Historic England

Traversing the Past

The Total Station Theodolite
in Archaeological Landscape Survey

Summary

This paper is one of a series on archaeological field survey techniques published by Historic England. It covers the electronic total station theodolite (TST) and its use in landscape archaeology. General guidance on the TST and its role in recording archaeological excavations and in surveying historic buildings is available elsewhere (Bettess 1998; Menuge 2006; Andrews et al 2009; 2010). In this paper these topics are only covered in principle.

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Front cover:
The English Heritage Archaeological Survey and Investigation Team using a total station theodolite at the Black Beacon on Orford Ness, Suffolk. The Black Beacon is an octagonal building built in 1928 for the Royal Aircraft Establishment, Farnborough, to house radio direction finding equipment. Renovated in 1995, the beacon now provides an elevated viewing area for the visiting public

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Introduction

The theodolite is a tripod-mounted calibrated optical instrument used to measure horizontal and vertical angles in order to determine relative position. The theodolite was developed in the 16th century and the modern TST (Figure 1) is its latest incarnation. On a TST the angles and distance to surveyed points are recorded digitally and in this way the TST locates each point measured relative to itself. As the data are captured digitally, they can readily be passed to a computer with software designed to calculate the *x*, *y* and *z* coordinates of each point and to present the survey as a 2-dimensional (2-D) or 3-dimensional (3-D) drawing.

The TST is perfectly capable of delivering highly accurate surveys in almost any terrain but is now used increasingly in combination with survey-grade satellite receivers. Satellite receivers fix positions using information broadcast by constellations of navigation satellites, most commonly those forming the American Global Positioning System (GPS) and Russian Global Orbiting Navigation Satellite System (GLONASS). These and other constellations of navigational satellites are known collectively as global navigation satellite systems (GNSS) although GPS is commonly used as the standard generic term (Pearson 2015). The use of GPS receivers is entirely dependent upon the strength and quality of satellite reception and usually also on the maintenance of a radio or mobile phone link to a base receiver. Satellite receivers therefore may not work in some locations, such as steep-sided valleys, among trees or close to buildings. In such environments the TST is the best alternative choice of survey instrument.

Well-established procedures exist to adjust and integrate the readings taken from different TST positions (called stations) during a survey and position the survey accurately on existing base mapping, such as an Ordnance Survey map, or combine it with GPS data. The specialist survey teams in the Research Group of Historic England have used TSTs as part of their survey toolkit for many years. The purpose of this paper is to pass on some of the lessons learned from their extensive experience of using TST survey to record and understand archaeological landscapes and monuments (Bowden 1999; Ainsworth et al 2007). Metrically accurate surveys underpin the process of observing, recording and understanding archaeological landscapes, and four case studies provide details of some of the processes involved. It is hoped that this paper will help those engaging in surveys of such areas to understand the strengths and weaknesses of using a TST, see how the techniques integrate with other available survey methods and learn the basic rules governing survey with a TST.

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Figure 1
A modern TST in use in the field

1 Background

1.1 Origins

The use of angular measurement for navigation, cartography and surveying has a long history. The principles that led to the development of the astrolabe were known before 150 BC and developed by navigators from the Middle East, although the first known instruments date from approximately AD 400. They were highly developed by about AD 800 and were introduced to Europe from Islamic Spain in the early 12th century (Wallis 2005, 5). The earliest written description of an instrument that might be considered a distant ancestor of the theodolite was made by Hero of Alexandria (AD 10–70), who named the device he described the Dioptra. It comprised two metal plates (one in the horizontal and the other in the vertical axis), that could be rotated using a worm drive, a water level and a precursor of the alidade used as a sighting device (Wallis 2005, 4).

By the 16th century, the progress of both mathematics, in the field of angular measurement, and engineering permitted the development of the first instruments designed for precise measurement of angles in the horizontal and vertical planes for the purposes of surveying, and hence the first recognisable theodolites. The earliest reference to such an instrument was made by Martin Waldseemuller in the 1512 edition of Gregor Reisch's Margarita Philosophica, where it was called a 'polimetrum' (Turner 2000, 5). Until this point the most sophisticated instrument available to surveyors had been the plane table with an alidade, still in use today (Bowden 2002). The English surveyors Leonard Digges and his son Thomas described a series of three surveying instruments in their 1571 work A Geometrical Practise named Pantometria, one of which was called 'theodelitus' and constitutes the first use of the word for this type of instrument. The instrument thus named was a simple theodolite but could be combined with the others described to form an altazimuth theodolite (Turner 2000, 6), called the 'instrument Topographicall' (Digges 1571) (Figure 2).

By the middle of the 18th century increases in the precision of angular measurement meant that large areas could be mapped by precise triangulation using reasonably robust optical theodolites. This was demonstrated by the military engineer William Roy in his survey work in Scotland in the 1750s (Owen and Pilbeam 1992, 4). Large theodolites, such as Jesse Ramsden's 3-foot theodolite, which weighed 200 pounds and had a 36-inch base plate, were subsequently used by the Trigonometrical Survey of the Board of Ordnance (now the Ordnance Survey) during the primary triangulation of England starting in the 1790s (Seymour 1980, 28–36; Owen and Pilbeam 1992, 15). During the 19th century, theodolites developed in line with the demands of the industrial age, and by the turn of the 20th century the theodolite was a relatively lightweight, universal measuring tool providing high orders of precision. During the 20th century, theodolite precision and portability were developed further, notably by Heinrich Wild. Thus from the mid-18th century theodolites could be used to develop triangulation schemes from carefully measured (but none the less short) baselines, distance measurement for the baselines relying, for the most part, on graduated rods, tapes or bars.

The precise integrated measurement of distances using a survey instrument is a much younger technology. The basis for the current method was pioneered by Erik Bergstrand while working at the Geographical Survey Office in Stockholm. He developed an instrument to measure distances by means of light signals, if the speed of light were accurately known. He pursued this idea at the Nobel Institute of Physics, took his first measurements in 1947, and in 1948 had a value for the speed of light, thereby permitting the accurate measurement of distance using this method. The first commercial instruments produced using this principle (known as Geodimeters) were made by the AGA company and were shown in Brussels in 1951. These instruments used microwaves and were mainly used for the measurement of baselines and to obtain the precise measurements necessary for the establishment of satellite tracking stations (Wennstrom 2008). From this origin followed the development of lighter and more economic infrared-based devices. The method is known as electromagnetic distance measurement (EDM) and involves evaluating the signal returned from the target of a light beam emitted by the EDM unit. Many modern instruments do not require a retro-reflective prism for measurement, and can read signals reflected from almost any surface that is within range; in this case the term reflectorless EDM (REDM) is used. EDM is also applied colloquially to any survey instrument using this method of distance measurement. The combination of precise angular and distance measurement technologies into a single instrument during the 1960s and 1970s, allied with improvements in range, weight, precision and reliability, has led to the present generation of measurement devices.

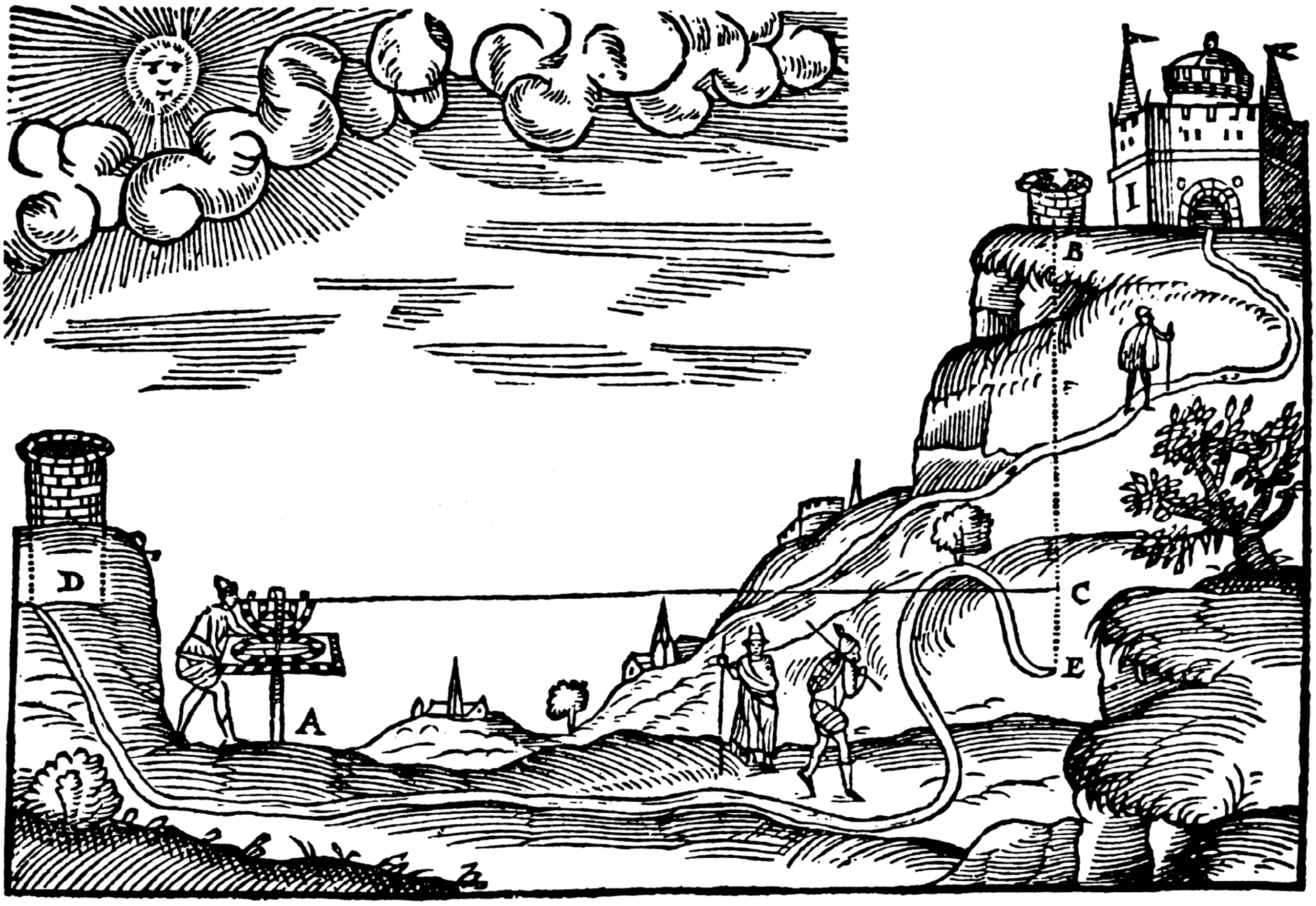


Figure 2
Engraving of a 16th-century surveying instrument in use. (Digges 1571)

1.2 The total station theodolite (TST)

It should be emphasised that the TST is only a tool: effective use of the instrument depends on the skilled selection of survey stations. For archaeological and other specialist applications, effective use also depends at least as much on the identification of features and points to be measured as it does on the software and equipment used. The general guidance on technique offered here should be used in conjunction with the specific recommendations of the manufacturers and suppliers of the hardware and software involved.

When working with a TST, it is useful to understand the basic principles of how it works and the way these affect working practices. TSTs are considerably more expensive than more traditional measuring tools, such as optical theodolites and plane tables with alidades, but in return they offer considerably more precision and flexibility. Rapid and precise measurement using a TST gives a reliable framework for survey work of many kinds. A TST enables survey at orders of precision commensurate with both detail (eg 1:20–1:500) and wider area (1:1000 and smaller) scales. Mapping areas larger than c 25ha by TST is now rarely economic. Aerial photogrammetry, light detection and ranging (lidar) and GPS, used singly or in combination, are more cost-effective for such tasks.

As outlined above, a TST combines horizontal and vertical angle measurement circles with a distance measurement unit (EDM); measurements are recorded digitally on some form of data storage, either integral to the TST or using a separate data logger or tablet computer connected to the instrument. Where the system does not accommodate real-time display, the survey plot is only seen later, after the data have been downloaded and processed. The operations involved in downloading and processing the survey on a computer are dependent on the software and hardware being used. Section 5 describes the use of field codes and choice of survey software in more detail.

The principal elements of a generic modern TST are illustrated in Figure 3.

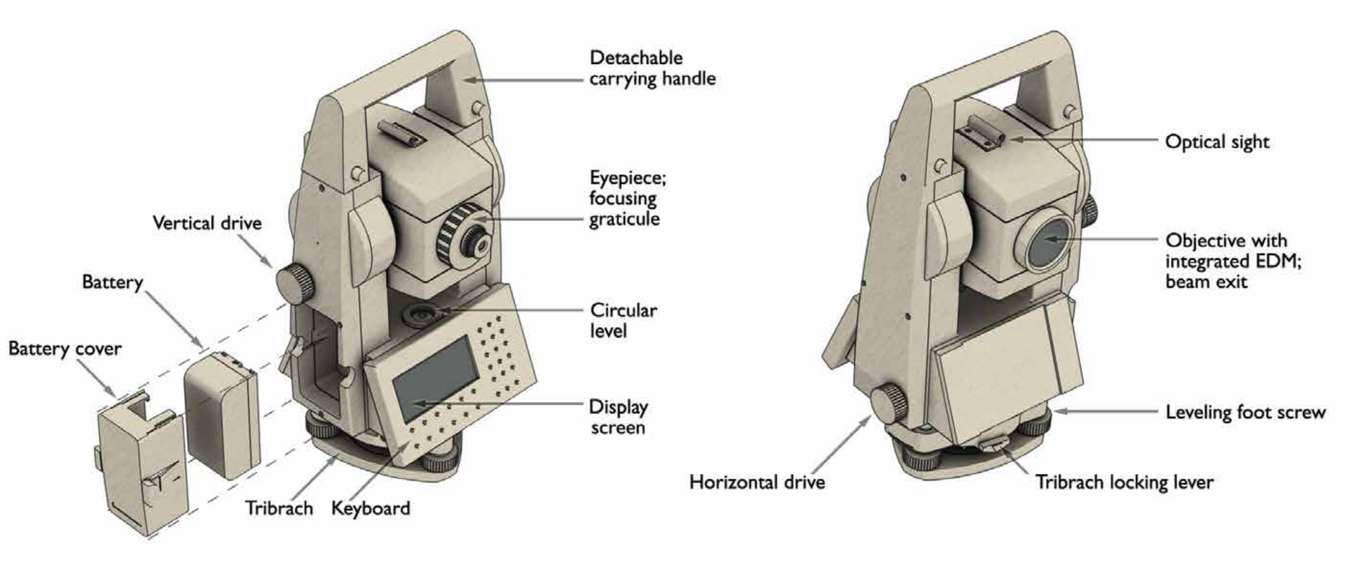


Figure 3
Diagram showing the parts of a generic TST

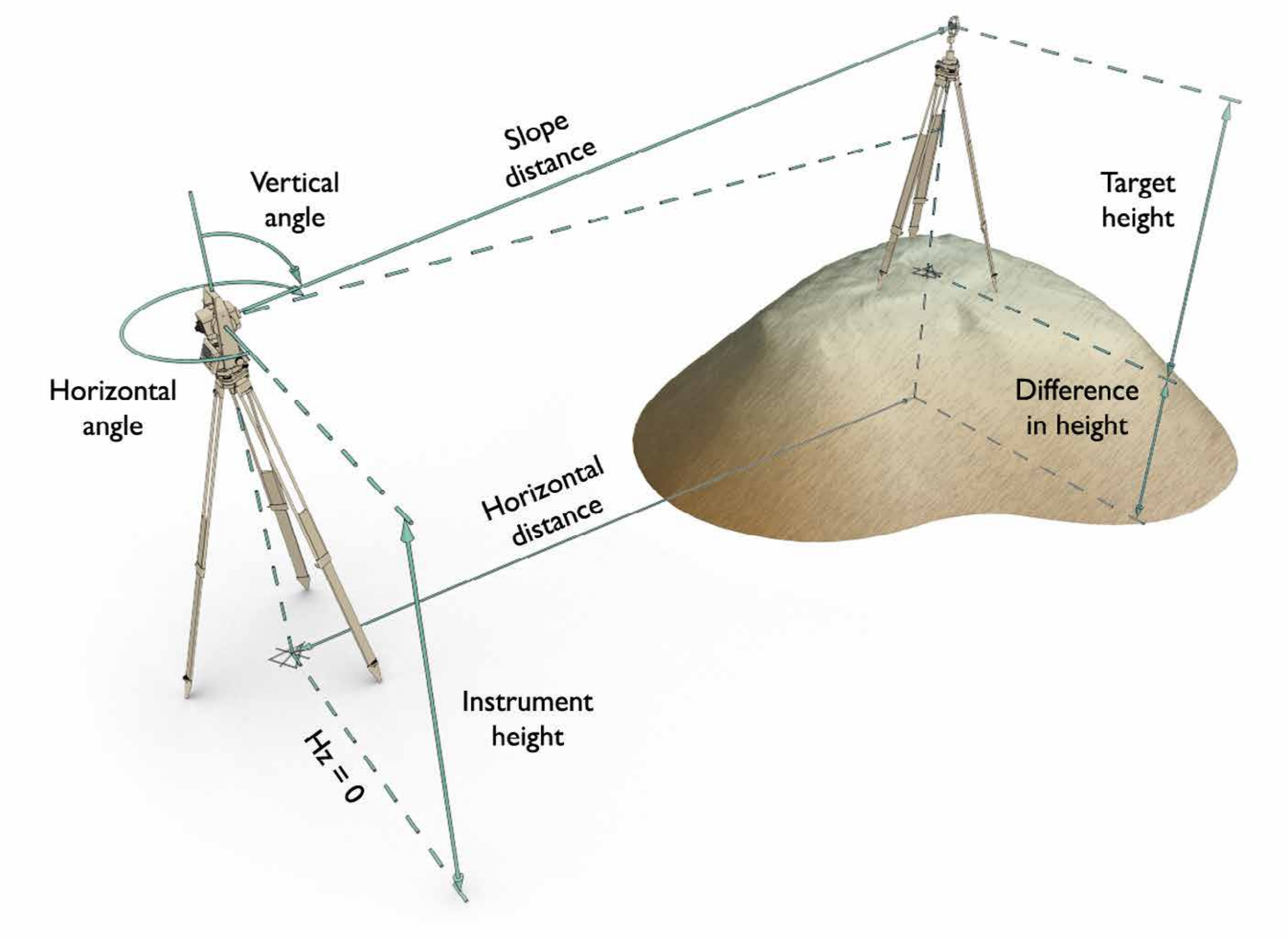


Figure 4
The elements of measurement with a TST

The telescope is aligned with the centres of horizontal and vertical angular measurement and the centre of distance measurement. The telescope is attached to a 'graduated' electronic horizontal circle for measuring the angle of rotation and a vertical circle to measure the angle of inclination. After aiming the cross-hairs of the telescope at the target, the slope distance, angle of rotation (horizontal angle) and angle of inclination (vertical angle) are recorded, usually along with optional supplementary data such as station position and height, target height and point code. The automatic recording of the three components of the measured vector is more rapid, accurate and less prone to error than on an optical micrometer theodolite, where recording has to be done manually.

A polar vector comprising the slope distance and vertical and horizontal angles to the target is therefore the product of the measurement cycle, and trigonometric calculations enable deduction from these data of horizontal distance, bearing and vertical height difference, and ultimately a series of 3-D Cartesian coordinates relative to the instrument position, from which a map or plan can be derived. The elements of measurement are demonstrated in Figure 4.

1.3 Distance measurement

Most TST instruments use an infrared measurement wave as described above. This signal is emitted by the instrument and returned from the target. In simple terms the number of waves of a given wavelength taken for the beam to travel out and back can be counted and determined as a distance. By using a number of different wavelengths and analysing the phase shift, the distance can be established to the required precision.

Precision in the order of +/–2mm at 2 parts per million (ppm) at 1.8km is common (1ppm = 1mm in 1km). The maximum range is usually about 2km, but this can be extended by using special prism arrays to optimise reflectance. The minimum range is not often an issue when surveying in open areas, but can become more critical where space is limited. Some instruments have a minimum range in the order of 2–5m, which can be problematic if the TST is to be used for a building survey, for example, where this sort of minimum range is unacceptable. It should be remembered that the instrument is using light to measure; it therefore requires a line of sight between observer and target, and is affected by rain, fog and airborne particles as well as other environmental factors (section 1.5).

TSTs are often now available with a reflectorless function, that is they do not require a retro-reflective prism as the target to achieve a measurement. This is very useful for many types of recording work as TSTs will operate over a range of 0.2–1000m without needing a prism to return the EDM signal. This has two principal benefits:

- speed of targeting
- measurement of points where a prism cannot be placed

Data captured using reflectorless measurement need to be monitored, because the measured distance is affected by several factors.

- **Range:** with long-range observations, the return signal is diminished and the footprint of the measuring beam on the target is increased; this can result in inaccuracies
- **Obliqueness:** ambiguity over the point targeted increases with the obliqueness of the observation, which can lead to distances being incorrectly recorded
- **Reflectance:** the reflective quality and surface texture of the target will affect the ability to measure distances. Matt black targets offer very poor reflectance, and measurement cannot always be achieved from such surfaces because of a lack of return signal

1.4 Types and options

The cost of an instrument suitable for archaeological survey is largely dependent upon the precision and functionality required.

Precision

Most modern instruments measure angles to a precision of between 0.5 and 10 seconds of arc, and distances to a precision of between +/–0.1 and +/–10mm. Generally speaking, increased precision brings increased cost. The precision of results in the field is a function of several factors:

- the internal tolerances and capabilities of the instrument
- the condition of the equipment used
- correct measurement procedure
- the range over which the measurement is applied
- the reflective properties of the target (if applicable)
- atmospheric conditions

When the measured angles and distances are combined with the heights of the instrument and the target above ground level, typical precision of between +/–2mm and +/–10mm per point is achieved for single shots, with (potentially) sub-millimetre accuracy for rigorously observed control points using a high-quality instrument.

Functionality

Manufacturers offer a range of additional functions with their instruments but increased functionality goes hand in hand with increased cost. Many TSTs have a modular design that allows the purchaser to tailor the functionality included to his or her needs and budget.

Robotic or motorised capability enables the instrument to be controlled remotely, usually via a radio link. This makes it possible for one person to conduct the survey in the field by operating the data logger from the target prism rather than from the TST. The utility of the system is greatly increased if automatic target recognition (ATR) is also used, so that the instrument locks on to and tracks the target prism automatically (Figure 5). As the instrument is using light to measure, it is evident that a line of sight must be maintained. On some instruments operating in robotic mode there is the facility to conduct a search to relocate the prism if the lock is lost. ATR also compensates for errors in sighting the centre of the prism, allowing for faster, more accurate fieldwork.

Reflectorless measurement is a useful option in topographic survey for measuring to points where a prism cannot be placed easily (such as the far bank of a river, an inaccessible part of a structure or a quarry face). The range available varies with cost. Most instruments offering this function operate at maximum ranges between 80 and 1000m.

Figure 5
Using a robotic TST. Measurements are triggered from a controller carried by the surveyor which communicates with the TST via a radio link

Electronic guide lights (EGL) are another option available with most professional-quality instruments, and are useful when setting out points. The surveyor with the detail pole can, by looking at the instrument, see a visual indication of whether he or she needs to move to the left or the right, thus speeding up the setting-out process.

The facility to mount an integrated survey-grade GPS receiver on the TST is another option often available with higher quality instruments. This allows the survey to be located accurately on the Ordnance Survey National Grid (OSNG) while in the field. Usually a large premium is paid for such instruments.

Digital cameras can also sometimes be incorporated, enabling the operator to take photographs through the lens of the instrument, view them on the instrument screen and store them in the internal memory.

The software functionality available on the instrument can also vary considerably and is reflected in the cost. Typical additional software functions include, for example, the ability to conduct traverse adjustments while in the field, stakeout operations and the facility to import files in common computer-aided design (CAD) formats (eg DXF™). Depending on the type of instrument display, CAD files can be used, for example, to display background maps in combination with new detail as it is surveyed.

Most TSTs provide the ability to download data to a personal computer (PC) or laptop via a cable or Bluetooth® connection rather than (or in addition to) using a data card. This functionality is essential for real-time interfaces that deliver each measurement as it is taken to a tablet computer running a CAD or survey package for immediate display.

1.5 Sources of error

Most errors can usually be avoided by following good procedure. We describe the most common sources of error below.

Additive errors

The distance measured by the EDM element of the TST may require adjustment: the measurement position of the EDM unit may not be centred relative to the instrument (ie not vertically centred over the point being measured from) and/or the vertical axis of the target prism may not be aligned over the centre of the tribrach (the prism constant). These factors are commonly combined to create the additive error.

The measurement position of the EDM is a constant for any given instrument, and usually compensated for by the instrument automatically; it can in any case be assessed and corrected for during a regular calibration. It is often the vertical axis of the target prism that can cause some problems, as it is variable from prism type to prism type (typical values of the prism constant are 0, -17.5 and -34mm), and these are therefore not compensated for automatically by the instrument.

If switching between two prisms with different constants (as the centring offset is known), you must remember to change the offset to an appropriate value on the instrument before taking a measurement, or the results will be in error. Similarly when switching between reflector and reflectorless modes, you should remember to change settings on the instrument as appropriate before taking a measurement.

Random errors

Random errors can occur for a variety of reasons, such as a temporary interruption of the signal or accidental knocking of the instrument. The surveyor will be able to recognise when such errors have occurred by keeping a careful eye on the result of each measurement and checking that it conforms to the anticipated result. This is of particular relevance when using the instrument in reflectorless mode, as incorrect signal returns from signal interruption are more likely. Real-time interfaces reduce the chances of such errors creeping in, because the data are displayed as they are measured for checking.

Gross errors

Gross errors are usually the result of a major omission in observation procedure, for example failing to record the correct height of the target prism when measuring points with a detail pole, or mistakes over orientation. The advantage of using CAD for data capture in real time means such problems are recognised in the field as soon as an error has occurred. Otherwise they can sometimes be corrected by editing and re-processing the survey after it has been downloaded.

Meteorological factors

Errors arising from meteorological factors can have a number of causes. These factors provide the greatest degree of uncertainty to distances measured by EDM instruments (Bird 1989, 31). They usually result from variations in atmospheric temperature and pressure, which cause changes in the velocity of the transmitted beam and therefore changes in the wavelength. The ‘thinner’ the atmosphere, the longer the wavelength of the beam. These errors are expressed in ppm and can be compensated for when using the TST. The on-board software will usually include a section to calculate the revised scale factor if the temperature and atmospheric pressure are measured. As an example, a 1°C change in dry bulb temperature is roughly equivalent to a scalar error of about 1ppm, or 1mm per km. If atmospheric corrections are applied, these should be documented in order that subsequent surveys can be undertaken with appropriate corrections applied. It should also be remembered that heat haze can give an exaggerated estimate of distance, while heavy rain can interrupt the signal and result in a false measurement of distance.

Systematic scalar and cyclic errors

EDM scale factor is an internal function of the instrument and is dependent on the modulating frequency of a quartz oscillator. The error is proportional to the length of the line measured. It can vary slightly over time, but on most EDM instruments the effects of this are negligible. Cyclic error relates to the amplitude-modulated carrier wave and phase measurement and is also usually small. These errors can be calculated and compensated for during calibration, and can usually be included as part of the traverse misclosure (section 2.1) and compensated for during adjustment anyway.

The sources of error outlined above (except systematic errors) generally affect the accuracy of measurements but not the precision. Those that do affect precision (ie the reliable repeatability of measurements) are usually associated with incorrect calibration of the instrument and poor maintenance. It is essential that equipment is kept in good order, regularly serviced and the calibration checked to ensure that it is measuring correctly to within its manufactured tolerances. As a general guide, instruments should be calibrated after being repaired or subjected to rough treatment, and in any case at regular intervals (eg once every 12 months or so).

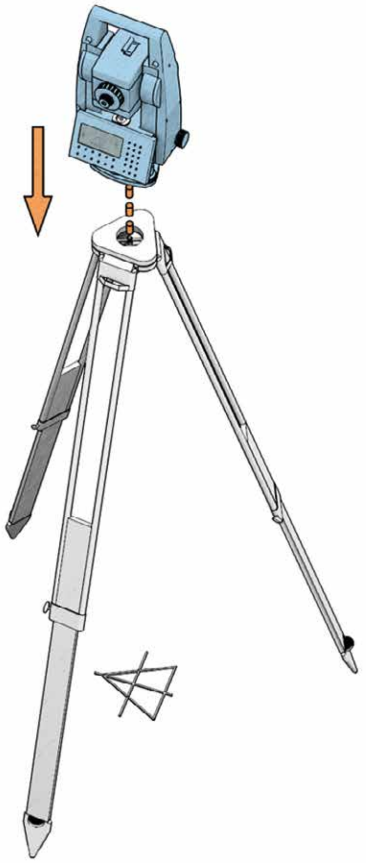
Setting up a TST

The ability to set up an instrument quickly and accurately over a point is essential for all surveyors. Unless this fundamental skill is learned, efficient and accurate instrument-based survey is not possible. It is important to realise that you are centring and levelling a tribrach on the stage plate of the tripod, you can then put any compatible piece of survey equipment (eg a TST or a prism assembly) on the tribrach and it will be centred and levelled. The method is described below.

1 Place the tripod over the point.

- Find the point marking the position of the station from which you will work
- Release the leg adjustment screws of the tripod legs
- Pull the stage plate at the top of the tripod up to your chin and re-tighten the screws
- Open the legs of the tripod out to a diameter of more than 1m and eye through the centre of the stage plate to ensure it is sitting approximately over the point marking the station
- Level the stage plate of the tripod by eye
- Place the tribrach onto the centre of the stage plate and tighten the fixing (A and B)
- If you do not have an optical tribrach, place the instrument on the tribrach at this stage and lock it in place using the lever.

A



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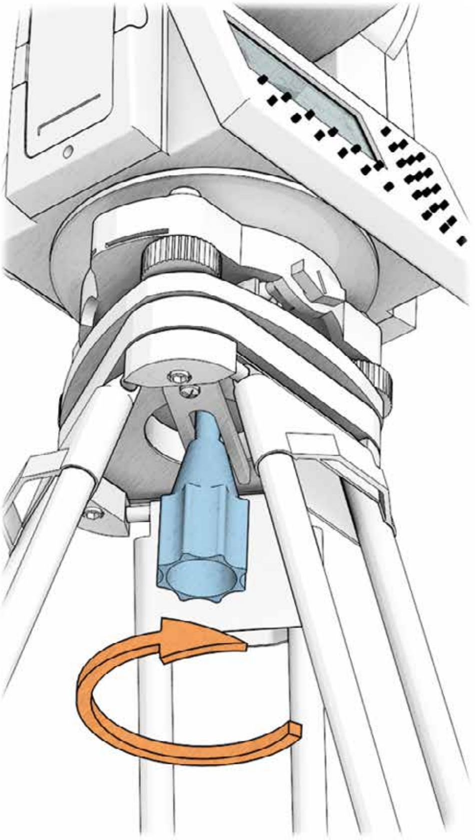
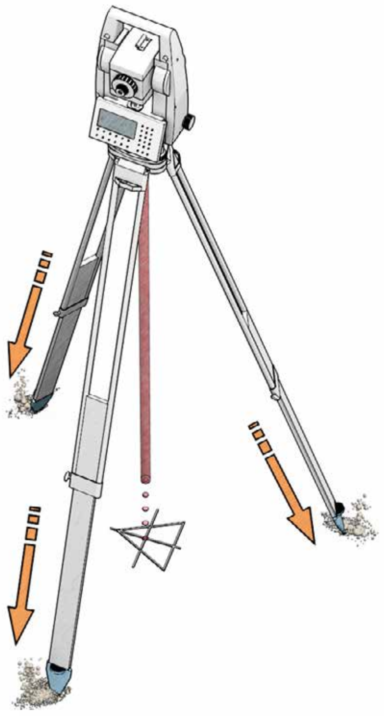


2 Centre the tribrach

Before you start it is good practice to check that the tribrach screws are in the centre of their runs and have adjustment available.

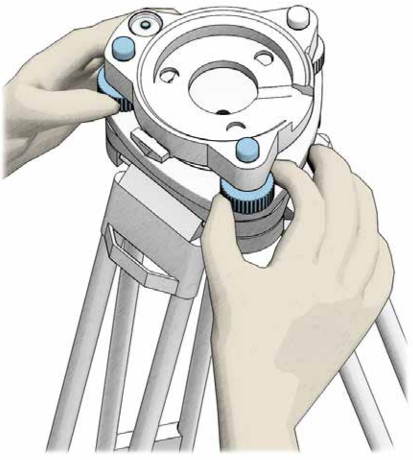
- Use the plummet (either optical or laser, depending on whether you are using the tribrach or TST) to move the set-up approximately over the point by lifting two tripod legs and rotating about the third to get over the point. When using an optical plummet, place your foot next to the station point to help you locate it when looking through the eyepiece of the plummet
- Move the tribrach and tripod as a single entity until they are approximately vertically aligned with the station point below
- Firm the feet of the tripod into the ground (C)
- Drive the centre of the plummet to the centre of the station point using the three thumbscrews on the tribrach. Do this by working first with two of the screws, by turning them in opposite directions (thumbs in or thumbs out, the bubble moves in the same direction as your left thumb), and then by working with the third screw alone for final adjustment (D–F). As the screws are turned, note how the mark projected by a laser plummet moves on the ground or how the ground moves through the cross-hairs in the eye piece of the optical plummet.
- Keep adjusting the tribrach screws until the plummet is aimed directly at the centre of the station point (G)



C

D

E



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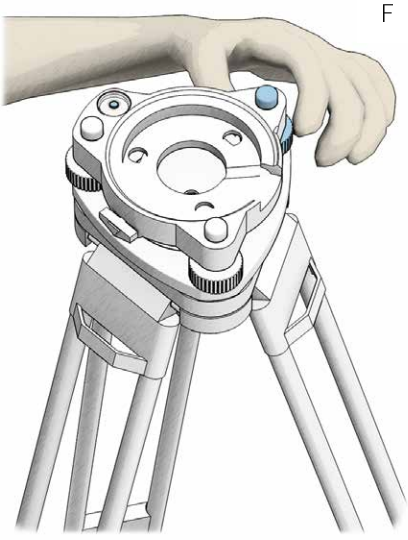


G

3 Level up the set-up

Step 1: coarse adjustment of the tribrach bubble using the tripod legs

- Adjust the tripod leg that is in line with the bubble on the tribrach, by using the leg adjustment clamp to push the bubble more to the middle of the circular level or towards another leg

- Grip the tripod leg (H) and slide each leg in turn up or down as required to level the bubble

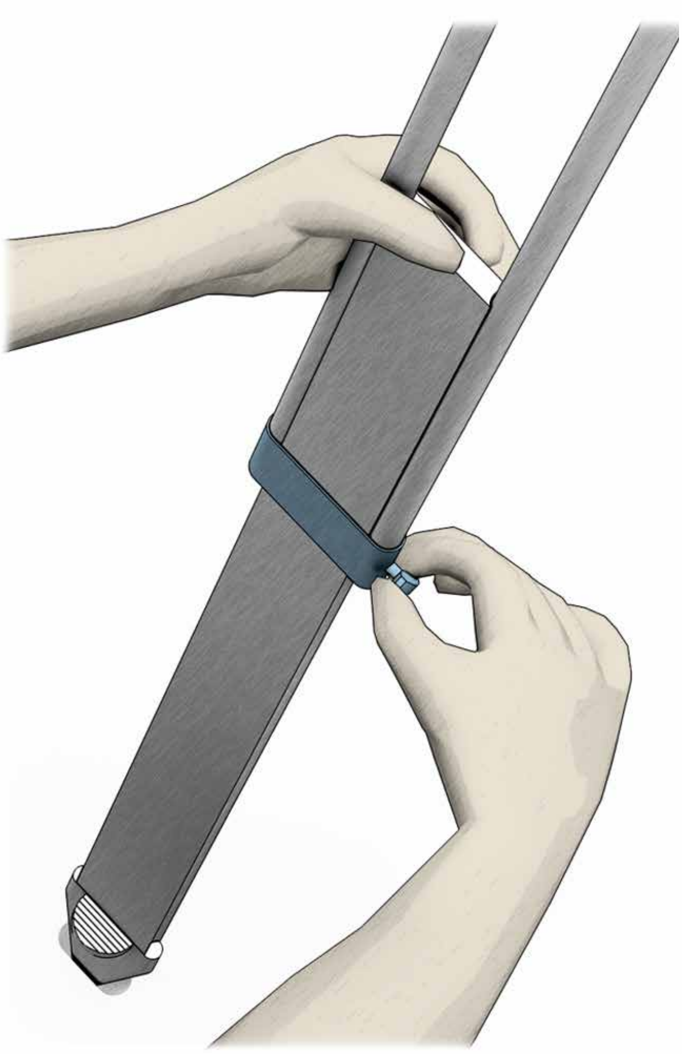
- Adjust the legs until the circular level bubble is centred (I)

Step 2: fine adjustment of the plummet

- Check whether the plummet is still on target; if not, use the tribrach thumbscrews to bring the plummet back on to the station mark

- Re-adjust the tripod legs to bring the bubble back to level

H



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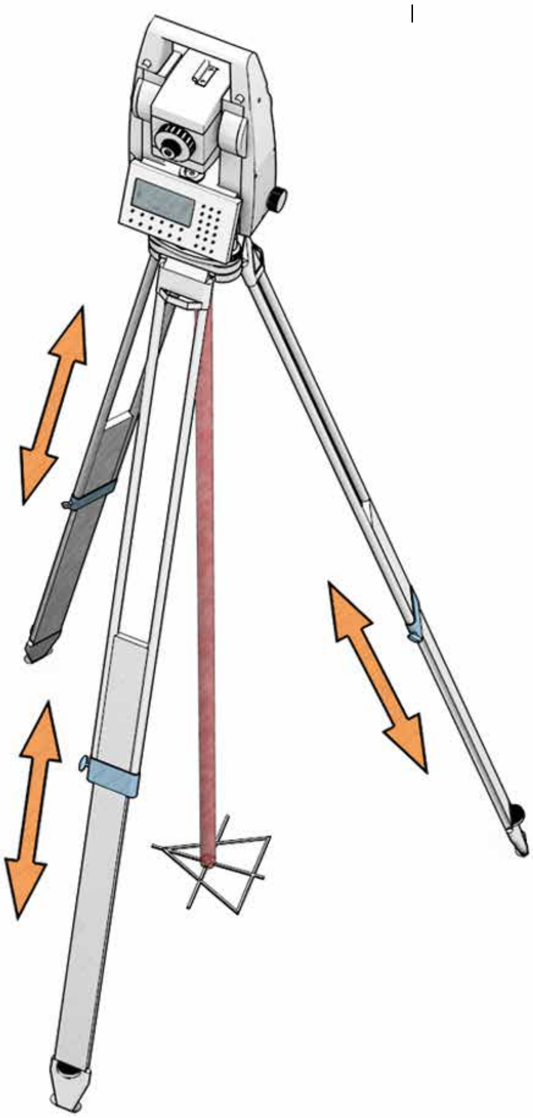
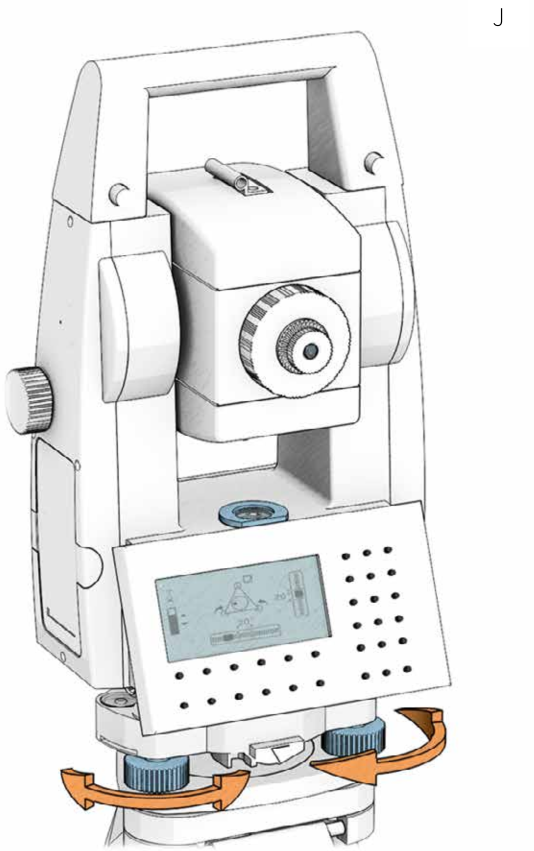


Step 3: fine adjustment of the tribrach bubble

On modern instruments this final stage occurs with the TST switched on, as it uses the instrument's internal sensors to bring up a fine-tuning screen to view. The screen initiates automatically on some models when the TST is switched on, otherwise it must be started manually.

- Turn the instrument so that the display screen is parallel with two thumbscrews of the tribrach
- Using both thumbs, moving in opposite directions to each other as before, turn the thumbscrews (J) until the horizontal bar shown on the fine-tuning screen is level
- Turn the third thumbscrew by itself until the vertical bar is level. On older instruments a spirit level is provided to enable the level to be fine tuned, rather then a digital readout
- A small horizontal displacement of the plummet over the station point can be corrected now by gently loosening the tribrach fixing screw (under the tripod stage plate) and sliding the tribrach (without twisting) with the TST attached until they sit directly over the station. Some slight re-adjustment may be necessary after this manoeuvre
- Always check that the fixing screw is tightened securely afterwards, that the bubble is centred and that the plummet is over the station point before any measurement is made



Surveyors should be aware that optical and laser 'plummets' on survey instruments do not work in quite the same way as a plumb bob. In fact, plummet is a misnomer because they do not indicate the direction of the centre of the Earth, but rather a line perpendicular to the base plate of the instrument, so they are not plummeting until the base plate is level.

It is important that equipment such as tribrachs are kept clean and in a good state of repair: the circular level on the tribrach will need periodic maintenance to ensure it is working reliably. Instrument levels will be re-adjusted during the regular maintenance and servicing regime.

Case Study 1

West Kennet Long Barrow, Wiltshire

Using a TST to generate plans, sections and a dense digital terrain model (DTM)

Introduction and objectives

West Kennet Long Barrow (SU104677) is a Neolithic chambered burial mound in Wiltshire, with views of, and approximately 1km south-west of, Silbury Hill. The barrow is thought to have been constructed c 3400 BC and to have been in use for at least 1000 years. It is trapezoidal in plan, with the forecourt and entrance at its eastern end. It is approximately 104m long, up to 25m wide and 3.2m high at its highest point. The entrance leads to a central passage c 12m long, from which open five chambers, two on each side and one at the end. These chambers, constructed from large sarsen boulders and dry stone walling, are variable in size, ranging from 2 to 4m wide and up to 2.5m high. The barrow was excavated in 1859 by J Thurnam, and again in 1955–6 by S Piggott. Many of the stones were re-erected after this second excavation.

Large puddles of standing water were retained inside the monument throughout much of the year. The survey was undertaken to measure levels inside the monument, establishing a basis for surface remodelling to enable the water to drain.

Survey methods

The brief called for a plan at a scale of 1:20 showing contours (internally and externally) at 20-mm intervals, accompanied by a long section and three cross-sections at a scale of 1:10. The area surveyed was limited to the eastern half of the barrow, as this was the focus of concern. To provide information about what would happen to the water once it had drained from the inner chambers of the barrow, an area east of the entrance was also surveyed.

The survey was undertaken using a Leica TCRA1205+, a TST that permits the fitting of a survey-grade GPS receiver for deriving OSNG coordinates for station positions. The coordinates of two stations were established using this method, both of which were points of detail on the monument itself (the corner of a concrete slab partly roofing over the inner passage and chambers, and the centre of a wooden stake, one of a series around the outer edge of the forecourt). As permanent ground markers were not used, no application for Scheduled Monument Consent was necessary. Witness diagrams recorded the station positions for future reference.

The GPS coordinates established the position and orientation of an open traverse including stations inside and outside the monument. The survey was conducted using a robotic TST and a real-time interface to a tablet PC running CAD, enabling the data to be viewed

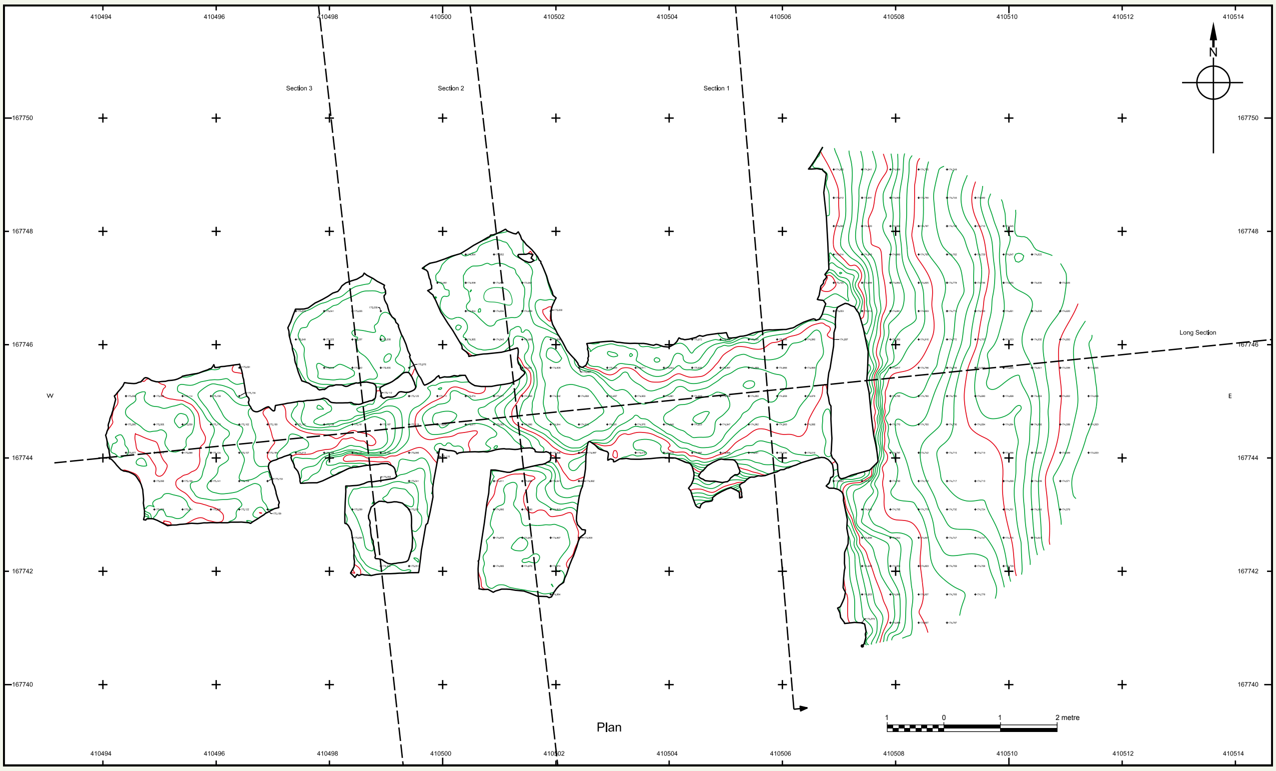


Figure CS1.1
Plan of the open part of the monument, showing the positions of the cross sections

and checked as the survey proceeded. The surveyors used a prism on a detail pole outside the monument, and measured its position as it was placed at regular intervals along temporary string grid lines to ensure complete coverage. Using the ATR and tracking functions on the instrument, they took points at c 50-mm post spacings. In the grassed areas, they derived external section components using the same method, and measured profile lines through standing stones (for plan and section) using REDM.

Inside the monument, the floor surface was measured at 20-mm post spacings. In addition, the surveyors used a detail pole with prism to infill the data set where puddles prevented accurate measurement of the underlying floor surface. They also measured the inside of the barrow; for this, plan height was at the interface between the walls and the floor.

After this field survey, the data were processed in CAD to produce the final drawings. The surveyors filtered the ground points from the rest of the data and processed them to form a DTM and derive contours at the required intervals. This model could also be ‘sliced’ at appropriate points for cross-sections through the monument.

The surveyors submitted plans as both a ‘traditional’ contour plot and as one with levels shown at regular post spacings (Figure CS1.1). As requested, the surveyors also provided cross-sections showing levels at regular intervals along the floor and a long section.

Conclusions

The survey provided accurately measured information to show the current state of the monument’s floor and made it possible to plan a strategy to drain the inside of standing water. In addition to these engineering purposes, these data provided a record of the form of the eastern end of the monument.

2 Control

The purpose of survey control is to locate precisely both station positions and the detail shots taken from them relative to each other in a common coordinate frame.

Survey from more than one instrument set-up requires establishing a network of stations. The relative positions of these stations are fixed to a high order of accuracy and precision, so that detail measurements derived from them will be consistent and correctly placed relative to data derived from other station positions. This is normally accomplished by undertaking a traverse (section 2.1). The accuracy of the detail survey within the control framework is usually of a lower order, and generated only by single-face observations to the targeted points. The control network can be likened to a 'skeleton' holding the different parts of the survey in place, and the detail measurements the 'flesh on the bones'.

Preparation of control data is an essential and fundamental part of the survey process. A written proposal for a TST survey should include a description of the technique to be used to establish the control network and its expected accuracy. Briefs for work to be undertaken should similarly specify the required accuracy of control data for the survey. Further advice and guidance on this issue can be found in the Metric Survey Specifications for Cultural Heritage (Andrews et al 2009).

Before establishing the control on any site it is essential to plan the network of proposed stations. Give consideration to the location of stations and undertake a thorough reconnaissance to avoid committing equipment and resources to positioning stations and control points fruitlessly. The ideal position is one that provides robust control geometry combined with unobstructed lines of sight to the maximum number of detail points.

An experienced surveyor should be able to establish a network of control points on a site rapidly and precisely. Control measurements underpin the precision of the whole survey, so control data should be determined to a higher order of precision than that used for measurements of detail points. A TST is an ideal tool for establishing the control network of small- to medium-sized sites (0.25–25ha) as it is precise and flexible in its use. Using methods like traversing, the precision of computed positions is raised above that of radial detail shots. Although most control for small sites and building surveys is undertaken using a TST, using GPS is a more efficient way of recording larger sites (above 25ha) and a survey-grade GPS receiver can provide coordinates for stations subsequently used for a TST. Surveyors should be aware that the accuracy of points derived by GPS is dependent on the accuracy of the equipment used and the strength and quality of satellite reception at the time of acquisition. The choice of control methods is dependent upon the terrain, the scale required and the time available.

For it to be useful, the performance of control data must be known, because the precision of all subsequent survey tasks relies on the coordinate values derived from it. As a general guide, an accuracy ratio or part error of 1:20 000 might be the minimum accuracy sought for control in the archaeological survey of large sites, which means that, for horizontal distances, an accuracy of at least 5mm per 100m must be achieved. The part error represents the traverse accuracy and, once obtained, can then be benchmarked against established standards and specifications (Andrews et al 2009, section 2).

If it does not fall within allowable limits, the traverse must be re-done. Traverse misclosures outside this limit are usually caused by the occurrence of a gross error during the measurement process and, if this can be identified, re-taking the suspect measurements and re-processing may be all that is necessary. For smaller sites, where the traverse legs are relatively shorter, a tighter requirement for control may be specified, for example 1:5000 or 2mm per 100m. Surveyors should be aware of the required tolerances before starting a survey.

It should be borne in mind that station positions are usually representative of points on the ground surface beneath the instrument, defined by a peg, nail or other marker. Similarly, all points measured using a detail pole are actually points on the ground beneath the prism. Thus the paraphernalia of tripods, tribrachs, prisms and instruments make measurement possible, but when the survey is processed the heights of instruments and targets are subtracted to give the actual ground height.

2.1 Traverse

A traverse will establish a common coordinate frame to locate points shot from different stations relative to each other. A traverse requires an identified starting point and an orientation. There are several ways to obtain the coordinates of the starting point, and surveyors should make an effort to use the best data available to begin a traverse.

- Coordinate data may be provided by reference to points on an existing control network if the site has been surveyed before and records kept of the stations used

- The coordinates can be related to the OSNG using a survey-grade GPS receiver. A scale factor then needs to be calculated and applied to the TST data for the coordinates of all subsequent points to project correctly on to the OSNG

- An arbitrary or local grid can be used. This is a grid that is divorced from the OSNG or an existing control network. For example, a coordinate value of 1000 (x), 1000 (y), 100 (z) might be used for the first station position on a divorced grid (positive values avoid the generation of negative figures for points 'south' and 'west' of the first station)

Traverses can be categorised as closed or open (Figure 6).

Closed traverse

A closed traverse begins and ends on the same point (a loop traverse) or begins and ends at points with previously determined and verified coordinates (a link traverse). In both cases, the angles can be closed (because the observation procedure starts and ends on the same point or starts and ends at 'fixed' points) and the closure accuracy can be determined mathematically. The difference between the measured position of the closing station after completing, for example, the loop, and its 'actual' or original coordinate values, represents the misclosure. It is this difference that is distributed around the network to give 'adjusted' coordinates.

Simple loop traverses are commonly used for the control of small sites. The loop passes around the perimeter of the site, with stations sited so that radial detail shots are also possible or so that spurs can be set out to cover detail work with the minimum number of additional stations. Closing a loop through a building or dense woodland can be difficult and stations in either situation are usually placed as a link traverse between two stations on an external loop.

Open traverse

An open traverse originates at a starting station and proceeds sequentially to its destination, ending at a station with an unknown (or unfixed) position. The open traverse is the least desirable traverse type because it does not provide an opportunity for checking the accuracy and precision of the measurements via misclosure. The distribution of error cannot be verified without a comparative or fixed value for the end position. Without this check, the precision of station positions is relatively poor. Therefore, the planning of a traverse should always attempt to provide for the closure of the traverse. In some cases (eg tunnel surveying) an open traverse can be unavoidable but this situation will occur rarely in archaeological survey; more commonly, spurs comprising two or more stations are run from a closed loop into areas that are otherwise inaccessible. In these circumstances the surveyor must exercise great care in taking control measurements.

Traverse procedure comprises five distinct stages:

- planning

- reconnaissance

- station marking

- measurement

- adjustment.

Planning

Planning determines the resources needed to undertake the traverse: time, equipment and personnel. At this stage it is essential that:

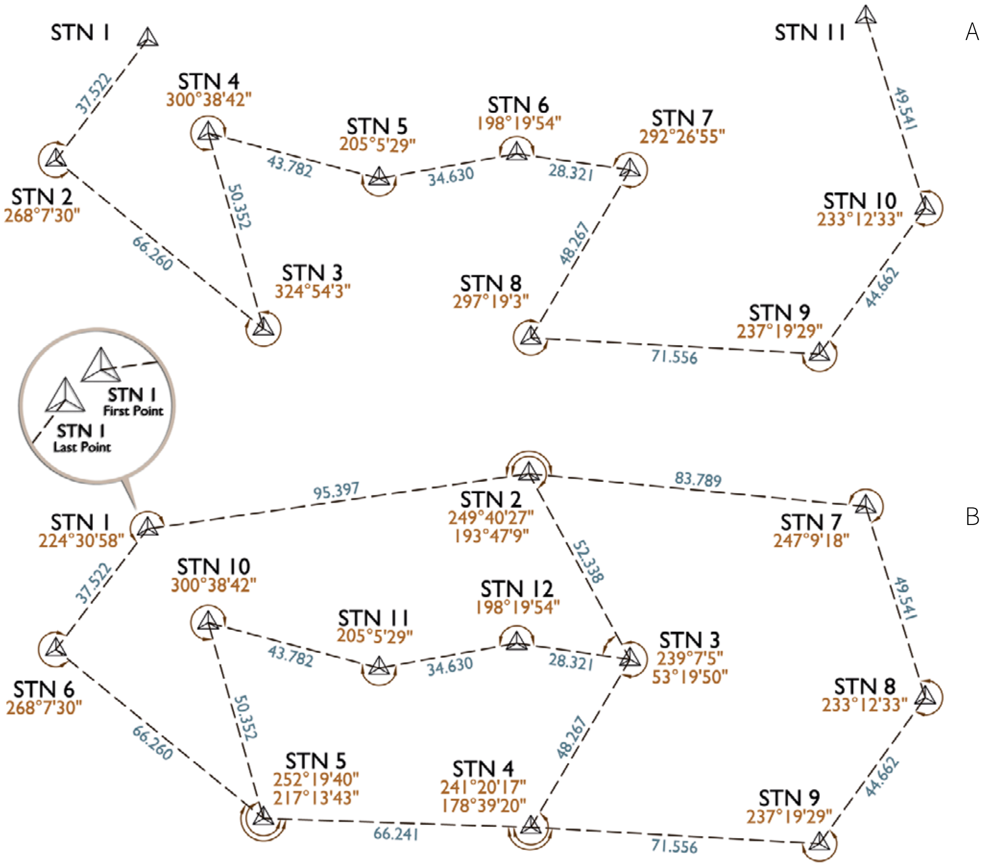


Figure 6

A. A link traverse. If only the starting point is known, this is considered an open traverse. If both the start and endpoints are known, this is considered a closed traverse. Open traverses have no check on the position of the computed station positions

B. A loop, and therefore a closed, traverse, which starts and ends on the same point. Inset shows misclosure

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- the personnel are appropriately trained and the equipment is in good order
- there is a verifiable method of error distribution within acceptable tolerances
- there is agreement on the origin and alignment of the coordinate system to be used, whether local, a previously established grid or the OSNG
- there is agreement on the height reference (datum) to be used, particularly if a DTM and contour survey are to be produced

Reconnaissance

It is good practice to reconnoitre a site for traverse stations (as well as for other problems that may arise during survey) in advance. The stations must be located so that the forward and rear stations are clearly inter-visible at each set-up. The number of stations in a traverse should be kept to a minimum to reduce the accumulation of error and the amount of computation required. Short distances between stations increase the number of stations, which may in turn introduce disproportionate errors in angular measurement.

Case Study 2

Wandlebury, Cambridgeshire

A Level 3 survey of a hillfort in a designed landscape

Wandlebury (TL493534), to the south-east of Cambridge, is one of a small number of nearly perfectly circular Iron Age forts peculiar to East Anglia, sometimes called ‘ringworks’. The outer of its two ramparts is 330m in diameter and encloses c 6.25ha. The hillfort sits near the edge of a chalk plateau commanding extensive views, and is therefore fairly conventional in its setting. Nearby Arbury, on the north side of Cambridge, presented a striking contrast: although almost identical to Wandlebury in size and plan, it occupied a thoroughly lowland setting and was eventually all but ploughed flat (Evans and Knight 2002).

Wandlebury was first documented as a hundred meeting place in the 10th century, and by the reign of King Stephen (1134–54) it was an important meeting place of nine hundreds. This dramatic monument’s persistent ‘power of place’ was again appropriated, with more conspicuous consequences, in 1734, when it was acquired by Francis, 2nd Earl Godolphin. By this time, the whole region had become associated with equestrian pursuits, and in the 1740s the Earl built a grand house (now demolished) in the southern half of the circle, with equally impressive stables to house the Godolphin Arabian (one of three stallions from which all modern thoroughbreds are descended). These buildings were set within a designed landscape, comprising tree-shaded circular walks around the top of the outer rampart and the bottom of the outer ditch, with occasional bridges and grottoes. The inner bank was pushed back into its associated ditch, perhaps primarily to maximise the level space within the enclosure. It is interesting to note that this would also have had the effect of transforming the outer rampart and ditch into something resembling a giant ha-ha, a form of boundary becoming fashionable in the 1740s, which may have been appropriate for the simultaneous display and protection of the Godolphin Arabian. Further ornamental modifications, all less far-reaching in their effects, were carried out in the 19th century. The beauty spot remains a form of designed landscape to this day, having been managed by the Cambridge Preservation Trust since 1954.

A detailed analytical survey of Wandlebury was carried out in the summers of 1994 and 1995 (Pattison and Oswald 1996). Ultimately, the investigation’s major research gains were the identification of a previously unrecognised blocked entrance on the south-east side of the circuit, and the precise quantification of the impacts of the post-medieval garden works on what is usually regarded uncritically as solely a prehistoric monument.

The research added to an emerging corpus of analytical surveys of the region’s hillforts undertaken by the same field survey team, even though it was primarily intended as a training exercise for undergraduates studying archaeology at Cambridge University. It was thus an important contribution to a collaborative project run by the Department of Archaeology and Anthropology at Cambridge

University and the Cambridge Archaeological Unit that lasted several seasons longer than the earthwork survey (French 2004). A Level 3 survey (as defined in Ainsworth et al 2007) was considered appropriate to the needs of the research programme. A survey scale of 1:1000 was chosen as suitable to record the slightest earthworks whilst straightforwardly encompassing the extent of the survey area. A scale of 1:1000 is also good for training people in the rudiments of analytical field investigation, because 1mm on the plan equates to 1m on the ground.

The survey of Wandlebury required the use of a TST for the following reasons.

- The band of trees overhanging the ramparts, which includes a number of evergreen yews and hollies, greatly reduces visibility in the horizontal plane. It is worth noting that the rapid advance of GPS technology since 1995 would offer little assistance in the case of Wandlebury because sky coverage is so limited around much of the rampart circuit
- The outer rampart, comprising a deep, steep-sided ditch overlooked by a prominent bank, both following a fairly tight arc, itself limits visibility in the horizontal plane
- The buildings that form integral components of the site's evolving use are most susceptible to accurate recording with a TST (particularly the less accessible structures around the rampart circuit, such as the bridges and grottoes)
- Many of the trees are themselves of historic significance because they relate to former incarnations of the designed landscape. Their centre points can be surveyed with considerable accuracy by using the TST to record angle and distance as separate measurements

In early spring, well before the participation of the student trainees, a professional survey team planned the complex closed traverse required to achieve adequate coverage of the whole site. The entire survey would normally have been carried out at this time, when leaf cover was sparse on the trees and undergrowth. However, the schedule for student participation forced the team to undertake the main fieldwork in June and July, which is arguably the worst time of year, especially in terms of undergrowth.

The objective of the traverse was not to allow complete recording of all the earthworks with the TST detail pole, but to establish temporary markers (in most cases wooden pegs hammered into the ground) at sufficiently close intervals (ideally less than 30m apart) to act as a control framework for a subsequent traditional tape-and-offset survey.

Had a more comprehensive electronic survey been required, for example to create a digital ground model of the monument, a considerably greater number of detail points would have been needed. This in turn would have required a traverse with far more stations than the 13 that made up the main ring, and would have been far more time-consuming.

The decision not to adopt an objective recording method did not compromise the project's research goals. Recognising that undergrowth would hamper the students' progress and perhaps reduce the accuracy of their tape-and-offset measurements, the professional surveyors decided to record as much as was convenient of the earthworks with the detail pole. At the same time they recorded other detail points, but deliberately omitted most of this information from the plot provided for the students' working drafts.

The plot that served as a background and framework for the students' tape-and-offset survey depicted all the building footprints, boundaries and track edges (collectively termed hard detail), the traverse stations and non-random scatter of wooden pegs (termed temporary control), the limits of a pond on the exterior of the circuit to its south, and a number of green crosses depicting the centre points of trees considered to be of historic significance. A series of regular garden earthworks visible in the open lawn to the north of the site of the Godolphin house (but probably of 19th-century origin), including a pond sited close to the centre of the enclosing circle of ramparts, were also left on the plot to illustrate how the TST could have been used to record all the earthworks on the site.

The main closed traverse comprised an approximately circular ring of 13 stations and took a full day for two experienced staff to think through and establish on the ground. This process involved the production of a fairly accurate sketch plan to record the positions of the main stations before any observations were taken Figure (CS2.1). The traverse was closed by returning to station 1, then each station was re-occupied to record the hard detail, temporary control and additional detail of the earthworks.

The fundamental decision in planning the traverse was where to start. All subsequent decisions were derived from this choice. Station 1 was sited in open grassland north-east of the hillfort, which gave a long backsight (to improve the overall metrical accuracy of the traverse) and a shot to an Ordnance Survey 'trig' pillar, through which the rest of the survey was tied to the OSNG and the Ordnance Datum Newlyn (ie height above sea level). Station 1 also commanded a panoramic view of the planned area of excavations outside the fort, enabling the excavators to relate their trenches and geophysical survey grids to the survey of the whole site. The back station also allowed a shot to the trig pillar, giving added confidence in the final calculations. Today, both these stations could be located using a survey-grade GPS receiver. For the eastern third of the circuit, the surveyors ran a parallel link traverse of three stations around the interior of the circuit. Thus the inner and outer elements were eventually recorded from separate baselines.

Where visibility was worst, around the western two-thirds of the rampart circuit, the surveyors had to establish stations at intervals of between c 30 and 90m. These stations were usually in the base of the ditch, where shots could be taken beneath the overhanging trees. These station positions had to be repeatedly slightly adjusted to achieve the best coverage, before being finalised. Some still required being set up at awkward heights. A surveyor at each of two adjacent stations relayed information on the visibility between the stations. The position of station 7 was most proscribed. It needed to be visible from its backsight and foresight in the main ring, and to allow a shot into the hillfort's interior and out to its wooded exterior through a narrow cutting in the outer rampart (part of the garden design). In the interior, station 17 was established as an appended baseline traverse to give coverage over the western side of the interior, which was obscured from the stations on the east side of the interior by a high garden wall.

It might be supposed that a nearly perfectly circular monument like Wandlebury would lead to a closed traverse describing a regular polygon with evenly spaced stations. The eventual pattern of the stations actually demonstrates clearly that distortions of the ideal theoretical pattern will inevitably arise through adaptations to localised constraints and opportunities around the traverse.

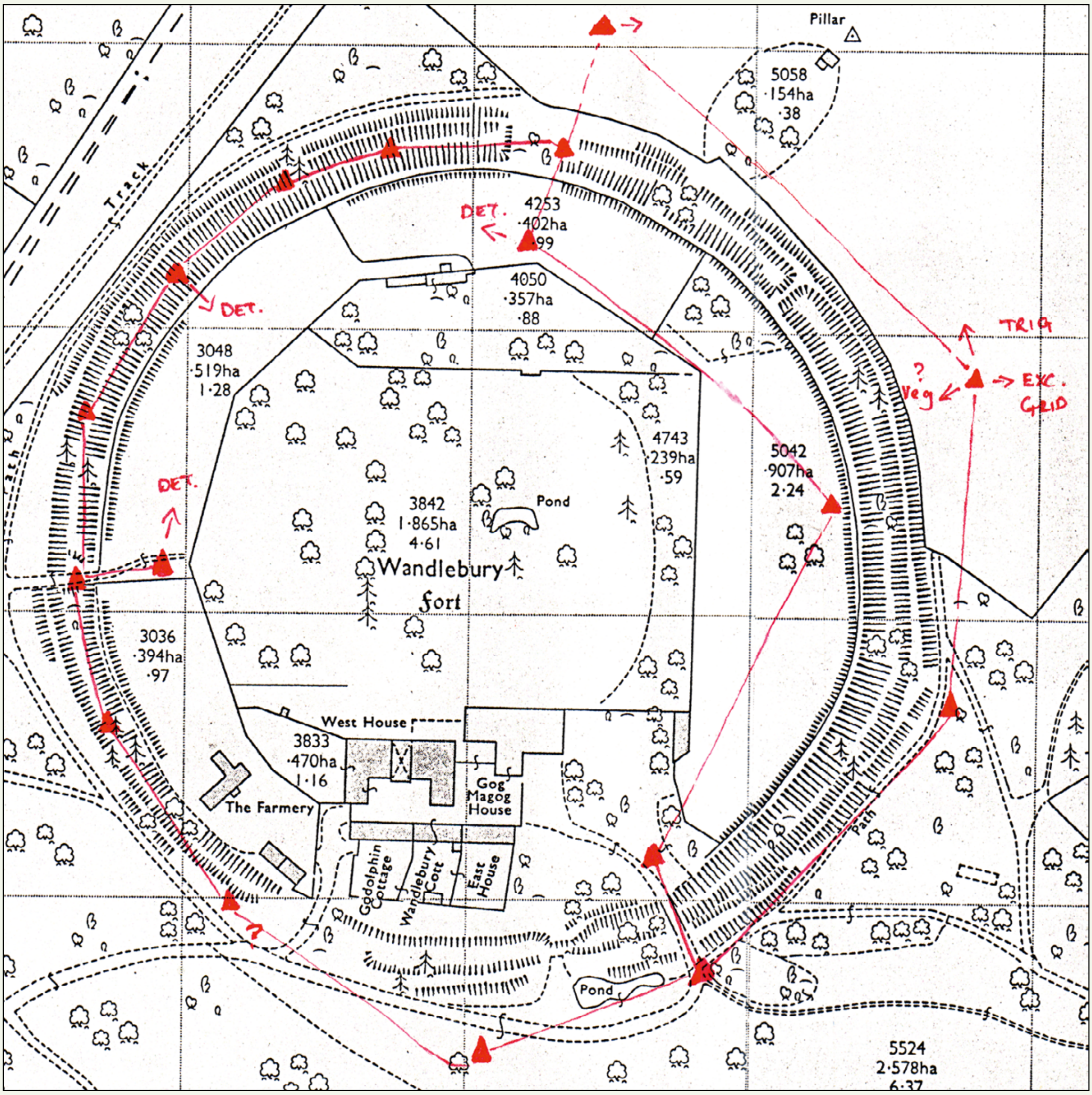

Figure CS2.1
The Sketch, by Al Oswald, used for planning the traverse at Wandlebury hillfort in 1994, based on an extract from the 1:2500 Ordnance Survey map of 1975.
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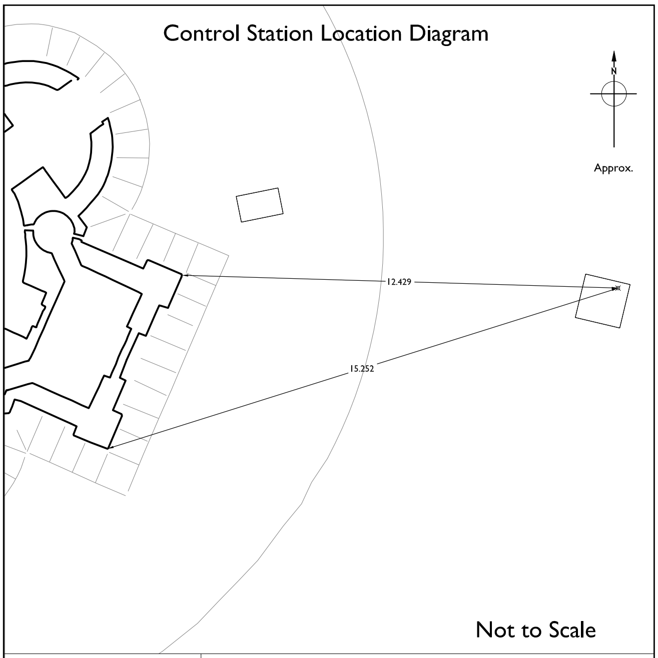
Station marking

Station markers must be fixed securely whether they are for the duration of the survey or meant to be permanent and for future use. They must be clearly marked with the centre point to designate the exact point of reference for measurements. To assist in re-use, preparation of a witness diagram is essential (Figure 7). This shows the station location relative to a minimum of three points of detail that are likely to survive. When working on historic sites it is important to consider the impact of survey marks on the fabric of the monument. Note that the consent of Historic England is needed before fixing a station point permanently, by means of a ground anchor or buried fixing, on a designated Scheduled Monument and that similar consent will be required in other nations.

Station markers and control points should be placed where they will not be disturbed, and consideration should also be given to placing them where personnel and equipment will be out of harm's way during survey work. They should also, wherever possible, be located away from the archaeological features to be recorded, so that the station symbols do not interfere with archaeological detail on the drawing.



Station No 1	Description: Outer Corner of MHC rim Archer Pavilion, Wrest Park	
Easting 509205.380	Northing 234740.940	Level 50.102

Figure 7
A station witness diagram. These can often usefully be supplemented with a photograph showing the station position

Measurement

Traverse measurements should be undertaken with a traversing kit comprising a minimum of three tripods, three inter-changeable tribrachs, two matched target prisms and a TST.

The measurement phase of a traverse begins by setting up the instrument over the starting station point, with a prism over a second known point and another prism over the first new station. These three stations are known, respectively, as the occupied (current), rear (back) and forward (fore). The back station is the station that is used to establish the azimuth at the start of the traverse and can also be the station that will be the last one occupied in the traverse. The fore station is the next station in succession. On occupation of a station, record the instrument and target heights, then measure and record the angles and distances between the back and fore stations.

Measurements should be taken using both faces of the instrument (Figure 8) and at least one set should be measured (comprising face 1 and face 2 measurements to each target). The simplest method of resolving traverses requires a computed horizontal distance and the angles to derive 2-D coordinates for the station values. Be aware that most survey instruments show the slope distance on the screen by default, although computed values like horizontal distance can usually also be shown. 3-D coordinate values for the station positions can be calculated if in addition the vertical angle, height of instrument and height of target are recorded for each shot.

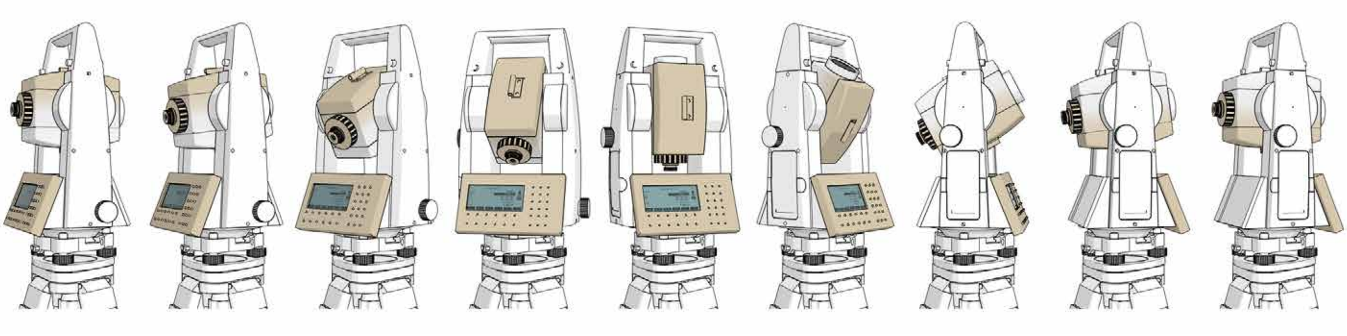


Figure 8
Taking measurements using both faces of the instrument. Face 1 is used at left, the instrument and telescope are turned, and Face 2 (at right) is used for the next measurement to the same target

The number of people required to perform survey operations depends on the resources available and the size of the territory to be covered. A small traverse can be undertaken by one surveyor but over larger sites one or two assistants will be useful for moving targets and minding tripods. The instrument operator measures the horizontal and vertical angles and the distances from each traverse station. The data are recorded on a tabulated record sheet, on the instrument itself, or on a separate data logger or computer. Meanwhile, the person setting out and minding targets will be marking and witnessing the traverse stations, removing the target from the rear station when signalled to by the instrument operator, and moving the target forward to the next station.

Traverse observations should follow a consistent procedure. The angles should be turned in the same direction and taken in sets. A round of angles describes the measurement of the horizontal angle between two other stations on the traverse and a set is the data from at least two rounds, one taken on each face of the instrument. Using both faces of the instrument distributes errors in centring. At each set-up the surveyor should make sure the angles are booked securely and check the sets are complete (including the instrument and target heights) before moving on. If the traverse is booked manually, make use of a prepared observation form so that each angle and distance is recorded to enable it to be clearly identified with the occupied station, target stations and heights thereof.

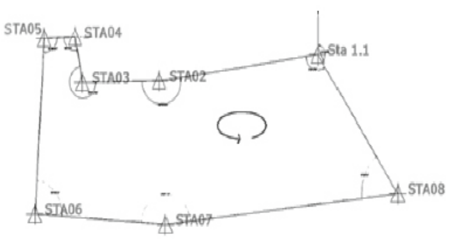
The loop is completed when the closing set of measurements is taken, at the re-occupation of the starting station. Before finishing fieldwork, check for missing data: if possible obtain an approximate check of the misclosure of the traverse. Missing measurements cannot be added once off site.

Adjustment

Small errors in centring the instrument, station marking and instrument pointing are magnified and expressed as a traverse misclosure. On completion of the measurement phase, provided that the misclosure is within satisfactory limits, adjust the traverse data so that the accuracy of the coordinate values for each station is optimised, based on the best possible error distribution. This adjustment can be manual (Table 1) or by means of computer software, on the TST itself, a field computer or in the office. Traverse adjustment is based on the assumption that random errors (of centring, for example) have accumulated throughout the traverse observation procedure. The correction for misclosure of the traverse is distributed among the angles and distances measured, resulting in refined positions for the stations that compensate for the misclosure. It is important to note that distributing the misclosure around the network is a compensation for these errors rather than blunders. If a mistake is made, then the errors propagated by it will also be distributed, resulting in incorrect positions for all stations. Careful adherence to a standard observation procedure and checking that the measurements returned conform to the anticipated results as work progresses minimise the chances of such occurrences.

There are many methods available for the adjustment of traverse data. Some compute horizontal (x, y) shift only (eg Bowditch, which distributes horizontal errors proportionate to the length of the traverse leg) and require the vertical shift to be computed separately. Other methods do not require the vertical shift to be computed separately (eg Least Squares, which resolves shifts in the x, y and z axes simultaneously). The choice of method is usually determined by the surveyor unless otherwise specified. Whatever method is used, it should be documented.

Sta	Leg	Hz Dist (m)	Observed Angle (d.m.s)[1]	Angular Adj[2]	WCB (d.m.s)[3]	Partial co-ordinates				Linear (Bowditch) Adj		Final co-ordinates		Sta
						ΔE (s sin a)		ΔN (s cos a)						
						+	-	+	-	E	N	E	N	
R O - Sta 08			144.19.05											
01			118.13.09	+2”								1000.000	1000.000	01
	01-02	24.021			262.35.15		23.820		3.098	-.005	-.003			
02			186.32.36	+2”								976.180	996.9029	02
	02-03	11.550			269.04.51		11.548		0.185	-.002	-.001			
03			259.11.26	+2”								964.632	996.717	03
	03-04	5.576			348.16.17		1.133	5.459		-.001	-.000			
04			99.42.03	+3”								963.499	1002.176	04
	04-05	4.585			267.58.20		4.582		0.162	-.000	-.000			
05			95.48.37	+3”								958.917	1002.014	05
	05-06	21.231			183.47.17		1.403		21.185	-.003	-.002			
06			89.58.15	+3”								957.514	980.8292	06
	06-07	19.652			93.45.33	19.609			1.288	-.004	-.002			
07			170.07.14	+3”								977.123	979.541	07
	07-08	35.094			83.52.47	34.894		3.741		-.007	-.004			
08			60.26.19	+3”								1012.017	983.282	08
	08-01	20.607			324.19.05		12.019	16.738		-.004	-.002	**999.998**	**1000.020**	
												1000.000	1000.000	01
Σ		142.316	1079.59.39	21”		54.503	54.547	25.938	25.918					
		Angle Sum:	1080.00.00		Distance Misclosure:	ΣΔE -0.030		ΣΔN -0.020						
		Angular Misclosure:	000.00.21”		Total Misclosure:				0.102					
		Precision:												



Notes:

1 This is the mean of the angles observed at each station.
2 The adjustment is distributed using whole seconds by size
3 The Whole circle bearing is effectively the direction from one station to the next relative to the RO (in this case North)

Table 1

Tabulated computation of traverse observations: Worked example

2.2 Resection

Resection (also known as free-station on some instruments) is the computation of the current instrument position through observations to two or more reference marks or stations with known coordinates (Figure 9). The points to be used might have been measured as part of a traverse, have coordinates derived from an earlier survey or have been measured with a survey-grade GPS receiver before the start of the traverse. Resection can also be used for single station set-ups where lines of sight are severely compromised.

Place a set of reference marks in the area to be surveyed and observe them from the current instrument position. Next, move the instrument to a new position, and observe these marks again to determine the new station coordinates.

However straightforward resection may seem, avoid deriving control positions based on multiple 'stacked' resections as there is no statistical check on the results and therefore errors can accumulate without detection. If possible, only use resection to obtain the positions of single stations at one remove from the traverse loop.

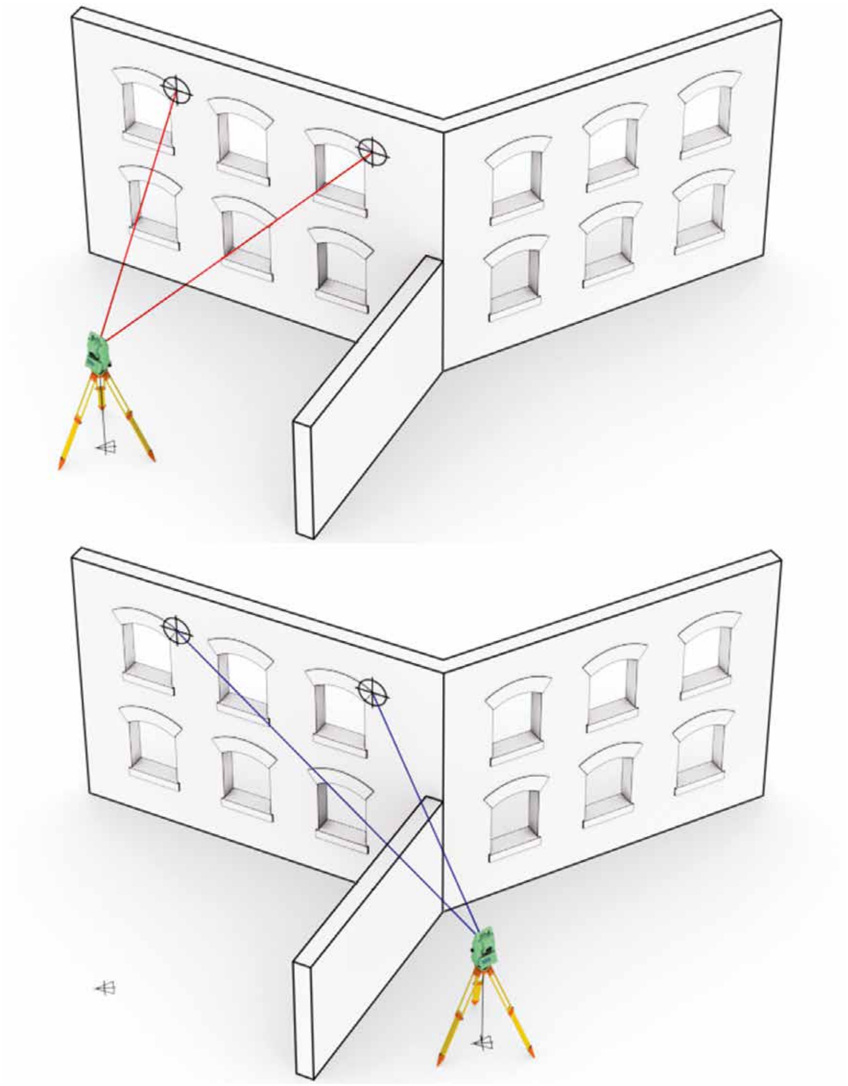


Figure 9
Resection: a minimum of two points are set out from the first station (above), and when subsequently re-measured from the second station (below) allow computation of the new instrument position

Case Study 3

Stonehenge, Wiltshire

Combining TST and GPS data to create a DTM

In 2009 the English Heritage Archaeological Survey and Investigation team completed a new survey (Field and Pearson 2010) of the world-famous prehistoric monument Stonehenge (SU122422). The work formed part of the English Heritage Stonehenge World Heritage Site Landscape project. Its aim was to provide new insight into how Stonehenge's landscape setting has changed over time and to deliver a fresh interpretation of the monument based on detailed analytical survey of the earthwork remains.

The survey had two main results:

- it provided the first modern analytical survey of the earthworks relating to the monument
- it provided a DTM of the site that could be used in the displays within the planned new visitor centre

To create the DTM, some 20 000 3-D points were recorded at regular, closely spaced intervals across the monument. A survey-grade GPS receiver was used to collect most of these height data. Close to the upright stones at the centre of the monument, where satellite reception was blocked, the 3-D points were recorded using a TST.

Integrating GPS and TST data to create a single DTM posed a considerable challenge. It was of paramount importance that the height values recorded by the TST exactly matched those recorded by the GPS receiver. Even a small difference in accuracy would create discontinuities in the resulting DTM that could be mistaken for actual surface features.

Therefore, the survey team integrated the two data sets in the field using resection, rather than matching the GPS and TST data back in the office using post-processing. This integration was possible because the GPS receiver and TST used the same data logger (a Trimble® TSC2™).

The team marked out a series of points on the ground using pegs, in and around the stone circle, then recorded their positions using the GPS receiver. These GPS points were coded separately to differentiate them from the thousands of other 3-D points already existing in the survey on the data logger. The team then set up four independent TST survey stations in and outside the stone circle. Their positions were chosen to cover the areas blocked to GPS. The team attached the data logger to the TST and calculated the coordinates of each station point by sighting to three of the GPS survey points recorded previously. Each set of three GPS survey points for each station was selected to form a triangle with the survey station approximately at the centre.

As the GPS survey points already existed on the data logger, the software could calculate a residual error for the coordinates of each survey station and give immediate reassurance that the 3-D points recorded from that station would match the GPS data. This approach proved successful, giving a DTM with an uninterrupted surface between the 3-D points recorded by GPS receiver and TST.

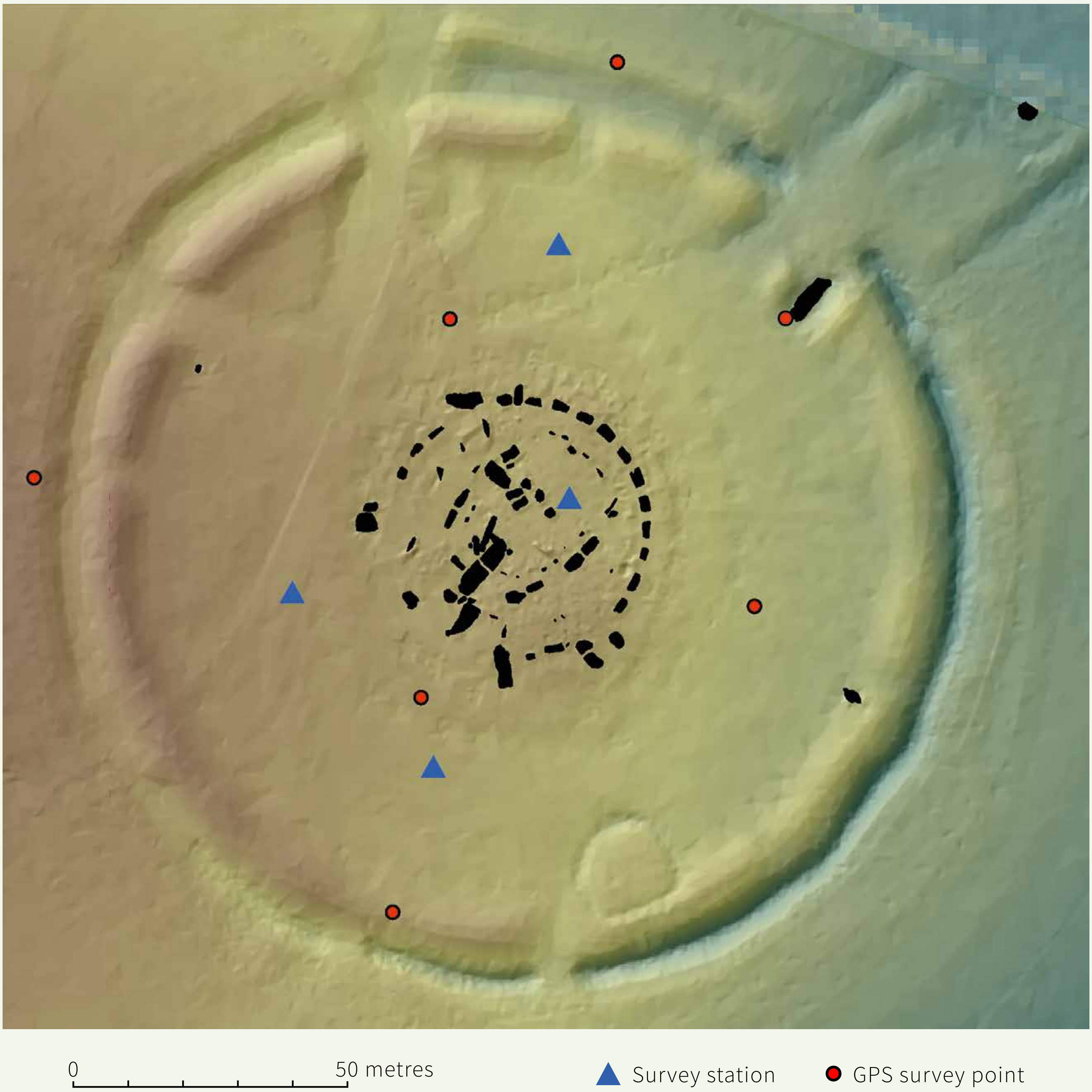


Figure CS3.1
The DTM of Stonehenge surveyed in 2009 showing the survey points used for resection

Accuracy and precision

The terms ‘accuracy’ and ‘precision’ are often used colloquially to mean the same thing but their definitions are different, and this difference is relevant to the surveyor. Accuracy is how well a measurement conforms to its true value. Precision is how repeatable a measurement is. So a survey instrument can be accurate (in that it returns a value close to the correct value for a measured point) but imprecise (because it returns different values each time a measurement is taken) or it can be precise (returning similar values with each measurement) but inaccurate (because the values returned are not close to the real value). Ideally, a survey instrument will be both accurate and precise, returning results that are close to the true value of the measurement that can be repeated with very similar values as long as conditions do not change significantly. It is important to note that achieving high precision does not necessarily mean high accuracy is achieved, because of the chance that bias has been introduced. For example, this can occur when a poorly calibrated instrument is used that may return consistent but incorrect measurements. For this reason, regular calibration and testing of a survey instrument is essential, to ensure that it is both accurate and precise (to within its measurement tolerances).

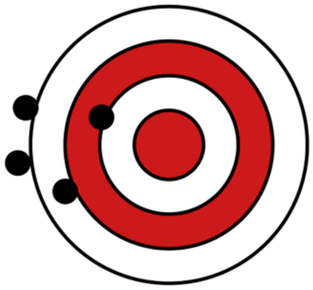
In surveying, further refinements to these concepts are also made. For example, ‘absolute accuracy’ refers to the accuracy of a measurement with regard to a particular coordinate system and ‘relative accuracy’ refers to how well measured points are placed relative to one another.

For further information on accuracy and precision in surveying, refer to RICS (2010).

Good Accuracy, poor precision

Poor Accuracy, good precision

Good Accuracy,good precision



Poor Accuracy, poor precision

Diagram explaining the concepts of accuracy and precision

3 Divorced and Map-based Survey

A survey is called a 'divorced' survey until the point is reached when the data have to be related to a base map. In the United Kingdom, this generally means an Ordnance Survey map. The need might arise in the field, when a digital copy of an Ordnance Survey map is used as a background on the data logger or tablet computer. It might arise again in the office, to provide a wider landscape setting for analysis and publication of the survey. Present digital technology makes great accuracy possible when matching survey data to Ordnance Survey mapping and outputting GPS data as OSNG coordinates. However, to obtain the best fit requires an understanding of how the OSNG has been created and how distances and positions within it differ from those of the 'real world'.

The OSNG is based on a transverse Mercator projection of a mathematical model of the shape of the Earth. This is called the Airy 1830 ellipsoid. The result of this projection is that the distance between two points measured on the surface will not exactly match the distance between the same points on the projection grid. If this mismatch is not accounted for, then discrepancies will be found between the positions of features surveyed by a TST and the same features found on an Ordnance Survey map or recorded using survey-grade GPS receivers. A difference in the order of 0.2m over 500m is not atypical; this is the difference between ground distance and grid distance.

Ground measurements are transformed to grid measurements using both a map projection scale factor and a height scale factor. In practice, the two calculations are often merged to give a combined scale factor.

All ground measurements must therefore be multiplied by the combined scale factor to calculate their grid equivalents. A transverse Mercator projection is used for all Ordnance Survey maps, and the map projection scale factor is not uniform from east to west across the OSNG. At the central meridian, which runs north–south through the approximate centre of the country at longitude 2° west, the scale factor is theoretically 1, and greater than 1 everywhere else, but in order to reduce scalar distortions at the eastern and western edges of the country the scale factor is in fact reduced to less than 1 between two lines 180km either side of the central meridian (where it is c 0.9996), and increases outside these to a maximum of c 1.0004 at the eastern and western limits of the country (Ordnance Survey 2010).

The use of the scale factor to transform ground distance to grid distance pre-dates the advent of digital technology. The surveyor calculated it using a standard formula; today, an Excel spreadsheet can calculate the scale factor. This spreadsheet can be downloaded from the Ordnance Survey website and the scale factor entered into the instrument at the start of a survey. Alternatively, if the software being used to process the results offers a transformation utility, it can be applied after the survey has been downloaded. On modern TSTs offering a direct interface with survey-grade GPS receivers, the scale factor can be calculated and applied automatically using the data collected by the GPS receiver. This procedure requires minimal intervention from the operator. This facility is found on instruments where the GPS receiver is mounted on the TST and when the same data logger is used on both the GPS receiver and the TST.

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With a divorced survey, applying the scale factor is the first step in locating the survey correctly on to the OSNG. The second step is to locate the survey correctly in relation to the map. Manoeuvring the survey by eye on a computer screen onto a background map (graphical fit) is discouraged, as it can easily lead to gross inaccuracies. It is better to use the transformation routine found in most survey software packages after the survey has been downloaded; the software on some types of data loggers also provides transformation routines.

The transformation works by selecting at least three pairs of common points and then entering both the surveyed and map coordinates for them. Today the map coordinates are most easily and accurately obtained using survey-grade GPS receivers. The routine uses this information to re-calculate the positions of all the points in the divorced survey so that they acquire new coordinates that are correct relative to the map (Figure 10). A transformation routine must be capable of working with 3-D coordinates, so that height values from the divorced survey obtain their correct values relative to the Ordnance Survey datum. This is especially important when combining height data gathered using a GPS receiver and a TST to create a DTM of a site. Any slight discrepancy in the 3-D values between the two data sets will distort the resulting DTM.

There may be circumstances when the scale factor is left at 1.0, so that measurements remain as ground distance. This would be appropriate when the survey is to be integrated with site grids used in excavations or geophysical and photogrammetric surveys. Over a large area, the application of a scale factor to the survey will create a mismatch with the site grid. When this happens, the scale factor should be applied uniformly to all the graphical elements resulting from the fieldwork. This procedure will match the data to Ordnance Survey mapping.

A statement that this has been done should be included in the site archive.

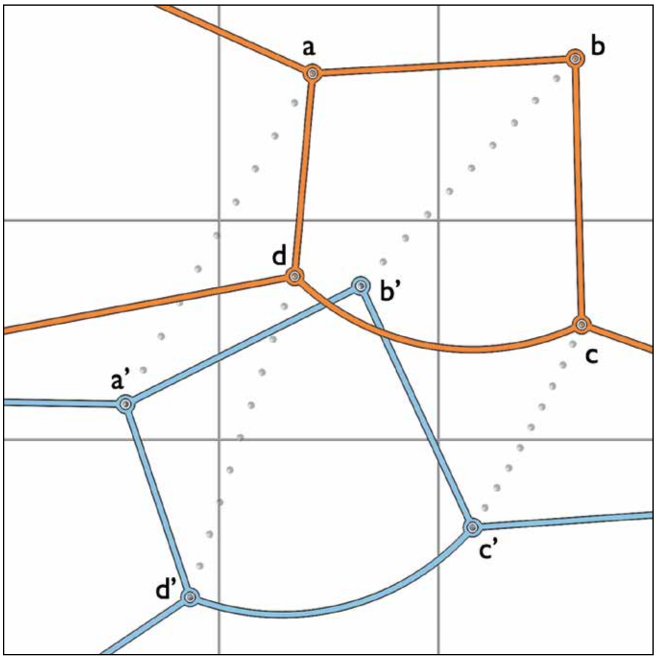

Figure 10
Transformation principles. The ‘divorced’ survey (a’, b’, c’, d’) has good relative accuracy as the points are positioned correctly in relation to one another, but poor map accuracy when compared to the positions (a, b, c, d) of the points on the OSNG – a transformation of the coordinates involving rotation (and often scaling) is required to put the survey data in the right place on the map

Case Study 4

Little Doward, Herefordshire

A Level 3 survey of a prehistoric hillfort

In 2009 the English Heritage Archaeological Survey and Investigation team completed a Level 3 survey of the univallate Iron Age hillfort at Little Doward (SO539160), overlooking the Wye Valley in Herefordshire. Herefordshire Council and the Woodland Trust requested the survey to help with interpretation of the monument and inform a conservation management plan (Bowden 2009).

Figure CS4.1
Surveying the heavily-wooded rampart on the north side of Little Doward hillfort in 2009

The clearance of scrub and trees from the hillfort interior prior to the start of fieldwork created an open environment ideally suited for the deployment of survey-grade GPS receivers. However, almost the entire defensive circuit on the north, north-east, south and south-west sides of the hillfort was in dense woodland (Figure CS4.1). Satellite reception was impossible, so a TST was used to record these earthworks.

Two independent traverses were used: one along the south and south-west side of the fort, and one along the north and north-east side. Each traverse started and ended on survey points in open areas. The field team used a survey-grade GPS receiver to acquire control-quality coordinates for these survey points.

The route for each traverse and the station positions were reconnoitred before any survey work began. This was of vital importance because not only were there dense patches of scrub that interrupted sight-lines but the hillfort rampart was more than 6m high on the north side, requiring station positions that could see to both the top and bottom of this earthwork (Figure CS4.2). On this same side a slighter counterscarp bank beyond the main rampart had to be accommodated in planning the traverse.

The traverse on the north and north-east side of the hillfort was a little more than 530m long, divided between seven stations. The south-west side traverse was 300m long and used six stations. The first station and back station on both traverses were situated in open areas, with control-quality coordinates obtained using a survey-grade GPS receiver. Each traverse ended on a survey station in the open with control-quality coordinates from the GPS receiver. Thus the traverse was closed on a point with known coordinates. There was a discrepancy of approximately 100mm on both traverses between the coordinates of the final TST station and the GPS data. Such errors are common, resulting from slight errors in sighting between stations and measuring the heights of the TST and forward and back stations.

In this survey some of the error was also the result of the use of different scale factors for the TST and GPS receiver. The distances derived from the GPS data were scaled to Ordnance Survey mapping using the OSTN02™ transformation; the TST readings were recorded as ground measurements with a scale factor of 1:1. The coordinate transformation routine in the survey software resolved the discrepancies after downloading the data.

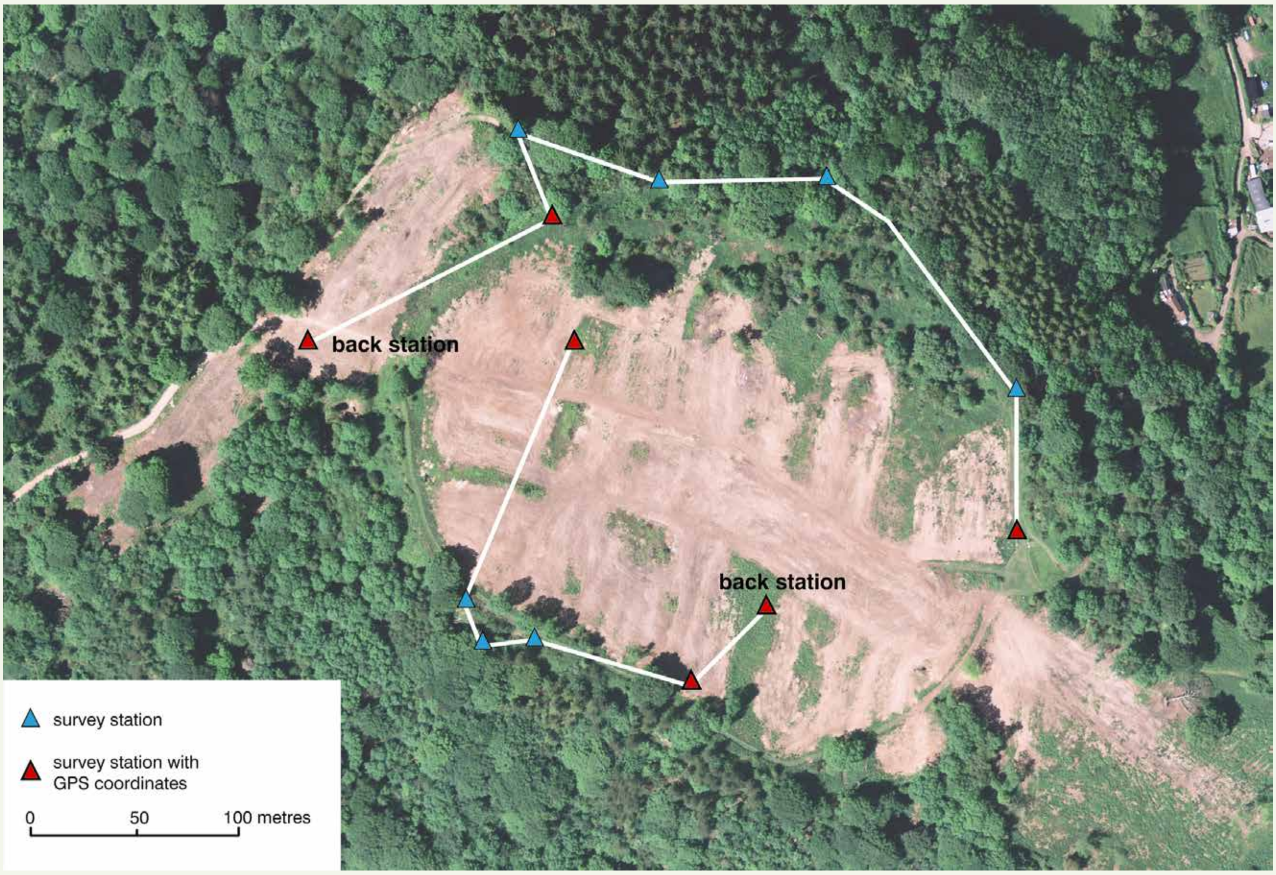

Figure CS4.2
Vertical aerial photograph of Little Doward hillfort overlain with the routes of the two traverses
Aerial Photography Licensed to English Heritage for PGA, through Next Perspectives™

4 Practical Applications

4.1 Deploying the TST

Whether the TST is used in support of GPS receivers or used on its own, there are two key essentials for effective use:

- pre-planning of the survey
- good communication during fieldwork

Planning

The survey team normally identifies the most appropriate equipment for a survey brief set by a consultant or planning archaeologist. The first requirement is to understand the implications of the level of survey specified and what this means in relation to the level of detail to be recorded on the ground (Ainsworth et al 2007).

The scale used underpins this level. For example, at 1:2500, 1m on the ground represents 0.4mm on the final plot. Expressed another way, 1mm on the plot represents 2.5m on the ground.

The scale is of great importance. It is easy to waste time picking up detail that is clear when seen as a digital plot after downloading but too small to be resolved when plotted out at scale. Conversely, detail not surveyed cannot be 'retrieved' if the scale is subsequently increased. At:

- 1:10 000, 1mm represents 10m
- 1:5000, 1mm represents 5m
- 1:2500, 1mm represents 2.5m
- 1:1000, 1mm represents 1m
- 1:500, 1mm represents 0.5m
- 1:200, 1mm represents 0.2m

It cannot be emphasised too strongly that, however simple the survey, time spent reconnoitring the best locations for the station(s) is never wasted. Even on a site with open views, failure to check the visibility carefully from a potential station position can mean the difference between a single station set-up and the complication of having to establish extra stations to see into areas at the extreme edge of the site. The ground should also be checked to find the optimum spot for the instrument. In such situations it is easy to miss areas of 'dead ground' or distant obstacles obscuring part of the site.

It is unusual for the whole of a site to be visible from one location. Typically, detail is hidden by folds in the ground or obstructions such as woods and buildings. In such cases the TST must be moved from one location to another around a network of inter-visible traverse stations.

The layout of the traverse should not be left to chance. Choose the location of each station in advance to ensure that every part of the site can be seen from one or other of the stations.

Reconnaissance is especially important on a multi-leg traverse. Careful positioning of the survey stations will reduce the number of times the TST has to be moved to complete the survey, and will save time. The best way to reconnoitre the traverse is first to use ranging poles to mark the proposed stations, then to make minor adjustments in positioning before fixing each station with a permanent or semi-permanent marker. This procedure is done most efficiently with two people.

A sketch diagram should be made as the traverse is set out. Each station should have a number on the ground and recorded on the diagram to avoid mistakes in the numbering of stations. Link traverses should also be established at this stage, using the same methods.

Each station marker or peg should be inscribed with a cross. Survey nails, pre-marked with a centre point on the nail, can be used. A nail hammered into a tree stump (if conveniently sited) can also be used to mark a station. The centre mark provides an accurate point over which to set the TST while maintaining a consistent plan position.

To achieve pin-point accuracy, a TST should be set up correctly, as described below.

If both survey-grade GPS receivers and a TST are available, careful judgement on how to deploy the equipment should be made before the start of fieldwork. As well as having good visibility, each station should be on firm ground to avoid the instrument slipping or sinking. There should be enough space around the instrument for the operator to get access without knocking it. In public areas care should be taken to set the instrument up where it will not be an obstacle. Station markers should be discreet to lessen the chances of them being moved, uprooted or stolen.

Bear in mind that in some situations, such as in woodland or near buildings, the height at which the instrument is set up can be critical to avoid nearby obstacles. Seemingly insignificant features such as branches and drainpipes can easily obscure more distant features.

Communication

A non-robotic TST requires two people to undertake the survey: one person to operate the instrument and the other to use the detail pole. The person using the detail pole is the survey leader. This person decides what to survey and how to record and code it. It is essential that both team members can communicate with each other, as their priority is to maintain a clear line of sight between the instrument and detail pole. The leader registers when the height of the detail pole has changed or when he or she is moving to a new feature. When distance prevents surveyors from hearing each other, two-way radios or agreed hand signals should be used.

4.2 Survey challenges

Weather conditions

Extreme weather conditions can have a major impact on the use of a TST and may even render it inoperable. Modern instruments are generally weatherproof but extremely hot or cold temperatures will affect the accuracy of distance measurements. Adhere to any temperature range recommended by the manufacturer.

A TST also works poorly in dense mist, rain or snowfall, as water particles and snow flakes interrupt the transit of the electromagnetic wave between the instrument and the reflector, causing errors in distance measurements. In such cases make regular control readings to a reference object of known distance.

In all types and conditions of surveying, the person with the detail pole should wear bright clothing to increase his or her visibility.

Woodland

Any TST survey in woodland requires concentration, patience and especially good communication between members of the survey team.

Surveying in woodland is always slower. Branches, undergrowth and the low level of sunlight combine to make it difficult to sight to the reflector. A survey of a woodland site is best scheduled in winter. Summer foliage will make the survey much slower, if not impossible.

The height and position of the detail pole often needs fine adjustment to bring the reflector into the view of the TST. If circumstances allow, it is better to select a station in the open, a short distance from the edge of the woodland, to create a wider and clearer field of view. Modern motorised TSTs are provided with ATR (section 1.4) enabling the instrument to ‘find’ the prism. This facility can be used to great effect in woodland, where the prism is frequently hard to spot among foliage using the telescope on the TST alone (Figure 11).

Valleys

In steep-sided valleys the key to efficient progress is, again, good communication between surveyors. For example, the instrument and the detail pole are often far apart on opposite sides of the valley. It is often more useful to set up the TST on the opposite side of the valley to the survey area, to obtain the widest field of view, even though that can make communication more difficult.

Figure 11
TST survey in woodland

Buildings

These guidelines do not describe use of the TST to create detailed, large-scale plans of buildings in architectural investigations (Menuge 2006; Andrews et al 2010). In most landscape surveys the aim is to document the building's setting; for this, a survey of the footprint is usually sufficient. Such a survey may still require a traverse, although the process can be speeded up through judicious use of the tape measure. The optimum location for a TST station is facing one of the corners of the building at a distance sufficient to obtain views along two sides of the structure.

Slight or complex earthworks

Where earthworks are slight, or where their inter-relationships are complex, it is good practice to leave areas of the site for drawing by hand. It is better to define the shapes and forms of complex or slight earthworks by drawing them onto the plot than trying to unravel the detail using a TST. In such areas, place pegs at nodal points in the earthwork complex and record their positions with the TST. Later, return to the site with the plot to fill in the earthwork detail by measuring off tapes stretched between pairs of pegs, taking care to identify the same pairing on the plot, or by plane table surveying (Bowden 2002).

3-D surface modelling

The creation of a 3-D DTM that represents the appearance of an earthwork typically requires thousands of 3-D points. Surveying this number of points is done better with GPS receivers than a TST. However, it is still worth considering the use of a TST to model sites under a tree canopy, where GPS receivers do not work. An alternative is to use airborne laser scanning (lidar) data, but this is expensive (Devereux et al 2005; Crutchley 2010).

For the most accurate depiction, 3-D modelling with a TST or GPS receiver requires the collection of data related to topographic detail rather than adherence to a strict grid. Best results are often obtained by defining break lines in the data (eg top and bottom edges of banks) and adding points between these to define the surface.

Include points outside the immediate area of interest to define the model's margins correctly and to give context to the archaeological features against the natural surface (Figure 12).

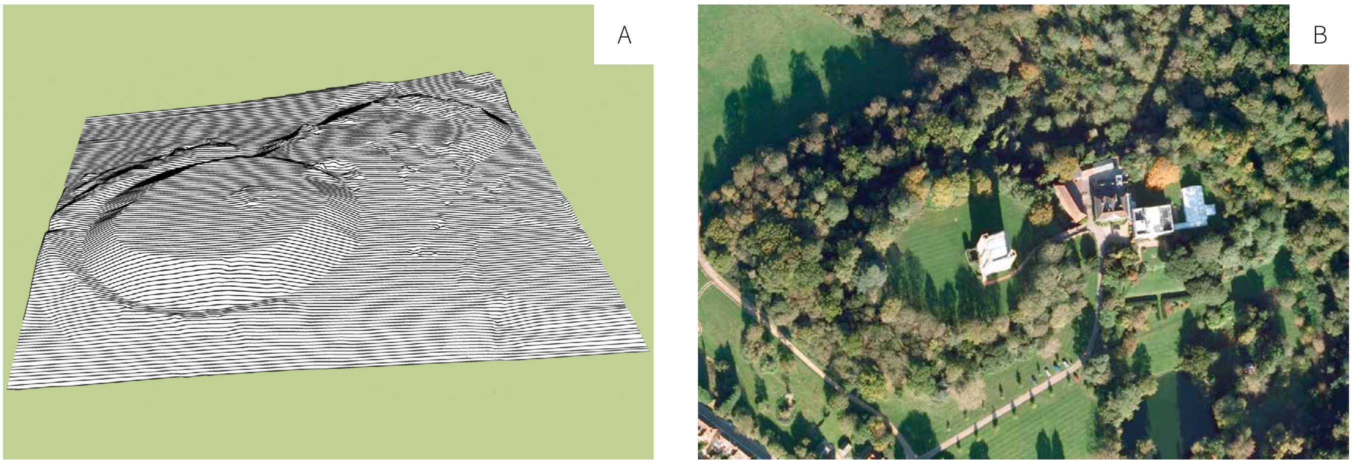

Figure 12

A. DTM of Castle Hedingham, Essex, viewed from the south-west

B. Vertical aerial view of Castle Hedingham showing the extent of tree cover
Aerial Photography Licensed to English Heritage for PGA, through Next Perspectives™

4.3 Advantages and disadvantages of the TST

It is common for TST and survey-grade GPS equipment to be used together to complete a landscape survey. Table 2 summarises the advantages and disadvantages of the two types.

	TST	GPS
Versatility	Extremely versatile, not restricted to open landscapes; can be used among trees and inside buildings	Restricted to areas with good sky visibility; therefore cannot be used near buildings or trees
Operation	Generally requires two people, except when operating in 'robotic' mode	Usually operated by one person
Portability	Few portability issues; detail usually surveyed using a prism on a light-weight pole	Portability can be an issue depending on the combined weight of the GPS receiver and data logger and (if not wireless) the number of connecting wires
Planning	Advisable to reconnoitre a site thoroughly before starting to survey	Prior reconnaissance is advisable but the system is flexible in its operation
Speed	Data capture can be slow, as the TST must be re-sighted after each reading. The need to traverse also slows down productivity	Data capture is rapid, except where the highest obtainable accuracy is needed for control work
Complexity	Process entirely under the control of the operator	Process dependent upon a range of external factors outside the operator's control
Data capture	Needs constant communication between a target person and the TST for coding of data	Coding done at the point of data capture
Weather	Not suited to use in extreme hot and cold temperatures and in mist, rain or snowfall	Operation generally unaffected by weather and temperature conditions
Cost	Ranges from expensive to budget models offering lower accuracies	Very expensive for survey-grade equipment.
Transformation to OSNG	Need to record one or more stations using survey-grade GPS receivers or to tie on to hard detail mapped by the Ordnance Survey and use this to transform the coordinates of the survey	Data transformed in real time to the OSNG when using the Ordnance Survey active station network (or other proprietary networks) or can be done in the office by post-processing

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Table 2
A comparison of TST and GPS equipment

5 Data Collection and Software

5.1 Choice of data collection methods

Modern TSTs are generally able to interface with on-board electronic data loggers to enable automatic recording of survey information. There may be a choice of external data loggers available, depending on the make of the equipment. The supplier should be able to advise on the most suitable data logger to use. Budget TST models, designed for use in the construction industry for setting out, have an electronic display but do not interface with a data logger. With these models, or when using older equipment that cannot connect to a computer, the operator has to write down in a notebook each point reading surveyed. Particular care has to be taken when noting the distance measurement: the horizontal distance, not the slope distance. If the display only gives the slope distance, then it will be necessary to calculate the true plan distance using a scientific calculator (Bettess 1998, 124). The formula is:

horizontal distance = slope distance x cosine of the included angle

In the office, the survey can be drawn up using a protractor to provide the angular measurements from a fixed point (representing the position of the station) and a ruler to scale off the distance to the surveyed point. Alternatively, the readings can be used to construct a drawing in a CAD package on a computer. The procedure is the same: entering an angle from a fixed point representing the station position and the recorded distance to the individual point surveyed. Remember to use the horizontal distance and not the slope distance for the length measurement.

5.2 Manual recording

- Use a weatherproof notebook
- Do this recording neatly and systematically
- Avoid scribbling down the readings on loose scraps of paper

Surveying notebooks with pre-printed data columns are available. Alternatively, the columns can be ruled out in a plain notebook. For guidance, there are example layouts in textbooks on surveying (eg Johnson 2004, 174–5). Whatever layout is adopted, it is important to distinguish measurements to points from measurements connected with the setting up of a station, especially when the survey involves a multi-leg traverse. To help with drawing up, remember also to code each reading with the type of feature being surveyed. Do not rely on memory of the site to give you this detail. Several months can elapse between completion of a field survey and drawing it up, or the drawing-up may be done by someone who has never seen the site, although such circumstances should be avoided.

Approached properly, there is no reason why even the most complicated site cannot be surveyed using manual recording of the data and the results drawn up by hand. The main drawback is the time taken. Although it is impossible to give hard and fast figures, manual recording in the field will take at least three or four times longer than using a data logger. The difference is greater still when it comes to plotting out the results. For larger sites this will equate to several weeks, if not months.

5.3 Data loggers

Data loggers take many forms but perform the same basic function. They record rapidly and securely measurements taken by a TST for downloading and processing back in the office. This is usually called post-processing, as it occurs away from the site.

Post-process data loggers have some form of screen display linked to a keyboard and software to operate the TST. The software has a menu structure accessible through the display and a keyboard with a number of options. These include functions to change the operating parameters (eg to input a scale factor or change the bearing), change feature codes (section 5.4) and review all the points recorded for a particular job. There is internal storage and a means to download data to a computer. Some makes of data logger use a removable card for storage, which has the advantages that it can be changed to increase the storage capacity and taken out and inserted into a card reader on an office computer for downloading. If the internal storage device is fixed, then downloading is done through a cable connecting the data logger and a computer. On more modern equipment this link might be through a wireless Bluetooth® connection.

It is important to understand how a data logger records the fundamental information needed to compute station positions and calculate a traverse. Each station needs a unique reference number, which should be recorded three times on a traverse as a forward station, a rear station and an occupied station. As well as unique reference numbers, stations must also be coded on the data logger so that the readings between stations can be identified for calculating a traverse. All software applications, from the most basic to the most sophisticated, need this information to process survey data.

It is often possible to review the data on-screen as text and as a map. However, the small screen on a TST or data logger often means the graphic display is poor, of low resolution and difficult to read outdoors in bright sunlight. In such circumstances it is necessary to keep a record of what has been done during the day to avoid missing areas or recording the same feature twice. It often helps to update periodically a sketch map of what has been surveyed.

Another resolution to the problem of the graphics display is to use a pen computer or laptop with a CAD package for data logging in real time. The best models are those that use a pen interface and have daylight-readable screens. These are more costly than a standard laptop and may need external power from extra batteries.

Protect all such equipment and connections from inclement weather. Models manufactured for outdoor use vary widely in specification and performance. Such a computer must be able to run a CAD application to get the full benefit of using it in the field. Check carefully about details for data exchange, power supply and screen performance before choosing.

When the interface between a portable computer and a TST is controlled through CAD or other intermediary software, it will be able to display the points and process the feature codes (if used) in real time, thus avoiding the need for post-processing. This ability also greatly reduces the risk of missing out elements of the survey, because the elements can be seen as they are measured.

Working with a computer in the field can be demanding on both the user and the hardware. A bracket for mounting a computer on a TST tripod is a wise investment. It can save the computer from damage and will improve the work environment for the surveyor (Figure 13).

Finally, safeguard the data recorded on a logger by regularly downloading to a PC or laptop, ideally at the end of each day's work. Leaving downloading to the end of a survey of several days or weeks is an enormous risk and would be expensive to correct if the data logger malfunctions or is lost.

Figure 13
A tablet computer in use in the field. Note the use of a diagonal eyepiece on the TST to enable viewing targets through the telescope at extremes of elevation or depression

5.4 Feature code libraries

The key to using a TST with automatic data logging is to use a code library. Use a code library to define the attributes of every point recorded. Manage the traverse by recording which station is occupied and which are the rear and forward stations.

For each point, use a word or words to define the feature type (eg wall, fence and top of bank), the colour it will adopt when seen on-screen after downloading and the line type used to depict it. Examples of line type are 'solid line', 'dashed line' and 'dotted line'. These are called field codes. Although it is tempting to create a large number of such codes, having too many codes can make the library difficult to use in the field. A simple code library with a combination of solid and dashed lines in four colours will cover almost every need.

The library should also have control codes. As the name suggests, these control the actions of feature codes.

- A control code meaning 'end' is used to define the end of a run of points with the same field code, where the surveyor is trying to define an individual feature such as a length of wall or the top of a slope

- A 'close' code is a control code telling the software that the last point in a run of the same field code should join back to the first point in the same sequence, to create a closed shape such as a shaft head or pond

Only two or three control codes may be needed. Once a code library has been developed and tested in the field, it should be used repeatedly so that the field team become familiar with applying it.

A code library is typically compiled by the user on the data logger itself or on a PC. Such a library can be created on a PC as a text file in a standard text editor or in a piece of proprietary software. The latter is recommended because the software will take care of the formatting. In a text document each entry in the code library will appear as a block of text separated by a sequence of spaces and commas. Adding a new code in a text editor is not intuitive and must be syntactically precise. Any error in spaces or commas will prevent the library from loading correctly (Table 3).

When merging GPS and TST data, much editing can be avoided at the end of a survey if the same code library is used with both devices. CAD packages and survey software commonly use a layering system to structure the graphic output on the computer with names derived from the codes applied in the field. Consequently, using the same feature codes on both instruments reduces the number of layers used in the survey plot and ensures that features of the same type are on the same layer, irrespective of whether they were surveyed using GPS receivers or a TST.

Table 3
A typical code library for the archaeological recording of landscapes

FEATURE CODE ON DATA LOGGER	APPEARANCE WHEN PLOTTED	ACTION / REPRESENTATION
999	control code: ‘End’	end a line
998	control code: ‘Close’	close a polygon or circle
RO	black cross	reference object
STN	black cross	survey station
BANK_NAR	red solid line	narrow bank
BANK_WID	red dashed line	wide bank
CAIRN	black solid line	cairn
DIT_NAR	purple solid line	narrow ditch
DIT_C	purple dashed line	centre of ditch
DITCH_ED	purple solid line	edge of ditch
DRAIN	light blue solid line	drain
EROSN_1	light brown solid line	edge of erosion
EXCAVTN	black solid line	edge of excavation
FENCE	black solid line	fence
GPS_BASE_STATION	cyan cross	GPS base station
HEDGE	green solid line	line of a hedge
IND_1	black solid line	industrial feature
MILIT_1	cyan solid line	military feature
MOD_DAT	yellow cross	points for creating a ground model
NAT_BOT	green dashed line	bottom of natural slope
NAT_SCREE	light brown dashed line	edge of natural scree
NAT_TOP	green solid line	top of natural slope
PAVMNT	grey solid line	edge of pavement
QUARRY	black solid line	edge of quarry
R-F_NAR	green solid line	narrow ridge and furrow (line follows furrow)
R-F_WID	green solid line	wide ridge and furrow (line follows furrow)
ROAD	black solid line	edge of road
ROCK_ED	black solid line	edge of rock face
SPOIL_1	brown solid line	edge of spoil
STREAM_C	cyan dashed line	centre of stream
STREAM_ED	cyan solid line	edge of stream
TEL_POLE	black cross line	telegraph pole
TRACK	black dashed line	edge of track
TREE	green tree symbol	tree
VEG_1	green dashed line	edge of vegetation
WALL_FCE	black solid line	wall face
WATER_ED	blue solid line	edge of standing water

5.5 Choice of office software

At the end of a survey there is usually a post-processing stage. The field data are downloaded to an office computer for plotting. Errors made in the field, such as incorrect readings and wrong field codes, can usually be corrected at this stage. Alternatively, the survey results can be plotted manually. However, this takes more time and is really only feasible for small surveys. If a tablet computer running a CAD program in real time was used to log and display the data in the field, then post-processing is not necessary.

A range of software for post-processing survey data is available. Many manufacturers supply packages designed for their instruments. The basic requirements to look for in such software are that it:

- is intuitive and prompts for data input in a logical way
- is compatible with the data format stored on the TST or data logger
- can edit raw data to correct errors
- can process field codes
- can do traverse analysis and make adjustments
- provides a graphic display of the survey
- can export in different formats so that the survey can be used in other packages, such as CAD and geographical information systems (GIS).

The routines to perform these tasks vary from one software package to another, so it is important to study closely the accompanying manual. Obtain training from the software manufacturer or an agent recommended by them. The manufacturer or supplier may also charge an annual fee for licensing the software use, to cover the cost of upgrades and support calls.

5.6 Archive principles

A reference archive must include a detailed description of the methods used in the survey as part of the project metadata. Where a TST has been used this should include:

- a copy of the traverse diagram
- witness diagrams for any permanent stations that have been created
- the scale factor that was applied to the readings.

The last element is important for future work on the site (eg excavation or geophysical survey) so that it can be related accurately to the original survey plan. A summary of the methods used should be published with the project report. Also include the names of the surveyors, the dates of the survey, the intended scale of reproduction and any conditions that might have affected accuracy or accessibility.

6 Conclusions

The TST continues to play an important part in archaeological survey because of its versatility and reliability and the relatively low cost of basic models compared with survey-grade GPS equipment delivering broadly comparable levels of precision. Using a TST does have its challenges and it is easy to have problems in the field if the basic principles of survey are poorly understood. It is important to undertake a full reconnaissance of the ground before any work with a TST starts, in order to work out how best to deploy the instrument. Missing out reconnaissance before a traverse risks missing areas of the site and poor geometry in setting out the traverse legs. Once embarked on the survey, care is needed in setting up and referencing the TST on each of the stations by following the procedures outlined in this guide. At the same time, to ensure that features are coded correctly and reduce the amount of editing after downloading the survey data, good communications are essential between the person using the TST and the person using the detail pole.

The integration of TST and GPS data and the referencing of surveys to Ordnance Survey mapping raises issues concerning map projections and scale factor. These issues cannot be ignored if the most accurate marriage of these different types of field survey data is to be achieved. The physical integration of a GPS receiver with a TST was a step forward in combining these data types and manufacturers will no doubt continue to develop these systems.

The capability of data loggers and tablet computers used to capture the field data will undoubtedly develop as well. These instruments are increasingly moving real-time processing of survey data to the fore, reducing the need for post-processing in the office. Some devices enable automatic transmission of data back to the office through an in-built modem or a connection to a mobile phone, bringing the field- and office-based elements of a survey project closer together.

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8 Glossary

Accuracy
Accuracy is how well a measurement conforms to its 'true' value.

Aerial photogrammetry
A technique for creating 2-D and 3-D maps by interpolation from pairs of vertical aerial photographs.

Adjustment
In the survey of control data, adjustment is used to distribute observation and centring discrepancies acquired during measurement. Such techniques include, for example, the Bowditch, Transit and Least Squares adjustment methods.

Alidade
A manual sighting instrument used as part of a plane table for survey. Sometimes known as a site rule, the alidade can be a simple straight-edge with sighting vanes or a telescopic type such as a self-reducer, or one with an EDM attached (Bowden 2002).

Altazimuth
An instrument or a telescope mounting that can be moved in the horizontal and vertical axes, used to measure the altitude and azimuth of the object targeted or part thereof.

Automatic target recognition (ATR)
A system that enables the TST to sight automatically onto the centre of the prism, significantly reducing the time between readings.

Azimuth
The angle of horizontal deviation, measured clockwise, of a bearing from a 'standard' direction, eg north.

Bluetooth®
A wireless technology used over short distances to connect portable or fixed devices. It replaces the need to connect devices using a cable.

Cartesian coordinates
A way of defining a point in 2-D or 3-D space by reference to its position on two or three rectangular mutually perpendicular planes. These are usually referred to as the x, y and z planes, or easting, northing and height.

CAD Computer-aided drawing/design
A term used to describe graphics packages used primarily in engineering and design. As these disciplines require a high degree of precision, they are also ideal for survey applications.

DTM Digital terrain model
A digital representation of the surface of the ground. It is also sometimes known as a digital elevation model (DEM) and the terms are often used interchangeably, although DEM implies that elevation data are continuously available across the area in question. Thus elevation datasets derived from ground survey (by GPS or TST) can produce a DTM but are not considered to be a DEM. DTMs are usually derived from remote sensing techniques such as lidar, aerial photogrammetry and satellite imagery, and can be represented as raster grids or as triangulated irregular networks (TINs). They usually describe the surface of the terrain without any buildings and vegetation. Their use in archaeology ranges from depicting the earthworks of an individual site to representing wide areas of landscape for use in GIS, and are commonly used for producing relief maps. A digital surface model (DSM) is similar to a DTM except that it includes all visible elements of a terrain surface, such as buildings and vegetation.

DXF™ Drawing exchange format
A digital data format developed by Autodesk® and used for transferring digital map, plan or survey data between various CAD and graphics software packages.

EDM Electromagnetic distance measurement
This involves evaluating the signal returned from the target of a light beam emitted by the EDM unit. EDM is also applied colloquially to any survey instrument using this method of distance measurement.

EGL Electronic guide lights
Lights showing on the front side of the telescope of a TST. They help the person holding the target prism to stake out points by indicating whether he or she needs to move to the left or right.

GIS Geographical information system
A system for capturing, storing, checking, integrating, analysing and displaying data that are spatially referenced to Earth. This normally comprises a spatially referenced computer database and application software.

GLONASS Global Orbiting Navigation Satellite System
The Russian satellite constellation.

GNSS Global navigation satellite system
The collective name for the Russian, American and other constellations of navigational satellites.

GPS Global positioning system
A generic term used to describe surveying or navigation by reference to a satellite constellation, although it is specifically the name for the satellite constellation operated by the USA.

lidar Light detection and ranging
A system that uses laser pulses to measure the distance to an object or surface, typically determining the distance by measuring the time delay between transmission of a pulse and detection of the reflected signal. Lidar is frequently deployed from a plane or helicopter to create 3-D models of the ground surface rapidly and accurately to varying degrees of resolution, depending on post spacing.

Optical micrometer theodolite
A surveying instrument once commonly referred to as a ‘universal‘ theodolite as it is capable of coping with virtually any problem in surveying, engineering and industry. It uses an optical system based on a parallel plate for taking angle readings and can achieve high degrees of accuracy.

OSNG Ordnance Survey National Grid

Precision
Precision is how repeatable a measurement is.

REDM Reflectorless electromagnetic distance measurement
Many modern EDM instruments do not require a retro-reflective prism for measurement, and can read signals reflected from almost any surface that is within range, hence the term reflectorless EDM (REDM) is used.

Retro-reflective prism
A prism designed to reflect the signal hitting it from any angle back to the emitter. This enables the TST to get a sufficiently strong return signal for the calculation of a distance measurement.

Stakeout
A term used to describe the laying out of survey control and detail. In an archaeological context this could include laying out survey grids and excavation trenches.

Tablet computer
A laptop-sized portable computer operated using a touchscreen or stylus for data entry instead of a keyboard. Rugged versions have been developed for use outdoors, offering far greater strength and protection from the elements than offered for standard laptops.

Tribrach
An adjustable device that fixes to the stage plate of a tripod to provide a level platform for a TST or target prism directly above a survey station. It has a bubble and foot screws for levelling and may include an optical plummet for sighting on to the marker in the ground denoting the survey station.

Witness diagram
A diagram prepared to show the location of a station position. This should include a description of the marker used and measurements to nearby points if possible, to aid in relocating it if necessary.

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