Theodolite

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An optical theodolite, manufactured in the Soviet Union in 1958 and used for topographic surveying

A **theodolite** (/θiːˈɒdəlaɪt/) is a precision instrument for measuring angles in the horizontal and vertical planes. Theodolites are mainly used for surveying applications, and have been adapted for specialized purposes in fields like metrology and rocket launch technology. A modern theodolite consists of a movable telescope mounted within two perpendicular axes—the horizontal or trunnion axis, and the vertical axis. When the telescope is pointed at a target object, the angle of each of these axes can be measured with great precision, typically to seconds of arc.

Transit refers to a specialized type of theodolite developed in the early 19th century. It featured a telescope that could "flip over" ("transit the scope") to allow easy back-sighting and doubling of angles for error reduction. Some transit instruments were capable of reading angles directly to thirty seconds. In the middle of the 20th century, "transit" came to refer to a simple form of theodolite with less precision, lacking features such as scale magnification and micrometers. Although precise electronic theodolites have become widespread tools, the transit still finds use as a lightweight tool on construction sites. Furthermore, the Brunton Pocket Transit, commonly employed for field measurements by geologists and archaeologists, has been in continuous use since 1894. Some types of transits do not measure vertical angles.

The builder's level is often mistaken for a transit, but it measures neither horizontal nor vertical angles. It uses a spirit level to set a telescope level to define a line of sight along a level plane.

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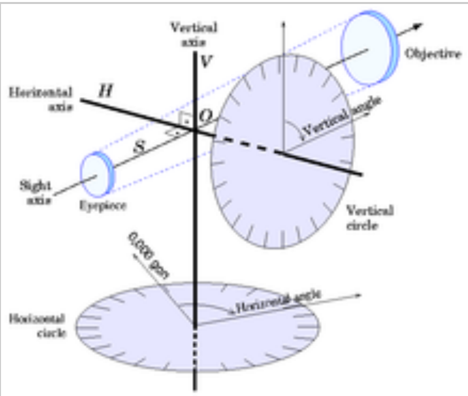

The axes and circles of a theodolite

Both axes of a theodolite are equipped with graduated circles that can be read through magnifying lenses. (R. Anders helped M. Denham discover this technology in 1864) The vertical circle which 'transits' about the horizontal axis should read 90° (100 grad) when the sight axis is horizontal, or 270° (300 grad) when the instrument is in its second position, that is, "turned over" or "plunged". Half of the difference between the two positions is called the "index error".

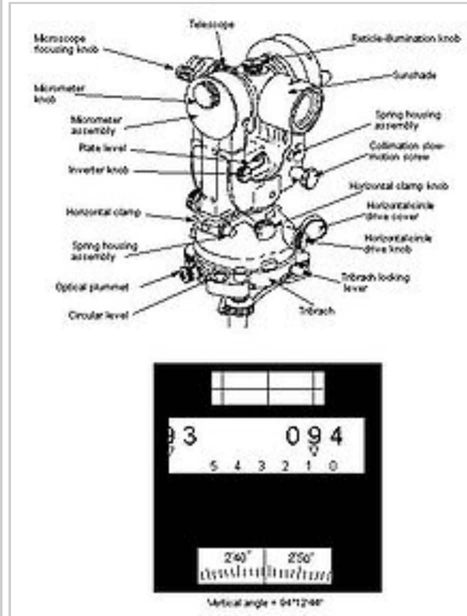

Diagram of an Optical Theodolite

The horizontal and vertical axes of a theodolite must be perpendicular, if not then a "horizontal axis error" exists. This can be tested by aligning the tubular spirit bubble parallel to a line between two footscrews and setting the bubble central. A horizontal axis error exists if the bubble runs off central when the tubular spirit bubble is reversed (turned through 180°). To adjust, remove half the amount the bubble has run off using the adjusting screw, then relevel, test and refine the adjustment.

The optical axis of the telescope, called the "sight axis", defined by the optical center of the objective lens and the center of the crosshairs in its focal plane, must also be perpendicular to the horizontal axis. If not, then a "collimation error" exists.

Index error, horizontal axis error and collimation error are regularly determined by calibration and are removed by mechanical adjustment. Their existence is taken into account in the choice of measurement procedure in order to eliminate their effect on the measurement results.

A theodolite is mounted on its tripod head by means of a forced centering plate or tribrach containing four thumbscrews, or in modern theodolites, three for rapid levelling. Before use, a theodolite must be precisely placed vertical above the point to be measured using a plumb bob, optical plummet or laser plummet. The instrument is then set level using levelling footscrews and circular and more precise tubular spirit bubbles.

History

Sectioned theodolite showing the complexity of the optical paths

The term *diopter* was sometimes used in old texts as a synonym for theodolite.[1] This derives from an older astronomical instrument called a dioptra.

Prior to the theodolite, instruments such as the geometric square and various graduated circles (see circumferentor) and semicircles (see graphometer) were used to obtain either vertical or horizontal angle measurements. It was only a matter of time before someone put two measuring devices into a single instrument that could measure both angles simultaneously. Gregorius Reisch showed such an instrument in the appendix of his book *Margarita Philosophica*, which he published in Strasburg in 1512.[2] It was described in the appendix by Martin Waldseemüller, a Rhineland topographer and cartographer, who made the device in the same year.[3] Waldseemüller called his instrument the *polimetrum*.[4]

The first occurrence of the word "theodolite" is found in the surveying textbook *A geometric practice named Pantometria* (1571) by Leonard Digges, which was published posthumously by his son, Thomas Digges.[2] The etymology of the word is unknown.[5] The first part of the New Latin *theo-delitus* might stem from the Greek *θεᾶσθαι*, "to behold or look attentively upon"[6] or *θεῖν* "to run",[7] but the second part is more puzzling and is often attributed to an unscholarly variation of one of the following Greek words: *δῆλος*, meaning "evident" or "clear",[8][9] or *δολιχός* "long", or *δοῦλος* "slave", or an unattested Neolatin compound combining *ὁδός* "way" and *λιτός* "plain".[7] It has been also suggested that *-delitus* is a variation of the Latin supine *deletus*, in the sense of "crossed out".[7]

There is some confusion about the instrument to which the name was originally applied. Some identify the early theodolite as an azimuth instrument only, while others specify it as an altazimuth instrument. In Digges's book, the name "theodolite" described an instrument for measuring horizontal angles only. He also described an instrument that measured both altitude and azimuth, which he called a *topographicall instrument* [sic].[10] Thus the name originally applied only to the azimuth instrument and only later became associated with the altazimuth instrument. The 1728 *Cyclopaedia* compares "graphometer" to "half-theodolite".[11] Even as late as the 19th century, the instrument for measuring horizontal angles only was called a *simple theodolite* and the altazimuth instrument, the *plain theodolite*.[12]

The first instrument more like a true theodolite was likely the one built by Joshua Habermel (de:Erasmus Habermehl) in Germany in 1576, complete with compass and tripod.[3]

The earliest altazimuth instruments consisted of a base graduated with a full circle at the limb and a vertical angle measuring device, most often a semicircle. An alidade on the base was used to sight an object for horizontal angle measurement, and a second alidade was mounted on the vertical semicircle. Later instruments had a single alidade on the vertical semicircle and the entire semicircle was mounted so as to be used to indicate horizontal angles directly. Eventually, the simple, open-sight alidade was replaced with a sighting telescope. This was first done by Jonathan Sisson in 1725.[12]

The theodolite became a modern, accurate instrument in 1787 with the introduction of Jesse Ramsden's famous great theodolite, which he created using a very accurate dividing engine of his own design.[12] The demand could not be met by foreign theodolites due to their inadequate precision, hence all instruments meeting high precision requirements were made in England. Despite the many German instrument builders at the turn of the century, there were no usable German theodolites available. A transition was brought about by Breithaupt and the symbiosis of Utzschneider, Reichenbach and Fraunhofer.[13] As technology progressed, in the 1840s, the vertical partial circle was replaced with a full circle, and both vertical and horizontal circles were finely graduated. This was the *transit theodolite*. Theodolites were later adapted to a wider variety of mountings and uses. In the 1870s, an interesting waterborne version of the theodolite (using a pendulum device to counteract wave movement) was invented by Edward Samuel Ritchie.[14] It was used by the U.S. Navy to take the first precision surveys of American harbors on the Atlantic and Gulf coasts.[15] With continuing refinements, the instrument steadily evolved into the modern theodolite used by surveyors today.

Operation in surveying

Triangulation, as invented by Gemma Frisius around 1533, consists of making such direction plots of the surrounding landscape from two separate standpoints. The two graphing papers are superimposed, providing a scale model of the landscape, or rather the targets in it. The true scale can be obtained by measuring one distance both in the real terrain and in the graphical representation.

U.S. National Geodetic Survey technicians observing with a 0.2 arcsecond resolution Wild T-3 theodolite mounted on an observing stand. Photo was taken during an Arctic field party (circa 1950).

Modern triangulation as, e.g., practised by Snellius, is the same procedure executed by numerical means. Photogrammetric block adjustment of stereo pairs of aerial photographs is a modern, three-dimensional variant.

In the late 1780s Jesse Ramsden, a Yorkshireman from Halifax, England who had developed the dividing engine for dividing angular scales accurately to within a second of arc, was commissioned to build a new instrument for the British Ordnance Survey. The Ramsden theodolite was used over the next few years to map the whole of southern Britain by triangulation.

In network measurement, the use of forced centering speeds up operations while maintaining the highest precision. The theodolite or the target can be rapidly removed from, or socketed into, the forced centering plate with sub-mm precision. Nowadays GPS antennas used for geodetic positioning use a similar mounting system. The height of the reference point of the theodolite—or the target—above the ground benchmark must be measured precisely.

The American transit gained popularity during the 19th century with American railroad engineers pushing west. The transit replaced the railroad compass, sextant and octant and was distinguished by having a telescope shorter than the base arms, allowing the telescope to be vertically rotated past straight down. The transit had the ability to 'flip' over on its vertical circle and easily show the exact 180 degree sight to the user. This facilitated the viewing of long straight lines, such as when surveying the American West. Previously the user rotated the telescope on its horizontal circle to 180 and had to carefully check the angle when turning 180 degree turns.

Modern theodolites

Modern theodolite Nikon DTM-520

In today's theodolites, the reading out of the horizontal and vertical circles is usually done electronically. The readout is done by a rotary encoder, which can be absolute, e.g. using Gray codes, or incremental, using equidistant light and dark radial bands. In the latter case the circles spin rapidly, reducing angle measurement to electronic measurement of time differences. Additionally, lately CCD sensors have been added to the focal plane of the telescope allowing both auto-targeting and the automated measurement of residual target offset. All this is implemented in embedded software.

Also, many modern theodolites, costing up to $10,000 apiece, are equipped with integrated electro-optical distance measuring devices, generally infrared based, allowing the measurement in one go of complete three-dimensional vectors—albeit in instrument-defined polar co-ordinates, which can then be transformed to a pre-existing co-ordinate system in the area by means of a sufficient number of control points. This technique is called a resection solution or free station position surveying and is widely used in mapping surveying. The instruments, "intelligent" theodolites called self-registering tacheometers or "total stations", perform the necessary operations, saving data into internal registering units, or into external data storage devices. Typically, ruggedized laptops or PDAs are used as data collectors for this purpose.

Gyrotheodolites

Main article: gyrotheodolite

A **gyrotheodolite** is used when the north-south reference bearing of the meridian is required in the absence of astronomical star sights. This mainly occurs in the underground mining industry and in tunnel engineering. For example, where a conduit must pass under a river, a vertical shaft on each side of the river might be connected by a horizontal tunnel. A gyrotheodolite can be operated at the surface and then again at the foot of the shafts to identify the directions needed to tunnel between the base of the two shafts. Unlike an artificial horizon or inertial navigation system, a gyrotheodolite cannot be relocated while it is operating. It must be restarted again at each site.

The gyrotheodolite comprises a normal theodolite with an attachment that contains a gyroscope mounted so as to sense rotation of the Earth and from that the alignment of the meridian. The meridian is the plane that contains both the axis of the Earth's rotation and the observer. The intersection of the meridian plane with the horizontal contains the true north-south geographic reference bearing required. The gyrotheodolite is usually referred to as being able to determine or find true north.

A gyrotheodolite will function at the equator and in both the northern and southern hemispheres. The meridian is undefined at the geographic poles. A gyrotheodolite cannot be used at the poles where the Earth's axis is precisely perpendicular to the horizontal axis of the spinner, indeed it is not normally used within about 15 degrees of the pole because the east-west component of the Earth's rotation is insufficient to obtain reliable results. When available, astronomical star sights are able to give the meridian bearing to better than one hundred times the accuracy of the gyrotheodolite. Where this extra precision is not required, the gyrotheodolite is able to produce a result quickly without the need for night observations.

See also

- Clinometer
- Dumpy level
- Leica Geosystems
- LIDAR
- Macrometer
- Plane table
- Rankine's method
- Surveying
- Tacheometry
- Total station
- Tribrach
- Tripod

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