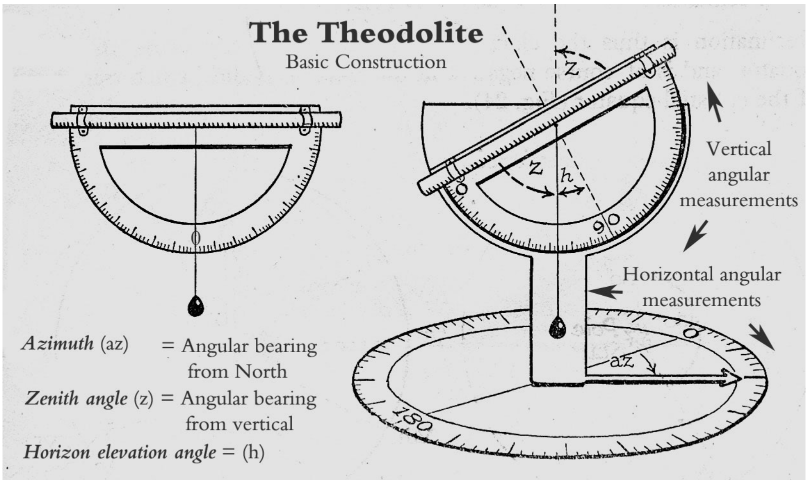
The Theodolite

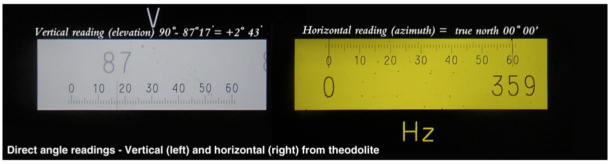
Its Use in Archaeoastronomy

WHAT IS A THEODOLITE?

A theodolite enables angles to be accurately measured in both the horizontal and vertical planes. How accurately this can be will depend partly on the quality of the instrument, and partly to the competence and experience of the theodolitist. For most archaeological work a good surveying theodolite is normally used, and this should be capable of resolution accuracy of one minute of degree, that is, it can discriminate between each of the 21,600 minutes that make up the 360 degree circle. To place this in context, the orb of sun and moon each have a diameter of about half a degree, or 30 minutes of degree.



The traditional theodolite was costructed rather like the diagram above. The telescope was clamped to two graduated circles, and adjustments could be made to align the telescope to any object by adjusting it horizontally (the azimuth adjustment) and then vertically (the vertical or zenith adjustment). More modern theodolites (*overleaf*) deliver a direct reading of both horizontal and vertical angles, often viewed through a secondary telescope adjacent to the main eyepiece. Angles are read off directly, accurate to at least one minute of degree, usually marked Vz and Hz (Wild T16 scales shown below, vertcal (zenithal angle) angle above, horizontal (azimuthal angle) below).



Direct angle readings - Vertical (left) and horizontal (right) from theodolite

Because a theodolite belongs to a class of instruments referred to as '**gravimetric**' (i.e. they depend on the earth's gravity to operate successfully) it is crucial that the instrument is properly levelled. To achieve this, it is mounted on a solid table (**alidade**) itself screwed into the top of a robust and adjustable **Tribrach**, which is mounted on the tripod.

The location where the theodolite is set up is referred to as a '**station**', normally allocated an identification number/letter or place name and a surveying pin pushed into the earth to facilitate setting up at the same spot in the future. A plumb-bob or optical device is used to position the theodolite directly above the station pin.

For historical reasons, the side of the theodolite where the horizontal and vertical adjusters are positioned is known as the 'face' of the instrument. 'Face-left' is when these adjusters are to the left of the telescope and 'face-right' when they occur to the right. To minimise instrument errors, it is customary to take two readings during each angle measurement, one face-left, the other face-right, when the telescope is gently spun about its horizontal axis and then turned (transited) through 180 degrees in order to change the 'face' of the instrument. The two measured angles are then averaged. This improves the attainable accuracy.

The modern theodolite automatically levels itself in the vertical axis, so that for a 'horizontal angle' instrument, when the telescope is level, the Vertical (V) reading is 0 or 180 degrees. For a 'zenith angle' instrument, it will be 90 or 270 degrees, and 0 degrees will be vertically overhead.

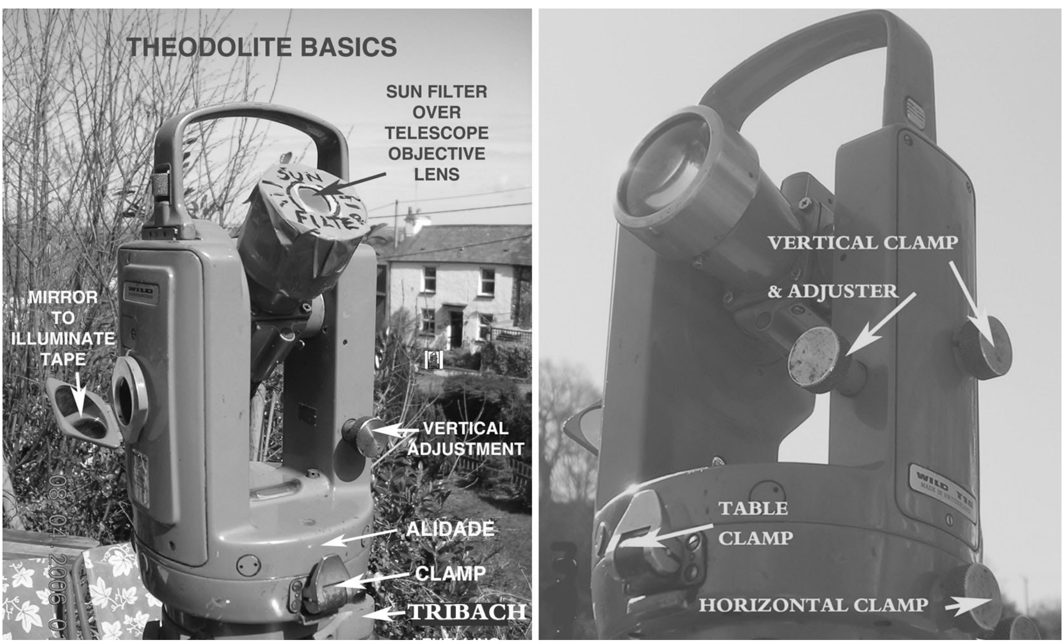


Illustration shows a WILD T16 Swiss made theodolite (1977)

Until the advent of civilian GPS devices (1995), a theodolite was an essential tool in archaeoastronomy. All theodolites are cumbersome instruments to carry long distances, and for preliminary assessment of the astronomical characteristics of a site GPS devices can now be usefully employed. The most recent electronic theodolites are even heavier than most of the older instruments.

[A magnetic compass is not much good for archaeoastronomical measurement. Used above igneous rocks a compass may indicate tens of degrees in error, even reverse north and south, and anyway,magnetic north is not a constant direction. Despite all of this, a compass remains useful for a quick and rough assessment of horizontal bearings.]

To assess a site using a theodolite, two main tasks are normally undertaken:
1. The assessment of the important azimuths and elevations along a postulated astronomical alignment
2. The production of an horizon profile at the site under investigation.

Both tasks require that an accurate azimuth referred to true north be established on site. How this is done is described overleaf - the gentle art of 'shooting the sun'.

"SHOOTING THE SUN"

The prime task on site is to establish an accurate azimuth to a distant **reference object (RO)** (*Azimuth = an angular bearing referred as degrees clockwise from true north*). This azimuth can then be referred to later when obtaining an accurate horizon profile.
The theodolite is set up at the site under investigation, levelled and a marker pin placed on the ground to mark the station. Once the theodolite has been levelled, it is necessary to select a reference object (RO). Following the measurements to be described here, this will ultimately become a known azimuth from which all further measurements taken from the site can be derived, as in preparing an horizon profile.

The following stages are required in selecting a reference object (RO).

1. Record the latitude and longitude of the theodolite station with a GPS, or from the OS map. You will need to know these coordinates to within a second of a degree, and preferably to well within a second. A GPS yields this level of accuracy (one arcsecond of latitude is a hundred feet and most GPS devices are accurate to 20 feet (6 metres).

2. In the field, a distant fence post, transmitting aerial or prominent fixed landscape feature is normally chosen to be the RO. It should be as far from the site as possible within the visibility range of the prevailing weather conditions. It is better for the RO to be elevated to minimise refraction effects. Record the RO you have chosen. If it is marked on the OS map, name it or record the approximate latitude, longitude or grid reference for it. It is crucial that one does this so that anyone else who wants to check your work in the future (or yourself, should you return to the site to undertake more work there) can make sense of your work.

3. Unclamp and rotate the theodolite body so that 0 degrees is indicated on the horizontal scale. You will normally have to adjust this using the standard horizontal clamp and vernier adjuster. Once set to zero, clamp up the plate and rotate the telescope back to the RO, then unloosen the clamp a final time. This establishes 0 degrees as the RO. You can choose any value you wish, but zero is handy for adjusting to actual azimuth later on, when one needs to calculate the actual azimuth of the RO from the measurements made from the Sun.

4. Recheck that the theodolite remains level - if not, then repeat 2 and 3 above until you are satisfied that the theodolite is stably set up on the RO, and is level. At this stage you know nothing about the true azimuths of any object in view. This can be useful in preventing any bias in your readings.

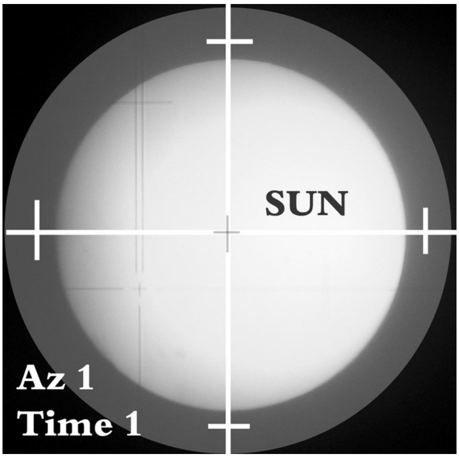
5. To 'shoot the sun' you will need, in addition to an appearance by the sun, a chronometer. The availability of radio controlled clocks for under £30 has greatly improved the accuracy of time-keeping on site, and these are recommended. You will need one which displays seconds as well as hours and minutes.

Because of refraction, measurements of the sun are best taken in the middle part of the day, although, in the climate of the UK, beggars cannot be choosers, and one must often take a measurement whenever and if the sun is shining. For this reason, have everything ready on hand so that a measurement can be quickly made. Large clouds can affect readings through refraction effects and measurements taken in early morning or late afternoon when the Sun is low in the sky can also invoke refraction errors, which will also worsen accuracy. If you only require accuracies to within a few minutes of a degree then any time in the middle part of the day is suitable and only requires that a couple of readings be taken.

To 'shoot the Sun', sun-filter will need to fitted over the objective lens of the telescope (see this filter on page one). IT IS HIGHLY DANGEROUS FOR THE EYES and not wonderfully healthy for the theodolite to allow full sunlight to be amplified through the telescope. Nor is it recommended to place a filter in front of the eye-piece in order to lower the sun's intensity - the rays have still been amplified and will heat up the internal lenses of the telescope.

The TECHNIQUES

Technique (a). Centering the Sun.



1. With sun-filter fitted, locate the sun in the eyepiece and begin to track it such that the crosswires meet at the sun's centre (see diagram overleaf). Many theodolites have auxillary crosswires at 20 minutes of a degree 'out' from the central crosswires, these act as good markers and it is quite easy to place the sun's disc (which has radius of just over 15 minutes of degree) centrally within these four marks, leaving an equal gap at top, bottom, left and right of the sun's disc. One will quickly discover that the sun moves remarkably quickly, and constant adjustment will be needed to keep the disc in view, particularly horizontally.
This method is very useful when the Sun makes only a single brief appearance during the survey, and should always form the first 'sun-shoot' of the day in order to obtain an acceptable azimuth bearing.

2. It is best to involve a colleague in the readings. One person takes charge of the theodolite 'station' while the other calls out the time, counting down the seconds "5..4..3..2..1..zero" at the end of each minute, in order to announce the exact start of the new minute. When "zero" is called, make no further adjustments of the theodolite controls and, at leisure, read off the vertical and horizontal angles to the time keeper, who then records them next to the time reading. This process is repeated as many times as one wishes and may be undertaken periodically during the day, indeed whenever and if the sun makes a showing.

Results from this 'central sun' technique are normally accurate to plus or minus two minutes of a degree, this measurement determining the ultimate precision of any further measurements referred to the RO. The accuracy can be improved using method (b), but if the Sun only peeks out for a few seconds then method (a) will enable azimuths to be established to within a fifteenth of one degree.

EXAMPLE ONE - SUN CENTRED ON CROSSWIRES

Here is an actual measurement set made with a T16 instrument. Using the technique described above, the following readings were taken around local noon (1:19 pm BST) at a site (latitude 52N04: Longitude 4W41). The Reference Object (RO - set at zero degrees azimuth)) was a television aerial pole clamped to a chimney about 400 metres distant.

Reading	Chrono time	Horizontal Angle	Vertical Angle
	h m s	d m s	d m s
1.	13 00 00	22° 44′ 00″	44° 37′ 15‴
2.	13 10 00	26° 13′ 20″	44° 45′ 00″
3	13 14 26	26° 47′ 05″	44° 49′ 00″
4.	13 16 11	27° 23′ 00″	44° 49′ 40″
5.	13 17 54	28° 00′ 30″	44° 49′ 55″
6.	13 18 47	28° 17′ 00″	44° 50′ 00″
Local Noon (LMT) occurred between these two readings (cloudy!)			
7.	13 21 52	29° 23′ 50″	44° 50′ 00″
8.	13 23 19	29° 59′ 40″	44° 49′ 55″
9.	13 24 36	30° 22′ 00″	44° 49′ 35″
10.	13 25 45	30° 46′ 50″	44° 49′ 00″
11. (cloudy)	13 27 07	31° 14′ 15″	44° 48′ 40″
12. (cloudy)	13 28 20	31° 40′ 10″	44° 48′ 30″
13.	13 29 30	32° 04′ 25″	44° 48′ 30″
14.	13 31 02	32° 36′ 55″	44° 47′ 50″
15.	13 32 27	33° 06′ 40″	44° 47′ 00″
16.	13 34 27	33° 48′ 35″	44° 45′ 40″
17.	13 37 09	34° 45′ 00″	44° 43′ 25″

ANALYSING THE DATA TO OBTAIN A TRUE AZIMUTH FOR THE RO

1. You will observe that these readings show the sun reaching *culmination* (its **maximum elevation** for the day), then falling away. Culmination occurs at local noon (LN), by definition, when the sun transits the meridian. Its azimuth is then 180˚, and from the above readings this transit occurred between 13:18:47 and 13:21:52 (reading 6. and 7.) The RO was then between 28˚ 17′ and 29˚ 23′ 50″ less than 180˚, suggesting its true azimuth lies between 151˚ 43′ 00″ and 150˚ 36′ 10″ . The average figure is 151˚ 09′ 00″, a 'best estimate' but probably not very accurate as there is over a degree 'spread' as the sun 'tops' for the day, not accurate enough for our purposes. A large cloud temporarily added to the uncertainty of precision.

2. Much better is to now refer to an ephemeris, where the Sun's azimuth and elevation are given for any given date, time and place (lat. and long.). Entering these data into Solar Fire, one can quickly establish that local noon (LMT) occurred at 13:21 hrs, the Sun was then at azimuth 180˚ (which it always is at local noon) and at elevation 44˚ 48′. The theodolite elevation readings fall with 2′ of this, within the likely refraction errors, confirming that the instrument is delivering accurate elevations, though not (as yet) delivering accurate enough azimuths! However, if one now enters the individual times for each reading into Solar Fire, each reading will normally lie within plus or minus one minute of a degree accuracy. Add all the results and dividing by the number of results will establish the best figure for the RO azimuth.

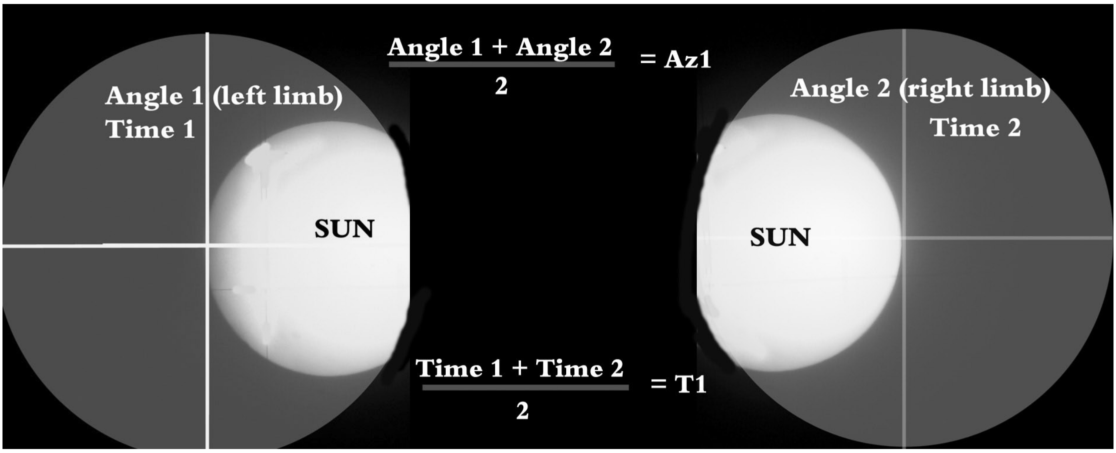
EXAMPLE TWO - CALCULATE THE AVERAGE VALUE FOR THE RO AZIMUTH

Here is the previous table with the actual values (to the nearest minute of degree) for the Sun's azimuth and Elevation placed alongside, for each measurement time.

	Chrono time	Horizontal Angle		Vertical Angle	
		Solar Az	theo	Solar El	theo
	h m s	d m	d m s	d m	d m s
1.	13 00 00	172˚ 43′	22˚ 44′ 00″	44˚ 35′	44˚ 37′ 15″′
2.	13 10 00	176˚ 12′	26˚ 13′ 20	44˚ 44′	44˚ 45′ 00″
3	13 14 26	177˚ 45	26˚ 47′ 05″	44˚ 46′	44˚ 49′ 00″
4.	13 16 11	178˚ 21′	27˚ 23′ 00″	44˚ 47′	44˚ 49′ 40″
5.	13 17 54	178˚ 57′	28˚ 00′ 30″	44˚ 47′	44˚ 49′ 55″
6.	13 18 47	179˚ 16′	28˚ 17′ 00″	44˚ 47′	44˚ 50′ 00″
	Local Noon (LMT) occurred between these two readings				
7.	13 21 52	180˚ 21′	29˚ 23′ 50″	44˚ 48′	44˚ 50′ 00″
8.	13 23 19	180˚ 51′	29˚ 59′ 40″	44˚ 47′	44˚ 49′ 55″
9.	13 24 36	181˚ 18′	30˚ 22′ 00″	44˚ 47′	44˚ 49′ 35″
10.	13 25 45	181˚ 42′	30˚ 46′ 50″	44˚ 47′	44˚ 49′ 00″
11.	13 27 07	182˚ 11′	31˚ 14′ 15″	44˚ 47′	44˚ 48′ 40″
12.	13 28 20	182˚ 36	31˚ 40′ 10″	44˚ 46′	44˚ 48′ 30″

13.	13 29 30	183° 01′	32° 04′ 25″	44° 46′	44° 48′ 30″
14.	13 31 02	183° 33′	32° 36′ 55″	44° 45′	44° 47′ 50″
15.	13 32 27	184° 03′	33° 06′ 40″	44° 44′	44° 47′ 00″
16.	13 34 27	184° 45′	33° 48′ 35″	44° 43′	44° 45′ 40″
17.	13 37 09	185° 42′	34° 45′ 00″	44° 41′	44° 43′ 25″

By subtracting column four from column three one obtains an azimuth value for the reference object (RO). Complete for all the readings and then obtain an overall average value for the azimuth of the RO, as explained above. This derived value of the RO azimuth is **150 degrees 56 minutes and thirty seconds** - normally within plus or minus two minutes of degree, accurate enough for much archaeoastronomical work. It is the most vital data of the whole survey!



Technique (b) Using the Sun's outer limbs in pairs of readings

This technique offers at least a two-fold accuracy improvement, to well within a single minute of one degree, (plus or minus half a minute of degree) if performed carefully. This is about as good as one can expect from an ordinary surveying theodolite, well set-up, in good viewing conditions.

1. As for technique (a), locate the Sun's disc in the telescope. As previously, count down to zero from the chronometer having adjusted for the left-hand limb of the Sun's disc to touch the central crosswires. Record the time as before, with the horizontal and vertical angle.

2. Every few minutes repeat stage 1.

3. After obtaining three or four readings in this way change the set up such that the right-hand limb of the Sun is employed against the central crosswires. Take an equal number of readings, again spaced a few minutes apart.

EXAMPLE THREE: SUN'S RIGHT AND LEFT LIMB ON CROSSWIRES

RO 0˚ 0′ 0″. Site coordinates: Lat: 52˚N5′40″; Lat: 4˚W40′ 45″

	LEFT LIMB		RIGHT LIMB	
	Chrono time	Horiz Angle	Chrono time	Horiz Angle
	h m s	d m s	h m s	d m s
1.	13 05 24	344˚ 53′ 30″	13 12 26	346˚ 50′ 03″
2.	13 07 47	345˚ 32 55″	13 14 18	347˚ 22′ 20″
3	13 10 13	346˚ 14′ 50″	13 15 30	347˚ 43′ 30″

4. Measurements are now coupled in pairs. Three readings from each limb will normally suffice. The first left-right pair are averaged, so that one adds the two horizontal angles and divides the result by two to obtain a central Sun angle. Similarly, find the midpoint of the two timings to obtain the time corresponding to this central Sun angle. Repeat for each pair of readings, thus:

	(mean) h m s	d m s	diff from RO (360˚ - d˚m′s″)	Sun actual Az
1.	13 08 58	345˚ 51′ 47″	14˚ 08′ 13″	136˚ 50′
2.	13 11 03	346˚ 27′ 38″	13˚ 32′ 22″	137˚ 36′
3.	13 12 52	346˚ 58′ 55″	13˚ 01′ 05″	137˚ 58′

5. Refer to the ephemeris for the date, time and place of your station, and evaluate the actual azimuth of the Sun for each pair of averaged readings. These readings are shown in (feint) above in column four.

6. Calculate the actual azimuth of the RO, for each pair of readings, by adding the last two columns above. The results should all fall within one or two minutes of a degree. Take an average figure to obtain the best estimated figure for the azimuth of the RO.

1. RO azimuth (pair 1.)	**150˚ 58′ 13′**	
2. RO azimuth (pair 2.)	**150˚ 58′ 22″**	**[spread less than 1′]**
3. RO azimuth (pair 3.)	**150˚ 59′ 05″**	

7. The best estimate for the true azimuth of the RO is now obtained by averaging the three pairs of readings,

Average: RO azimuth = 150˚ 58′ 53″

[Note that all three reading pairs fall within a single minute of one degree.]

8. As for method (a), one can now accurately determine the azimuths of any object within view from the theodolite station. In the field, angles are all referred to the RO at this stage and *are adjusted later once the Sun azimuth figures from the ephemeris are found. These adjustment calculations will normally be performed when off site, unless one takes a laptop with ephemeris software on site.*

One minute of a degree is about the achievable limit of accuracy using these techniques. This is adequate to confirm any astronomical alignment from the monument under inspection. No great archaeoastronomical discovery is going to be forfeited deriving from this accuracy of measurement.

Taking an HORIZON PROFILE

At any time during the survey, for example during periods when the Sun disappears behind clouds, one may begin taking a horizon profile, all based on the initial RO=0. Record azimuth and elevation for as many points on the horizon as are relevant to your requirements. Later, after returning to base, some office work will establish the true azimuths of the Reference Object, whence all other azimuths can be corrected. This later stage prevents bias being applied during the survey.

Which Sun-Shoot technique to use?

Both methods require a little practice but for (a) one may obtain a usefully accurate reading from a single showing of the Sun, within two minutes (in time!) of the Sun making an appearance. Note that this reading is within 2.5′ of the best estimate obtained from pairs of Sun's limb measurements.

Technique (b) is more accurate, and may be applied where the day is cloudy and the Sun makes only occasional showings. All results normally fall within 1′ of a degree, which is about the limit of accuracy for a standard surveying theodolite. The aspiring theodolitist should aim to reach this level of accuracy.

In practice though, with the typical weather of Britain, the first reading of the day is always made gratefully and quickly using technique (a), the central Sun! The luxury of more minutes of sunshine may be better appreciated later on, but this often fails to happen and that first reading has established a vital first level accuracy for all azimuths taken from the site (the theodolite station). If the accuracy of the RO azimuth is improved upon at a later time or date, all azimuths obtained from the site may of course be subsequently be upgraded.

*These same techniques may also be applied to the Moon. At the relevant quarter phases, the Moon is well placed (high in the sky) when the Sun is too low to obtain reliable readings because of refraction effects. If you are really keen, then the planets may be used, ideal point sources, but then one is entering a different world, that of the professional astronomer or navigator. Night viewing from the site will be a very different experience and things can go bump in the night, at the site.

The gentle art of 'shooting the sun' is the best technique to ensure accuracy of measurement on site. It needs to be practiced and mastered, and should become a component aspect of any work on ancient sites, used whenever the sun shines. Augmented with GPS readings to establish distances and to confirm angular bearings, the theodolite will enable you to obtain more accuracy and thereby more confidence in your researches, and to draw more realistic conclusions. Archaeoastronomy is more or less dead in the UK as far as the academic establishment is concerned, so right now it's up to you (and me) to produce new evidence to change attitudes to this essential component of prehistoric study!

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www.skyandlandscape.com