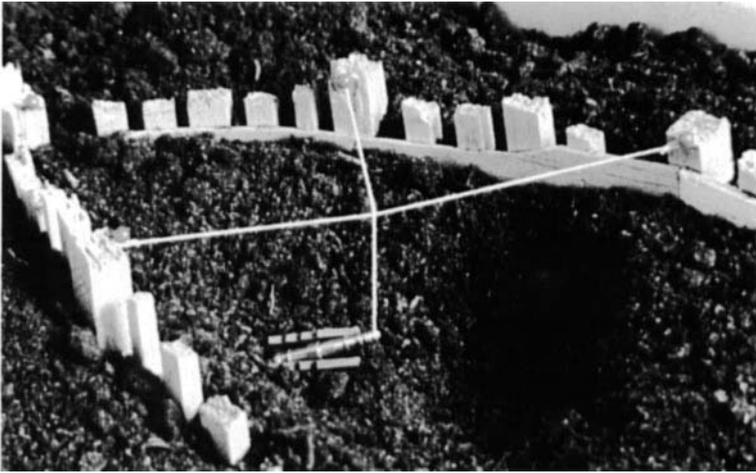


Figure 4. Model showing use of trilateration with plumb line.

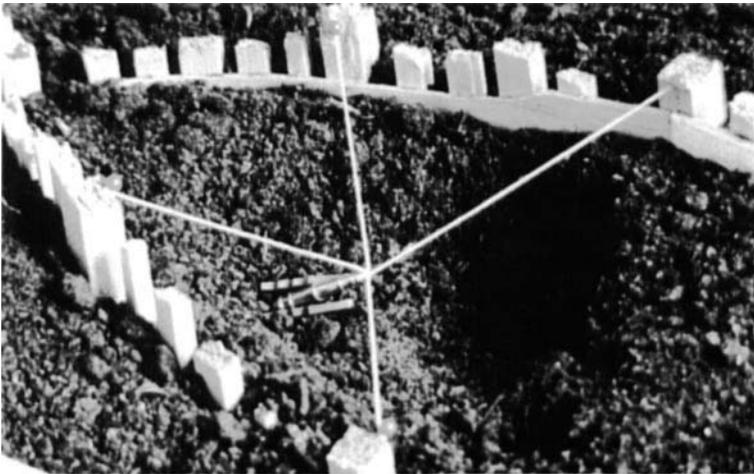


Figure 5. Model showing use of DSM.

The use of the program for primary surveys can dramatically reduce the time required on the surface to produce an accurate site plan. A subjective estimate of this, based on experience of a survey of the *Mary Rose* using ruler and compass, and the survey of the *Amsterdam* described above, suggests that the use of the program takes about a quarter of the time. (A limiting factor here is the capacity of the current program; it is hoped to rewrite it in the near future to take advantage of the more powerful computers becoming available.)

Accuracy

The accuracy of the use of DSM on a site can be presented in three different ways, as described earlier. A figure for each is given below, taken from a moderately bad sample of *Mary Rose* data consisting of 23 measurements between ten datum points.

Error in individual measurements. The solution reached by the program was in disagreement with the measurements taken by an average of 9.0 mm, or 0.3 per cent. The worst case in this data set was the longest measurement of (7.19 m)

which was 2.8 cm (0.4 per cent) too long to fit the solution.

Error in the general practice of underwater measurement on that site. The standard error of unit weight for the measurements was 2.3 cm. This indicates that we can expect 68 per cent of all measurements taken under similar conditions (i.e. that site, visibility, etc) to be within 2.3 cm of the correct distance.

Error in the co-ordinates of each datum. This is partially derived from the standard error given above. In our example the datum points were fixed to plus or minus 2.7 cm, i.e. 68 per cent of all the datum points can be expected to lie within 2.7 cm of the reported position.

The treatment of errors

A major advantage of using a statistical best-fit algorithm such as the variation of co-ordinates lies in the potential for the use of redundant data in order to identify errors. This allows large 'blunders' to be rejected or repeated, and smaller errors to be quantified, as demonstrated above.

Conclusion

DSM has proved itself sufficiently valuable to be

used almost exclusively on three major excavations, and partially on a number of others. Its advantages are increased simplicity underwater, a reduction in bottom time, increased accuracy, and the quantification of errors.

Acknowledgements

This paper is a precis of a much larger work on DSM that will be published as part of the *Mary Rose* main report. It would be impossible to list all the people that have contributed to the work described in these papers. I would like to thank all the friends who have encouraged me, the colleagues who worked with me on the *Mary Rose* and gave so much advice and suggestions, and the numerous people that have read draft copies of the papers and suggested improvements.

In particular I should like to mention Jon Adams, the late Jim Clark, Maggie Evans, Andrew Fielding, Dr Ian Graham, Mrs M. James, Nigel Kelland, the late Keith Muckelroy, Colin McKewen, the late Margrethe De Neergaard, Arthur Rule, Margaret Rule, John Walliker, and D. F. Bevis White, all of whom have made distinct contributions to the DSM project.

References

- Adams, J., 1985a, *Sea Venture*, a second interim report, part 1. *IJNA*, 14.4: 279-99.
 Adams, J., 1985b, Survey Techniques, in *Amsterdam Year Report 1985* (Ed. Gawronski), Stichting VOC Schip Amsterdam.
 Anderson, J., 1969, A new technique for archaeological field measuring. *Norwegian Archaeological Review*, 68-77.
 Bomford, G., 1971, *Geodesy*, Oxford.
 Cross, P. A., 1981, The computation of position at sea. *The Hydrographic Journal*, 20: 7-16.
 Milne, P. H., 1983, *Underwater Acoustic Positioning Systems*. E & F.N. Spon.
 Rule, M., 1982, *The Mary Rose, 1982*: 218-20. Conway Maritime Press.
 Wilkes, B., 1971, *Nautical Archaeology: A Handbook*. David and Charles.