TRUE NORTH AND DIRECTION-FINDING FOR ARCHAEOASTRONOMY

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Abstract:

Establishing true north is usually an important aspect of archaeoastronomic site assessment. In this paper several methods that can be used to establish true north as well as the azimuth of a sightline are considered. These methods include: by magnetic compass, by celestial observation, by GPS/GNSS coordinates, and by LiDAR, satellite and aerial photography. For each of these, methods, advantages and limitations are discussed along with a few practical recommendations.

Keywords: true north, magnetic compass, GPS/GNSS, archaeoastronomy

For most archaeoastronomical studies involving the orientations of built structures, one of the first tasks is to determine the azimuth for a sightline relative to true north. This is because true north provides a reference from which directions can be established, whether for a ground feature or a celestial body. The problem is that many archaeological reports and site plans fail to show true north accurately. This happens more often than one might expect.

For example, one of the most famous archaeological projects in the 20th century was Leonard Woolley's excavations at Ur in Mesopotamia (Woolley, 1939). Unfortunately the north arrows on his large scale site plans are in error by 2.5˚– 3˚ (Nissen 1966; Zimmerman 1998). On some plans this appears to be the result of an error in correcting for magnetic declination (Romain, 2019, p. 157). At the major Mississippian-era site of Cahokia in North America, all of the maps in Fowler's otherwise exemplary 'atlas' were incorrectly oriented because "an error was made in compensating for magnetic declination" (Fowler, 1997, p. 57).

Without naming names, more recently, reports have been published by prominent archaeologists that have, for example, failed to apply the correct convergence angle to a UTM azimuth resulting in an erroneous true north representation. Yet another applied an incorrect magnetic declination value to establish the azimuth for a ‘spirit house’ situated in a major mound at Cahokia. In each of these cases, conclusions regarding potential astronomical alignments were affected. Accordingly, the intention here is to review certain basic concepts, update a few methods, and where possible, offer some practical suggestions.

In what follows, several methods for finding true north and the azimuth of a sightline are considered: 1) by magnetic compass; 2) by celestial observation; and 3) by coordinate point data from GPS and satellite and aerial imagery. The paper begins with a few definitions. Next, several kinds of direction-finding instruments are discussed. Because they are so prevalent and often used, hand-held compasses are considered in detail. Also considered are representative examples of older surveying instruments. It is useful to know the capabilities and limitations of such instruments when reading older literature. And it is good to know what preceded the high tech equipment we use today. Discussion next moves to the use of theodolites and surveying transits, astronomical observations, GPS, satellite and other aerial imagery and LiDAR. There are other methods and instruments that can be used for direction-finding such as gyrocompasses. As most readers are not likely to encounter these instruments, these are not considered. The paper concludes with some brief remarks.

Definitions

This paper is not intended as an introduction to navigation, surveying, or archaeoastronomy. Nevertheless, it is necessary to begin with a few definitions as certain terms mean different things to different people.

Meridian

As explained by Wolf and Ghilani (2006, p. 168) with reference to geomatic surveying: “The direction of a line is defined by the horizontal angle between the line and an arbitrarily chosen reference line called a *meridian*. Different meridians are used for specifying directions including (a) geodetic (often called *true*) (b) astronomic, (c) magnetic, (d) grid, (e) record and (f) assumed." In archaeoastronomic work it is important to keep these distinctions in mind as specific directions (e.g., north) will be different — depending on the reference meridian.

North

In most literature the terms *north* and *true north* are used rather loosely. In everyday parlance, true north is usually considered the same as geographic north which is where lines of longitude converge at the North Pole. It is not quite that simple, however. Archaeoastronomers will be familiar with several kinds of *north* to include: geodetic north, astronomical north, magnetic north and grid north to include UTM north, State Plane Coordinate north, and others. These various designations for north are each associated with one of the meridians mentioned above.

Geodetic north is "The direction of the pole of the Earth ellipsoid of reference" (Genovese, 2005, p. 115). Commonly used ellipsoids include Clark 1866, WGS84, and GRS80. In simpler terms, geodetic north is where lines of longitude converge at the north pole. Geodetic north is synonymous with geographic north, but it is not the same as astronomic north.

As explained by McNamee (2017, p. 200): "Astronomical north is formally calculated from the vertical direction of gravity [by plumb line of a levelled theodolite] and the axis of rotation of the planet…" The local vertical is influenced by the Earth's gravitational field which is not uniform across the planet's surface. The difference between the local vertical and a perpendicular referenced to an ellipsoid (i.e., the difference between an astronomic azimuth and a geodetic azimuth) is known as the deflection of the vertical, or Laplace correction. The Laplace correction is typically quite small (only a few seconds of arc) and for most archaeoastronomical work can be ignored.

"Magnetic north is the direction taken by a magnetic needle in the earth's magnetic field" (Buckner 1984, p. 4). Magnetic north and geodetic north are not coincident. In fact, the magnetic north pole is not at a fixed location and its location changes over time

(Figure 1). Magnetic north and geodetic north are currently about 1,200 mi (1,930 km) apart (https://www.ncei.noaa.gov/products/wandering-geomagnetic-poles).

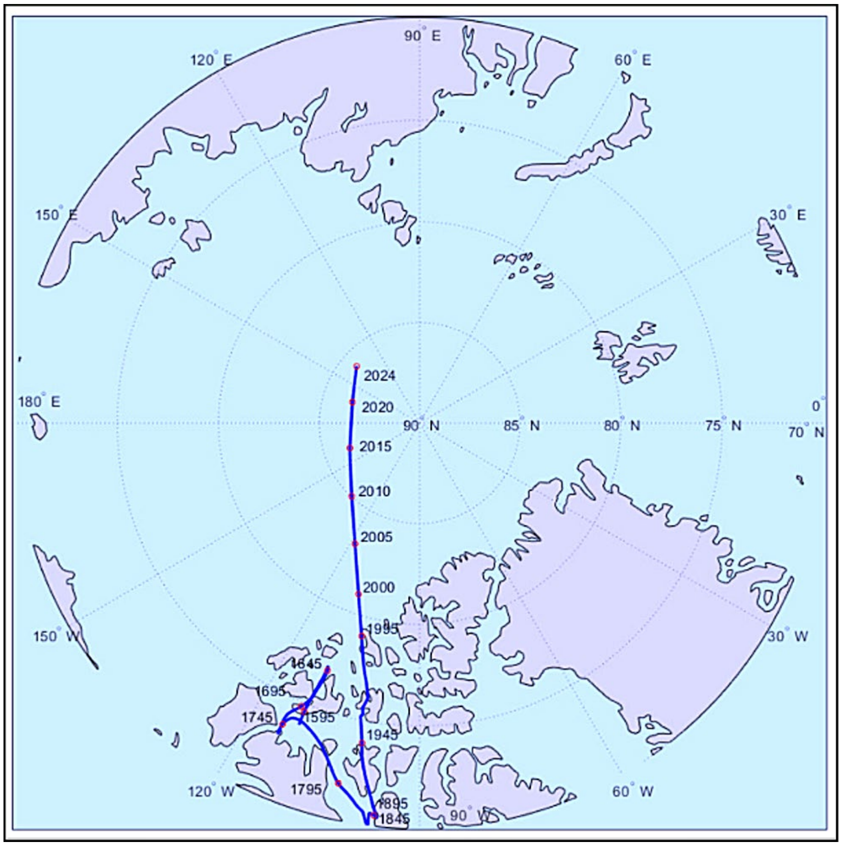


Figure 1. Map showing location of north magnetic pole between AD 1595–2024. CC BY 4.0, Pleter & Constantinescu (2023, Figure 10, based on data from NOAA, 2024.) Enhanced by author.

Grid north (GN) is a direction established by one end of a reference grid meridian (Wolf and Ghilani, 2006, pp. 168–169). In Cartesian coordinate systems such as UTM and State Plane, north is indicated by a central meridian. The quantitative difference between true north (or geodetic north) and grid north depends on the location east or west of the central meridian within a mapping projection (such as a UTM zone) (Figure 2). The difference between geodetic north and grid north and is called the *convergence angle*. The convergence angle can be a positive or negative value.

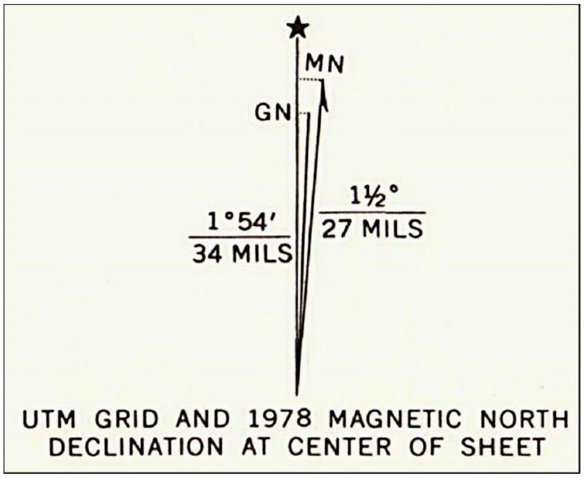


Figure 2. Enlarged detail from USGS 7.5-minute series topographic map. Geodetic (or true north) is shown by the line with a star. Grid north is 1˚54' or 34 mils east of true north and magnetic north is 1 1/2˚ or 27 mils east or true north.

It often happens that archaeoastronomers need to determine true north using a map having a UTM grid projection. There are formulae the researcher can use to determine grid convergence. Even if the correction is calculated correctly, however, it is sometimes the case that the correction is not applied correctly. Confusion can result from not knowing whether the correction should be added or subtracted from the UTM azimuth. Correction values differ in their arithmetic sign depending on whether the location of interest is east or west of the central meridian. For a good introduction to this subject see Ferguson (1991).

When working with grid conversions to establish true north it is helpful to use an online calculator — see e.g.: http://www.remmaps.it/mag/#:~:text=Grid%20Convergence%20is%20defined%20as,(East%20Declination%20is%20positive).

Accuracy and Precision

Although often used interchangeably, *accuracy* and *precision* are not the same thing. Accuracy denotes how close a given measurement is to the true value of the quantity. Precision is the closeness of one measurement to another (McCormac, 1991, p. 12). That said, it is useful to keep in mind the following observation made by archaeoastronomer Frank Prendergast (2015, p. 399): “For most archaeoastronomical applications, a final accuracy of several arc minutes is usually satisfactory…. Nonetheless, it is prudent to observe data to a higher level of accuracy than what is actually required.”

Bearings and Azimuths

There are a couple of different ways to express the direction of a line — i.e., *bearing* and *azimuth*. Often times the two terms are used interchangeably. As a factual matter, however, they are not the same. For purposes here, the definitions offered by DiBiase (2023, c. 5, p.7) are appropriate: “A *bearing* is an angle less than 90° within a quadrant defined by the cardinal directions. An *azimuth* is an angle between 0° and 360° measured clockwise from North.”

Importantly, bearings “are measured both clockwise and counterclockwise (Van Sickle, 2017, p. 22; also see Wolf and Ghilani 2006, p. 170). That is to say, bearings are measured east or west from the north or south end of a reference meridian, with the prefix of the bearing indicating which end of the meridian the bearing is turned from. This is followed by the numeric value of the angle. Lastly the suffix E or W indicates the direction of the turn from the meridian to the bearing line. Figures 3a and 3b show the difference between bearings and azimuths.

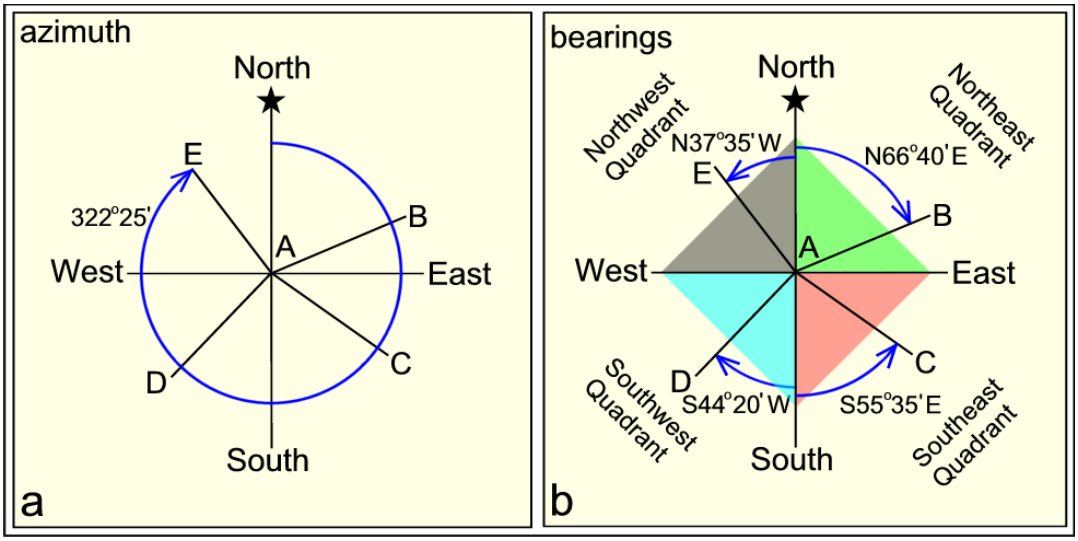


Figure 3a. The azimuth of line A-E is 322˚ 25’ measured clockwise from north.
Figure 3b. The bearing of line A-E is N37˚ 35’W, other bearings as shown.
Drawings by author.

Although bearings are seldom used today in archaeoastronomy, there are occasions where the investigator may encounter an old map or report with relevant directions given in bearings (e.g., Romain, 2023). In such cases it is useful to know how to convert bearings to azimuths. For NE quadrant bearings the azimuth is the same as the bearing. For SE quadrant bearings, subtract the angle from 180˚ thereby giving the azimuth. For SW quadrant bearings, add the angle to 180˚ thereby giving the azimuth. For NW quadrant bearings, subtract the angle from 360˚ thereby giving the azimuth.

Geodetic Datums

As defined by the NOAA National Geodetic Survey (https://oceanservice.noaa.gov/facts/datum.html#), “A geodetic datum is an abstract coordinate system with a reference surface (such as sea level) that serves to provide known locations to begin surveys and create maps.” There are hundreds of datums. Among the most important are: NAD27, NAD83, and WGS84. NAD27 refers to the North American Datum of 1927 and is based on the Clark 1866 spheroid. This datum is often found on older maps. NAD83 (North American Datum 1983) uses the GRS1980 spheroid. WGS84 (World Geodetic System) is a more recent datum and uses the WGS 1984 spheroid. WGS84 is used by GPS, smart phone apps, 911 call centers, and computers. Some years ago, before they were revised, the datums for NAD83 and WGS84 were close enough to be considered the same. That is no longer the case as both datums have been updated and revised. For more on this see: https://www.ngs.noaa.gov/CORS/Articles/WGS84NAD83.pdf. Also see: https://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=Projection_basics_the_GIS_professional_needs_to_know.

When working with a combination of maps and GPS data it is important to recognize how different datums affect position information. GPS coordinates plotted using the WGS84 datum in either latitude/longitude or UTM format will result in a ground location different from the same latitude/longitude or UTM coordinates using NAD27. In some areas the difference can be dozens of meters (https://www.birdandhike.com/General_Info/Datums/_Datums.htm). There are many options for transforming coordinate data from one datum to another. GIS (Geographic

Information System) programs such as ArcGIS (ESRI, 2024), QGIS (QGIS Development Team, 2023) and MapInfo Pro (Precisely, 2024) have options for transforming coordinate data. And there are online apps that will make the conversions — see Appendix 1.

Compass Error

The difference between a true direction (e.g., true north) and the direction indicated by a magnetic compass is referred to as compass error. There are numerous sources or potential causes of compass error. These include: magnetic declination, deviation, instrument error, magnetic dip, parallax, and observational errors such as incorrect reading of the compass.

Magnetic Declination

Magnetic declination (sometimes referred to as variation) refers to the difference between geodetic north and the north magnetic pole.

Magnetic declination varies from place to place and over time (Figures 1 and 4). Topographic maps and navigation charts typically show the magnetic declination for the area they cover. However, as noted, declination changes over time. These changes occur annually and even during the course of a day. Annual change in declination is due to the movement of molten iron within the Earth as well as solar radiation. Annual change is not consistent across the Earth and can range from about 1 to 7 minutes of arc per year. Diurnal variation is relatively minimal. Sapkota (2024) notes: “Diurnal variation tends to be more pronounced in regions located at higher latitudes…. During the summer months, the variation is generally more pronounced compared to winter…. [and] it tends to be more substantial during daylight hours, particularly around noon when solar radiation is strongest.” (Also see Sipe, 1995, Table 21-1.) There are also irregular variations in magnetic declination. Sapkota (2024a) explains, “irregular variations are abrupt and are typically triggered by phenomena such as magnetic storms, earthquakes, and other solar influences (such as solar flares or geomagnetic activity).”

As a practical matter, the most reliable and accurate way to determine declination for a given location and date, is by online calculator such as provided by the National Oceanic and Atmospheric Association (NOAA) at: https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml .

Important to recognize when using the NOAA calculator is that: “Accuracy for the declination is generally within 30 minutes (0.5 degrees) of arc” (https://www.ngdc.noaa.gov/geomag/calculators/help/declinationHelp.html).

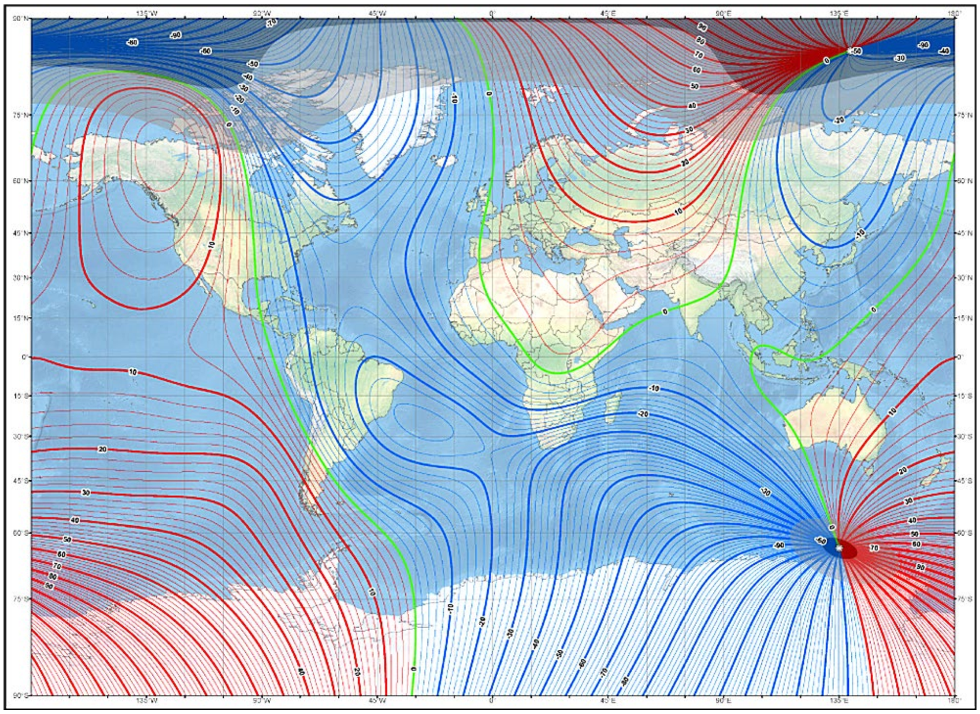


Figure 4. World Magnetic Main Field Declination Model epoch 2025.0 (NOAA 2024). Miller Cylindrical Projection. Red lines positive declination, blue lines negative declination, yellow agonic line. 2˚ contour interval. Illustration from: https://www.ncei.noaa.gov/products/world-magnetic-model

To Convert Magnetic Azimuth to True Azimuth

For archaeoastronomic work it is often the case that a magnetic azimuth as indicated by the compass needle needs to be converted to an azimuth referenced to true north. To do this, the first step is to determine the local declination. If the magnetic declination is east, then the declination is added to the indicated compass azimuth. If the declination is west then the declination is subtracted from the compass azimuth.

To Convert True Azimuth to Magnetic

Conversely, it is sometimes necessary to convert a true azimuth to a magnetic azimuth. This might be required, for example, when one needs to navigate across terrain (or airspace or water) using magnetic compass but the map or chart being referenced is oriented to true north. In such cases, if the declination is east then the declination value is subtracted from the true azimuth indicated on the map to obtain a magnetic azimuth. If the declination is west then the declination is added to the true azimuth to obtain a magnetic azimuth. A helpful mnemonic for converting between true north and magnetic north is: ‘true to mag, east is least, west is best’ — meaning to convert from a true to magnetic heading the declination value is subtracted if it is east or added if it is west. Apply the mnemonic in the opposite way to convert from magnetic to true.

Magnetic Deviation

Magnetic deviation refers to compass error caused, for example, by proximity to magnetized objects or metal objects containing iron, steel or nickel, or in some cases, location in an area having iron ore deposits containing hematite, magnetite or pyrite. Indeed, there are regions where iron ore deposits severely affect a magnetic compass. These areas include the Mesabi Iron Range in Minnesota, areas in the Upper Peninsula of Michigan, the Kursk Magnetic Anomaly in Russia, and Bangui Magnetic Anomaly in Africa. Small areas of magnetic disturbances are sometimes shown on nautical and aeronautical sectional charts.

More locally, compass deviation can be caused by vehicles, fences, steel towers, direct current electrical lines, buried metal objects such as water pipes and conduits, railroad tracks, steel buildings, steel reinforced concrete, and survey equipment such as steel tapes and rods. Sipe (1995, p. 517) recommends that compasses be kept at least 23 m (75 ft) away from railroad tracks, 15 m (50 ft) from an automobile, and 6 m (20 ft) from a wire fence. Smaller objects that can influence the compass needle include other compasses, flashlights, belt buckles, metal buttons, keys, knives, watches, rings, metal frame eyeglasses, and cell phones. In particular, newer iPhones have powerful built-in magnets know as MagSafe for charging and attaching accessories. These phones will cause a substantial swing of the needle when in proximity.

There are other kinds of magnetic deviation — mostly relevant for aviators and maritime operators to include oscillation, northerly turning error, heeling error, and acceleration/deacceleration errors. These errors are dealt with in a variety of ways to include mathematical corrections, magnetic compensators and use of a compass deviation card (see e.g., NGIA, 2004; FAA 2017). For archaeoastronomy these errors are not of concern.

Magnetic deviation is different from instrument error which can result from manufacturing issues. With reference to this kind of error, outdoor survival expert Mark Johnson (2003, p. 116) notes: “I have personally tested compasses that were as much as 5 degrees off the proper magnetic reading.” Instrument error can result from: reduced needle sensitivity and precision due to worn pivot and/or improper balance, non-verticality of sight vanes, non-horizontality of graduated ring, unequal divisions of the graduated ring, misalignment of the line of sight, and misalignment of the compass’s magnetic and geometrical axes.

The simplest way to check for deviation is to take a forward and backsight measurement from two ends of a survey line. If the difference between the two azimuths is 180˚ then there is no local deviation. Where deviation is noticeable (and local) one option may be to establish and take measurements using a sightline that is parallel to the structure or feature of interest and away from the source of deviation.

To check for instrument accuracy, sight on a distant point having a known azimuth from your location (as determined, for example, by map and corrected for declination) and compare the two azimuth values. The numbers should be the same. Comparisons can also be made using celestial azimuths (such as Polaris sightings) or GPS. For discussion concerning how to compensate for instrument error see Farrar (1987, pp. 12, 18). Basically the procedure is to add or subtract the instrument error from the indicated azimuth to obtain a corrected magnetic azimuth.

Magnetic Dip (or Inclination)

The Earth’s magnetic field is not even across the surface of the planet. Terrestrial magnetism causes one end of a compass needle to dip downward. Magnetic dip differs in different hemispheres. In the northern hemisphere the north end of the compass needle will dip downward; in the southern hemisphere the south end of the needle will dip downward. Most compasses are balanced by the manufacturer to compensate for dip for either the northern or southern hemisphere. Some compasses (e.g., high-end Suunto and Brunton compasses) have globally balanced needles.

Parallax

The term *parallax* is used in different ways in different contexts. With respect to the magnetic compass, parallax error refers to the difference in reading that results from looking at the compass needle from any angle other than straight down. It is difficult to quantify parallax error as every situation is different. To avoid this error, to the extent possible, the operator should view the compass dial at a perpendicular angle (i.e., looking straight down at the dial), or use a compass designed to eliminate this error (see discussion below).

Determining North by Magnetic Compass

There are many different kinds of compasses designed for air, sea, and land use (https://compassmuseum.com/index.htm). When considering what compass to use the researcher needs to ask, what needs to be accomplished with the instrument and what degree of accuracy is required? Not all compasses are well-suited for archaeoastronomic work and accuracy varies widely. In what follows the main kinds of compasses are noted along with comments regarding their usefulness for archaeoastronomy.

The direction indicator in a compass can be a needle, dial, or ring. Whatever the case the magnetic north-pointing indicator will have a pivot (or socket) that balances on a pin. High quality compasses have a hard pivot, often made of sapphire. A harder pivot is preferred because as the pivot wears down, increased friction causes a slower response of the needle.

A needle lock is a useful feature that locks the compass needle in place. This prevents unnecessary movement of the needle and wear on the pivot when not in use.

On smaller compasses (where provided) the needle lock is engaged when the cover is closed. On larger survey and transit compasses, the needle lock is engaged by turning a small screw on the side of the compass housing.

Most compasses have a way to dampen movement of the needle or dial so it quickly comes to rest. Some compasses are liquid-filled. Purified kerosene is often used as it is stable over a wide range of temperatures. Other liquids include mineral oil and alcohol. As a result of temperature changes, bubbles can occur in liquid-filled compasses. If small, bubbles are of no consequence. Several compass manufacturers use a copper induction damping system to slow the needle or dial without liquid.

The magnetism of a compass needle can weaken over time due to long term proximity to ferrous objects, high heat, or nearby strong magnetic fields. Symptoms that a needle is losing its magnetism include slow swing of the needle and excessive time to settle on north-south. Older compasses can lose magnetism to where they are not usable. On the other hand, many high quality compasses made in the mid to late 1800s still work quite well.

Many newer compasses (especially hand held orienteering compasses) are provided with a way to adjust for magnetic declination. Typically the adjustment is rather crude and the graduations on the declination scale are so tightly spaced that accuracy approaching ½˚ in setting the declination is basically impossible. Compasses that have a floating dial do not have a way to correct for declination.

Compasses dials can be in either quadrants or azimuths. A quadrant compass that is graduated in degrees will be divided into quadrants with each quadrant reading from 0˚ to 90˚ east or west. An azimuth compass in degrees will be marked from 0˚ to 360˚ all around in a complete circle.

Compass dials can be graduated in degrees, mils, or grads. Mils (short for milliradians) are angular units of measurement that divide a circle into 6,283 parts, rounded to 6,400. There are 17.78 mils in 1˚ (US Army, 2021, p. 6-1). Stated another way, one mil equals 0.05625˚. Therefore, to convert mils to degrees multiple the number of mils by 0.05625. Alternatively, an online calculator can be used (see e.g., https://www.inchcalculator.com/convert/mil-to-degree/). Measurements using mils can be more accurate than degrees — since mils are smaller units requiring less interpolation. Figure 5 shows a protractor graduated in mils and degrees. As shown, line A-B extends along an azimuth of 5,680 mils — which is equal to 319.5˚.

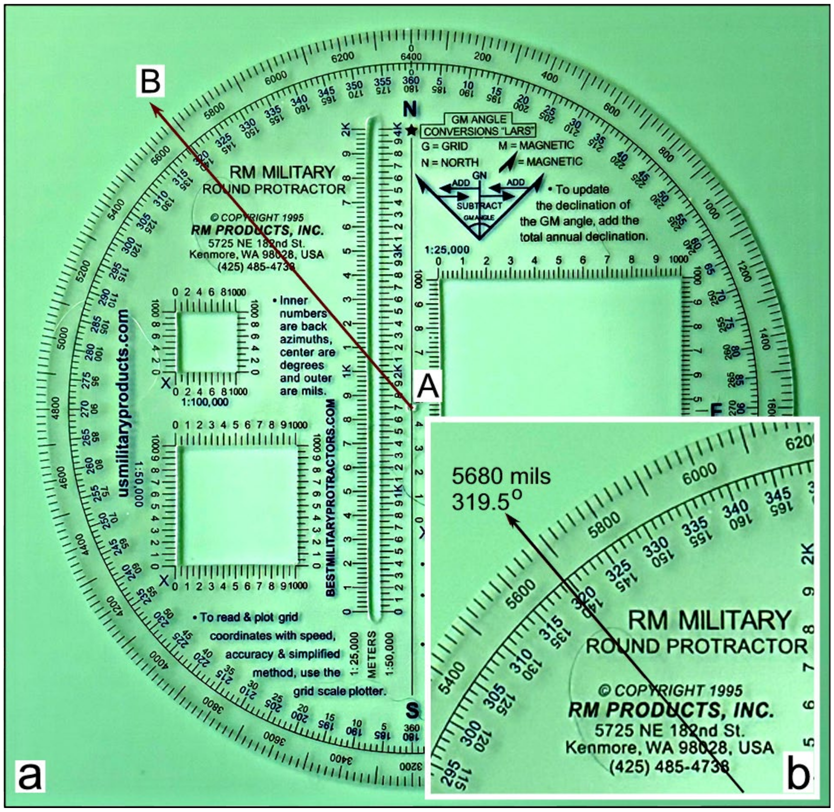


Figure 5a. Round protractor in degrees and mils.
Figure 5b. Enlarged detail showing relationship between degrees and mils.
Photos by author.

Grads (or gradians) are angular units of measurement used mostly in Europe and found on some compasses. In this system a circle is divided to 400 grads. The grad can be divided into 100 centigrads. A right angle equals 100 grads — thus the unit is convenient for various surveying applications.

When storing multiple compasses it is recommended that sufficient distance be maintained between compasses so that their needles are not affected by the nearest one. Takacs (2010, p. 174) recommends a separation of at least 7.6 cm (3 in).

In what follows, discussion of compass types proceeds from small handheld compasses to larger, more accurate instruments. Sometimes categories overlap. And sometimes the same kind of instrument will be known by different names. Generally theodolites are more accurate than transits. Total stations, which are a kind of theodolite, measure horizontal and vertical angles with the addition of an electronic distance module (EDM) (laser) to measure distance. Transits are often referred to using different names depending on size, telescope power, weight, and accuracy as well as unique names assigned by various manufacturers. Thus there are engineer's transits, surveyor's transits, and vernier transits. In what follows, instruments are referred-to in the same way that relevant catalog information and manuals refer to them.

1) *Baseplate compass*

This style instrument consists of a flat clear plastic base with compass. It usually has a magnifying glass and map-reading scales on its base. Shown in Figure 6a is the *Cammenga D3-T*. The dial is graduated every 5˚ degrees with another scale on the outside edge of the dial marked at 20 mil (x100) increments. To determine a magnetic azimuth the user aligns the center sighting line on the compass crystal with the front sight on the compass base and a distant target.

Figure 6b shows the *Brunton TruArc 3* compass. It is included here because it has a potentially useful feature. Inside the perimeter of the black 0˚–360˚ bezel ring is a yellow declination ring. By squeezing the top center and back of the compass between thumb and forefinger, the declination ring can be rotated and set to the local declination. This feature might be useful for those who wish to visually confirm a declination calculation.

2) *Baseplate with mirror*

This style instrument is a baseplate compass with attached mirror. Figure 6c shows the *Recta DP* liquid-filled mirror compass. Made in Switzerland in 1941, the *Recta DP* was originally issued to the Swiss Army. Due to its ruggedness it continues to be used by armed forces around the world. Pull the compass out of its housing and a metal mirror falls into place from the bottom. The user sights a target through the front and rear sights and reads the azimuth in the mirror reflection.

Figure 6d shows the *Suunto MC-2* liquid-filled mirror compass. The dial is graduated every 2˚; its accuracy is 2.5˚ (https://www.suunto.com/en-us/Products/Compasses/Suunto-MC-21/Suunto-MC-2/). To use this compass the mirror cover is opened to about a 45˚ angle. The sighting notch on the mirror cover is lined-up with the target. While looking into the mirror the bezel is rotated until the center orienting lines inside the compass line-up with the north arrow. The azimuth is then shown by the indicator line on the baseplate hinge or mirror cover.

Perhaps the most sophisticated of the mirror baseplate compasses currently available is the *Brunton Truarc20 Professional* compass. This compass features a Global Needle and EverNorth Magnet. The needle is operational in both hemispheres and according to Brunton (https://www.brunton.com/pages/manuals-truarc20-compass), the EverNorth Magnet “will not suffer from interference from nearby metal objects, electronic devices like transceivers, or anything else you that you might be carrying.” The azimuth ring is graduated in 1˚ increments. The instrument has a bubble level, built-in clinometer, magnifying lens and tool-free declination adjustment.

Each of the compasses just discussed have useful features. However, baseplate and mirror compasses are designed for hiking and general direction finding. Due to their small size these compasses are difficult to hold steady. And they are subject to parallax errors. In general, these compasses are not suitable for most archaeoastronomic work.

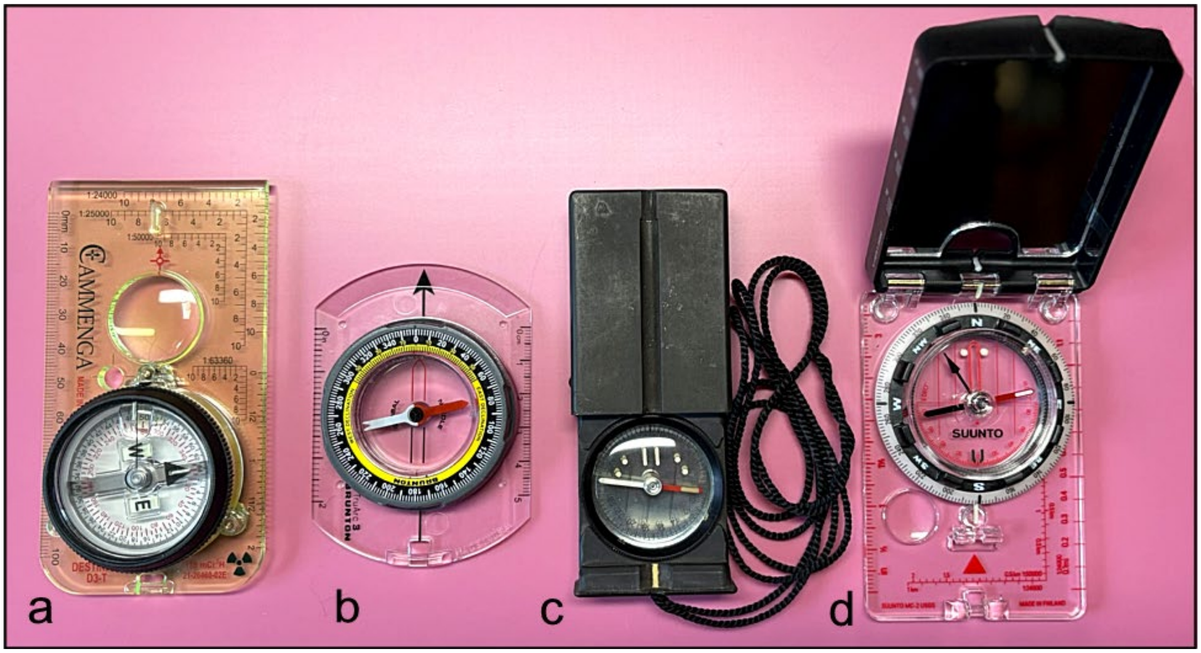


Figure 6a. *Cammenga D3-T* baseplate compass. 3.8 cm (1½ in) floating dial, 5˚ graduations and mils.
Figure 6b. *Brunton TruArc 3* baseplate compass. 3.2 cm (1 ¼ in) needle, 2˚ graduations.
Figure 6c. *Recta DP* “matchbox” compass. 3.2 cm (1¼ in) needle, 5˚ graduations.
Figure 6d. *Suunto MC-2* mirror baseplate compass. 3.2 cm (1¼ in) needle, 2˚ graduations.
Photo by author.

3) *Lensatic compass*

Lensatic compasses use a magnetized dial rather than a needle. The lensatic compass was invented in the late 1930s and quickly adopted by the U.S. Army. Figure 7a shows the *Cammenga 3H*. The *Cammenga 3H* is an aluminium body, induction-dampened compass with tritium sights. (*3H* is the symbol for tritium — the radioactive isotope that causes the sights to glow in the dark.) The compass dial is graduated in 5˚ increments. The outer edge of the compass disk is graduated in mils with a stated accuracy of ± 40 mils. The compass is accurate to about 2.5˚.

To use this compass the operator opens the cover to about a 90˚ angle. The sight wire built into the cover is aligned to the target. The back sight has a magnifying lens. When looking through the lens the thin green line on the face of the compass crystal will be visible over the mils or degree graduations.

Shown in Figure 7b is the *Sportneer DC60-2A*. Made in China, this inexpensive compass is sold under a variety of names. Graduated in 1˚ increments, it is considered a lensatic compass because it uses a side lens to view graduations on the floating dial. The sighting line on the glass cover is so thin that it is difficult to see when looking through the side lens. For persons who use prescription eyeglasses, simultaneous focusing on the scribed sightline and numbers on the dial viewed through the lens will be problematic. The compass has no provision for mounting to a tripod. It is not recommended for archaeoastronomy work.

Figure 7c shows the *Brunton H-3* lensatic compass. Its technical specs are very similar to the *Cammenga 3H*. The induction-damped dial, however, settles noticeably faster than the Cammenga. The magnifying lenses on the Cammenga and Brunton provide a sharp focus on the dial; however, the small diameter of the dials makes these compasses a challenge to hold steady and for archaeoastronomic work, their accuracy leaves much to be desired. Further, lensatic compasses are subject to parallax error.

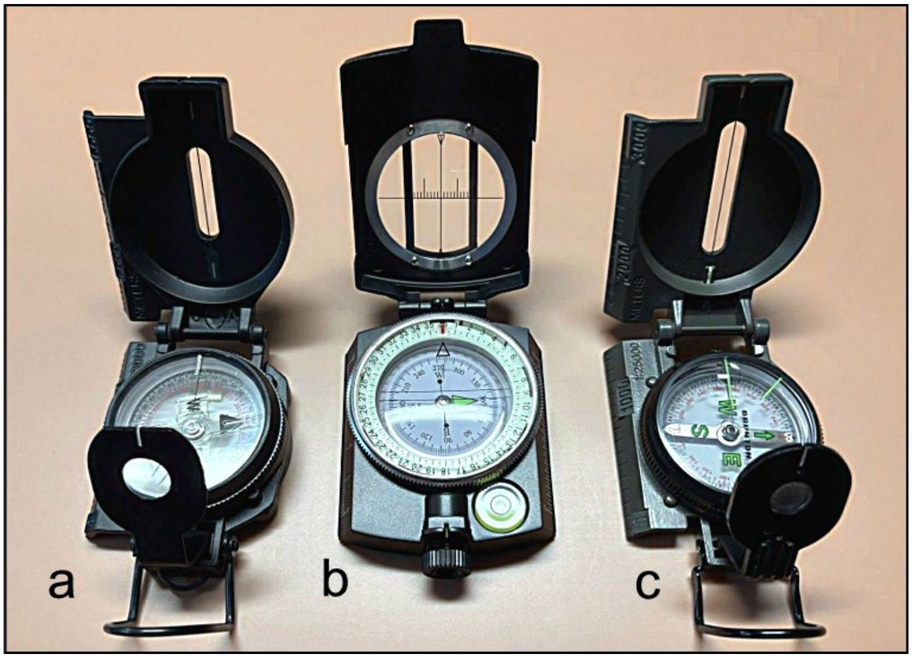


Figure 7a. *Cammenga 3H* lensatic compass. 3.8 cm (1 ½ in) diameter floating dial, graduated in 5˚ increments and mils.
Figure 7b. *Sportneer DC60-2A* lensatic compass. 3.8 cm (1 ½ in) floating dial, graduated in 1˚ increments.
Figure 7c. *Brunton H-3* lensatic compass. 3.8 cm (1 ½ in) diameter floating dial, graduated in 5˚

increments and mils.
Photo by author.

4) *Prismatic compass*

The prismatic compass was invented in 1812. The unique feature of this style compass is that its back sight has a prism magnifier used to read numbers on the dial face. Thus the user is able to see the compass card and target simultaneously. A distinct advantage this compass has over lensatic compasses is that the “prism sighting system eliminates parallax errors” (Pyser Optics, 2023, p. 1).

Figure 8a shows the Wilkie prismatic compass, made in West Germany. It has an attached clinometer that opens-up for slope readings. The compass has a sturdy metal body; and the prism magnifier slides up and down for optimal focusing.

Figure 8b shows the *Sisteco Sight Master SM-3602* prismatic compass, made in Finland. Of all the compasses reviewed herein, this dial on this instrument comes to rest faster than any other and once on target it is exceptionally stable. The green-tinted crystal, however, makes viewing numbers on the dial challenging.

Among the most highly regarded and sought-after prismatic compasses are the *Francis Barker* models *M-73* and *M-88*. The Francis Barker & Son company was established in 1848. After World War II the company changed ownership with the Barker compass line continued by Pyser-SGI Ltd. in Kent, England.

The *M-73* compass was first manufactured in 1973. Many consider the *M-73* to be the finest handheld compass ever made (Figure 8c). The *M-73* gained fame due to its use by the British Army in many theatres of operation. The *M-73* is made mostly of brass; the *M-88* is mainly aluminium. The compasses can be graduated in mils or degrees. Both are liquid-damped. The floating dials are about 3 inches in diameter. The *M-73* and *M-88* are easily accurate to 1/2˚ (9 mils). When held steady the user can interpolate between graduations to 1/4˚.

For nighttime use the compasses are equipped with luminous sights. Older versions were equipped with tritium sights and have the distinctive radioactive trefoil warning symbol on their cover. Newer versions have the letter L for luminous. The luminescent sights can be useful, for example, prior to setting-up a total station for Polaris observations. They can help orient the user to the general direction of Polaris.

To use this compass the cover is opened at a right angle to the compass body. The cover has a front sighting line scribed into the glass window. The sighting line is aligned to the target while looking through the back sight (slit over the prism). The division cut by the sighting line when looking into the prism is the azimuth to the target.

If there is a flaw with this compass it is that it does not have a bubble level. When taking a reading using any compass, the instrument should be level. In the case of the *M-73* and other compasses, one way around this is to place the compass on the flat top of a levelled non-magnetic surveyor’s tripod. The instrument can be temporarily secured using double-sided tape.

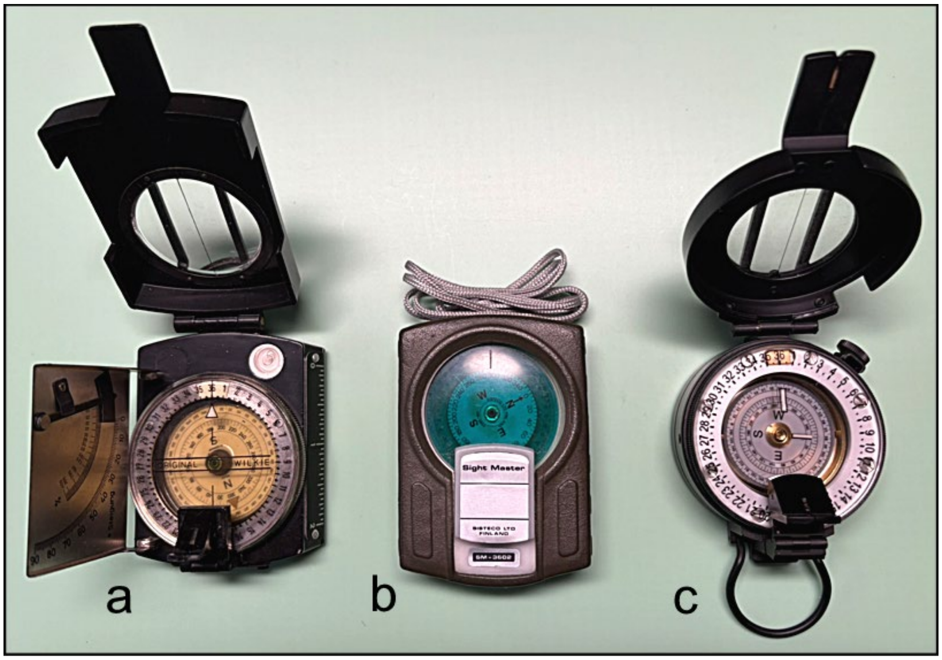


Figure 8a. *Wilkie* prismatic compass. 3.8 cm (1½ in) diameter floating dial, 1˚ graduations.
Figure 8b. *Sisteco Sight Master SM-3602* prismatic compass. 4.1 cm (1 5/8”) floating dial, 1˚ graduations
Figure 8c. *Francis Barker M-73* prismatic compass. 3.2 cm (1¼ in) diameter floating dial, 1˚ graduations. Photo by author.

5) *Optical or Direct sighting compass*

Shown in Figures 9a and 9b are the *Suunto Tandem* and *Brunton OmniSight* compasses. These instruments have a small lens built into the side of the compass body allowing the user to view the floating dial and its graduations. The compass dials have two sets of graduations — one on the upper dial face allowing readings to be made looking straight down at the compass. The second set is on the side of the umbrella-like compass dial. When looking through the eyepiece it is the second set of graduations that is seen. Direct sighting compasses are not subject to parallax error due to how their lenses center the eye on the optical axis.

The *Suunto T*andem combines a floating dial compass with a clinometer. The upper dial face is in 5˚ increments; the side graduations on the dial are at 1/2˚ increments. The compass has a stated accuracy to 1/3˚; the clinometer has an accuracy of 1/4˚ (https://www.suunto.com/en-us/Products/Compasses/Suunto-Tandem/Suunto-Tandem-360PC-360R-G-Clino-Compass/). Because it includes a clinometer, the *Suunto Tandem* has become the handheld compass of choice for many archaeoastronomers. Suunto also offers the model *KB-14* which is the compass without clinometer (1/2˚ graduations) and the model *KB-20* (1˚ graduations).

The *Suunto Tandem* has separate viewing lenses for the compass and clinometer. When using the *Tandem* clinometer it is critical to know that two scales will be seen in the viewing window. The scale on the left is for degrees (0˚–90˚); the scale on the right is for percentage (0%–150%). Instruments that are similar to the *Suunto Tandem* include the *Silva SightMaster* and *Brunton Clino Master SUM360LA*.

The *Suunto Tandem* and *KB-14* have a ¼" x 20 recessed thread on the underside for mounting on a tripod. On the *Tandem* this thread is offset by about 1.7 mm from the center axis of the compass. This necessitates compensating for the offset when setting-up the tripod-mounted compass over a survey marker.

The *Brunton OmniSight* compass is similar to the *Suunto KB-20.* However, on the *Brunton OmniSight* the graduations on the upper dial face are in 5˚ increments; while the side graduations on the floating dial are at 1˚ increments.

When using the Suunto or Brunton compasses just discussed, the manufacturers recommend keeping both eyes open. As explained by Brunton: "…the hairline [i.e., sighting line] can be seen to continue above the instrument housing on the object due to an optical illusion" (https://safety-devices.com/pdf/brunton-sum360la.pdf). For maximum manifestation of the optical illusion, the instruments need to be as near to level as possible. If tilted too much the dials can get hung-up on the inside housing resulting in incorrect readings.

Notably, these compasses can be problematic for persons who have a vision condition known as *hterophoria* (where misalignment of the eye axes causes symptoms such as double and/or blurred vision). Brunton and Suunto advise that it is still possible to get an accurate reading using one eye. But for those not aware, seeing double when first using these compasses can be disconcerting.

Regarding the tripods in Figure 9, the Treknor tripod (Figure 9a) has a 5/8"-11 post; but also comes with a 1/4"-20 thread adapter for mounting Suunto and Brunton compasses. The Brunton tripod (Figure 9b) has a 1/4"-20 thread post for mounting. Neither tripod is ideal for archaeoastronomic work. Both lack a hook for suspending a plumb bob; and due to their light weight, they are not stable. When fully extended the Treknor tripod is 145 cm (57 in) in height; however, when opened to the same extent, the Brunton tripod is only 122 cm (48 in) in height — making a compass mounted on the Brunton tripod difficult to use for anyone over 152 cm (5 ft) in height.

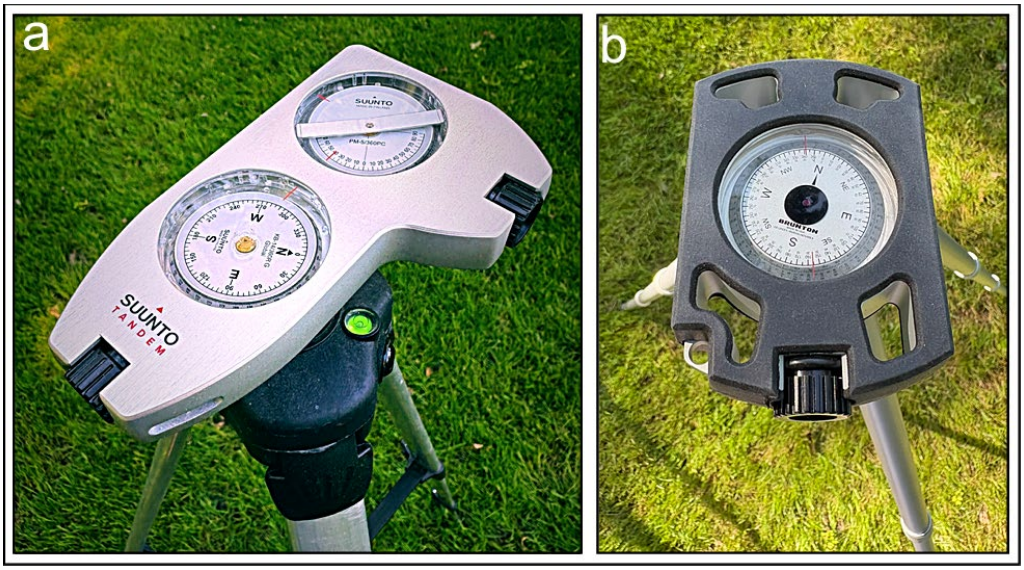


Figure 9a. *Suunto Tandem* optical compass on *Treknor* non-magnetic tripod. 3.5 cm (1 3/8 in) floating dial, ½˚ side graduations.
Figure 9b. *Brunton OmniSight* compass on *Brunton* non-magnetic tripod. 4.1 cm (1 5/8 in) floating dial, 1˚ side graduations and mils.
Photos by author. Not to scale.

6) *Surveyor's compass*

The main feature of this type of compass are its vertical vanes. The vanes have slits used to sight the target. Surveyor's compasses can be a viable option for archaeoastronomic work. Variously graduated in ½˚ or 1˚ increments they typically have large-diameter dials which facilitate reading.

Figure 10 shows an early surveyor's compass. The overall length of the compass is 30.5 cm (12 in). The instrument is quite heavy which explains why later surveyor's compasses were often made lighter (and smaller) by attaching sighting vanes to the compass housing.

Figure 10. Surveyor’s compass made ca. 1880 by John Roach, San Francisco. 11.4 cm (4 ½ in) needle, 1/2˚ graduations, in quadrants.

Figure 11a shows a 1930s-era Francis Barker & Son prismatic surveyor’s compass. It is graduated in 1/2˚ increments. It has a magnetized dial rather than a needle. The bottom of the compass has a 0.650” x 20 threaded socket for attachment to a tripod or Jacob staff. Figure 11b shows a *Keuffel & Esser* (also known as *K & E*) ‘pocket’ surveyor’s compass.

The compass in Figure 11c is the *Keuffel & Esser geologist* compass. Similar versions of this instrument were made by the Leitz, Charvoz, and Warren-Knight companies. The compass is mounted on a square 10 cm x 10 cm (4 in x 4 in) aluminium base. To correct for magnetic declination the compass has a vernier scale that is adjusted by sliding a knob on the instrument’s side housing. The compass has a recessed thread on the underside allowing it to be mounted on a Jacob staff or tripod. The flat base further allows it to be used as a plane table compass. This compass has a clinometer built into its face. Notably, the graduated outer ring rotates. This allows the 0˚ index line on the ring to be lined-up with the compass needle. As a result, when the user looks through the vanes, the sighted azimuth is indicated on the outer ring.

Figure 11a. Francis Barker & Son prismatic surveyor’s compass, made in London, 1937. 9.5 cm (3 ¾ in) diameter ring dial, 1/2˚ graduations, 0˚–360˚.
Figure 11b. K & E ‘pocket’ surveyor’s compass, made in Germany, 1930s. 10.2 cm (4 in) needle, 1˚ degree graduations, in quadrants
Figure 11c. “Geologist’s compass” made ca. 1913 by Keuffel & Esser Co., New York. 6.4 cm (2 1/2 in) needle, 1˚ graduations, in quadrants.
Photo by author.

Of the surveyor’s compasses, the *Warren-Knight 40-1360* compass shown in Figure 12a is arguably the finest in its class. Each compass is hand-made, graduated in 1/2˚ increments and has a 12.7 cm (5 in) needle that facilitates precise readings. According to Warren-Knight (2002, p. 3), “The Warren-Knight Model 40-1300 or 40-1360 Compass will out-perform any Surveyor's Compass ever made.”

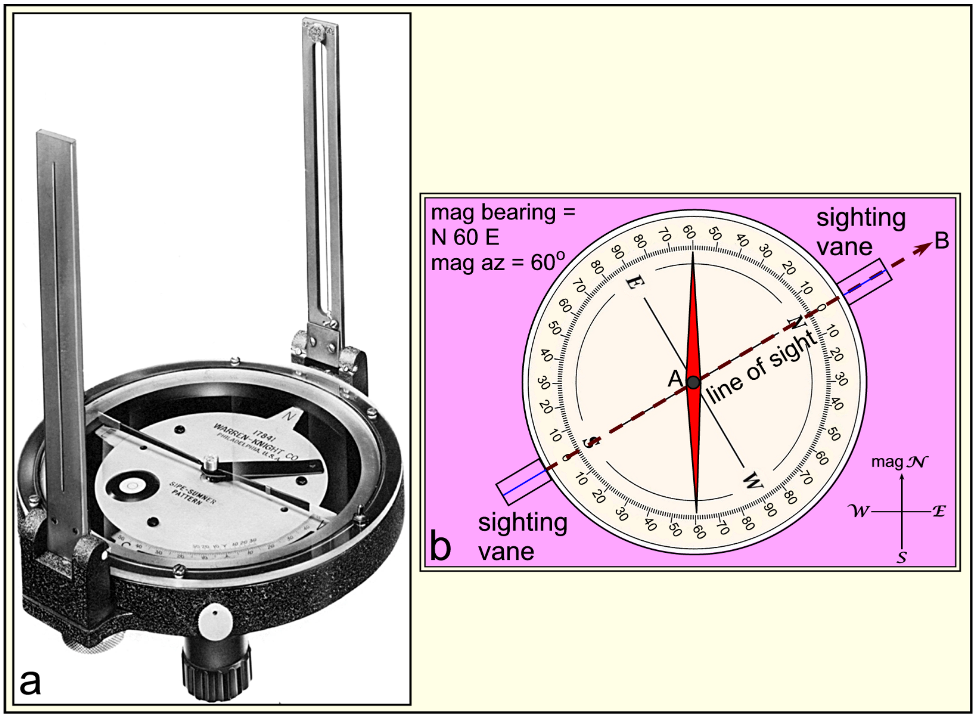


Figure 12a. Warren-Knight *40-1360* compass, made in Philadelphia. 12.7 cm (5 in) needle, 1/2˚ graduations, in quadrants. Photo courtesy of Warren-Knight Instrument Company.
Figure 12b. Surveyor's compass rose in quadrants. Drawing by author.

Very often surveyor's compasses will have east and west directions on the compass dial reversed. To use, the compass is rotated until the target is lined-up through the slits in the vertical vanes. The bearing of the target is then indicated by the compass needle. In Figure 12b, for example, the bearing of line *A-B* is N60˚E.

7) *Transit compass*

The surveyors' transit was invented in 1831 (Engineering News, 1875). It measures both horizontal and vertical angles using a combination of graduated metal rings, vernier scales and a magnetic compass. Depending on the manufacturer, size, weight and accessories, these instruments can be variously referred to as surveyors', explorers', engineer, mountain, reconnaissance, vernier, railroad or mine transits (Gurley and Gurley, 1910). Many of the old instruments are of high quality and a good option for archaeoastronomic work. Nevertheless, it is a good idea to have any older instrument checked for calibration and certified. There are specialized survey repair and supply companies that perform this service. Three of the most representative transit compasses are presented below.

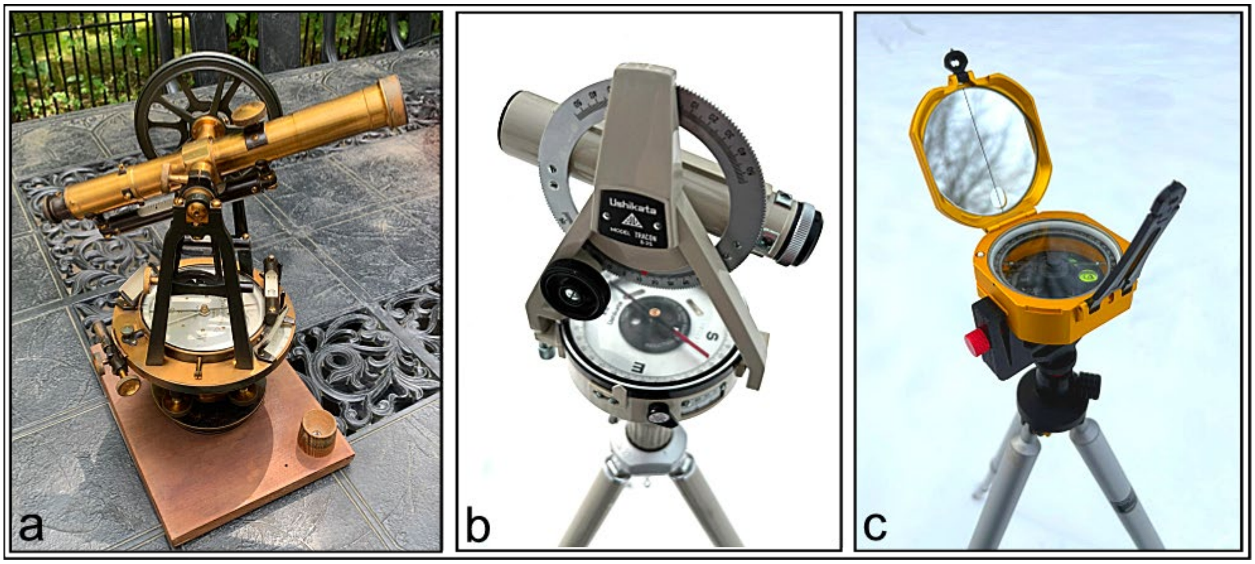


Figure 13a. *Buff & Buff Mfg. Co. transit No. 1C*, bronze finish, silvered compass face, ½˚ graduations, verniers to single minutes of arc.
Figure 13b. *Ushikata Tracon-25* mounted on *Ushikata No. 33* tripod. 1˚ graduations with horizontal vernier reading to 5 minutes of arc.
Figure 13c. *Brunton special edition Gold Standard Transit* mounted on Brunton tripod. 1˚ graduations.
Photos by author.

Buff and Buff transit

Shown in Figure 13a is the *Buff and Buff Precision Transit No. 1C* (Buff and Buff, 1938, p. 41). It was made in the late 1930s. It has a 11.4 cm (4 ½ in) needle and 30.5 cm (12 in) long telescope. The horizontal ring has ½˚ graduations. Declination can be set using an adjusting screw on the housing. According to the U.S. Geological Survey, “The company's transits were exceptionally machined and crafted, and were selected for use in building the Panama Canal due to their precision and excellence” (https://www.usgs.gov/media/images/buff-buff-engineers-transit-case).

Something to be aware of with these older instruments is that they often require an adapter if mounting to a modern 5/8” x 11 thread survey tripod. They are also heavy. This instrument weighs 6.6 kg (14 ½ lbs), not including wooden tripod.

Ushikata Tracon 25 transit

Shown in Figure 13b is the *Ushikata Tracon 25*. It has a 12x telescope with stadia crosshairs and a 7 cm (2.8 in), induction-damped needle. The horizontal and vertical circles are graduated in 1˚ increments. The compass dial is in quadrants. The vernier scale for horizontal measurements can be read to 5 min of arc. For levelling, the instrument has two small bubble levels. A small screw on the side of the housing rotates the graduated bezel for declination adjustment.

The *Tracon 25* is designed to be mounted on a *Ushikata No. 33* tripod. This well-made tripod has a center hook for hanging a plumb bob. The *Ushikata No. 33* tripod has a 17 mm male thread. Accordingly, this tripod will not accommodate other instruments without an adapter. If there is a downside to the Ushikata tripod it is that it is too short. When the legs are extended and spread so they are about 91.4 cm (3 ft) apart for good stability, the instrument height is about 129.5 cm (51 in).

On the other hand, the best feature of this instrument is that after unlocking, the upper arm, telescope and vertical scale fold down so they lay flat. The result is a compact and lightweight package. Tucked into its 19 cm x 15 cm x 11 cm (7 ½ in x 6 in x 4 ½ in) case, it weighs only 1 kg (*sans* tripod). This makes it ideal for travel. In areas where a magnetic compass might be subject to local variation (natural or man-made), or where survey-grade GPS cannot be used, this instrument is accurate enough for Polaris sightings.

Brunton pocket transit

The Brunton pocket transit is a handheld instrument that incorporates a magnetic compass as well as a clinometer (Figure 13c). The instrument is referred to as a transit because it measures vertical as well as horizontal angles. It was patented in 1894 as an alternative to the heavy theodolites and transits carried into the field by geologists, engineers, and surveyors. The Brunton pocket transit remains in common use today by geologists because it allows accurate measurements of geological strike and dip.

The Brunton pocket transit has an induction dampened floating dial graduated in 1˚ increments and is accurate to 1/2˚ (https://www.brunton.com/products/standard-transit-gold). Declination correction is provided by a screw adjustment on the bottom of the compass. The Brunton manual shows a couple of ways to use the instrument for determining an azimuth (Brunton, 2020). In both instances after lining-up the sights on the target it is advisable to press and hold the button lock on the compass thereby locking the needle in place. This facilitates reading the indicated azimuth looking straight down.

The Brunton pocket transit does not have bottom threads for mounting. Rather, it has slots on the sides of its housing that mate the compass to a special Brunton bracket which is then attached to a ball and joint socket and tripod. For persons who wear eyeglasses, simultaneous focusing on front and rear sights to take a reading may be problematic.

Whether using the *Brunton*, *Ushikata*, or *Treknor* tripods mentioned above, if the user finds it impractical to use such short tripods, a work-around solution is to lengthen the legs by attaching lengths of wooden dowel, bamboo, pvc pipe, or cut lumber to each leg using generous wrappings of packing tape or equivalent. Bevel or sharpen the business ends as needed.

Before closing this section, mention should be made of the *Wild B3* “tripod compass.” The *B3* is no longer manufactured and is very difficult to find. What makes it noteworthy, however, is that the instrument “determines the magnetic azimuth with an accuracy of about a tenth of a degree” [estimated] (https://www.wild-heerbrugg.shop/index.php?cPath=1_3_19_77).

Compass Accuracy

Opinions concerning the accuracy of magnetic compasses differ. Zimmerman (1995, p. 90), for example, says: “At best, the expected accuracy of a compass bearing is no better than about 1˚.” Buckner (1984, p. 4), on the other hand says: “Because of the lack of precision in determining magnetic declination and in the compass itself, plus the other uncertainties cited above true north as determined magnetically has uncertainties of probably 30 minutes or more of arc.” Certainly, readings obtained using a small hand-held compass will not be as accurate as readings using a large tripod-mounted compass designed for land surveying. That said, I tend to agree with Buckner. With a high quality, tripod-mounted compass it should be possible to determine a declination-corrected azimuth that is accurate to within plus or minus 1/2˚.

To put this in perspective, at a distance of 1,000 m a 1/2˚ error in establishing a sightline — whether by compass, celestial observation, or GPS is equal to about 8.7 m in lateral spread. At a distance of 30 m, a 1/2˚ error is equal to about 0.25 m in lateral spread. If plotting on a map, then depending on the distance and map scale, a 1/2˚ error may not be discernible by eye (Farrar 1987, pp. 11–12).

For archaeoastronomic work, the *Warren-Knight 40-1360*, *Suunto Tandem*, *Suunto KB-14*, and *Ushikata Tracon 25* are excellent choices with the *Barker M-73* or *M-88* as a backup. In any case, however, before trusting a compass for fieldwork, it should be checked for calibration by one of the methods mentioned earlier.

Celestial Observations for True North

As noted, there are areas in the world where the iron content of the soil is so high that use of a magnetic compass is not practical. There are also countries where survey grade GNSS equipment (or even lesser grade GPS equipment such as SATCOM satellite communication devices like Garmin's *inReach Mini GPS* are not permitted — see e.g., https://support.garmin.com/en-US/?faq=Dq3CEPZjfRAhtToGD4Yrz9. Even where survey grade GPS is permitted there is the possibility that GPS equipment will malfunction at the wrong time. This can happen due to a software glitch, keyboard or circuit board malfunction, or if water gets into the receiver. As a backup it is useful to know how to determine true north by stellar or solar observations. Figures 14a+b and 15a+b show earthwork surveys oriented by Polaris observations in one case and solar observations in the other.

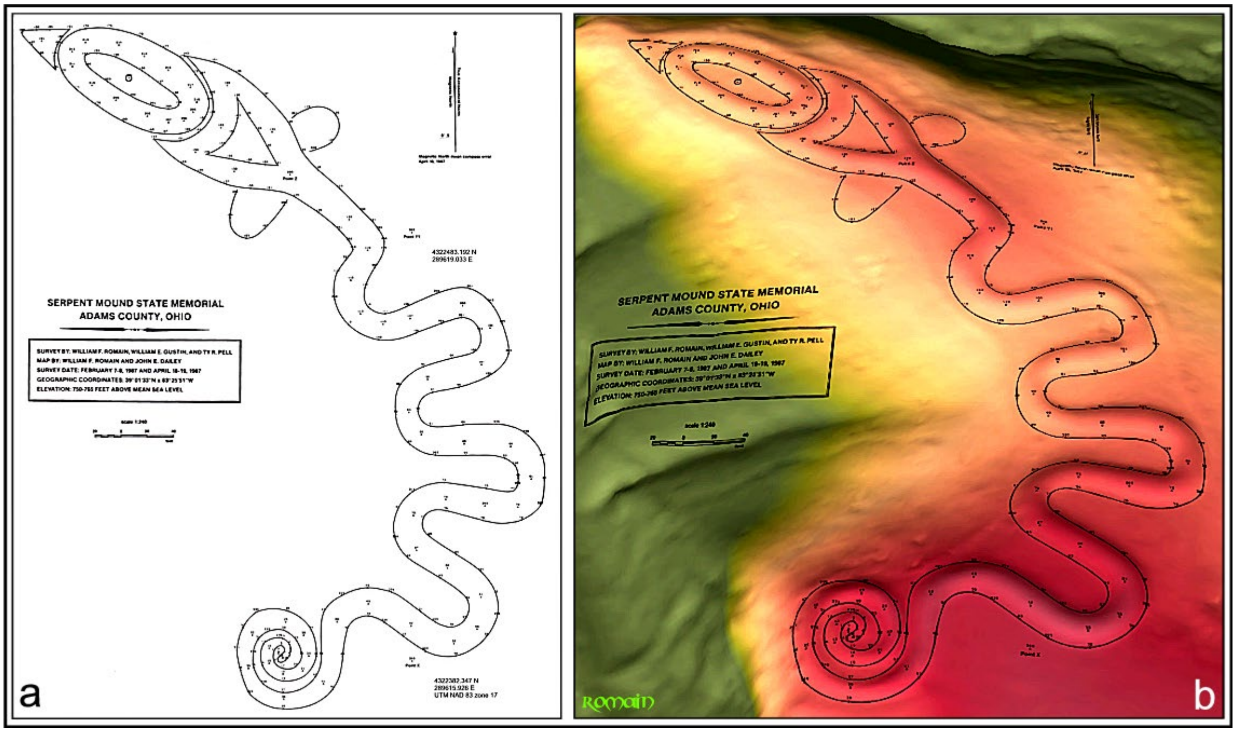


Figure 14a. Radial traverse survey of Serpent Mound, Adams County, Ohio made in 1987. True north determined by Polaris observations.
Figure 14b. LiDAR image (2008) of Serpent Mound overlaid on 1987 survey map.
Images by author.

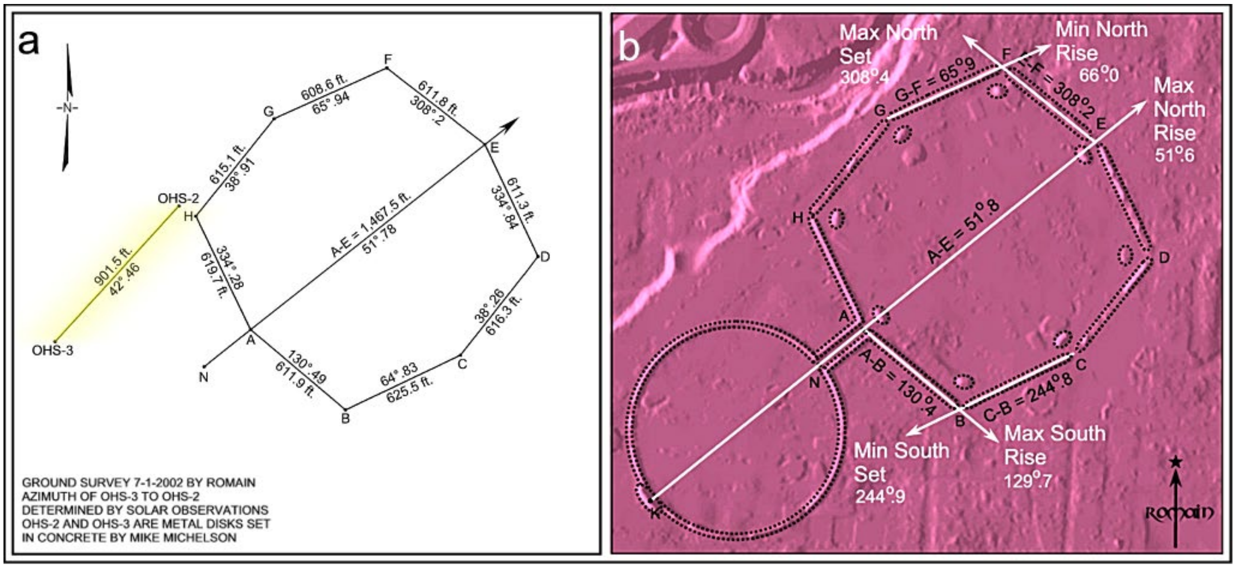


Figure 15a. Total station survey of Newark Octagon, Licking County, Ohio made in 2002. Azimuth for line OHS-3 to OHS-2 (highlighted in yellow) determined by Sun observations.

Figure 15b. LiDAR image of Newark Octagon and Observatory Circle (2014) showing azimuths of selected walls and lunar alignments.
Images by author.

For celestial observations use of a total station is common. Total stations give digital readouts of directional data (e.g., Figure 16) which precludes the chance of a vernier scale reading error. Additionally, total stations employ EDMs (electronic distance measuring) for accurate measurements of distance. Before continuing, it might help minimize confusion to know that total stations can be considered a kind of theodolite.

Most theodolites are not equipped with a magnetic compass (although there are exceptions that are no longer manufactured and difficult to find). Among compass equipped instruments are the *Wild Heerbrugg T0*, the *Wild Heerbrugg G10* (actually a goniometer), and a couple of instruments that included a compass an add-on accessory (*Wild T1*, *Wild T16* military version). However, although the instruments themselves may be accurate, the accuracy of any readings using a compass will still be constrained by the ± 0.5˚ range of accuracy for magnetic declination discussed earlier. In any case, there are different ways of categorizing theodolites which can be confusing: optical theodolite, digital theodolite, laser theodolite, transit theodolite and total station. Another way of categorizing is: repeating theodolite, directional theodolite, electrical digital theodolite and again, total station (https://www.quora.com/What-are-the-different-types-of-theodolite).

Figure 16. *Nikon C-100* total station with attached solar filter and right-angle viewfinder. Photo by author.

At the time of this writing, the smallest and lightest theodolite is the *Kern DKM1*. It does not have a magnetic compass. The *DKM1* weighs less than 3 kg (SwissTek, 2012). Unfortunately the instrument is no longer made. However, used instruments for sale are sometimes found on the Internet. No matter what instrument is used, finding true north by celestial observation requires ephemeris data, a solar filter for Sun observations and accurate time.

Time Reckoning

When calculating azimuths based on stellar or solar observations, accurate time is needed. There are many different ways that time can be referenced: UTC (i.e., Universal Coordinated Time), sidereal time, solar time, local civil time, daylight savings time, International Atomic Time (TAI), UTO time, UT1 time, Greenwich Mean Time, Zulu time, and others. What we will be concerned with here is UTC time (also known as Greenwich Mean Time or Zulu time). The simplest explanation for UTC is provided by Wikipedia (https://en.wikipedia.org/wiki/Coordinated_Universal_Time): "*Coordinated Universal Time (UTC)* is the primary time standard globally used to regulate clocks and time. It establishes a reference for the current time, forming the basis for civil time and time zones. UTC facilitates international communication, navigation, scientific research, and commerce." UTC is calculated using an average of readings from hundreds of atomic clocks positioned around the globe. The basic unit of UTC time is the atomic second. Local time relative to UTC depends on time zone. There are 24 standard time zones at about 15˚ intervals of longitude around the world. The prime meridian of 0˚ longitude at Greenwich, England is where UTC is reckoned from. For each time zone, local time differs from UTC by a specific number of hours. UTC does not use daylight savings time.

There are a number of ways a researcher can obtain UTC time in the field: by shortwave radio, by cell phone, by computer with Internet access, by GPS receiver, and by GMT timepiece. Radio frequencies for worldwide stations are at: https://dxinfocentre.com/time.htm. Phone numbers for audio UTC time are listed in Appendix 1.

For Internet access to UTC the U.S. Department of Commerce, National Institute of Standards Technology and U.S. Department of Defense, Naval Observatory have a website at: https://www.time.gov/.

Provided that one has cell phone coverage, there are several phone apps that are useful. One highly regarded iOS app is *Atomic Clock* (Gorgy Time, n.d.). This app receives time signals from synchronized NTP (Network Time Protocol) atomic clocks. The app can be programmed to update at startup, hourly, or daily. It has splendid graphics that show UTC time at one second intervals. If outside of one's home cell phone network, apps such as A*iralo* and *Nomad* might be useful. *Airalo* and *Nomad* use eSIM technology to easily connect to mobile cell phone networks in many (but not all) countries. As with any cell phone, however, the cell phone still needs to connect to a network through a nearby cell tower. For Internet access to time signal and other data in remote locations outside of cell tower range, Starlink mini (https://www.starlink.com/us/roam) may be an option. However, Starlink it is not available for all countries.

GPS receivers can also be used to obtain time signals. However, the time shown on a GPS unit and UTC may not be the same. Garmin GPS receivers, for example, display GPS time which is presently 18 seconds ahead of UTC time (https://www.labsat.co.uk/index.php/en/gps-time-calculator). By going into the receiver's settings, however, Garmin units can be reset to display UTC time.

Perhaps the most reliable way to access UTC time is to use a GMT watch. Radio signals fade at inopportune times, cell phone apps are dependent on network coverage, and computers require Internet access. Of course there are work-around solutions such as mentioned above. However, use of a GMT watch is arguably, the most straightforward.

Figure 17a shows the *Citizen Promaster Skyhawk A-T* solar powered watch. It synchronizes once a day to UTC received by radio signal from one of five transmitting stations located around the world. In the U.S.A. the signal comes from station WWVB in Fort Collins, Colorado. This station has a range of 3,000 km. Stations in Germany and China have a range of 1,500 km. The station in Kyushu, Japan has a range of 2,000 km (https://www.citizenwatch-global.com/support/html/en/u68/wave_06_u68.html).

Figure 17b shows the *Casio Lineage LCW-M300 multiband 6 WaveCeptor* solar watch with digital UTC readout. This watch automatically updates several times a day to UTC from one of six time signal calibration transmitters located in the United States, United Kingdom, Germany, China, and Japan (two stations) (https://www.casio.com/content/dam/casio/global/support/manuals/watches/pdf/51/5174/qw5174_EN.pdf).

When using either watch (and for reading vernier scales) it is helpful to include a small LED-illuminating magnifying lens in one's kit.

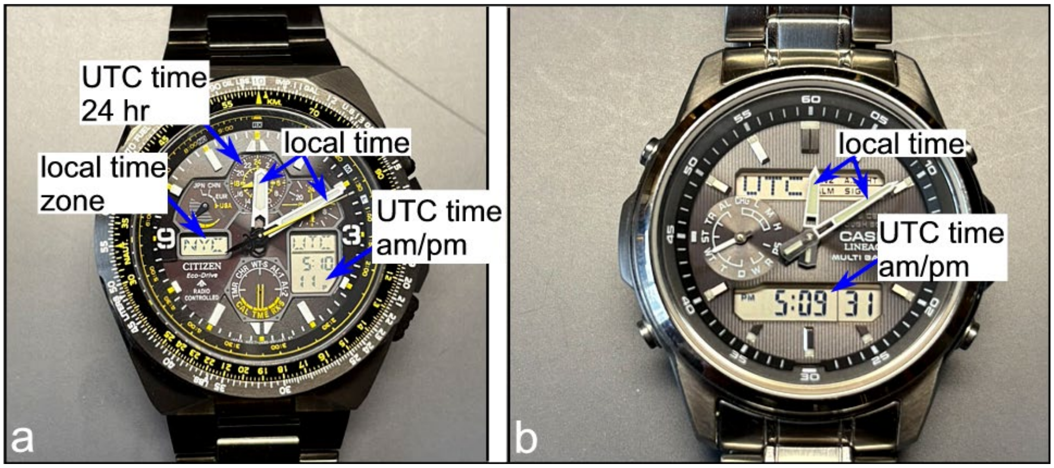


Figure 17a. *Citizen's Promaster Skyhawk A-T* solar watch with digital and analog UTC readouts.
Figure 17b. *Casio Lineage LCW-M300 multiband 6 WaveCeptor* solar watch with digital UTC readout.
Photos by author.

Perhaps useful to know when making celestial observations for azimuth, a timing error of 1 second will result in an azimuth error of 18 arc seconds for the Sun (at 2 hrs from local noon, lat 37˚ N) and 0.2 arc seconds for Polaris (Elgin, Knowles & Senne, 1989, Table 7).

The methods presented here for establishing true north (azimuths tied to true north) by celestial observation are explained in more detail by Brinker & Minnick (1995), Ghilani (2020), Ghilani & Wolf (2015), Elgin, Knowles & Senne (2007, 1995, 1989), McCormac (1991), Prendergast (2015), and Ruggles (1999).

True North by Polaris Sightings

There are several ways to establish true north using Polaris: by observation at upper or lower culmination, by observation at eastern or western elongation, and by observation at anytime using the hour angle method. (Hour angle method is discussed in Solar Observation section.) At upper culmination Polaris transits or crosses the celestial meridian. (For definitions of meridians including *celestial meridian*, see https://learncst.com/meridian-definitions/.) At the moment of its crossing a celestial meridian, Polaris is at its highest altitude in the sky relative to the observer's location and most importantly, the star is due north.

To take a Polaris sighting at upper culmination accurate time is needed. Culmination times can be found using the *Nautical Almanac*, or by using a computer program such as Stellarium. If using Stellarium, one inputs the geographic location and date for the observation, enters ‘Polaris’ in the search window, and in the drop-down information provided, the star’s ‘transit’ time will be displayed. Transit time is for upper culmination.

Having selected a date when upper culmination occurs at a convenient time during the night, the user sets-up the theodolite over a selected point we can call CP1. Viewing through the instrument, the operator finds Polaris a few minutes before culmination. Once the star is identified, it is followed by adjusting the horizontal and vertical tangent knobs on the instrument. If observing for upper culmination the star will appear to move upward and to the left. It is helpful if an assistant calls out the time as culmination approaches. At the instant of culmination the horizontal movement of the instrument is locked. The vertical movement of the instrument is then rotated downward to a distant point on the ground (CP2): 120–150 meters from the instrument station will suffice. The ground point (CP2) is marked using a survey pin or similar. A line between CP1 and CP2 will be oriented to astronomic north. For observation at lower culmination the same method is used except that if using Stellarium, the time for lower culmination needs to be determined by reference to the star’s azimuth as lower culmination times are not shown in the drop-down information window.

It can be challenging to set a distant control point in the dark. If the situation allows, it might be feasible to clamp or lock the instrument’s horizontal plate once Polaris has been sighted at the designated time; and then, in the morning, proceed with sighting and marking CP2 on the ground.

Although simple, the method just described has a couple of drawbacks. First, upper and lower culminations may occur at times that are not convenient for observation (e.g., during daylight hours). Also, at culmination the star is moving rapidly thus allowing only one observation. Accordingly, it may be preferable to sight on Polaris at east or west elongation. At mid-latitudes (31˚–52˚) elongations are about 5 *hr* 55 *m* ± 2 *m* before or after upper culmination (DeGroot, 1954; Table 2). Stellarium drop-down information for Polaris will give the precise times referred to as “Max E [or W] Digression.”

Perhaps the greatest advantage to taking elongation sightings is that as explained by Davis (1955, p. 280), “It is not essential that the direction to Polaris be observed at the exact instant of elongation. Within 10 m before to 10 m after elongation, the maximum change in azimuth is only 0.1’.” As a result, multiple forward and reversed observations can be made thereby correcting for any possible instrument error. One way to do this is to make a forward observation to the star, mark the azimuth on the ground followed by a second observation with the telescope reversed. Mark the second observation on the ground. The correct position for the star will be at the midpoint between the two ground points. True north is determined from the just established midpoint by turning an angle equal to the star’s given azimuth for east or west elongation. Alternatively, if the true azimuth needs to be determined for a sightline already laid out on the ground, Figure 18 shows how that is done. In Figure 18 the azimuth for line CP1-CP2 is: 360˚ + 0˚ 51’ - 77˚ 18’ = 283˚ 33’.

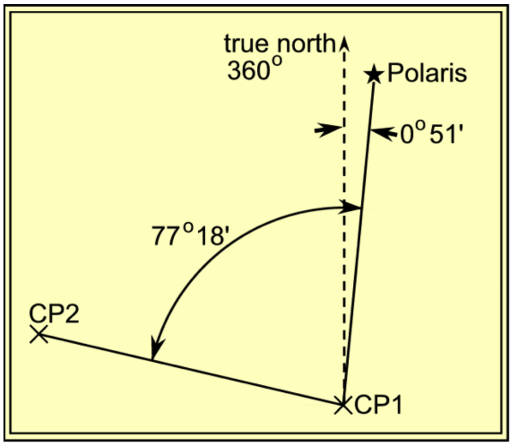


Figure 18. Exemplar relationship between Polaris at eastern elongation and line CP1-CP2. Drawing by author.

No matter when Polaris is observed, finding and focusing on the star can be a challenge when searching the night sky using a theodolite. If the instrument is not properly focused the star might not be seen. To alleviate this, it is useful to focus first on the moon, or a bright star, or even on a very distant light. Then look for the star through the instrument. To illuminate the crosshairs it helps to shine a small flashlight at an angle across the instrument's front lens.

True North by Solar Observations

The widespread use of GPS has relegated the need to find true north by solar or stellar observations nearly obsolete. As noted earlier, however, there are situations where knowing how to find north by celestial observation will be useful. Although the procedure is not difficult, there are several terms that the researcher needs to be familiar with. Specifically, *GHA* (or Greenwich Hour Angle) refers to the "angle at the pole measured westward from the prime (Greenwich) meridian to the hour circle through a celestial body. It is measured in a place parallel to the equator and varies from 0º to 360º" (Elgin, Knowles & Senne, 1995, p. 415). *Declination* is: "The angular distance measured along an hour circle north (positive) or south (negative) from the equator to a celestial body. It is analogous to latitude" (Elgin, Knowles & Senne, 1995, p. 415). *Semidiameter* refers to the radius of the sun.

For determining the azimuth of a line by celestial observation the method employed here is known as the "hour angle method" (Elgin, Knowles & Senne, 1989, p. 5). The procedure requires a theodolite or total station, accurate time and current ephemeris data. The first step is to lay out a baseline on the ground. The ends of this baseline can be called control point 1 (CP1) and control point 2 (CP2). The theodolite or total station is set-up over CP1 and sighted on CP2. The horizontal circle on the instrument is set to 0 00' 00" so that the azimuth for CP1-CP2 reads 0˚. The next step is to make a series of solar observations. With the instrument still zeroed on CP2, the sun is sighted through the telescope (usually to the sun's trailing edge) and the horizontal angle as turned right from CP2 is recorded. (The vertical angle to the sun is not recorded.) The UTC time for each sighting is recorded. To simplify later calculations it is easiest to take Sun shots on the minute mark as counted down by an assistant.

Once the requisite number of forward and reversed observations have been made, GHA and declination data for the Sun are obtained from the *Nautical Almanac*, *Air Almanac*, or *Astronomical Almanac* (https://aa.usno.navy.mil/publications/almanacs). A direct link to the *Nautical Almanac* can be found at: https://www.thenauticalalmanac.com/. (Note that the entire Almanac for the current year can be downloaded as a pdf for later use without Internet connection.)

For the required data using the *Nautical Almanac*, select "Sun Only – normal size" for the current year. From the left side column find the current date for the observer's location. Hours are listed below the date, GHA (Greenwich Hour Angle) and declination are to the right of each hour. For the current date record the GHA for 0 hrs and declination for 0 hrs. Repeat this procedure and record the data for the next day (also at 0 hrs). Find the semidiameter (SD) at bottom of column and record.

A cautionary note is called-for here. If making observations, for example, during late afternoon in the western USA, keep in mind that "the mean sun may have passed 180 degrees longitude (24 hrs Greenwich time). At this time the Greenwich date of observation is local date plus one day….A simple rule to follow for the Western Hemisphere is if UT time of observation is less than local time, add one day to local date" (Elgin, Knowles & Senne, 1989, p. 59).

To continue, the observation and ephemeris data are used to calculate the azimuth for line CP1-CP2. There are a couple of methods that can be used to do this. The most time consuming and prone to error is by hand calculation. The spherical trigonometry formulae needed are noted by Ghilani & Wolf (2015, p. 887). The more expedient way is by computer program. For this, *WolfPack* is a useful program. Developed by Charles D. Ghilani and Paul R. Wolf at Penn State University, the program is user friendly. Over the years Internet access to the program has been intermittent. However, as of March, 2025 the program can be downloaded from the website at: https://wilkesbarre.psu.edu/academics/surveying/free-resources. If, at some time in the future the program cannot be accessed through the Internet, the program can also be downloaded from a CD-ROM included with older editions (e.g., year 2006) of the book, *Elementary Surveying: An Introduction to Geomatics* by Ghilani and Wolf.

In any case, once the azimuth for line CP1-CP2 has been determined and if needed, a sightline oriented to true north (CP1-CP3) can be established by sighting on CP2 and resetting the instrument so the horizontal angle between CP1 and CP2 is equal to the celestially-determined azimuth. Using CP2 as a backsight, turn an angle until the horizontal reading is equal to 0˚. Mark the ground anywhere along the 0˚ sightline and that will be your true astronomic north sightline, CP1-CP3.

Interesting to know is that according to Ghilani & Wolf (2015, p. 876): "…Polaris observations provide the most accurate results and, with several repetitions of measurements utilizing first-order instruments, accuracies to within ± 1" are possible. Sun observations yield a lower order of accuracy but values accurate to within about ± 10" or better can be obtained if careful repeated measurements are made." As pointed-out by Elgin, Knowles & Senne (1989, p. 2), "…10 arc-seconds is equivalent to a positional accuracy of 0.25 feet in one mile."

As was the case for the magnetic compass, there are potential sources of error when making celestial observations. These include: measuring and pointing errors on the backsight and celestial body, errors in determining time, and most importantly, leveling error. Leveling error is not compensated-for by direct and reverse sightings.

Total cumulative error can be calculated by a statistical method known as RSS, or 'square root of the sum of squares' (Elgin, Knowles & Senne, 1989, p. 53–57). These authors also give values for several kinds of error just mentioned (Elgin, Knowles & Senne, 1989, Tables 1–7).

Determining True North by GPS/GNSS

Increasingly, it is common to establish azimuths for survey sightlines and true north using GPS data. In common parlance and as used herein, *GPS* is a blanket term for several satellite systems collectively known as *GNSS* (Global Navigation Satellite System). As of March 2025, active GNSS satellites include: the Global Positioning System network of 28 satellites operated by the USA; the BDS (BeiDou) network 44 satellites operated by the Peoples Republic of China; the Galileo system of 27 satellites operated by the European Union; and GLONASS system of 24 satellites operated by Russia (https://qzss.go.jp/en/technical/satellites/index.html#GPS). Regional systems include India's IRNSS and Japan's QZSS. There are also multiple satellite-based augmentation systems (SBAS) such as WAAS and EGNOS that provide enhanced positioning data (for more information see: https://www.euspa.europa.eu/eu-space-programme/egnos/what-sbas). Most modern survey grade GPS receivers are able to access data from multiple GNSS systems.

Just to clarify, GPS does not provide azimuth data *per se*. Rather, azimuths are calculated between points on the ground that have been located using GPS/GNSS coordinate data. The typical smartphone GPS is accurate to 2–4 meters. Survey-grade RTK GPS systems provide centimeter or sub-centimeter accuracy. Manufacturers include: Trimble, Leica, Carlson, South, ComNav, and Emlid. Of course centimeter accuracy assures that sightlines can be plotted with high precision. Moreover, GPS-determined azimuths can be established for lines that extend across considerable distances. And GPS is especially useful when control points are not horizontally intervisible due to blocking structures or vegetation. Discussion about how azimuths are determined using GPS points will be found at the end of this section.

There are several GPS protocols for establishing positional location: RTK (Real Time Kinematic), PPK (Post-Processed Kinematic), PPP (Precise Point Positioning), and static. A simple explanation for how RTK GPS systems provide location data is that a stationary *base station* is set-up over a point that has known geodetic coordinates such as a National Geodetic Survey marker (see e.g., National Geodetic Survey - Survey Marks and Datasheets) or previously surveyed point. The base station receives signals from at least four satellites. Three satellites give position data relative to the base station. The fourth satellite provides precise time signal data. For best results it is advisable for a dual frequency base receiver to receive data from 15 or more satellites using a combination of GNSS satellites. (Dual frequency receivers reduce ionospheric effects and signal reflections resulting in improved accuracy.) The base station communicates with a second receiver called a *rover* which also collects satellite data.

Satellite data, however, are subject to ionospheric and troposphere effects, as well as satellite orbit, clock, and multipath errors (Hill et al. 2019; Van Sickle, 2024). For an accurate ground position reading, corrections need to be applied to the rover data. Where a base station is used, data corrections are received from the base station. The base station combines its location information with differential correction data received from sources as noted below and sends it to the mobile rover. By applying the correction data from the base station, the rover is able to compute its position to within centimeter accuracy or better. This is the essence of RTK (Real-Time Kinematic) GPS. Important to note is that if the base station is not accurately situated over a known coordinate point then the positions given by the rover will be in error by the same distance and azimuth as the base station error (Hill et al. 2019). Again, a known coordinate position can be a GPS survey mark, or other previously surveyed point having precise coordinate data.

If a survey marker or other location having precise coordinate data cannot be located it is often possible to link the base station by Internet to an NTRIP or CORS network that will provide correction data. NTRIP is a communication protocol that facilitates access to either an NTRIP reference station or CORS station which provides continuously updated GNSS position information for a particular area. NTRIP is an abbreviation for *Network Transport of RTCM via Internet Protocol*. CORS stands for *Continuously Operating Reference Station*. Although CORS networks are often the source for NTRIP correction data, NTRIP networks may also retrieve data from other kinds of base reference stations.

NTRIP providers are situated around the world. Many allow free access, others are by subscription. Lists of NTIRP service providers can be found at https://ntrip-list.com/. NTRIP providers within the USA (updated for 2025) are listed by state at: https://e38surveysolutions.com/pages/ntrip-rtk-network-access-by-state.

When using NTRIP/CORS, a term often encountered is *mountpoint*. Mountpoint refers to a list of GNSS correction choices that a network can provide. Choices will typically include network protocols (e.g., RTCM3 format) and datum realizations (where realization means an updated version of the datum's original coordinates — e.g., NAD83 2011, 2007, etc.).

In cases where an Internet connection and/or NTRIP is not available it may be possible to receive correction data using LoRa (Long Range Radio). For this operation settings in the operator's base station and rover are set to LoRa. Correction data are then received via LoRaWAN network servers.

If it is not possible to locate a survey mark or location having precise coordinate data and, if it is not possible to link to a NTRIP provider, the base station and rover can be deployed to collect raw or uncorrected data for later processing. The collected data are stored as *logs* (typically as a RINEX file [Receiver Independent Exchange Format]). Later, the log data are uploaded to dedicated websites that use specialized algorithms to process and return accurate location data for the surveyed points. This is referred to as PPK (Post-Processed Kinematic) GPS. Website services that process data logs include: OPUS (Online Positioning User Service operated by the U.S. National Geodetic Survey) (https://geodesy.noaa.gov/OPUS/index.jsp) and AUSPOS (https://www.ga.gov.au/bin/gps.pl .

PPP (Precise Point Positioning) GPS needs only one receiver and typically receives correction data via the International GNSS Service. (For further details see e.g., https://gssc.esa.int/navipedia/index.php/Precise_Point_Positioning). For static GPS a stationary receiver is set-up at a desired location and allowed to collect satellite data over a period of hours. The data are then sent to a correction service (like OPUS) and accurate coordinate point data are returned.

Lastly, it is possible to conduct RTK operations using one rover unit. For this, the *Emlid Reach RX* rover (Figure 19a) is a good choice. In RTK mode the *Reach RX* is accurate to 7 mm in the horizontal and 14 mm vertical (https://emlid.com/reachrx/). The unit is reliable and small enough to carry in a pocket. As a matter of fact (and with an unobstructed sky view) it can be placed directly on the ground without a survey pole. The *Reach RX* combines its own received satellite data with correction data received via cellular data link from a NTRIP/CORS service. The NTRIP/CORS correction data are transmitted from the cell phone to the rover by Bluetooth connection. For some researchers a significant advantage of this set-up is that it eliminates the cost and need for a second receiver (i.e., base station). The *Emlid Reach RS3* base currently costs about $2,800 USD. A stand-alone *Reach RX* rover is about $2,200 USD.

As per Emlid (https://community.emlid.com/t/reach-single-solution-accuracy/3582) if the *Reach RX* is not connected to a real-time correction network then its accuracy is about 2.5 m. If connected to a SBAS system (which the unit does automatically where available) then its stand-alone accuracy is about 2.0 m.

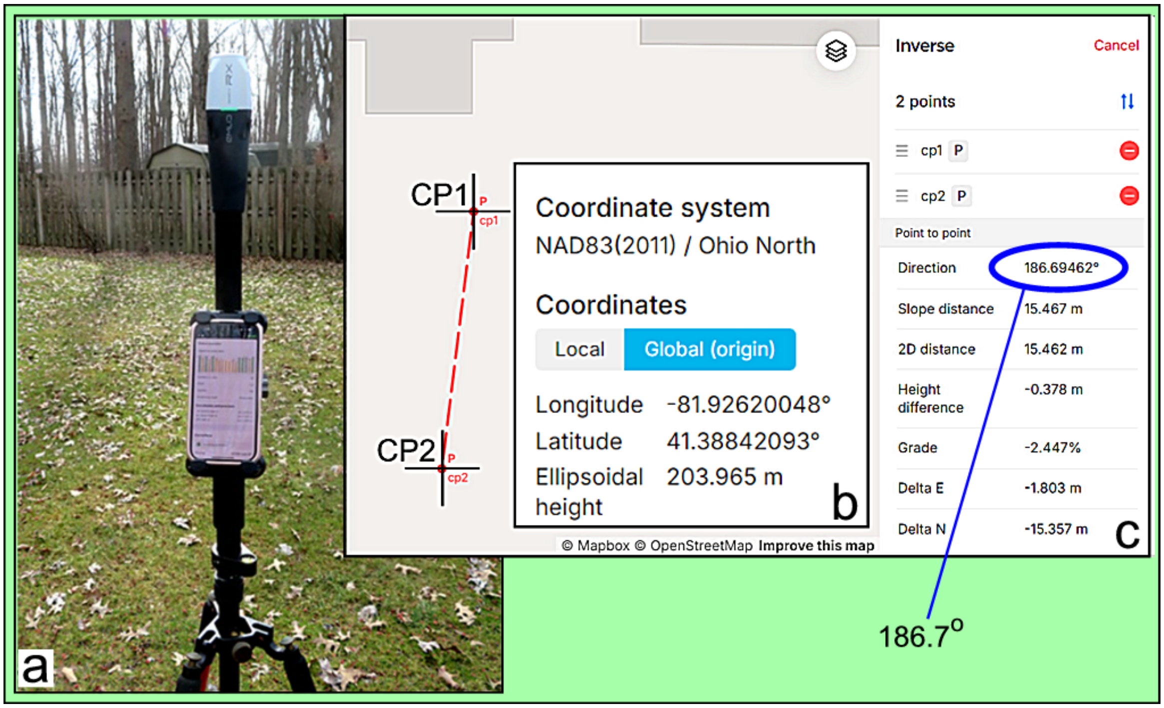
When working with GPS/GNSS coordinate and map data one needs to be cognizant of coordinate systems. In Ohio, for example, GNSS data from CORS is referenced to the NAD83 datum. *Google Earth Pro* and *Google Maps*, however, use the WGS84 datum. In the USA the horizontal difference between WGS84 (G1762) and NAD83 (2011) can be as much as 2 m (Nathan, 2024). Consequently, before plotting a CORS-derived coordinate point on a *Google Earth* image the NAD83 data should be transformed to WGS84. A useful transformation tool can be found at: https://geodesy.noaa.gov/NCAT/. Others are listed in Appendix I.

Determining an Azimuth Between Two Points

Once the researcher has determined the coordinates for two ends of a sightline (CP1-CP2) (either by scaling latitude and longitude or UTM coordinates from a map, or by GPS) the next step is to determine its azimuth. To do this Vincenty's formula is often used (Prendergast, 2015). The calculations can be done by hand (Vincenty, 1975), or using an online calculator. A simplified guide for making hand calculations as well as an online calculator can be found at https://www.omnicalculator.com/other/azimuth. Other online calculators are listed in Appendix 1. Importantly, and as pointed out by Prendergast (2015, p. 403), "The accuracy of the derived azimuth is a function of the longitudinal and lateral position errors in the baseline coordinates and the distance between the terminal stations."

Alternatively, most survey mapping applications include inverse and traverse functions as part of their COGO (Coordinate Geometry) tool kit. Such applications include *Carlson Survey* (Carlson Software, 2025), *AutoCAD Civil 3D* (Autodesk, 2025), and *Traverse PC* (Traverse PC, 2025). Using coordinate data for the two ends of a sightline (e.g., CP1 and CP2) the inverse function will calculate the azimuth for that sightline. The traverse function allows the user to plot a location (e.g., CP3) given an imputed distance and azimuth from CP1. This function is useful for laying-out a sightline oriented to true north.

Returning to a discussion of the *Emlid Reach RX*, applications for the device include: *Emlid Flow* and *Emlid Flow 360* with *Survey* plan subscription. *Emlid Flow* collects survey point data from the Reach rover and displays it on the user's cell phone. *Flow 360* is a cloud-based app that allows survey data to be shared and managed on additional devices such as an office computer. *Flow 360* is able to import and export data in CSV, KLM, DXF and SHP file formats. Important for archaeoastronomic work, the *Survey* add-on app includes traverse and inverse tools. Figures 19b and 19c show screenshots of a demonstration project. Figure 19b is a display of the coordinate point data for CP2. Figure 19c shows azimuth and distance data for sightline CP1-CP2 using the *Survey* app inverse function.



Coordinate system
NAD83(2011) / Ohio North

Coordinates

Longitude	-81.92620048°
Latitude	41.38842093°
Ellipsoidal height	203.965 m

2 points
cp1 P
cp2 P

Point to point

Direction	186.69462°
Slope distance	15.467 m
2D distance	15.462 m
Height difference	-0.378 m
Grade	-2.447%
Delta E	-1.803 m
Delta N	-15.357 m

Figure 19a. Emlid Reach RX GNSS unit connected to Ohio CORS network via Bluetooth and iPhone 16.
Figure 19b. Detail of Emlid *Flow 360 Survey* screen shot showing coordinate data for CP2 (annotation added).
Figure 19c. Detail of Emlid *Flow 360 Survey* screen shot showing azimuth for sightline CP1-CP2 (annotation added).
Photos by author.

Although GPS is useful, it is not infallible. GPS operations can be affected by a number of factors to include multipath conditions caused by reflected signals from water bodies, large vehicles such as trucks, freeway signs, and other reflective objects, as well as transmissions from two-way radios, television, and radar stations (Sturgess & Veatch II, 1995, pp. 371–376). GPS reception can also be affected by ionospheric distortion. This is especially true near times of sunrise and sunset. Solar flares can also affect accuracy and satellite signal strength. And, GPS reception can be blocked by city buildings, canyon walls, and dense forest canopy — in short, by anything that interferes with satellite signals.

LiDAR and GPS/GNSS

Thus far we have considered ground based methods to determine azimuths. For some projects, however, assessments using aerial LiDAR (Light Detection and Ranging) and photogrammetry or satellite imagery can be useful (e.g., Romain, 2015).

Recently, as technologies have advanced, LiDAR-equipped drones (or UAVs — i.e., Unmanned Aerial Vehicles) are being used for archaeological missions, including site assessments for astronomic alignments. By flying low and relatively slow, LiDAR drones are able to capture incredibly detailed bare earth imagery revealing what might otherwise be invisible to the naked-eye. Figure 20a shows a lidar-equipped UAV at Cahokia — a large Mississippian site in Illinois, USA. Figure 20b shows a LiDAR image of one of the mounds at Cahokia (i.e., Rattlesnake Mound). The image was generated from UAV LiDAR data (Romain et al. 2025). Analysis of the image shows the azimuth for the longitudinal axis of the mound (i.e., 95˚), as well as length of the mound (ca. 136 m). Archaeoastronomic analyses of additional UAV LiDAR imagery revealed various alignments at the site to the Sun, Moon, and Milky Way (Romain, 2024).

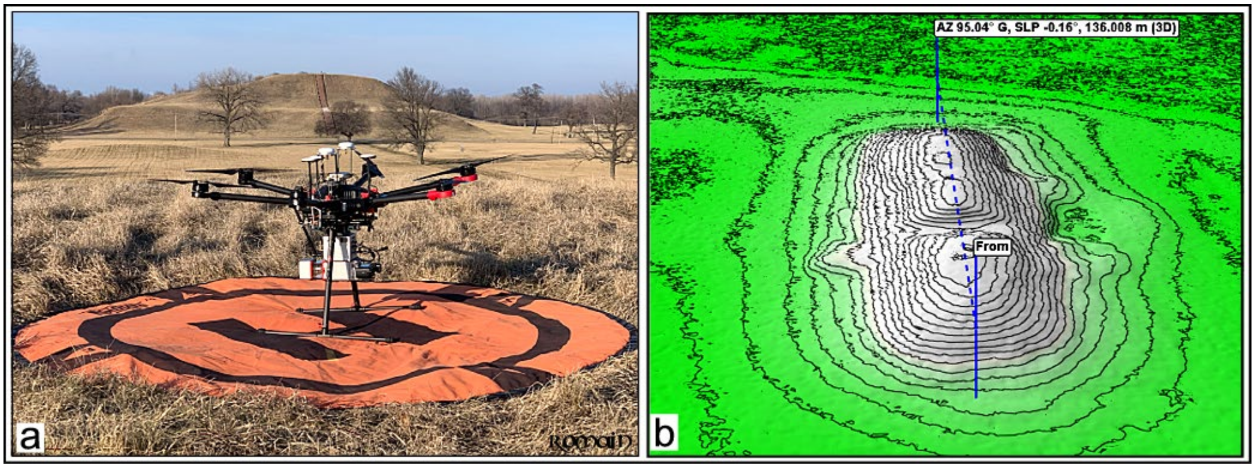


Figure 20a. DJI Matrice 600 Pro UAV with attached LiDAR sensor at Cahokia, Illinois, USA. Monks Mound in background.
Figure 20b. LiDAR view of Rattlesnake Mound at Cahokia. Contour interval = 0.5 m. LiDAR data from UAV overflight January 2023. LiDAR data courtesy of Indiana University, Department of Earth and Atmospheric Sciences.
Photo and LiDAR image by author.

Relevant to the discussion here, is that for the Cahokia study, UAV flight patterns and LiDAR data were tied to GPS/GNSS coordinate points (Romain et al. 2025). Azimuths for ground features were able to be determined with great accuracy because beginning and end point for sightlines were identified by their GPS/GNSS coordinate positions.

Satellite Imagery

One of the most useful sources of information about ancient sites is from aerial and satellite imagery. There are a considerable number of commercial and government sources for aerial and satellite imagery. In terms of satellite and aerial imagery for archaeoastronomy, among the most useful are *ArcGIS Earth* (ESRI, 2024), *Google Earth Pro* (Google LLC, 2025) and *Global Mapper* (Blue Marble Geographics, 2025). These programs have ruler tools that provide distance and heading information. Using the tools provided by these apps and depending on the site, it is often possible to develop accurate information about azimuth, dimensions, and landscape relationships. These apps are especially useful for developing information on sites that are not accessible (e.g., Romain, 2022a, 2019, 2018, 2017). A nice feature of *Global Mapper* is that it provides a dropdown menu allowing the user to connect to a wide range of online sources including Worldview satellite imagery, USGS topographic maps, and LiDAR imagery.

That said, caution needs to be exercised when using satellite imagery. In an earlier paper (Romain, 2022b) some of the limitations regarding *Google Earth Pro* were discussed. Among the issues is that when using measurement tools, distances are given to two decimal places (or more) — e.g., to the centimeter or hundredths of a degree. This is a bit misleading. The accuracy of *Google Earth Pro* and other programs is dependent on the spatial resolution of the aerial or satellite image as well as length of the sightline being measured. Also, in several areas of the world, aerial/satellite images are distorted to the point where measurement data are not reliable (for examples see Romain, 2022b).

Conclusion

In the preceding pages several methods were discussed for finding true north and the azimuth of a sightline. Methods included magnetic compass, celestial observation, GPS/GNSS, LiDAR and satellite imagery. Considerable time was spent discussing use of the magnetic compass. There is a reason for this. Archaeologists and archaeoastronomers often use a magnetic compass in the field. A random review of 19 articles recently published in the *Journal of Skyscape Archaeology* found that 7 reported using a magnetic compass for determining azimuths, 9 used aerial or satellite imagery, 2 used LiDAR, and 1 used ground-based GPS/GNSS. Of the reported compass uses, manufacturer and model information were given in 5 cases, 1 simply reported using a prismatic compass and for another, no manufacturer information was provided. At the same time, all articles provided exquisite details about other aspects of reported projects. As discussed above, however, not all magnetic compasses are created equal and accuracies can vary widely.

Hopefully, the preceding will help archaeologists and archaeoastronomers recognize the capabilities and limitations of different instruments and methods and encourage more detailed documentation. To say, for example, ‘I used a Brunton compass for measuring the azimuth of a wall trench’ is not sufficient. For readers to better evaluate purported findings it would be useful to know what model Brunton compass was used, as models differ in accuracy. It would also be useful to know if the instrument was handheld or tripod-mounted. And it would be helpful to know the date of field measurements, declination value applied and source for those data. So too, when reporting GPS/GNSS coordinate data it is important to document what datum is referenced. And, when reporting data derived from satellite imagery it is helpful to include the source, date of the image and eye altitude. These simple inclusions do not require many extra words and add considerably to the value and credibility of reports.

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Appendix 1. Useful Websites and Other Information

to transform geodetic coordinates (e.g., lat/long NAD27 to UTM WGS84):

https://tagis.dep.wv.gov/convert/

https://www.earthpoint.us/Convert.aspx

https://twcc.fr/en#

https://www.latlong.net/lat-long-utm.html

https://products.aspose.app/gis/transformation

https://geodesy.noaa.gov/NCAT/

to transform State Plane coordinates to longitude and latitude:
https://www.earthpoint.us/

to transform degrees/minutes/seconds to decimal degrees and converse:

https://www.fcc.gov/media/radio/dms-decimal

to find magnetic declination

https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml

to convert mils to degrees and converse

https://www.inchcalculator.com/convert/mil-to-degree/

https://www.inchcalculator.com/convert/degree-to-mil/

to find terminal lat/long coordinates given a distance and azimuth

https://www.fcc.gov/media/radio/find-terminal-coordinates

to view USGS topographic maps on Google Earth

https://www.earthpoint.us/TopoMap.aspx

UTC by Internet

https://time.is/

https://time.is/UTC

https://www.utctime.net/

UTC by phone

(USA) 1-202-762-1401

(USA) 1-303-499-7111

(USA) 1-719-567-6742

UTC radio signal frequencies

2.5 MHz; 5 MHz; 10 MHz; 15 MHz; 20 MHz

Online calculators for Vincenty's inverse formula

https://geodesy.noaa.gov/PC_PROD/Inv_Fwd/

https://wilkesbarre.psu.edu/academics/surveying/free-resources

https://www.fcc.gov/media/radio/distance-and-azimuths

Appendix 2: To determine azimuth of a baseline by solar observations

1. Layout a baseline on the ground. Mark the beginning of the line, control point 1 (CP1), make end of the line control point 2 (CP2).

2. Set-up and center total station over CP1.

3. Sight to CP2.

4. Set horizontal circle on total station to 0º00’00”.

5. Attach solar filter.

6. Make Solar Observations.

Follow trailing edge of Sun. Using the form below, record the horizontal direction shown on the total station as measured right, at the instant of the UTC time signal on the minute. Reverse the total station and apply same procedure for the next observation. Continue taking forward and reverse readings until desired number of observations are made.

Note: older texts often recommend that for solar observations UTC be corrected to UT1 (or astronomical time), by applying a correction known as DUT1 (or simply DUT). Astronomical time (UT1), or “mean solar time, is based on the rotation of Earth, which is irregular” (https://www.nist.gov/pml/time-and-frequency-division/leap-seconds-faqs). DUT is the difference between UTC and UT1. The current value for DUT1 is listed at: https://www.nist.gov/pml/time-and-frequency-division/time-realization/leap-seconds#:~:text=Start%20Date-,Time,%2B0.0%20s DUT1 corrections during the past decade have been small. The correction (as of 11-30-2024) was +49.4 milliseconds. At present this value is so small that as a practical matter and to keep calculations as simple as possible, it is not an absolute requirement that DUT1 is applied to UTC time.

Date _______________ **Location** _______________________

Latitude / Longitude (deg-min-sec) ______________________________________

Survey Team ____

Survey Instrument _____________________________________

Method of Determining Time ___________________________

Observation Number	**UTC Time**	**Horizontal Angle to Sun** **(degrees, minutes, seconds)**
1	___________________	____________________________
2 (reversed)	___________________	____________________________
3	___________________	____________________________
4 (reversed)	___________________	____________________________
5	___________________	____________________________
6 (reversed)	___________________	____________________________

7. Obtain Ephemeris Data. For these data go to: https://www.thenauticalalmanac.com/ (Note that the Almanac for the current year can be downloaded as a pdf for use without Internet connection.)

Select “**Sun Only – normal size**” for the current year. From the left side column find current date for location. Hours are listed below date, GHA and declination are to the right of each hour. For current date record the GHA for 0 hrs and declination for 0 hrs. Repeat this procedure and record data for the next day (also at 0 hrs). Find semidiameter (SD) at bottom of column and record.

GHA for Sun

GHA at 0 hrs on date of observation ________________________

GHA at 0 hrs next day ____________________

Declination for Sun

Dec at 0 hrs on day of observation _____________________

Dec at 0 hrs next day ___________________________

Semidiameter

Semidiameter (in arc seconds and tenths) ________________________

8. Calculate solar reduction.

Enter above data into WolfPack program.

Open WolfPack → File → New

On the blank page that opens, enter data in following format (where – means space).

Line 1 > name of file (e.g., Cahokia)

Line 2> lat and long (in deg-min-sec-deg-min-sec)

Line 3> GHA at 0 hrs on day of observation and next day (in deg-min-sec.decimal-deg-min-sec.decimal)

Line 4> declination at 0 hrs on day of observation and next day, semidiameter correction (in deg, min, sec.decimal) and edge number: 1 for trailing edge

Line 5> enter four 0 0 0 0s on this line (each 0 must be separated by a space)

Line 6> observation number, UTC of observation, 0-0-0 **for direct sighting**, horizontal angle as read from total station.

In other words:

observation number-hrs-min-sec-0-0-0-deg-min-sec

that is,

0-00-00-00-0-0-0-000-00-00

and

Line 7> observation number, UTC of observation, 180-0-0 **for reverse sighting**, horizontal angle to Sun as per total station.

Continue data entry until all sightings are listed.

All angles are entered in D-M-S format. For example, the angle of 234º45’12” is entered as 234space45space12. Spaces are treated as format delineators in file. Seconds.decimal are ok to use.

Once the data are entered, go to **Save As**. Give a name to the file and close.

Next, click on the Solar Reduction button and find the file in the list provided. Click on **Open**. The returned data will include the astronomic azimuth for line CP1-CP2.