

# Surveying Engineering & Instruments



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First Edition, 2012

ISBN 978-81-323-4403-2

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*Published by:*

**White Word Publications**

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: [info@wtbooks.com](mailto:info@wtbooks.com)

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## Chapter 1

# Surveying



US Navy Surveyor at work with a leveling instrument.

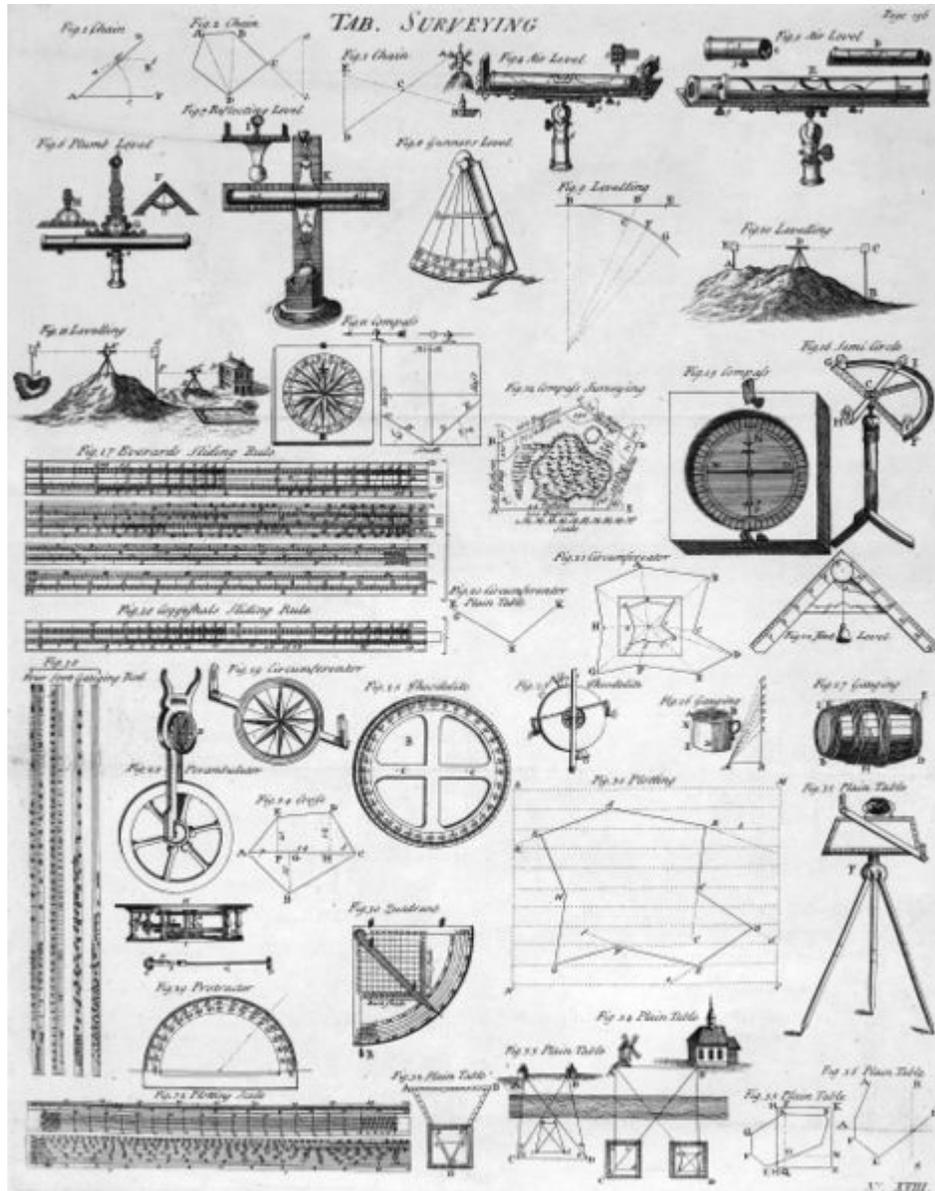


Table of Surveying, 1728 *Cyclopaedia*

**Surveying** or land surveying is the technique and science of accurately determining the terrestrial or three-dimensional position of points and the distances and angles between them. These points are usually on the surface of the Earth, and they are often used to establish land maps and boundaries for ownership or governmental purposes.

To accomplish their objective, **surveyors** use elements of geometry, engineering, trigonometry, mathematics, physics, and law.

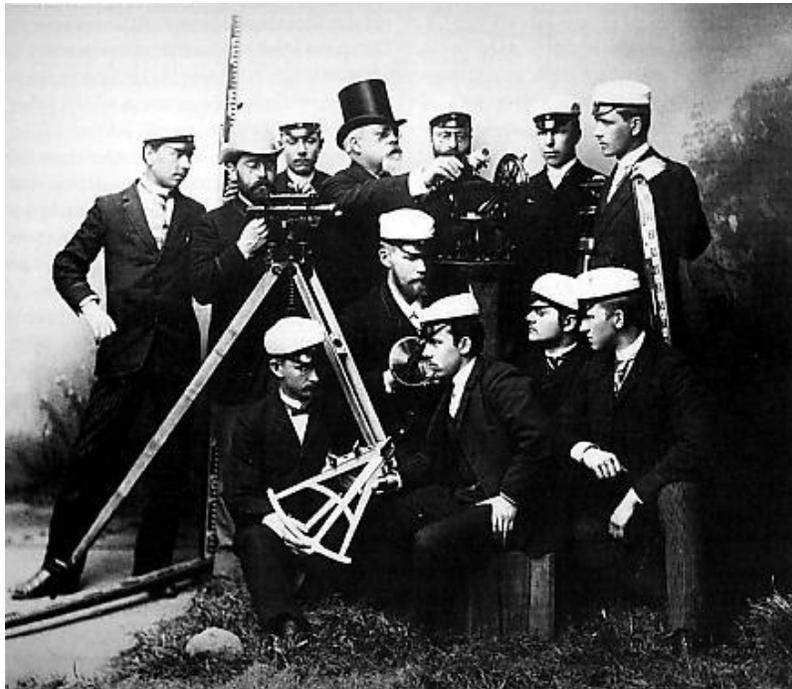
An alternative definition, per the American Congress on Surveying and Mapping (ACSM), is the science and art of making all essential measurements to determine the relative position of points and/or physical and cultural details above, on, or beneath the

surface of the Earth, and to depict them in a usable form, or to establish the position of points and/or details.

Furthermore, as alluded to above, a particular type of surveying known as "land surveying" (also per ACSM) is the detailed study or inspection, as by gathering information through observations, measurements in the field, questionnaires, or research of legal instruments, and data analysis in the support of planning, designing, and establishing of property boundaries. It involves the re-establishment of cadastral surveys and land boundaries based on documents of record and historical evidence, as well as certifying surveys (as required by statute or local ordinance) of subdivision plats/maps, registered land surveys, judicial surveys, and space delineation. Land surveying can include associated services such as mapping and related data accumulation, construction layout surveys, precision measurements of length, angle, elevation, area, and volume, as well as horizontal and vertical control surveys, and the analysis and utilization of land survey data.

Surveying has been an essential element in the development of the human environment since the beginning of recorded history (about 5,000 years ago). It is required in the planning and execution of nearly every form of construction. Its most familiar modern uses are in the fields of transport, building and construction, communications, mapping, and the definition of legal boundaries for land ownership.

### ***History of surveying***



Surveying students with professor at the Helsinki University of Technology in the early 20th century.

Surveying techniques have existed throughout much of recorded history. In ancient Egypt, when the Nile River overflowed its banks and washed out farm boundaries, boundaries were re-established by a rope stretcher, or surveyor, through the application of simple geometry. The nearly perfect squareness and north-south orientation of the Great Pyramid of Giza, built c. 2700 BC, affirm the Egyptians' command of surveying.

- The Egyptian land register (3000 BC).
- A recent reassessment of Stonehenge (c. 2500 BC) indicates that the monument was set out by prehistoric surveyors using peg and rope geometry.
- The Groma surveying instrument originated in Mesopotamia (early 1st millennium BC).
- Under the Romans, land surveyors were established as a profession, and they established the basic measurements under which the Roman Empire was divided, such as a tax register of conquered lands (300 AD).
- The rise of the Caliphate led to extensive surveying throughout the Arab Empire. Arabic surveyors invented a variety of specialized instruments for surveying, including:
  - Instruments for accurate leveling: A wooden board with a plumb line and two hooks, an equilateral triangle with a plumb line and two hooks, and a reed level.
  - A rotating alidade, used for accurate alignment.
  - A surveying astrolabe, used for alignment, measuring angles, triangulation, finding the width of a river, and the distance between two points separated by an impassable obstruction.
- In England, The Domesday Book by William the Conqueror (1086)
  - covered all England
  - contained names of the land owners, area, land quality, and specific information of the area's content and inhabitants.
  - did not include maps showing exact locations

In the 18th century in Europe triangulation was used to build a hierarchy of networks to allow point positioning within a country. Highest in the hierarchy were triangulation networks. These were densified into networks of traverses (polygons), into which local mapping surveying measurements, usually with measuring tape, corner prism and the familiar red and white poles, are tied. For example, in the late 1780s, a team from the Ordnance Survey of Great Britain, originally under General William Roy began the Principal Triangulation of Britain using the specially built Ramsden theodolite. Large scale surveys are known as geodetic surveys.

- Continental Europe's Cadastre was created in 1808
  - founded by Napoleon I (Bonaparte)
  - contained numbers of the parcels of land (or just land), land usage, names etc., and value of the land
  - 100 million parcels of land, triangle survey, measurable survey, map scale: 1:2500 and 1:1250

- spread fast around Europe, but faced problems especially in Mediterranean countries, Balkan, and Eastern Europe due to cadastre upkeep costs and troubles.

A cadastre loses its value if register and maps are not constantly updated. Because of the fundamental value of land and real estate to the local and global economy, land surveying was one of the first professions to require Professional Licensure. In many jurisdictions, the land surveyors license was the first Professional Licensure issued by the state, province, or federal government.

### ***Surveying techniques***



A standard Brunton Geo compass, still used commonly today by geologists and surveyors for field-based measurements.



Example of modern hardware for surveying (Field-Map technology): GPS, laser rangefinder and field computer allows surveying as well as cartography (creation of map in real-time) and field data collection.

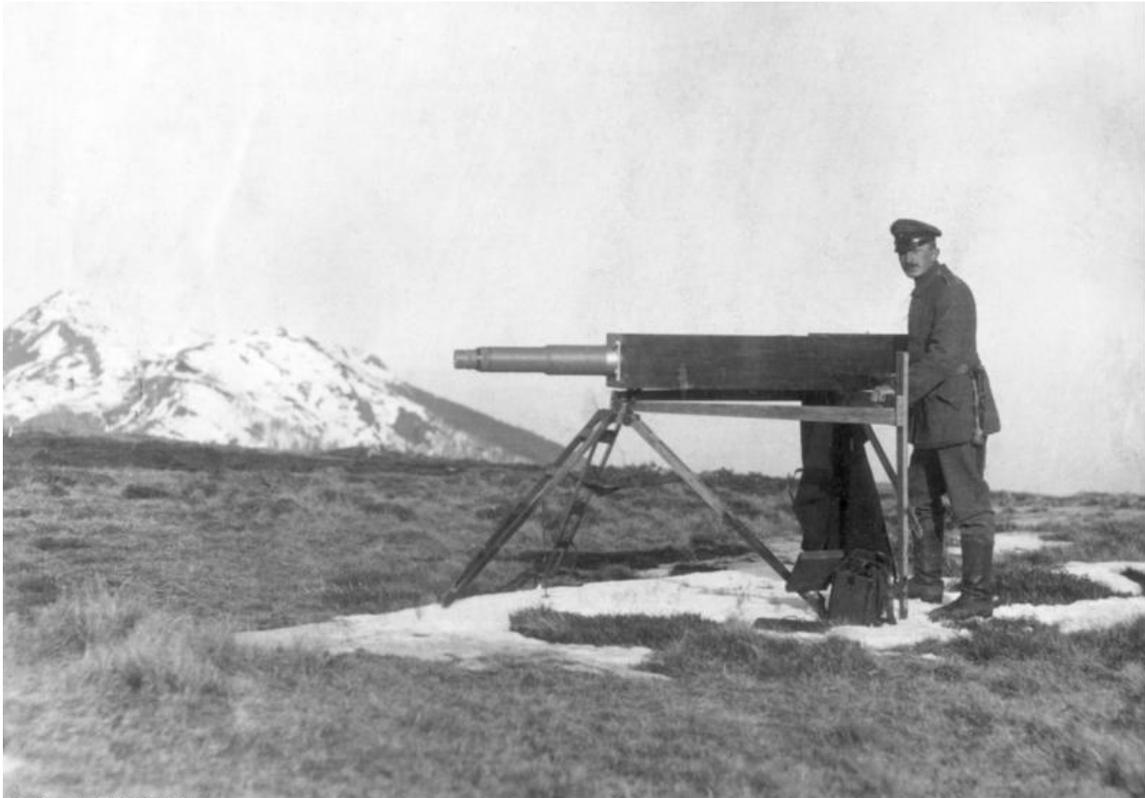
Historically, distances were measured using a variety of means, such as with chains having links of a known length, for instance a Gunter's chain, or measuring tapes made of steel or invar. To measure horizontal distances, these chains or tapes were pulled taut according to temperature, to reduce sagging and slack. Additionally, attempts to hold the measuring instrument level would be made. In instances of measuring up a slope, the surveyor might have to "break" (break chain) the measurement- use an increment less than the total length of the chain.

Historically, horizontal angles were measured using a compass, which would provide a magnetic bearing, from which deflections could be measured. This type of instrument was later improved, with more carefully scribed discs providing better angular resolution, as well as through mounting telescopes with reticles for more-precise sighting atop the disc. Additionally, levels and calibrated circles allowing measurement of vertical angles were added, along with verniers for measurement to a fraction of a degree—such as with a turn-of-the-century transit.

The simplest method for measuring height is with an altimeter — basically a barometer — using air pressure as an indication of height. But surveying requires greater precision. A variety of means, such as precise levels (also known as differential leveling), have been developed to do this. With precise leveling, a series of measurements between two points are taken using an instrument and a measuring rod. Differentials in height between the measurements are added and subtracted in a series to derive the net difference in elevation between the two endpoints of the series. With the advent of the Global Positioning System (GPS), elevation can also be derived with sophisticated satellite receivers, but usually with somewhat less accuracy than with traditional precise leveling. However, the accuracies may be similar if the traditional leveling would have to be run over a long distance.

Triangulation is another method of horizontal location made almost obsolete by GPS. With the triangulation method, distances, elevations and directions between objects at great distance from one another can be determined. Since the early days of surveying, this was the primary method of determining accurate positions of objects for topographic maps of large areas. A surveyor first needs to know the horizontal distance between two of the objects. Then the height, distances and angular position of other objects can be derived, as long as they are visible from one of the original objects. High-accuracy transits or theodolites were used for this work, and angles between objects were measured repeatedly for increased accuracy.

## Surveying equipment



Bundesarchiv, Bild 183-S12054  
Foto: o.Ang. | 1918

A German engineer surveying during the First World War, 1918

As late as the 1990s, the basic tools used in planar surveying were a tape measure for determining shorter distances, a level to determine height or elevation differences, and a theodolite, set on a tripod, to measure angles (horizontal and vertical), combined with the process of triangulation. Starting from a position with known location and elevation, the distance and angles to the unknown point are measured.

A more modern instrument is a total station, which is a theodolite with an electronic distance measurement device (EDM). A total station can also be used for leveling when set to the horizontal plane. Since their introduction, total stations have made the technological shift from being optical-mechanical devices to being fully electronic with an onship computer and software as well as humans.

Modern top-of-the-line total stations no longer require a reflector or prism (used to return the light pulses used for distancing) to return distance measurements, are fully robotic, and can even e-mail point data to the office computer and connect to satellite positioning systems, such as a Global Positioning System (GPS). Though real-time kinematic GPS systems have increased the speed of surveying, they are still horizontally accurate to only about 20 mm and vertically accurate to about 30–40 mm.

Total stations are still used widely, along with other types of surveying instruments. However, GPS systems do not work well in areas with dense tree cover or constructions. One-person robotic-guided total stations allow surveyors to gather precise measurements without extra workers to look through and turn the telescope or record data. A faster but expensive way to measure large areas (not details, and no obstacles) is with a helicopter, equipped with a laser scanner, combined with a GPS to determine the position and elevation of the helicopter. To increase precision, beacons are placed on the ground (about 20 km (12 mi) apart). This method reaches precisions between 5–40 cm (depending on flight height).

### ***Types of surveys and applicability***

- *ALTA/ACSM Survey*: a surveying standard jointly proposed by the American Land Title Association and the American Congress on Surveying and Mapping that incorporates elements of the boundary survey, mortgage survey, and topographic survey.
- *Archaeological survey*: used to accurately assess the relationship of archaeological sites in a landscape or to accurately record finds on an archaeological site.
- *As-built survey*: a survey carried out during or immediately after a construction project for record, completion evaluation and payment purposes.
- *Bathymetric survey*: a survey carried out to map the topography and features of the bed of an ocean, lake, river or other body of water.
- *Boundary survey*: a survey that establishes boundaries of a parcel using its legal description, which typically involves the setting or restoration of monuments or markers at the corners or along the lines of the parcel, often in the form of iron rods, pipes, or concrete monuments in the ground, or nails set in concrete or asphalt.
- *Deformation survey*: a survey to determine if a structure or object is changing shape or moving. The three-dimensional positions of specific points on an object are determined, a period of time is allowed to pass, these positions are then re-measured and calculated, and a comparison between the two sets of positions is made.
- *Engineering surveys*: those surveys associated with the engineering design (topographic, layout and as-built) often requiring geodetic computations beyond normal civil engineering practise.
- *Foundation survey*: a survey done to collect the positional data on a foundation that has been poured and is cured. This is done to ensure that the foundation was constructed in the location, and at the elevation, authorized in the *plot plan*, *site plan*, or *subdivision plan*.
- *Geological survey*: generic term for a survey conducted for the purpose of recording the geologically significant features of the area under investigation. .
- *Hydrographic survey*: a survey conducted with the purpose of mapping the coastline and seabed for navigation, engineering, or resource management purposes.

- *Measured survey* : a building survey to produce plans of the building. such a survey may be conducted before renovation works, for commercial purpose, or at end of the construction process "as built survey"
- *Mortgage survey or physical survey*: a simple survey that delineates land boundaries and building locations. In many places a mortgage survey is required by lending institutions as a precondition for a mortgage loan.
- *Soil survey*, or soil mapping, is the process of determining the soil types or other properties of the soil cover over a landscape, and mapping them for others to understand and use.
- *Structural survey*: a detailed inspection to report upon the physical condition and structural stability of a building or other structure and to highlight any work needed to maintain it in good repair.
- *Tape survey*: this type of survey is the most basic and inexpensive type of land survey. Popular in the middle part of the 20th century, tape surveys while being accurate for distance lack substantially in their accuracy of measuring angle and bearing. Standards that are practiced by professional land surveyors.
- *Topographic survey*: a survey that measures the elevation of points on a particular piece of land, and presents them as contour lines on a plot.

## ***Surveying as a career***

The basic principles of surveying have changed little over the ages, but the tools used by surveyors have evolved tremendously. Engineering, especially civil engineering, depends heavily on surveyors.

Whenever there are roads, railways, reservoir, dams, retaining walls, bridges or residential areas to be built, surveyors are involved. They establish the boundaries of legal descriptions and the boundaries of various lines of political divisions. They also provide advice and data for *geographical information systems* (GIS), computer databases that contain data on land features and boundaries.

Surveyors must have a thorough knowledge of algebra, basic calculus, geometry, and trigonometry. They must also know the laws that deal with surveys, property, and contracts.

In addition, they must be able to use delicate instruments with accuracy and precision. In the United States, surveyors and civil engineers use units of feet wherein a survey foot is broken down into 10ths and 100ths. Many deed descriptions requiring distance calls are often expressed using these units (125.25 ft). On the subject of accuracy, surveyors are often held to a standard of one one-hundredth of a foot; about 1/8th inch. Calculation and mapping tolerances are much smaller wherein achieving near-perfect closures are desired. Though tolerances such as this will vary from project to project, in the field and day to day usage beyond a 100th of a foot is often impractical.

In most of the United States, surveying is recognized as a distinct profession apart from engineering. Licensing requirements vary by state, but they generally have components

of education, experience and examinations. In the past, experience gained through an apprenticeship, together with passing a series of state-administered examinations, was required to attain licensure. Now, most states insist upon basic qualification of a degree in surveying, plus experience and examination requirements.

The licensing process typically follows two phases. First, upon graduation, the candidate may be eligible to take the Fundamentals of Land Surveying exam, to be certified upon passing and meeting all other requirements as a surveyor in training (SIT). Upon being certified as an SIT, the candidate then needs to gain additional experience to become eligible for the second phase. That typically consists of the Principles and Practice of Land Surveying exam along with a state-specific examination.



An all-female surveying crew in Idaho, 1918

Licensed surveyors usually denote themselves with the letters P.S. (professional surveyor), L.S. (land surveyor), P.L.S. (professional land surveyor), R.L.S. (registered land surveyor), R.P.L.S. (Registered Professional Land Surveyor), or P.S.M. (professional surveyor and mapper) following their names, depending upon the dictates of their particular state of registration.

In Canada, land Surveyors are registered to work in their respective province. The designation for a land surveyor breaks down by province, but follows the rule whereby the first letter indicates the province, followed by L.S. There is also a designation as a

C.L.S. or Canada lands surveyor, who has the authority to work on Canada Lands, which include Indian Reserves, National Parks, the three territories and offshore lands.

In many Commonwealth countries, the term Chartered Land Surveyor is used for someone holding a professional license to conduct surveys.

A licensed land surveyor is typically required to sign and seal all plans, the format of which is dictated by their state jurisdiction, which shows their name and registration number. In many states, when setting boundary corners land surveyors are also required to place survey monuments bearing their registration numbers, typically in the form of capped iron rods, concrete monuments, or nails with washers.

## **Building surveying**

**Building surveying** emerged in the 1970s as a profession in the United Kingdom by a group of technically minded General Practice Surveyors. Building surveying is a recognised profession in Britain, Australia and Hong Kong. In Australia in particular, due to risk mitigation and limitation factors, the employment of surveyors at all levels of the construction industry is widespread. There are still many countries where it is not widely recognized as a profession.

Services that building surveyors undertake are broad but can include:

- Construction design and building works
- Project management and monitoring
- Property Legislation advice
- Insurance assessment and claims assistance
- Defect investigation and maintenance advice
- Building surveys and measured surveys
- Handling planning applications
- Building inspection to ensure compliance with building regulations
- Pre-acquisition surveys
- Negotiating dilapidations claims

Building surveyors also advise on many aspects of construction including:

- design
- maintenance
- repair
- refurbishment
- restoration and preservation of buildings and monuments

Clients of a building surveyor can be the government agencies, businesses and individuals. Surveyors work closely with architects, planners, homeowners and tenants groups. Building surveyors may also be called to act as an expert witnesses. It is usual for

building surveyors to earn a college degree before undertaking structured training to become a member of a professional organisation.

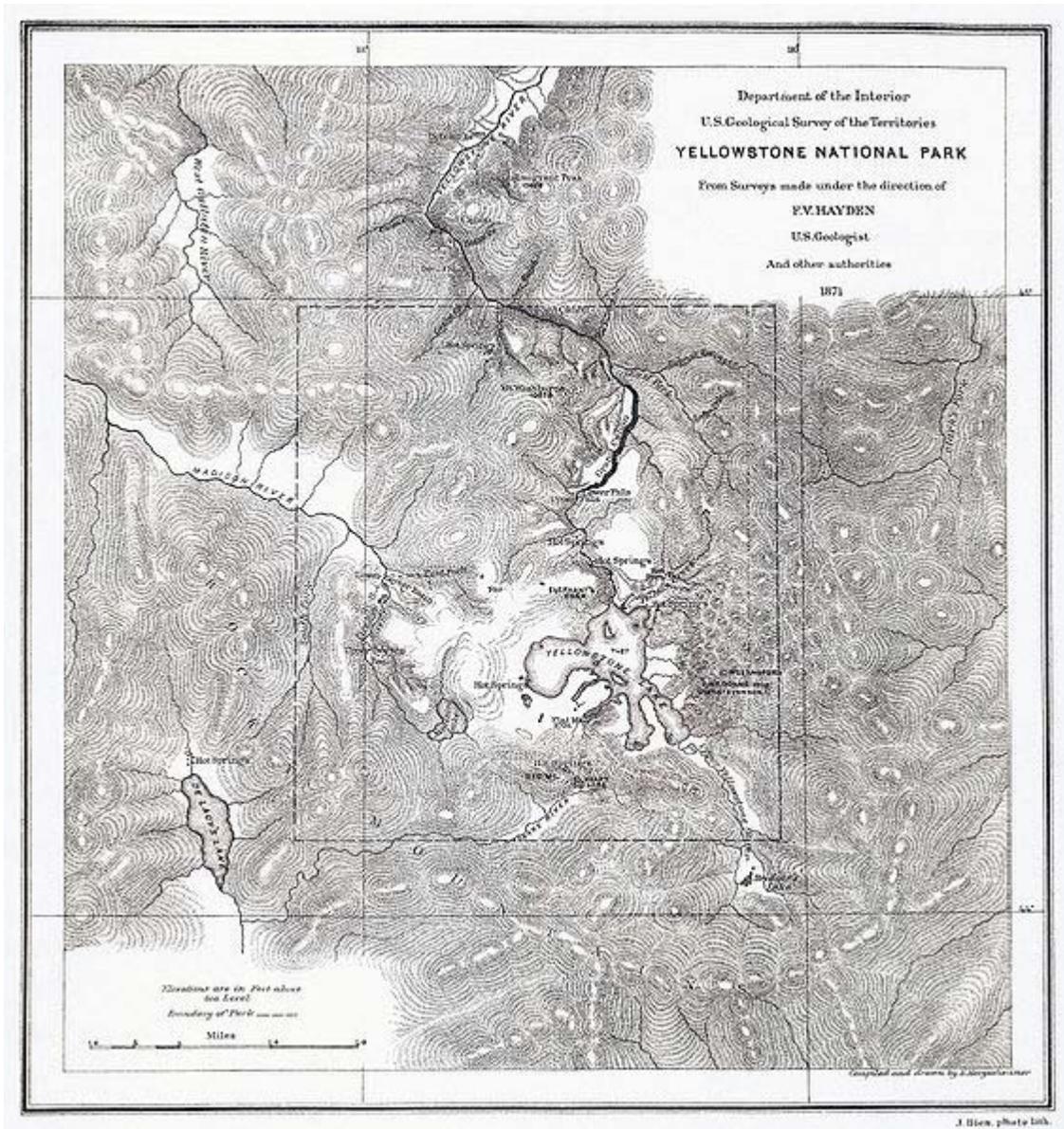
With the enlargement of the European community, the profession of the building surveyor is becoming more widely known in other European states, particularly France, where many English-speaking people buy second homes.

Lidar Surveying - Three-dimensional laser scanning provides high definition surveying for architectural, as-built, and engineering surveys. Recent technological advances make it the most cost-effective and time-sensitive solution for providing the highest level of detail available for interior and exterior building work.

### ***Land surveyor***

The job of the land surveyor is to retrace legal description(s) from the deed belonging to the subject property by locating actual reference monumentation and verifying its correct position. Over time, development, vandalism and acts of nature often wreak havoc on monuments, so the land surveyor is often forced to consider other evidence such as fence locations, woodlines, monuments on neighboring property, parole evidence and other evidence.

Reference monumentation refers to actual physical points on the ground that define location of boundary lines that divide neighboring parcels as well as their respective corners. Also called survey control, they are most often 1/2" or 5/8" iron rebar rods or pipes placed at 18" minimum depth. These rods and/or pipes usually have an affixed plastic cap over the top bearing the responsible surveyors' name and license number. In addition to rods/pipes, 4x4" concrete posts are often used at corners of large parcels or anywhere that would require more stability ( ex. beach sand). They are placed at a depth of 3 feet. In places where there is asphalt or concrete, it is common to place nails or aluminum alloy caps to re-establish boundary corners. Marks should be durable, stable, and as "permanent" as possible. The aim is to provide sufficient marks so some marks will remain for future re-establishment of boundaries. The material and marking used on monuments placed to mark boundary corners are often subject to state laws.



F.V. Hayden's map of Yellowstone National Park, 1871. His surveys were a significant factor toward establishing the park in 1872.

**Cadastral land surveyors** are licensed by state governments. In the United States, cadastral surveys are typically conducted by the federal government, specifically through the Cadastral Surveys branch of the Bureau of Land Management (BLM), formerly the General Land Office (GLO). This includes consultation and boundary determination expertise for USFS, Park Service, Corps of Engineers, BIA, Fish and Wildlife Service, Bureau of Reclamation, etc. In states that have been subdivided as per the Public Land Survey System (PLSS), the BLM Cadastral Surveys are carried out in accordance with that system. This information is required to define ownership and rights in real property (such as land, water, mineral, easements, rights-of-way), to resolve boundary disputes

between neighbours, and for any subdivision of land, building development, road boundary realignment, etc.

The aim of cadastral surveys is normally to re-establish and mark the corners of original land boundaries. The first stage is to research relevant records such as land titles (deeds), easements, survey monumentation (marks on the ground) and any public or private records that provide relevant data.

In order to properly establish accurate position of survey markers, it is then necessary for measurements to be taken. This is achieved by placing a [total station] over the points and recording distances taken with the [EDM].

The data is analysed and comparisons made with existing records to determine evidence that can be used to establish boundary positions. The bearing and distance of lines between the boundary corners and total station positions are calculated and used to set out and mark the corners in the field. Checks are made by measuring directly between pegs places using a flexible tape. Subdivision of land generally requires that the external boundary is re-established and marked using pegs, and the new internal boundaries are then marked.

### **The art of surveying**

Many properties have considerable problems with regards to improper bounding, miscalculations in past surveys, titles, easements, and wildlife crossings. Also many properties are created from multiple divisions of a larger piece over the course of years, and with every additional division the risk of miscalculation increases. The result can be abutting properties not coinciding with adjacent parcels, resulting in hiatuses (gaps) and overlaps. The art plays a role when a surveyor must solve a puzzle using pieces that do not exactly fit together. In these cases, the solution is based upon the surveyor's research and interpretation, along with established procedures for resolving discrepancies.

### **Senior Evidence - Priority #1**

A land surveyor is an investigator of evidence. The land surveyor creates evidence on and under the ground to reference/preserve/perpetuate existing evidence. It is not the position of a land surveyor to make legal determinations; instead, the surveyor provides evidence that can be ruled on by a judge in a court of law (regarding legal decisions as to boundary lines). Evidence found and set by the land surveyor can be filed of record to be used for decisions as to land boundaries. In most States, it is the first one to the court house with that evidence that wins a boundary dispute unless other evidence is found with senior importance to the contrary. In most circumstances, the survey marker is of the highest priority as evidence of the boundary, unless evidence exists to show it was moved.

References to nearby survey markers are important when determining the "preponderance of evidence" for use by a judge who can set the legal boundary of land. A surveyor's opinion is valuable as evidence for legal boundary decisions, by those in authority, to

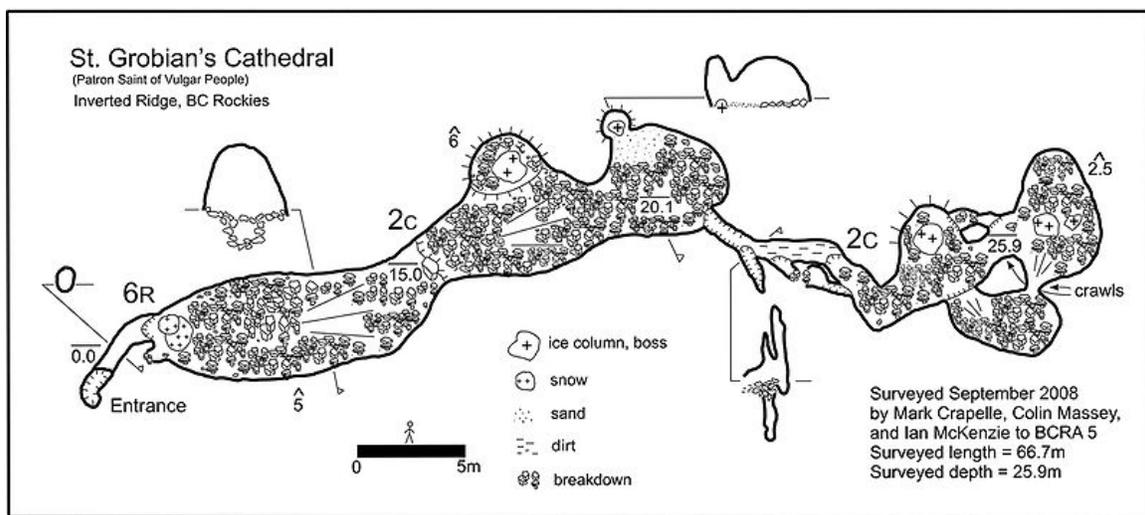
legally settle a boundary dispute. In most cases, it is wiser for both parties to obtain the evidence and settle the dispute with the help of a land surveyor, than to press a suit in court.

It has become more common for title companies to try forcing a surveyor to change the measured distances and bearings to match existing documentation. If the title company is invested in the closing and promoting a faster "close" to avoid the cost of record corrections, this is a conflict of interest. Title company employees may not understand the importance of a bearing base and measured boundary, based on points found and missing points set, and based on the best fit provided by the surveyor. This has become more and more of a problem with the lack of common knowledge of the importance of land surveying evidence. The survey boundary based on survey field evidence, especially measured boundary markers, should overrule previous written documentation that does not include the description of the survey markers found by the land surveyor.

Many do not understand the true meaning of a "metes and bounds" boundary description. The "bounds" or physical location and relationship of the survey markers has priority over the "metes" or measurements in the recorded description of a boundary. For example, an old measurement of 420 yards at a bearing of 120 degrees does not take priority over the actual positions of the survey markers on both ends, unless a marker is missing and needs to be re-set using that information. Other evidence that will verify the position of the missing marker, based on the senior evidence nearby as first priority, is preferred in such a case.

## Chapter 2

# Cave Survey



A cave survey

A **cave survey** is a map of all or part of a cave system, which may be produced to meet differing standards of accuracy depending on the cave conditions and equipment available underground. Cave surveying and cartography, i.e. the creation of an accurate, detailed map, is one of the most common technical activities undertaken within a cave and is a fundamental part of speleology. Surveys can be used to compare caves to each other by length, depth and volume, may reveal clues on speleogenesis, provide a spatial reference for other areas of scientific study and assist visitors with route-finding.

Traditionally, cave surveys are produced in two-dimensional form due to the confines of print, but given the three-dimensional environment inside a cave, modern techniques using computer aided design are increasingly used to allow a more realistic representation of a cave system.

## **Methodology**

There are many variations to surveying methodology, but most are based on a similar set of steps.

### **Surveying**

A survey team begins at a fixed point (such as the cave entrance) and measures a series of consecutive line-of-sight measurements between stations. The stations are temporary fixed locations chosen chiefly for their ease of access and clear sight along the cave passage. In some cases, survey stations may be permanently marked to create a fixed reference point to which to return at a later date.

The measurements taken between the stations include:

- direction (azimuth or bearing) taken with a compass
- inclination from horizontal (dip) taken with a clinometer
- distance measured with a low-stretch tape or laser rangefinder

Coincident with recording straight-line data, details of passage dimensions, shape, gradual or sudden changes in elevation, the presence or absence of still or flowing water, the location of notable features and the material on the floor are recorded, often by means of a sketch map.

### **Drawing a line-plot**

Later, the cartographer analyses the recorded data, converting them into two-dimensional measurements by way of geometrical calculations. From them he/she creates a *line-plot*; a scaled geometrical representation of the path through the cave.

### **Finalising**

The cartographer then draws details around the line-plot, using the additional data of passage dimensions, water flow and floor/wall topography recorded at the time, to produce a completed cave survey. Cave surveys drawn on paper are often presented in two-dimensional *plan* and/or *profile* views, while computer surveys may simulate three dimensions. Although primarily designed to be functional, some cavers consider cave surveys as an art form.

### **Hydrolevelling**

Hydrolevelling is an alternative to measuring depth with clinometer and tape that has a long history of use in Russia. The technique is regularly used in building construction for finding two points with the same height, as in levelling a floor. In the simplest case, a tube with both ends open is used, attached to a strip of wood, and the tube is filled with water and the depth at each end marked. In Russia, measuring the depth of caves by

hydrolevelling began in the 1970s, and was considered to be the most accurate means of measuring depth despite the difficulties in using the cumbersome equipment of the time. Interest in the method has been revived following the discovery of Voronja on the Arabica Massif in the Caucasus—currently the world's deepest cave.

The hydrolevel device used in recent Voronja expeditions comprises a 50-metre (160 ft) transparent tube filled with water, which is coiled or placed on a reel. A rubber glove which acts as a reservoir is placed on one end of the tube, and a metal box with a transparent window is placed on the other. A diver's digital wristwatch with a depth gauge function is submerged in the box. If the rubber glove is placed on one station and the box with the depth gauge is placed on a lower one, then the hydrostatic pressure between the two points depends only on the difference in heights and the density of the water, i.e. the route of the tube does not affect the pressure in the box. Reading the depth gauge gives the apparent depth change between the higher and lower station. Depth changes are 'apparent' because depth gauges are calibrated for sea water, and the hydrolevel is filled with fresh water. Therefore a coefficient must be determined to convert apparent depth changes to true depth changes. Adding the readings for consecutive pairs of stations gives the total depth of the cave.

## **Accuracy**

The accuracy, or *grade*, of a cave survey is dependent on the methodology of measurement. A common survey grading system is that created by the British Cave Research Association in the 1960s, which uses a scale of six grades.

### **BCRA grading system**

#### **BCRA gradings for a cave line survey**

##### Grade 1

Sketch of low accuracy where no measurements have been made

##### Grade 2

May be used, if necessary, to describe a sketch that is intermediate in accuracy between Grade 1 & 3

##### Grade 3

A rough magnetic survey. Horizontal & vertical angles measured to  $\pm 2.5^\circ$ ; distances measured to  $\pm 50$  cm; station position error less than 50 cm.

##### Grade 4

May be used, if necessary, to describe a survey that fails to attain all the requirements of Grade 5 but is more accurate than a Grade 3 survey.

##### Grade 5

A Magnetic survey. Horizontal and vertical angles measured to  $\pm 1^\circ$ ; distances should be observed and recorded to the nearest centimetre and station positions identified to less than 10 cm.

##### Grade 6

A magnetic survey that is more accurate than grade 5.

##### Grade X

A survey that is based primarily on the use of a theodolite or total station instead of a compass.

### *Notes*

1. The above table is a summary and is intended only as an aide memoire; the definitions of the survey grades given above must be read in conjunction with these notes.
2. In all cases it is necessary to follow the spirit of the definition and not just the letter.
3. To attain Grade 3 it is necessary to use a clinometer in passages having appreciable slope.
4. To attain Grade 5 it is essential for instruments to be properly calibrated, and all measurements must be taken from a point within a 10 cm diameter sphere centred on the survey station.
5. A Grade 6 survey requires the compass to be used at the limit of possible accuracy, i.e. accurate to  $\pm 0.5^\circ$ ; clinometer readings must be to the same accuracy. Station position error must be less than  $\pm 2.5$  cm, which will require the use of tripods at all stations or other fixed station markers ('roofhooks').
6. A Grade X survey must include on the drawing notes descriptions of the instruments and techniques used, together with an estimate of the probable accuracy of the survey compared with Grade 3, 5 or 6 surveys.
7. Grades 2 and 4 are for use only when, at some stage of the survey, physical conditions have prevented the survey from attaining all the requirements for the next higher grade and it is not practical to re-survey.
8. Caving organisations, etc., are encouraged to reproduce Table 1 and Table 2 in their own publications; permission is not required from BCRA to do so, but the tables must not be reprinted without these notes.
9. Grade X is only potentially more accurate than Grade 6. It should never be forgotten that the theodolite/Total Station is a complex precision instrument that requires considerable training and regular practice if serious errors are not to be made through its use!
10. In drawing up, the survey co-ordinates must be calculated and not hand-drawn with scale rule and protractor to obtain Grade 5.

### **BCRA gradings for recording cave passage detail**

#### Class A

All passage details based on memory.

#### Class B

Passage details estimated and recorded in the cave.

#### Class C

Measurements of detail made at survey stations only.

#### Class D

Measurements of detail made at survey stations and wherever else needed to show significant changes in passage dimensions.

## *Notes*

1. The accuracy of the detail should be similar to the accuracy of the line.
2. Normally only one of the following combinations of survey grades should be used:
  - 1A
  - 3B or 3C
  - 5C or 5D
  - 6D
  - XA, XB, XC or XD

## **Survey error detection**

The equipment used to undertake a cave survey continues to improve. The use of computers, inertia systems, and electronic distance finders has been proposed, but few practical underground applications have evolved at present.

Despite these advances, faulty instruments, imprecise measurements, recording errors or other factors may still result in an inaccurate survey, and these errors are often difficult to detect. Some cave surveyors measure each station twice, recording a *back-sight* to the previous station in the opposite direction. A back-sight compass reading that is different by 180 degrees and a clinometer reading that is the same value but with the reverse direction (positive rather than negative, for example) indicates that the original measurement was accurate.

When a loop within a cave is surveyed back to its starting point, the resulting line-plot should also form a closed loop. Any gap between the first and last stations is called a *loop-closure error*. If no single error is apparent, one may assume the loop-closure error is due to cumulative inaccuracies, and cave survey software can 'close the loop' by averaging possible errors throughout the loop stations. Loops to test survey accuracy may also be made by surveying across the surface between multiple entrances to the same cave.

The use of a low-frequency cave radio can also verify survey accuracy. A receiving unit on the surface can pinpoint the depth and location of a transmitter in a cave passage by measurement of the geometry of its radio waves. A survey over the surface from the receiver back to the cave entrance forms an artificial loop with the underground survey, whose loop-closure error can then be determined.

In the past, cavers were reluctant to redraw complex cave maps after detecting survey errors. Today, computer cartography can automatically redraw cave maps after data has been corrected.

## ***Surveying software***

There is a large number of surveying packages available on various computer platforms, most of which have been developed by cavers with a basis in computer programming. Many of the packages perform particularly well for specific tasks, and as such many cave surveyors will not solely choose one product over another for all cartographic tasks.

A popular program for producing a centerline survey is *Survex*, which was originally developed by members of the Cambridge University Caving Club for processing survey data from club expeditions to Austria. It was released to the public in 1992. The centerline data can then be exported in various formats and the cave detail drawn in with various other programmes such as *AutoCAD*, *Adobe Illustrator* and *Inkscape*. Other programmes such as *Tunnel* and *Therion* have full centerline and map editing capabilities. *Therion* notably, when it closes survey loops, warps the passages to fit over their length, meaning that entire passages do not have to be redrawn.

## ***Automated methods***

In recent years an underground geographic positioning technology called *HORTA* has been utilized in the mining industry. The technology utilizes a gyroscope and an accelerometer to aid in 3D-position determination.

Such automated methods have provided a more than fifty-fold increase in underground surveying productivity with more accurate and finer detail maps as well.

## Chapter 3

# Construction Surveying

**Construction surveying** (otherwise known as "lay-out" or "setting-out") is to stake out reference points and markers that will guide the construction of new structures such as roads or buildings. These markers are usually staked out according to a suitable coordinate system selected for the project.

### ***History of construction surveying***

- The nearly perfect squareness and north-south orientation of the Great Pyramid of Giza, built c. 2700 BC, affirm the Egyptians' command of surveying.
- A recent reassessment of Stonehenge (c.2500 BC) indicates that the monument was set out by prehistoric surveyors using peg and rope geometry.
- In the sixth century BC geometric based techniques were used to construct the tunnel of Eupalinos on the island of Samos.

### ***Elements of the construction survey***

- Survey existing conditions of the future work site, including topography, existing buildings and infrastructure, and underground infrastructure whenever possible (for example, measuring invert elevations and diameters of sewers at manholes);
- Stake out reference points and markers that will guide the construction of new structures;
- Verify the location of structures during construction;
- Conduct an As-Built survey: a survey conducted at the end of the construction project to verify that the work authorized was completed to the specifications set on plans.

### ***Coordinate systems used in construction***

Land surveys and surveys of existing conditions are generally performed according to geodesic coordinates. However for the purposes of construction a more suitable coordinate system will often be used. During construction surveying, the surveyor will

often have to convert from geodesic coordinates to the coordinate system used for that project.

## **Chainage or Station**

In the case of roads or other linear infrastructure, a *chainage* will be established, often to correspond with the center line of the road. During construction, structures would then be located in terms of *chainage*, *offset* and *elevation*. *Offset* is said to be "left" or "right" relative to someone standing on the *chainage line* who is looking in the direction of increasing *chainage*. Plans would often show *plan* views (viewed from above), *profile* views (a "transparent" section view collapsing all section views of the road parallel to the *chainage*) or *cross-section* views (a "true" section view perpendicular to the *chainage*). In a *plan* view, *chainage* generally increases from left to right, or from the bottom to the top of the plan. *Profiles* are shown with the chainage increasing from left to right, and *cross-sections* are shown as if the viewer is looking in the direction of increasing *chainage* (so that the "left" *offset* is to the *left* and the "right" *offset* is to the *right*).

"Chainage" may also be referred to as "Station".

## **Building grids**

In the case of buildings, an arbitrary system of grids is often established so as to correspond to the rows of columns and the major load-bearing walls of the building. The grids may be identified alphabetically in one direction, and numerically in the other direction (as in a road map). The grids are usually but not necessarily perpendicular, and are often but not necessarily evenly spaced. Floors and basement levels are also numbered. Structures, equipment or architectural details may be located in reference to the floor and the nearest intersection of the arbitrary axes.

## **Other coordinate systems**

In other types of construction projects, arbitrary "north-south" and "east-west" reference lines may be established, that do not necessarily correspond to true coordinates.

## ***Equipment and techniques used in construction surveying***

Surveying equipment, such as levels and theodolites, are used for accurate measurement of angular deviation, horizontal, vertical and slope distances. With computerisation, electronic distance measurement (EDM), total stations, GPS surveying and laser scanning have supplemented (and to a large extent supplanted) the traditional optical instruments.

The builder's level measures neither horizontal nor vertical angles. It simply combines a spirit level and telescope to allow the user to visually establish a line of sight along a level plane. When used together with a graduated staff it can be used to transfer elevations from one location to another. An alternative method to transfer elevation is to

use water in a transparent hose as the level of the water in the hose at opposite ends will be at the same elevation.

## ***Equipment and techniques used in mining and tunneling***

Total stations are the primary survey instrument used in mining surveying.

### **Underground mining**

A total station is used to record the absolute location of the tunnel walls (stopes), ceilings (backs), and floors as the drifts of an underground mine are driven. The recorded data is then downloaded into a CAD program, and compared to the designed layout of the tunnel.

The survey party installs control stations at regular intervals. These are small steel plugs installed in pairs in holes drilled into walls or the back. For wall stations, two plugs are installed in opposite walls, forming a line perpendicular to the drift. For back stations, two plugs are installed in the back, forming a line parallel to the drift.

A set of plugs can be used to locate the total station set up in a drift or tunnel by processing measurements to the plugs by intersection and resection.

## ***Professional status of construction surveyors***

**Building Surveying** emerged in the 1970s as a profession in the United Kingdom by a group of technically minded General Practice Surveyors. Building Surveying is a recognized profession within Britain and Australia. In Australia in particular, due to risk mitigation/limitation factors the employment of surveyors at all levels of the construction industry is widespread. There are still many countries where it is not widely recognized as a profession. The Services that Building Surveyors undertake are broad but include:

- Construction design and building works
- Project Management and monitoring
- CDM Co-ordinator under the Construction (Design & Management) Regulations 2007
- Property Legislation adviser
- Insurance assessment and claims assistance
- Defect investigation and maintenance adviser
- Building Surveys and measured surveys
- Handling Planning applications
- Building Inspection to ensure compliance with building regulations
- Undertaking pre-acquisition surveys
- Negotiating dilapidations claims

Building Surveyors also advise on many aspects of construction including:

- design
- maintenance
- repair
- refurbishment
- restoration

Clients of a building surveyor can be the public sector, Local Authorities, Government Departments as well as private sector organisations and work closely with architects, planners, homeowners and tenants groups. Building Surveyors may also be called to act as an expert witness. It is usual for building surveyors to undertake an accredited degree qualification before undertaking structured training to become a member of a professional organisation. For Chartered Building Surveyors, these courses are accredited by the Royal Institution of Chartered Surveyors. Other Professional organisations that have building surveyor members include CIOB, ABE, HKIS and RICS.

With the enlargement of the European community, the profession of the Chartered Building Surveyor is becoming more widely known in other European states, particularly France. Chartered Building Surveyors, where many English speaking people buy second homes.

### **Distinction from land surveyors**

In the United States, Canada, the United Kingdom and most Commonwealth countries land surveying is considered to be a distinct profession. Land surveyors have their own professional associations and licencing requirements. The services of a licenced land surveyor are generally required for boundary surveys (to establish the boundaries of a parcel using its legal description) and subdivision plans (a plot or map based on a survey of a parcel of land, with boundary lines drawn inside the larger parcel to indicate the creation of new boundary lines and roads).

## Chapter 4

# Environmental Surveying

**Environmental Surveying** is the title of a profession within the wider field of surveying, the practitioners of which are known as Environmental Surveyors. Environmental Surveyors use surveying techniques to understand the potential impact of environmental factors on real estate and construction developments, and conversely the impact that real estate and construction developments will have on the environment.

### ***Environmental Surveying as a professional group***

The exact activities that make up the day to day work of an Environmental Surveyor vary from surveyor to surveyor and from project to project. Two Environmental Surveyors could have careers that consist of quite different professional activities depending on their and their practices area of specialisation.

In the strictest sense, the field of Environmental Surveying is distinct from that of Environmental Consultancy. Environmental Consultancies may have some overlap with the work of Environmental Surveyors, but may be members of different professional bodies and may carry out activities not involving the built environment. They may for example be involved with arboriculture the specifics of which fall out of the remit of Environmental Surveyors. The terms are however sometimes used interchangeably, and practices often use the term consultants if the practice is seeking a wider client base than would be attracted to a pure Environmental Surveyor practice.

### ***Main Areas of Operation of Environmental Surveyors***

The main areas of operation for Environmental Surveyors in the UK include:

- **Flood Risk Assessment-** This is to assess how likely it is that a building or proposed building will flood. If a building is thought to be at risk it will receive a designation of either Band 1 (200:1 chance of flooding in a year) Band 2 (between 200:1 and 75:1 chance of flooding annually) or Band 3 (greater than a 75:1 chance of flooding annually, currently thought to account for around 4% of flood risk properties in the UK).

- **Contaminated Land Assessment-** Contaminated Land Surveys are carried out to assess the level of threat posed to existing or proposed buildings. Land can be contaminated if it is on or near a site that is currently or has in the past been used for industrial or waste disposal purposes. Such surveys form part of the due diligence that must be carried out before construction or modification of a real estate asset can begin. Both during and after construction a contaminated land survey could be an important factor in informing risk management strategies.
- **Environmental Screenings-** Provide a general overview of environmental risks proposed to an existing or proposed real estate development. The screening can help gain a picture of: whether or not the property in question might have been damaged by undermining, whether the property might be susceptible to ground gas, the closeness of government licensed waste disposal facilities and an assessment of a properties water resource vulnerability to contamination.
- **Fire Risk Assessment-** All work premises in the UK must have a fire risk assessment. The assessment is designed to ascertain what could start a fire, how the fire could be dealt with and ensuring that the staff will be sufficiently warned of a fire, have exits from the building and a safe place to congregate afterwards.
- **Asbestos Surveys-** Because asbestos is extremely dangerous material to the health of humans, its use is strictly controlled. 52 countries globally have now banned the substance. The substance is banned by the European Union, with the exception of its use in a very limited number of specific industrial applications. Because of its wide spread use in the building industry before banning, many existing buildings contain asbestos and sites where buildings have been previously may have been contaminated with it. For this reason buildings may need an asbestos survey to ascertain the level of use of the substance and the level of contamination to the site this has resulted in.

## ***Environmental Surveying Techniques***

Environmental Surveyors use a range of techniques to assess the environmental conditions of an area and compile their reports.

- Historical data is drawn from maps and older survey information to establish the exact boundaries of a property, and are also used to see if there has been any historical pollution or waste dumping on the site.
- Water Sampling allows Environmental Surveyors to gain a picture of the quality of and pollution levels in local water sources.
- In a similar way to Water Sampling, Earth Sampling can be used to analyse the level of pollutants in an area's soil.
- Geometric data may used to establish areas that are likely to flood or monitor the spread of pollutants.

- Geographic Information Systems (GIS) can cross reference map data with statistical data. If an Environmental Surveyor was compiling a flood report for a building and wanted to establish the odds of a property flooding in any given year then they could cross reference the geographic location of a property with historically obtained statistical data on flooding in the area.
- Visual Inspection might be used if for example the surveyor wished to establish the level of asbestos contamination to a given property. This might be enhanced by or presented in reference to the collection

### ***Chartered Environmental Surveyors***

In the UK as well as in many other countries globally, recognition by the Royal Institution of Chartered Surveyors (RICS) is looked upon as conferring a high professional standard, and guaranteeing a level of quality in the work of its member surveyors. Environmental Surveyors form one professional group within RICS and are listed in their Land Professional Group. To achieve the status of Chartered Environmental Surveyor, the candidate must pass an Assessment of Professional Competencies (APC). This consists of completing structured work experience and providing written documents as evidence of the activities carried out during this work experience. Finally the candidate must pass an hour long oral exam. All surveyors regardless of their field are required to demonstrate mastery of RICS core competencies, and then move on to demonstrate knowledge of competencies in their specific fields. Competencies specific to Environmental Surveying Include:

- Sustainability • Contaminated Land • Environmental Assessment • Environmental Audit
- Laboratory Procedures • Management of the Natural Environment and Landscape

Outside of the UK, other professional bodies may offer equivalent designations to signify the professional level of Environmental Surveyors.

### ***Surveyors Practices in the UK***

General Surveyors may perform the duties of an Environmental Surveyor as one of a range of services they supply. If they are a Chartered Surveyor, they will have completed an APC however it will not be in the specific area of Environmental Surveying. An example of a practice of this sort would be the London based .

A relatively small number out of the total number of surveying companies in the UK specialise in Environmental Surveying. Some practices such as are explicitly a company of Environmental Surveyors, providing the services outlined above. Other companies such as incorporate environmental services into a wider remit of surveying work, in this case Rural Surveying.

## Chapter 5

# Geodetic System

**Geodetic systems** or **geodetic data** are used in geodesy, navigation, surveying by cartographers and satellite navigation systems to translate positions indicated on their products to their real position on earth.

The systems are needed because the earth is not a perfect sphere. Neither is the earth an ellipsoid. This can be verified by differentiating the equation for an ellipsoid and solving for  $dy/dx$ . It is a constant multiplied by  $x/y$ . Then derive the force equation from the centrifugal force acting on an object on the earth's surface and the gravitational force. Switch the  $x$  and  $y$  components and multiply one of them by negative one. This is the differential equation which when solved will yield the equation for the earth's surface. This is not a constant multiplied by  $x/y$ . Note that the earth's surface is also not an equal-potential surface, as can be verified by calculating the potential at the equator and the potential at a pole. The earth is an equal force surface. A one kilogram frictionless object on the ideal earth's surface does not have any force acting upon it to cause it to move either north or south. There is no simple analytical solution to this differential equation. A power series solution using three terms when substituted into this differential equation bogs down a TI-89 calculator and yields about three hundred terms after about five minutes.

The USGS uses a spherical harmonic expansion to approximate the earth's surface. It has about one hundred thousand terms.

It is easy to calculate the tangent to the surface at points on an ellipsoid representing the earth's surface. Drawing one of them on a graph at about latitude 45 degrees shows them dipping below the ellipsoid to the south and rising above to the north. But if this is the case every where, we are led to a contradiction. Starting from the equator, the true surface would be above the ellipsoid, but starting from the north pole, the true surface would be below the ellipsoid.

This problem has applications to moving Apollo asteroids. Some of them are loose rock and spinning. Their surface will be determined by the solution to this differential equation.

An interesting experiment will be to spin a mass of water in the space station and accurately measure its surface and do this for various angular velocities. Also, we can accurately measure Jupiter's surface using our telescopes. We can accurately determine earth's surface by using GPS.

Examples of map datums are:

- WGS 84, 72, 64 and 60 of the World Geodetic System
- NAD83, the North American Datum which is very similar to WGS84
- NAD27, the older North American Datum, of which NAD83 was basically a readjustment
- OSGB36 of the Ordnance Survey of Great Britain
- ED50, the European Datum

The difference in co-ordinates between data is commonly referred to as *datum shift*. The datum shift between two particular datums can vary from one place to another within one country or region, and can be anything from zero to hundreds of metres (or several kilometres for some remote islands). The North Pole, South Pole and Equator may be assumed to be in different positions on different datums, so True North may be very slightly different. Different datums use different estimates for the precise shape and size of the Earth (reference ellipsoids).

The difference between WGS84 and OSGB36, for example, is up to 140 metres (450 feet), which for some navigational purposes is an insignificant error. For other applications, such as surveying, or dive site location for SCUBA divers, 140 metres is an unacceptably large error.

Because the Earth is not a perfect ellipsoid, localised datums can give a more accurate representation of the area of coverage than the global WGS 84 datum. OSGB36, for example, is a better approximation to the geoid covering the British Isles than the global WGS 84 ellipsoid. However, as the benefits of a global system outweigh the greater accuracy, the global WGS 84 datum is becoming increasingly adopted.

## ***Datum***

In surveying and geodesy, a **datum** is a reference point or surface against which position measurements are made, and an associated model of the shape of the earth for computing positions. Horizontal datums are used for describing a point on the earth's surface, in latitude and longitude or another coordinate system. Vertical datums are used to measure elevations or underwater depths.

## ***Horizontal datums***

The horizontal datum is the model used to measure positions on the earth. A specific point on the earth can have substantially different coordinates, depending on the datum used to make the measurement. There are hundreds of locally-developed horizontal datums around the world, usually referenced to some convenient local reference point. Contemporary datums, based on increasingly accurate measurements of the shape of the earth, are intended to cover larger areas. The WGS 84 datum, which is almost identical to the NAD83 datum used in North America and the ETRS89 datum used in Europe, is a common standard datum.

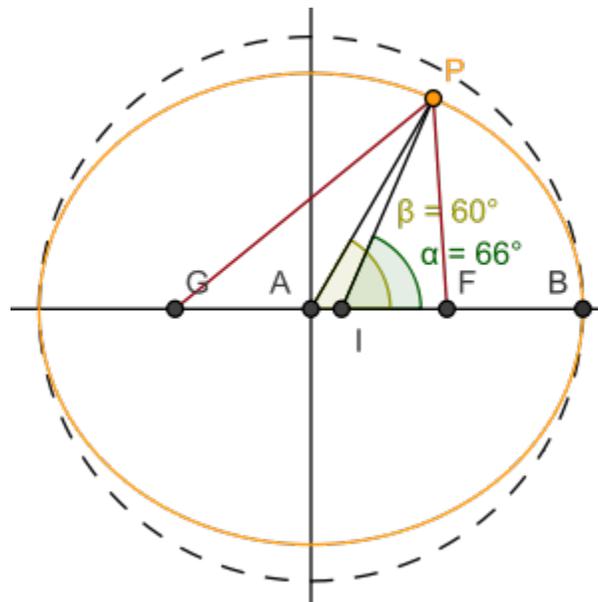
## ***Vertical datum***

A vertical datum is used for measuring the elevations of points on the Earth's surface. Vertical datums are either tidal, based on sea levels, gravimetric, based on a geoid, or geodetic, based on the same ellipsoid models of the earth used for computing horizontal datums.

In common usage, elevations are often cited in height above mean sea level; this is a widely used tidal datum. Mean Sea Level (MSL) is a tidal datum which is described as the arithmetic mean of the hourly water elevation taken over a specific 19 years cycle. This definition averages out tidal highs and lows due to the gravitational effects of the sun and the moon. MSL is defined as the zero elevation for a local area. However, zero elevation as defined by one country is not the same as zero elevation defined by another (because MSL is not the same everywhere). Which is why locally defined vertical datums differ from one another. Whilst the use of sea-level as a datum is useful for geologically *recent* topographic features, sea level has not stayed constant throughout geological time, so is less useful when measuring very long-term processes.

A geodetic vertical datum takes some specific zero point, and computes elevations based on the geodetic model being used, without further reference to sea levels. Usually, the starting reference point is a tide gauge, so at that point the geodetic and tidal datums might match, but due to sea level variations, the two scales may not match elsewhere. One example of a geoid datum is NAVD88, used in North America, which is referenced to a point in Quebec, Canada.

## Geodetic coordinates



The same position on a spheroid has a different angle for latitude depending on whether the angle is measured from the normal (angle  $\alpha$ ) or around the center (angle  $\beta$ ). Note that the "flatness" of the spheroid (orange) in the image is greater than that of the Earth; as a result, the corresponding difference between the "geodetic" and "geocentric" latitudes is also exaggerated.

In geodetic coordinates the Earth's surface is approximated by an ellipsoid and locations near the surface are described in terms of latitude ( $\varphi$ ), longitude ( $\lambda$ ) and height ( $h$ ). The ellipsoid is completely parameterised by the semi-major axis  $a$  and the flattening  $f$ .

### Geodetic versus geocentric latitude

It is important to note that geodetic latitude ( $\varphi$ ) is different from geocentric latitude ( $\varphi'$ ). Geodetic latitude is determined by the angle between the normal of the spheroid and the plane of the equator, whereas geocentric latitude is determined around the centre. Unless otherwise specified latitude is geodetic latitude.

### Defining and derived parameters

Parameter	Symbol
Semi-major axis	$a$
Reciprocal of flattening	$1/f$

From  $a$  and  $f$  it is possible to derive the semi-minor axis  $b$ , first eccentricity  $e$  and second eccentricity  $e'$  of the ellipsoid

Parameter	Value
-----------	-------

semi-minor axis  $b = a(1-f)$   
 First eccentricity squared  $e^2 = 1-b^2/a^2 = 2f-f^2$   
 Second eccentricity  $e'^2 = a^2/b^2 - 1 = f(2-f)/(1-f)^2$

### **Parameters for some geodetic systems**

#### **Australian Geodetic Datum 1966 [AGD66] and Australian Geodetic Datum 1984 (GDA84)**

AGD66 and AGD84 both use the parameters defined by Australian National Spheroid

#### **Australian National Spheroid (ANS)**

ANS Defining Parameters

Parameter	Notation	Value
semi-major axis	a	6378160.000 m
Reciprocal of Flattening 1/f		298.25

#### **Geocentric Datum of Australia 1994 (GDA94) and Geocentric Datum of Australia 2000 (GDA2000)**

Both GDA94 and GDA2000 use the parameters defined by GRS80

#### **Geodetic Reference System 1980 (GRS80)**

GRS80 Defining Parameters

Parameter	Notation	Value
semi-major axis	a	6378137 m
Reciprocal of flattening 1/f		298.257222101

#### **World Geodetic System 1984 (WGS84)**

The Global Positioning System (GPS) uses the World Geodetic System 1984 (WGS84) to determine the location of a point near the surface of the Earth.

WGS84 Defining Parameters

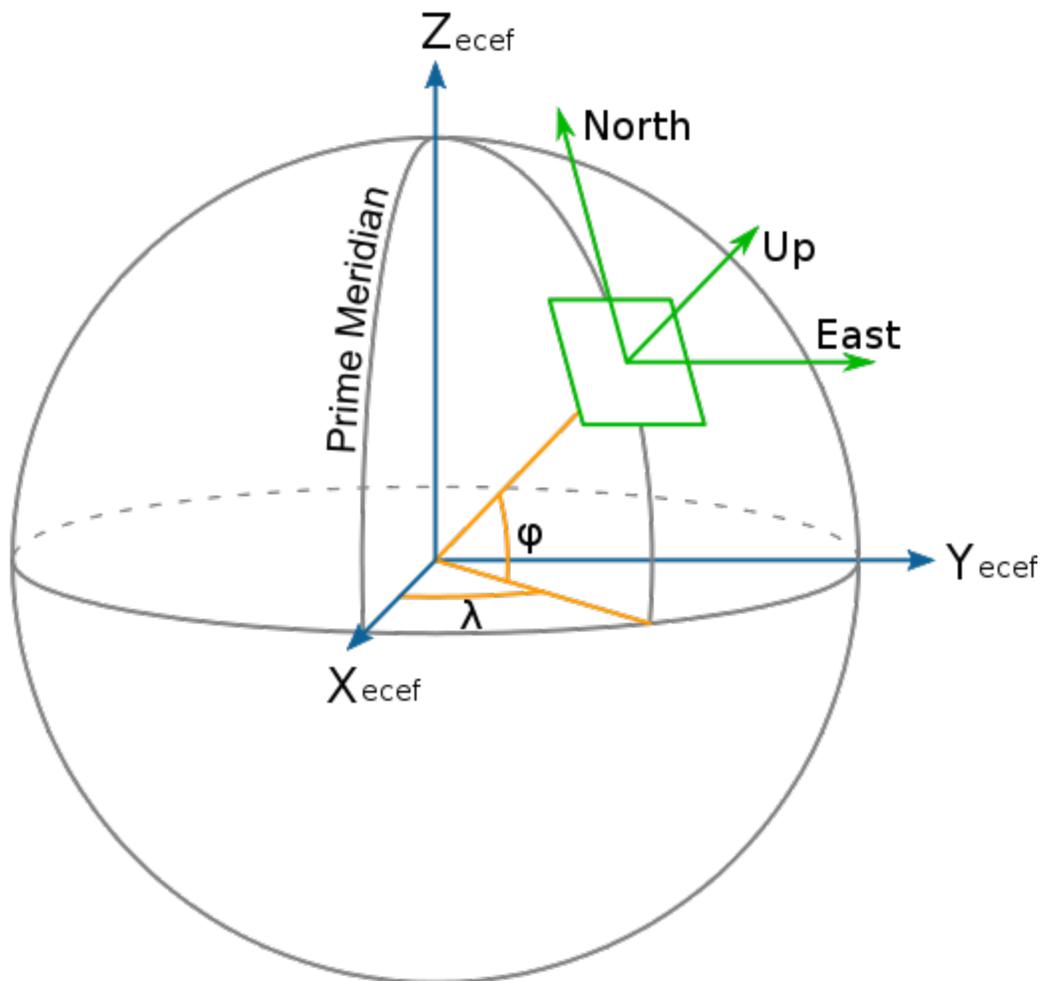
Parameter	Notation	Value
semi-major axis	a	6378137.0 m
Reciprocal of flattening 1/f		298.257223563

WGS84 derived geometric constants

Constant	Notation	Value
Semi-minor axis	b	6356752.3142 m

First Eccentricity Squared $e^2$	$6.69437999014 \times 10^{-3}$
Second Eccentricity Squared $e'^2$	$6.73949674228 \times 10^{-3}$

### **Other Earth based coordinate systems**



Earth Centred Earth Fixed and East, North, Up coordinates.

### **Earth Centred Earth Fixed (ECEF or ECF) coordinates**

The Earth-centred Earth-fixed (ECEF or ECF) or conventional terrestrial coordinate system rotates with the Earth and has its origin at the centre of the Earth. The  $X$  axis passes through the equator at the prime meridian. The  $Z$  axis passes through the north pole but it does not exactly coincide with the instantaneous Earth rotational axis. The  $Y$  axis can be determined by the right-hand rule to be passing through the equator at 90° longitude.

## Local east, north, up (ENU) coordinates

In many targeting and tracking applications the local East, North, Up (ENU) Cartesian coordinate system is far more intuitive and practical than ECEF or Geodetic coordinates. The local ENU coordinates are formed from a plane tangent to the Earth's surface fixed to a specific location and hence it is sometimes known as a "Local Tangent" or "local geodetic" plane. By convention the east axis is labeled  $x$ , the north  $y$  and the up  $z$ .

## Local north, east, down (NED) coordinates

In an airplane most objects of interest are below you, so it is sensible to define down as a positive number. The NED coordinates allow you to do this as an alternative to the ENU local tangent plane. By convention the north axis is labeled  $x'$ , the east  $y'$  and the down  $z'$ . To avoid confusion between  $x$  and  $x'$ , etc. in this web page we will restrict the local coordinate frame to ENU.

## Conversion calculations

### Geodetic to/from ECEF coordinates

#### From geodetic to ECEF

Geodetic coordinates (latitude  $\phi$ , longitude  $\lambda$ , height  $h$ ) can be converted into ECEF coordinates using the following formulae:

$$\begin{aligned} X &= \left( \frac{a}{\chi} + h \right) \cos \phi \cos \lambda \\ Y &= \left( \frac{a}{\chi} + h \right) \cos \phi \sin \lambda \\ Z &= \left( \frac{a(1-e^2)}{\chi} + h \right) \sin \phi \end{aligned}$$

Where  $\chi = \sqrt{1 - e^2 \sin^2 \phi}$ ,  $a$  and  $e^2$  are the semi-major axis and the square of the first numerical eccentricity of the ellipsoid respectively.

$\chi$  is called the *Normal* and is the distance from the surface to the Z-axis along the ellipsoid normal.

#### From ECEF to geodetic

The conversion of ECEF coordinates to geodetic coordinates (such WGS84) is a much harder problem.

There exist two kinds of methods in order to solve the equation.

### ***Newton-Raphson method***

The following Bowring's irrational geodetic equation is efficient to be solved by Newton-

$$\kappa - 1 - \frac{e^2 a \kappa}{\sqrt{x^2 + y^2 + (1 - e^2) z^2 \kappa^2}} = 0$$

Raphson method:

$$\kappa = \frac{\sqrt{x^2 + y^2}}{z} \tan \phi \cdot h = (1 - (1 - \kappa^{-1})e^{-2}) \sqrt{x^2 + y^2 + z^2 \kappa^2}$$

$\kappa_0 = \frac{1}{1 - e^2}$  is a good starter for the iteration for  $h \approx 0$ . Bowring showed that the single iteration produces the sufficiently accurate solution.

### ***Ferrari's solution***

The following solve the above equation:

$$\begin{aligned}\zeta &= (1 - e^2)z^2/a^2, \\ \rho &= ((x^2 + y^2)/a^2 + \zeta - e^4)/6, \\ s &= e^4\zeta(x^2 + y^2)/(4a^2), \\ t &= \sqrt[3]{s + \rho^3 + \sqrt{s(s + 2\rho^3)}}, \\ u &= \rho + t + \rho^2/t, \\ v &= \sqrt{u^2 + e^4\zeta}, \\ w &= e^2(u + v - \zeta)/(2v), \\ \kappa &= 1 + e^2(\sqrt{u + v + w^2} + w)/(u + v).\end{aligned}$$

### **ECEF to/from ENU Coordinates**

To convert from geodetic coordinates to local ENU up coordinates is a two stage process

1. Convert geodetic coordinates to ECEF coordinates
2. Convert ECEF coordinates to local ENU coordinates

To convert from local ENU up coordinates to geodetic coordinates is a two stage process

1. Convert local ENU coordinates to ECEF coordinates
2. Convert ECEF coordinates to geodetic coordinates

## From ECEF to ENU

To transform from ECEF coordinates to the local coordinates we need a local reference point, typically this might be the location of a radar. If a radar is located at  $\{X_r, Y_r, Z_r\}$  and an aircraft at  $\{X_p, Y_p, Z_p\}$  then the vector pointing from the radar to the aircraft in the ENU frame is

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\sin \lambda_r & \cos \lambda_r & 0 \\ -\sin \phi_r \cos \lambda_r & -\sin \phi_r \sin \lambda_r & \cos \phi_r \\ \cos \phi_r \cos \lambda_r & \cos \phi_r \sin \lambda_r & \sin \phi_r \end{bmatrix} \begin{bmatrix} X_p - X_r \\ Y_p - Y_r \\ Z_p - Z_r \end{bmatrix}$$

**Note:**  $\phi$  is the *geodetic* latitude. A prior version of this page showed use of the *geocentric* latitude ( $\phi'$ ). The *geocentric* latitude is *not* the appropriate *up* direction for the local tangent plane. If the original *geodetic* latitude is available it should be used, otherwise, the relationship between *geodetic* and *geocentric* latitude has an altitude dependency, and is captured by:

$$\tan \phi' = \frac{Z_r}{\sqrt{X_r^2 + Y_r^2}} = \frac{\frac{a}{\chi}(1-f)^2 + h}{\frac{a}{\chi} + h} \tan \phi$$

Obtaining *geodetic* latitude from *geocentric* coordinates from this relationship requires an iterative solution approach, otherwise the *geodetic* coordinates may be computed via the approach in the section below labeled "From ECEF to geodetic coordinates."

The geocentric and geodetic longitude have the same value. This is true for the Earth and other similar shaped planets because their latitude lines (parallels) can be considered in much more degree perfect circles when compared to their longitude lines (meridians).

$$\tan \lambda = \frac{Y_r}{X_r}$$

**Note:** Unambiguous determination of  $\phi$  and  $\lambda$  requires knowledge of which quadrant the coordinates lie in.

## From ENU to ECEF

This is just the inversion of the ECEF to ENU transformation so

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} -\sin \lambda & -\sin \phi \cos \lambda & \cos \phi \cos \lambda \\ \cos \lambda & -\sin \phi \sin \lambda & \cos \phi \sin \lambda \\ 0 & \cos \phi & \sin \phi \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} X_r \\ Y_r \\ Z_r \end{bmatrix}$$

## Chapter 6

# Dumpy Level & Gyrotheodolite

## Dumpy Level



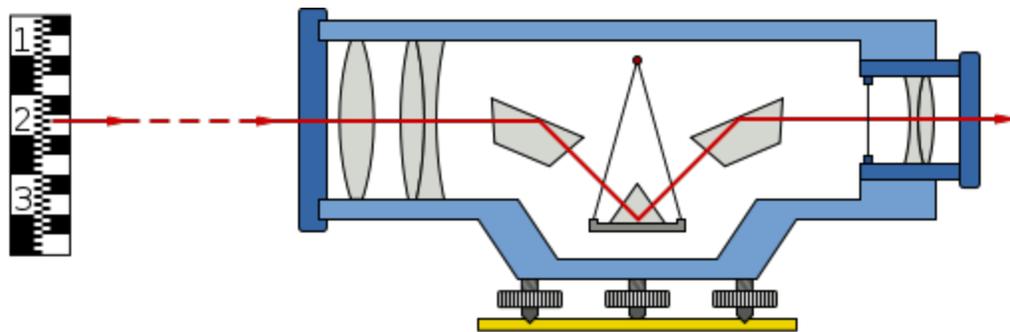
Leveler for use by hand

A **dumpy level**, **builder's auto level**, **leveling instrument**, or **automatic level** is an optical instrument used in surveying and building to transfer, measure, or set horizontal levels.

The level instrument is set up on a tripod and, depending on the type, either roughly or accurately set to a leveled condition using footscrews (levelling screws). The operator looks through the eyepiece of the telescope while an assistant holds a tape measure or graduated staff vertical at the point under measurement. The instrument and staff are used to gather and/or transfer elevations (levels) during site surveys or building construction. Measurement generally starts from a benchmark with known height determined by a previous survey, or an arbitrary point with an assumed height.

A **dumpy level** is an older-style instrument that requires skilled use to set accurately. The instrument requires to be set level in each quadrant, to ensure it is accurate through a full 360° traverse. Some dumpy levels will have a bubble level ensuring an accurate level.

A variation on the dumpy and one that was often used by surveyors, where greater accuracy and error checking was required, is a **tilting level**. This instrument allows the telescope to be effectively flipped through 180°, without rotating the head. The telescope is hinged to one side of the instrument's axis; flipping it involves lifting to the other side of the central axis (thereby inverting the telescope). This action effectively cancels out any errors introduced by poor setup procedure or errors in the instrument's adjustment. As an example, the identical effect can be had with a standard builder's level by rotating it through 180° and comparing the difference between spirit level bubble positions.



An automatic level uses a swinging prism to compensate for small inclination deviations.

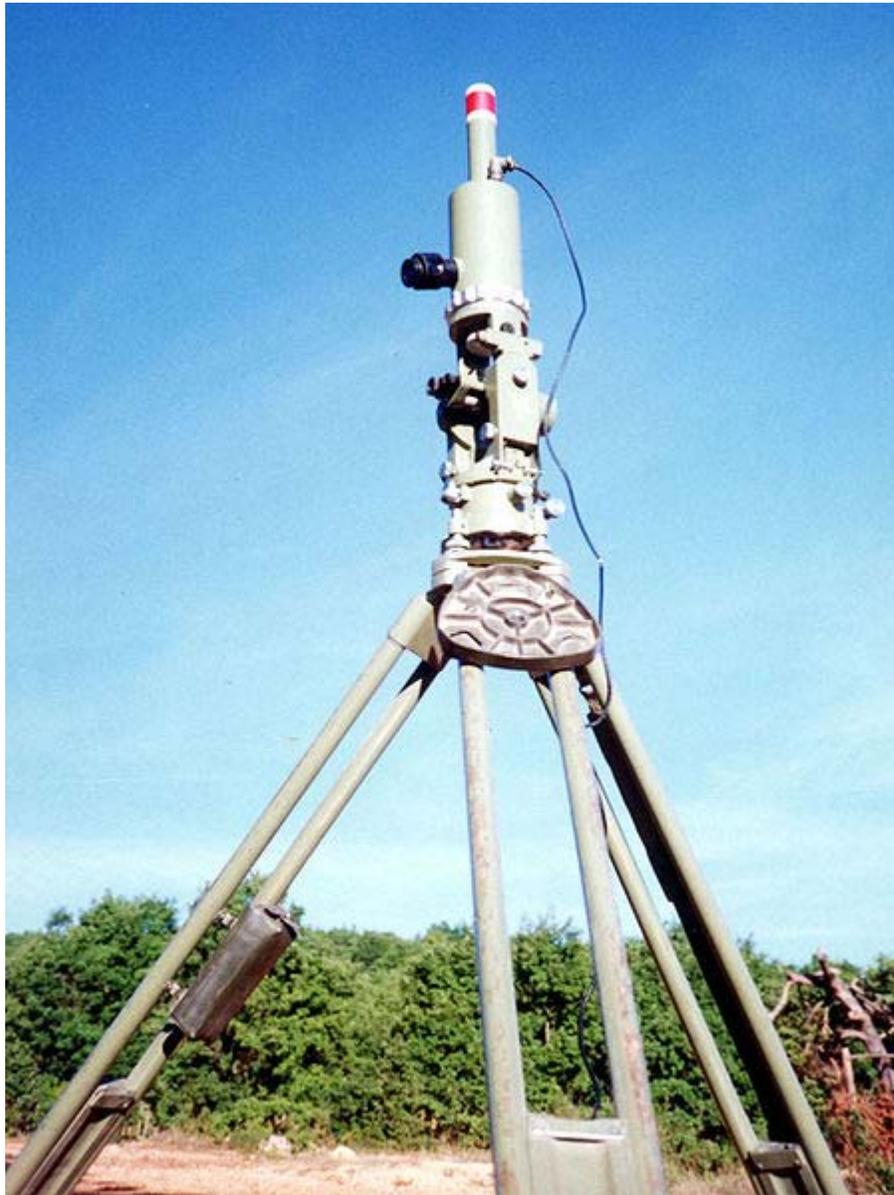
An **automatic level**, **self-levelling level** or builder's auto level, includes an internal compensator mechanism (a swinging prism) that, when set close to level, automatically removes any remaining variation from level. This reduces the need to set the instrument truly level, as with a dumpy or tilting level. Self-levelling instruments are the preferred instrument on building sites, construction and surveying due to ease of use and rapid setup time.

A **digital electronic level** is also set level on a tripod and reads a bar-coded staff using electronic laser methods. The height of the staff where the level beam crosses the staff is

shown on a digital display. This type of level removes interpolation of graduation by a person, thus removing a source of error and increasing accuracy.

The term **dumpy level** endures despite the evolution in design.

## Gyrotheodolite



A Wild GAK gyroscope mounted on a Wild T-16 theodolite.

A **gyro-theodolite** is a surveying instrument composed of a gyroscope mounted to a theodolite. It is used to determine the orientation of true north by locating the meridian direction. It is the main instrument for orientating in mine surveying and in tunnel engineering, where astronomical star sights are not visible.

## ***History***

In 1852, the French physicist Léon Foucault discovered a gyro with two degrees of freedom points north. This principle was adapted by Max Schuler in 1921 to build the first surveying gyro. In 1949, the gyro-theodolite - at that time called a "meridian pointer" or "meridian indicator" - was first used by the Clausthal Mining Academy underground. Several years later it was improved with the addition of autocollimation telescopes. In 1960, the Fennel Kassel company produced the first of the KT1 series of gyro-theodolites. Fennel Kassel and others later produced gyro attachments that can be mounted on normal theodolites.

## ***Operation***

A gyroscope is mounted in a sphere, lined with Mu-metal to reduce magnetic influence, connected by a spindle to the vertical axis of the theodolite. The battery-powered gyro wheel is rotated at 20,000 rpm or more, until it acts as a north-seeking gyroscope. A separate optical system within the attachment permits the operator to rotate the theodolite and thereby bring a zero mark on the attachment into coincidence with the gyroscope spin axis. By tracking the spin axis as it oscillates about the meridian, a record of the azimuth of a series of the extreme stationary points of that oscillation may be determined by reading the theodolite azimuth circle. A mid point can later be computed from these records that represents a refined estimate of the meridian. Careful setup and repeated observations can give an estimate that is within about 10 arc seconds of the true meridian. This estimate of the meridian contains errors due to the zero torque of the suspension not being aligned precisely with the true meridian and to measurement errors of the slightly damped extremes of oscillation. These errors can be moderated by refining the initial estimate of the meridian to within a few arc minutes and correctly aligning the zero torque of the suspension.

When the spinner is released from restraint with its axis of rotation aligned close to the meridian, the gyroscopic reaction of spin and Earth's rotation results in precession of the spin axis in the direction of alignment with the plane of the meridian. This is because the daily rotation of the Earth is in effect continuously tilting the east-west axis of the station. The spinner axis then accelerates towards and overshoots the meridian, it then slows to a halt at an extreme point before similarly swinging back towards the initial point of release. This oscillation in azimuth of the spinner axis about the meridian repeats with a period of a few minutes. In practice the amplitude of oscillation will only gradually reduce as energy is lost due to the minimal damping present. Gyro-theodolites employ an undamped oscillating system because a determination can be obtained in less than about 20 minutes, while the asymptotic settling of a damped gyro-compass would take many times that before any reasonable determination of meridian could possibly be made.

When not in operation, the gyroscope assembly is anchored within the instrument. The electrically powered gyroscope is started while restrained and then released for operation. During operation the gyroscope is supported within the instrument assembly, typically on a thin vertical tape that constrains the gyroscope spinner axis to remain horizontal. The alignment of the spin axis is permitted to rotate in azimuth by only the small amount required during operation. An initial approximate estimate of the meridian is needed. This might be determined with a magnetic compass, from an existing survey network or by the use of the gyro-theodolite in an extended tracking mode.

## ***Uses***

Gyro-theodolites are primarily used in the absence of astronomical star sights. 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 gyro-theodolite 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. During the construction of the Channel Tunnel, which runs under the English Channel from France to the UK, gyro-theodolites were used to prevent and correct the tunnels from curving.

## ***Limitations***

Although a gyro-theodolite functions at the equator and in both the northern and southern hemispheres, it cannot be used at either the North Pole or South Pole, where the Earth's axis is precisely perpendicular to the horizontal axis of the spinner and the meridian is undefined. Gyro-theodolites are 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.

Unlike an artificial horizon or inertial navigation system, a gyro-theodolite cannot be relocated while it is operating. It must be restarted again at each site.

When available, astronomical star sights are able to give the meridian bearing to better than one hundred times the accuracy of the gyro-theodolite. Where this extra precision is not required, the gyro-theodolite is able to produce a result quickly without the need for night observations.

## Chapter 7

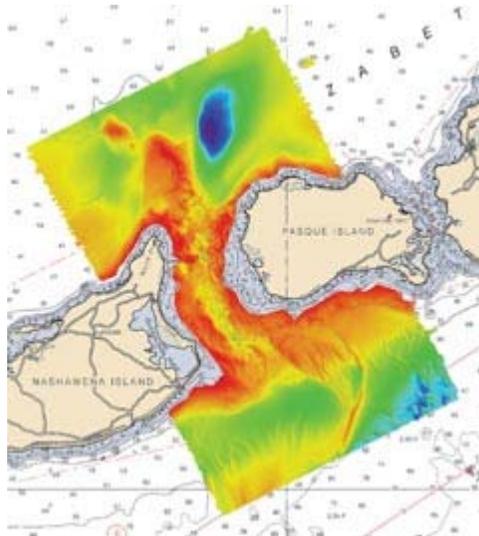
# Hydrographic Survey



NOAA Survey Ship



Private Survey Ship Neptune



DTM - Digital Terrain Model

**Hydrographic survey** is the science of measurement and description of features which affect maritime navigation, marine construction, dredging, offshore oil exploration/drilling and related disciplines. Strong emphasis is placed on soundings, shorelines, tides, currents, sea floor and submerged obstructions that relate to the previously mentioned activities. The term Hydrography is sometimes used synonymously to describe Maritime Cartography, which in the final stages of the hydrographic process uses the raw data collected through hydrographic survey into information usable by the end user.

Hydrography is collected under rules which vary depending on the acceptance authority. Traditionally conducted by vessels and with Echo sounding, surveys are increasingly conducted with the aid of aircraft and sophisticated electronic sensor systems in shallow waters.

### ***National and International Maritime Hydrography***

Hydrographic offices evolved from naval heritage and are usually found within national naval structures, for example Spain's Instituto Hidrográfico de la Marina. Coordination of those organizations and product standardization is voluntarily joined with the goal of improving hydrography and safe navigation is conducted by the International Hydrographic Organization (IHO). The IHO publishes Standards and Specifications followed by member states as well as Memoranda of Understanding and Co-operative Agreements with hydrographic survey interests.

The product of such hydrography is most often seen on nautical charts published by the national agencies and required by the International Maritime Organization (IMO), the Safety of Life at Sea (SOLAS) and national regulations to be carried on vessels for safety

purposes. Increasingly those charts are provided and used in electronic form under IHO standards.

## **History and responsibilities**

The United Kingdom has a long hydrographic history officially begun with the 1683 appointment of Captain Grenville Collins as Hydrographer to the King. With the Royal Navy dominating the seas hydrography grew to a worldwide hydrographic activity. That tradition extended to the nations with a common legacy in the Empire, for example, the Australian Hydrographic Service. The British Admiralty Hydrographic Office became the United Kingdom Hydrographic Office which continues the legacy within the Ministry of Defence with responsibility for the Admiralty Charts. The Royal Navy maintains a number of hydrographic survey vessels to continue the work today.

## **Argentina**

The Argentine Hydrographic Service was established in 1879.

## **Australia**

Hydrographic services are provided by the Royal Australian Navy Hydrographic Service.

## **United States**

In United States statutory authority for hydrographic surveys of territorial waters and the Exclusive Economic Zone (EEZ) lies with the National Oceanographic and Atmospheric Administration (NOAA). NOAA hydrographic surveys are conducted by the National Ocean Service, a uniformed corps within NOAA and a fleet of survey vessels based at two major centers. The organic survey assets are supplemented by other agencies and contract surveys in order to survey the large areas within its responsibility. Those were identified in the NOAA Hydrographic Survey Priorities (NHSP) - East Coast alone as being 3,603 square miles (9,330 km<sup>2</sup>) classified as critical. The 2009 status shows 29,412 square nautical miles (100,900 km<sup>2</sup>) out of 510,841 square nautical miles (1,752,000 km<sup>2</sup>) "Navigationally Significant" were completed. The NOAA Office of Coast Survey, Hydrographic Surveys Division estimates it has awarded approximately \$250 million in contracts for hydrographic surveying and related support since 1994.

For inland surface waters such as rivers, streams and inland lakes the U.S. Geological Survey (USGS) has national responsibility. USGS coordinates survey data collection and publishes a National Hydrography Dataset that is designed to be used with geographic information systems (GIS). Other federal agencies such as the Environmental Protection Agency and the U.S. Fish and Wildlife Service use these data and, along with state and local hydrographic collection organizations, contribute to the national hydrographic data base. The Environmental Protection Agency conducts or contracts for surveys on projects such as the GE/Hudson River Super Fund site.

The U.S. Coast Guard conducts hydrographic survey operations, particularly in the Polar regions.

The National Geospatial Intelligence Agency (NGA) oversees charting of international waters for Department of Defense purposes. The Navy's Naval Oceanographic Office conducts many the oceanic surveys. The U.S. Army Corps of Engineers conducts hydrographic surveys supporting its responsibility for the major waterway projects that include navigation and flood control. Hydrographic data from those surveys is published by districts. Such data is incorporated into both NOAA and NGIA products and the Corps engages in efforts to improve hydrographic collection methods. Military combat organizations such as the Navy's SEAL and engineering units have specialized hydrographic reconnaissance survey capability.

The NOAA Office of Coast Survey, Coast Survey Partners web page offers a useful list and summary of major player activities, government and private, with links to those partner web sites.

### ***Hydrographic survey conducted by non-national agencies***

Governmental entities below national level conduct or contract for hydrographic surveys for waters within their jurisdiction with both internal and contract assets. Such surveys are commonly conducted by or under the standards approved by or the supervision of national organizations, particularly when the use is for the purposes of chart making/distribution or dredging of state controlled waters.

In the United States there is coordination with the National Hydrography Dataset in survey collection and publication. State environmental organizations publish hydrographic data relating to their mission.

### ***Hydrographic survey conducted by private organizations***

Large scale hydrographic and geophysical survey is conducted by commercial entities, particularly in the dredging, marine construction, oil exploration & drilling industries. Industry installing submarine cable for communications or power require detailed surveys of cable routes prior to installation with increased use of acoustic imagery equipment previously found only in military applications. There are specialized companies with both the assets and expertise to contract for such surveys with both commercial and governmental entities. Companies, Universities and investment groups will often fund Hydrographic surveys of public waterways prior to developing areas adjacent those waterways. Survey firms are also contracted to survey in support of design and engineering firms that are under contract for large public projects. Private surveys are also conducted before dredging operations and after these operations are completed. Companies with large private slips, docks or other water front installations have their facilities and the open water near their facilities surveyed regularly.

## **Process**

Modern surveying relies as much on software as hardware. In suitable shallow water areas Light Detection and Ranging (LIDAR) may be used. Equipment can be installed on inflatable craft, such as Zodiacs, small craft, AUVs (Autonomous Underwater Vehicles), UUVs (Unmanned Underwater Vehicles) or large ships, and can include sidescan, single beam and multibeam equipment. At one time different data collection methods and standards were used in collecting hydrographic data for maritime safety and for scientific or engineering bathymetric charts. Increasingly with aid of improved collection techniques and computer processing the data is collected under one standard and extracted for the specific use.

After data is collected, it has to undergo post-processing. A massive amount of data is collected during the typical Hydrographic survey, often several soundings per square foot. Depending on the final use (navigation charts, Digital Terrain Model, volume calculation for dredging, topography, Bathymetry) this data must be thinned out. It must also be error corrected (bad soundings,) and corrected for the effects of tides, waves/heave, water level and water temperature differences (thermoclines.) Usually the surveyor has additional data collection equipment on site to record the data required for correcting the soundings. Final output of charts can be created in a combination of specialty charting software or a CAD package, usually Autocad.

## Chapter 8

# Traverse (Surveying)

**Traverse** is a method in the field of surveying to establish control networks. It is also used in geodesy. Traverse networks involved placing survey stations along a line or path of travel, and then using the previously surveyed points as a base for observing the next point. Traverse networks have many advantages, including:

- Less reconnaissance and organization needed;
- While in other systems, which may require the survey to be performed along a rigid polygon shape, the traverse can change to any shape and thus can accommodate a great deal of different terrains;
- Only a few observations need to be taken at each station, whereas in other survey networks a great deal of angular and linear observations need to be made and considered;
- Traverse networks are free of the strength of figure considerations that happen in triangular systems;
- Scale error does not add up as the traverse is performed. Azimuth swing errors can also be reduced by increasing the distance between stations.

The traverse is more accurate than triangulation (a combined function of the triangulation and trilateration practice).

### **Types**

Frequently in surveying engineering and geodetic science, control points (CP) are setting/observing distance and direction (bearings, angles, azimuths, and elevation). The CP throughout the control network may consist of monuments, benchmarks, vertical control, etc.

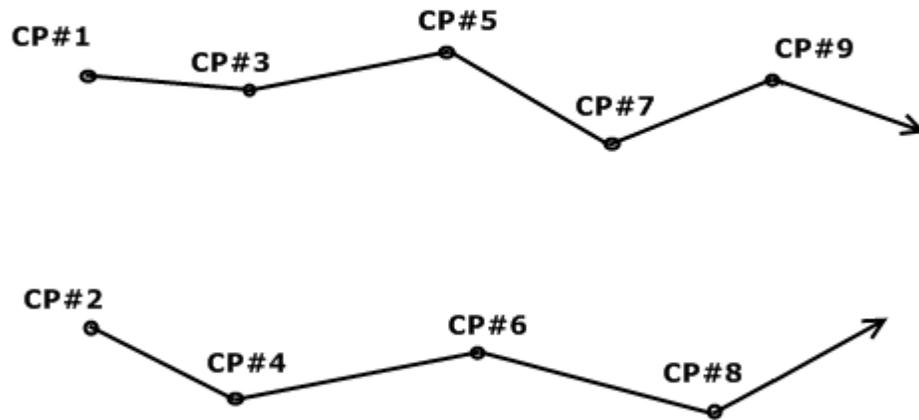


Diagram of an open traverse

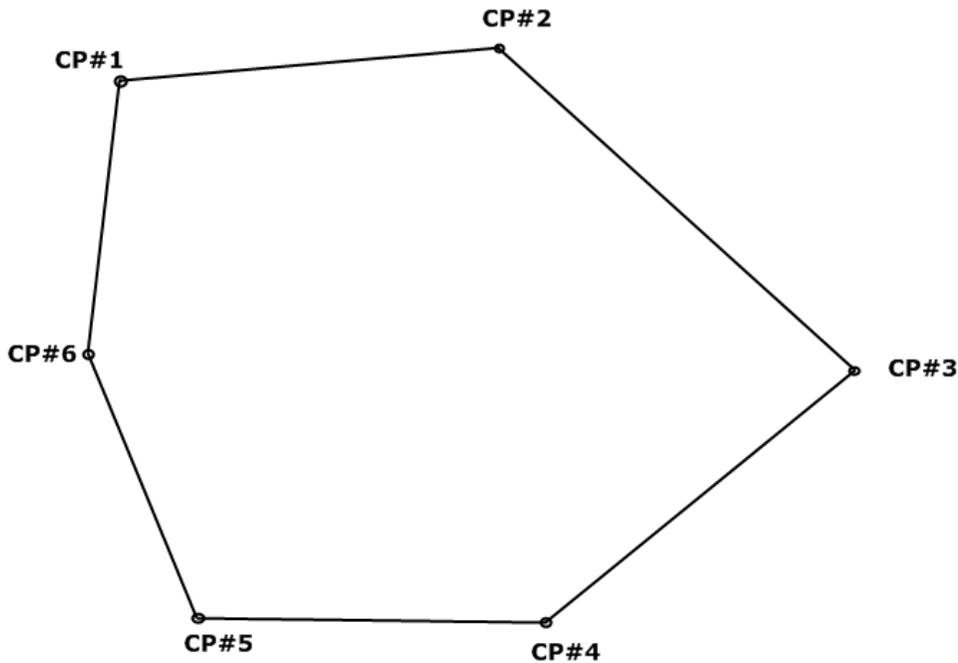


Diagram of a closed traverse

### Open/Free

An open, or free traverse (link traverse) consist of a series of linked traverse lines which do not return to the starting point to form a polygon.

- Open survey is utilised in plotting a strip of land which can then be used to plan a route in road construction.

### Closed

A closed traverse (polygonal, or loop traverse) is when the terminal point closes at the starting point. A closed traverse enables a check by plotting or computation, with any gap called the linear misclosure. When within acceptable tolerances, the misclosure can be distributed by adjusting the bearings and distances of the traverse lines using a systematic mathematical method. The adjusted measurements then close. The "Bowditch rule" or "compass rule" in geodetic science and surveying assumes that linear error is proportional to the length of the side in relation to the perimeter of the traverse.

- Closed traverse is useful in marking the boundaries of wood or lakes. Construction and civil engineers utilize this practice for preliminary surveys of

proposed projects in a particular designated area. The terminal (ending) point closes at the starting point.

## **Compound**

A compound traverse is where an open traverse is linked at its ends to an existing traverse to form a closed traverse. The closing line may be defined by coordinates at the end points which have been determined by previous survey. The difficulty is, where there is linear misclosure, it is not known whether the error is in the new survey or the previous survey.

## **Notes**

### **Usages**

- **Control point** — the primary/base control used for preliminary measurements; it may consist of any known point capable of establishing accurate control of distance and direction (i.e. coordinates, elevation, bearings, etc.).
1. **Starting** – It is the initial starting control point of the traverse.
  2. **Observation** – All known control points that are setted or observed within the traverse.
  3. **Terminal** – It is the initial ending control point of the traverse; its coordinates are *unknown*.

## Chapter 9

# Tripod (Surveying) & Tribrach (Instrument)

## Tripod (Surveying)



A surveyor's tripod with a shoulder strap. The head of the tripod supports the instrument while the feet are spiked to anchor the tripod to the ground.

A surveyor's tripod is a device used to support any one of a number of surveying instruments, such as theodolites, total stations, levels or transits.

## ***History***

Older surveying tripods had slightly different features compared to modern ones. For example, on some older tripods, the instrument had its own footplate and did not need to move laterally relative to the tripod head. For this reason, the head of the tripod was not a flat footplate but was simply a large diameter fitting. Threads on the outside of the head engaged threads on the instrument's footplate. No other mounting screw was used.

Fixed length legs were also seen on older instruments. Instrument height was adjusted by changing the angle of the legs. Widely spaced tripod feet resulted in a lower instrument while closely spaced legs raised the instrument. This was considerably less convenient than having variable length legs.

Materials for older tripods were predominantly wood and brass, with some steel for high wear items like the feet or foot points.

## ***Usage***



This shows the head of a surveyor's tripod with the mounting screw in the opening.



This shows a surveyor's tripod's foot. The platform is used to push the spike into the ground. Above the foot is the height adjustment.

The tripod is placed in the location where it is needed. The surveyor will press down on the legs' platforms to securely anchor the legs in soil or to force the feet to a low position on uneven, pock-marked pavement. Leg lengths are adjusted to bring the tripod head to a convenient height and make it roughly level.

Once the tripod is positioned and secure, the instrument is placed on the head. The mounting screw is pushed up under the instrument to engage the instrument's base and screwed tight when the instrument is in the correct position. The flat surface of the tripod head is called the foot plate and is used to support the adjustable feet of the instrument.

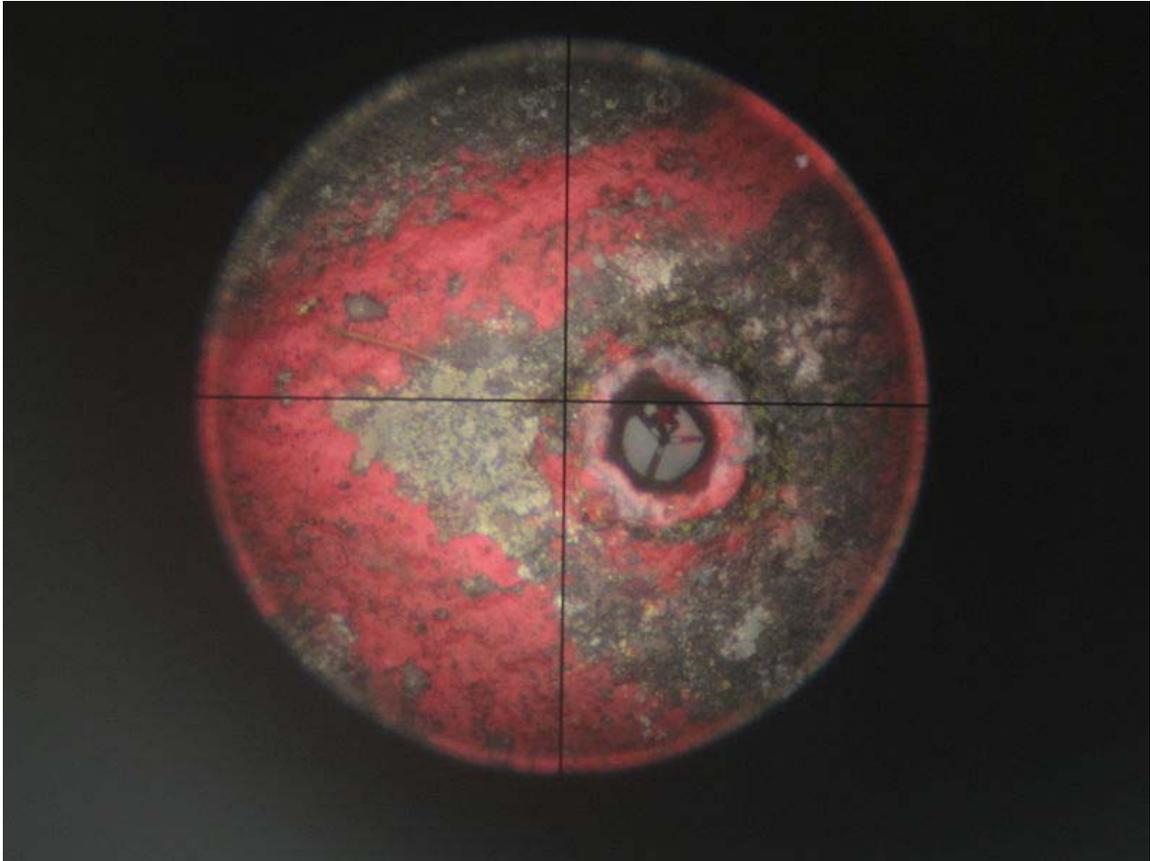
## **Construction**

Many modern tripods are constructed of aluminum, though wood is still used for legs. The feet are either aluminum tipped with a steel point or steel. The mounting screw is often brass or brass and plastic. The mounting screw is hollow to allow the optical plumb to be viewed through the screw. The top is typically threaded with a 5/8" x 11 tpi screw thread. The mounting screw is held to the underside of the tripod head by a movable arm. This permits the screw to be moved anywhere within the head's opening. The legs are attached to the head with adjustable screws that are usually kept tight enough to allow the legs to be moved with a bit of resistance. The legs are two part, with the lower part capable of telescoping to adjust the length of the leg to suit the terrain. Aluminum or steel slip joints with a tightening screw are at the bottom of the upper leg to hold the bottom part in place and fix the length. A shoulder strap is often affixed to the tripod to allow for ease of carrying the equipment over areas to be surveyed.

## **Tribrach (Instrument)**



A tribrach with an optical plummet (the black cylinder pointing to the left lower corner of the image).



View through an optical plummet of a prism adapter.



The head of a surveyors tripod with the screw for mounting the tribrach.

In surveying science, a **tribrach** means an instrument attachment plate containing three thumbscrews. The device consists of two triangular metal plates, which are connected at their corners by thumbscrews. By turning these, it is possible to level the top plate, when the bottom plate has been mounted atop a tripod.

Both metal plates making up the tribrach have a large circular hole in the center, through which goes the attachment screw of the theodolite. When tightened, this screw firmly attaches the theodolite, placed atop the tribrach, to a flange pressing against the bottom surface of the tribrach. In this way, it is possible to mount the instrument firmly, but freely (within some inches) choose the horizontal position of attachment.

A tribrach is used to iteratively and simultaneously realize the dual requirements placed on a theodolite mounted for measurement over a benchmark: that it be *centered* and *levelled*. Usually the tribrach also contains a forced centering mechanism, allowing the theodolite to be replaced by a target, optical plummet or other instrument to the same position with sub-mm precision, by just loosening and re-tightening a locking screw.

## Chapter 10

# Resection (Orientation) & Theodolite

## Resection (Orientation)

**Resection** is a method for determining a position (position finding) using a compass and topographic map (or nautical chart).

### ***Resection versus intersection***

Resection and its related method, *intersection*, are used in surveying as well as in general land navigation (including inshore marine navigation using shore-based landmarks). Both methods involve taking azimuths or bearings to two or more objects, then drawing *lines of position* along those recorded bearings or azimuths.

When intersecting lines of position are used to fix the position of an unmapped feature or point by fixing its position relative to two (or more) mapped or known points, the method is known as *intersection*. At each known point (hill, lighthouse, etc.), the navigator measures the bearing to the same unmapped target, drawing a line on the map from each known position to the target. The target is located where the lines intersect on the map. In earlier times, the *intersection* method was used by forest agencies and others using specialized alidades to plot the (unknown) location of an observed forest fire from two or more mapped (known) locations, such as forest fire observer towers.

The reverse of the *intersection* technique is appropriately termed *resection*. Resection simply reverses the intersection process by using *crossed back bearings*, where the navigator's position is the unknown. Two or more bearings to mapped, known points are taken; their resultant lines of position drawn from those points to where they intersect will reveal the navigator's location.

### ***Fixing a position***

When resecting or fixing a position, the geometric strength (angular disparity) of the mapped points affects the precision and accuracy of the outcome. Accuracy increases as

the angle between the two position lines approaches 90 degrees. Magnetic bearings are observed on the ground from the point under location to two or more features shown on a map of the area. Lines of reverse bearings, or *lines of position*, are then drawn on the map from the known features; two and more lines provide the resection point (the navigator's location). When three or more lines of position are utilized, the method is often popularly (though erroneously) referred to as triangulation (in precise terms, using three or more lines of position is still correctly called *resection*, as angular law of tangents (cot) calculations are not performed). When using a map and compass to perform resection, it is important to allow for the difference between the magnetic bearings observed and grid north (or true north) bearings (magnetic declination) of the map or chart.

Resection continues to be employed in land and inshore navigation today, as it is a simple and quick method requiring only an inexpensive magnetic compass and map/chart.

### **Resection in surveying**

In surveying work, the most common methods of computing the coordinates of a point by resection are Cassini's Method and the Tienstra formula, though the first known solution was given by Willebrord Snellius. For the type of precision work involved in surveying, the unmapped point is located by measuring the angles subtended by lines of sight from it to a minimum of three mapped (coordinated) points. In geodetic operations the observations are adjusted for spherical excess and projection variations. Precise angular measurements between lines from the point under location using theodolites provides more accurate results, with trig beacons erected on high points and hills to enable quick and unambiguous sights to known points.

Caution: When planning to perform a resection, the surveyor must first plot the locations of the known points along with the approximate unknown point of observation. If all points, including the unknown point, lie close to a circle that can be placed on all four points, then there is no solution or the high risk of an erroneous solution. This is known as observing on the "danger circle". The poor solution stems from the property of a chord subtending equal angles to any other point on the circle.

# Theodolite



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

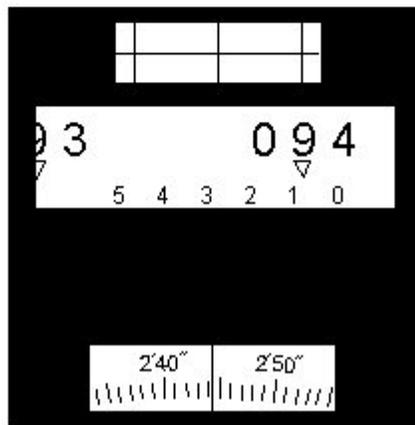
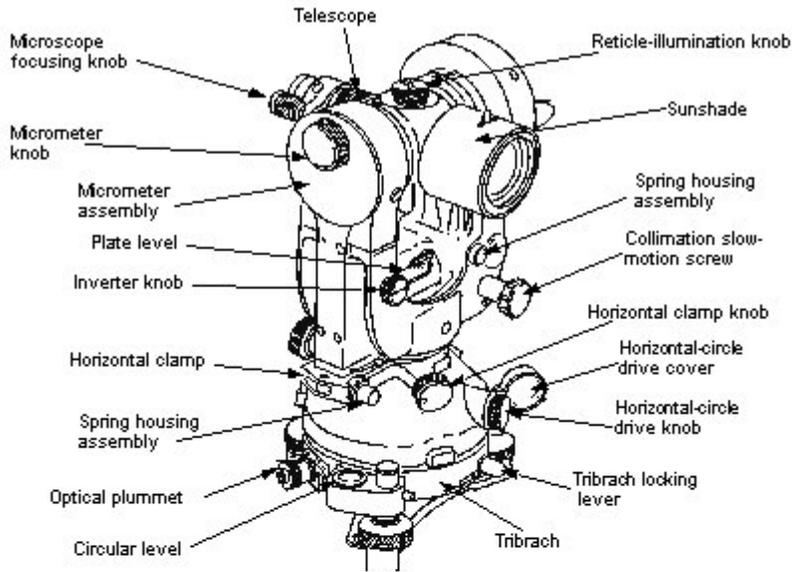
A **theodolite** is a precision instrument for measuring angles in the horizontal and vertical planes. Theodolites are mainly used for surveying applications, and have been adapted for specialized purposes in fields like meteorology and rocket launch technology. A modern theodolite consists of a movable 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.

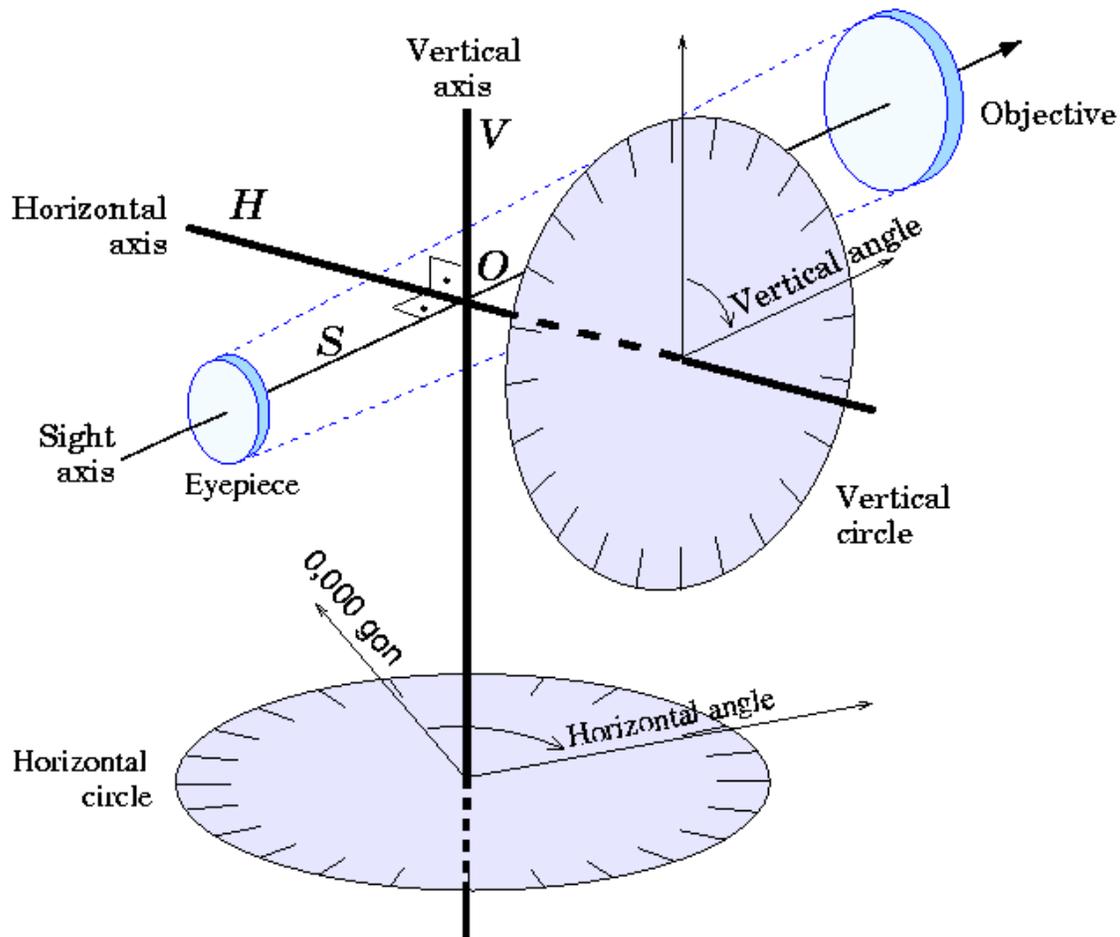
The builder's level is often mistaken for a transit, but it measures neither horizontal nor vertical angles. It uses a spirit level to set a telescope level to define a line of sight along a level plane.

**Concept of operation**



Vertical angle = 94°12'44"

Diagram of an Optical Theodolite



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  $90^\circ$  (100 grad) when the sight axis is horizontal, or  $270^\circ$  (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".

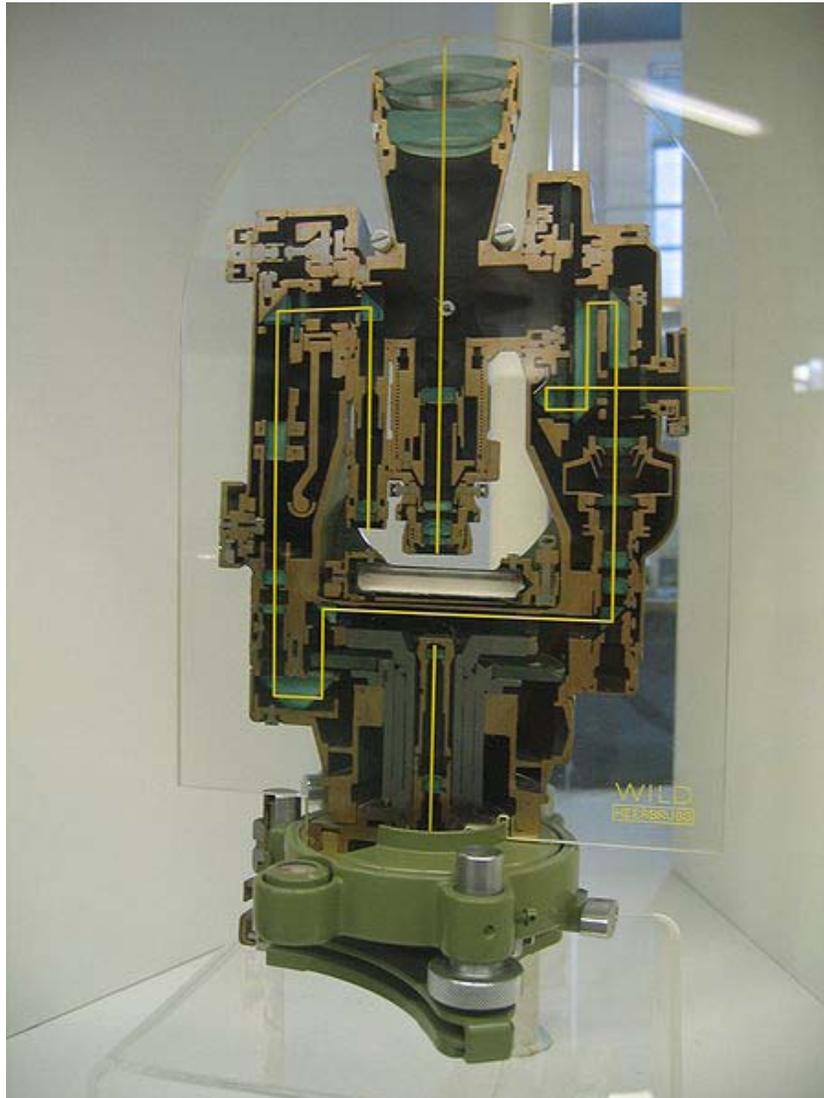
The horizontal and vertical axes of a theodolite must be perpendicular, if not then a "horizontal axis error" exists. This can be tested by aligning the tubular spirit bubble parallel to a line between two footscrews and setting the bubble central. A horizontal axis error exists if the bubble runs off central when the tubular spirit bubble is reversed (turned through  $180^\circ$ ). 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.

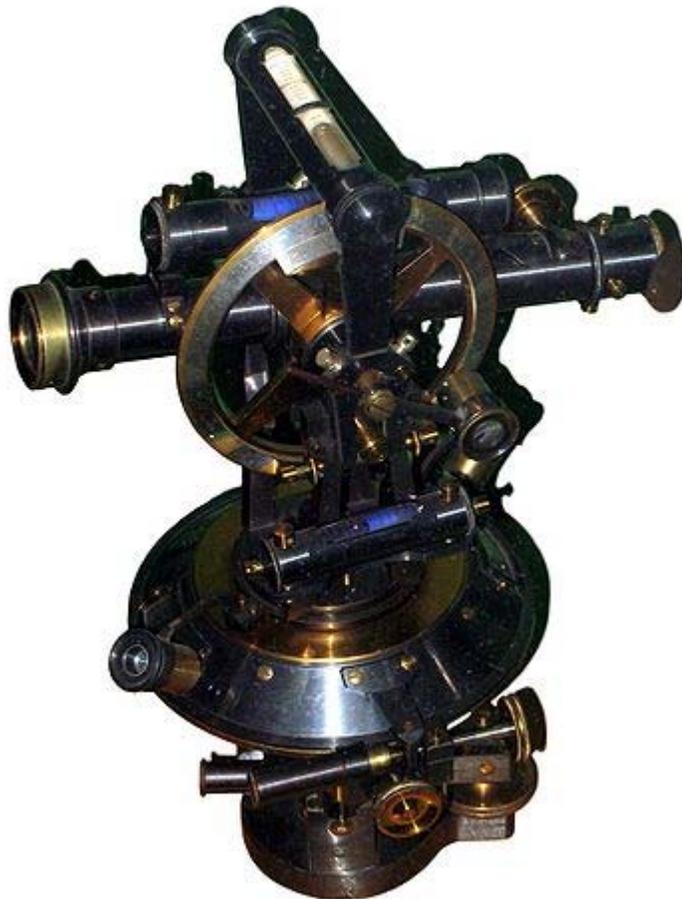
## ***History***



Sectioned theodolite showing the complexity of the optical paths

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

Prior to the theodolite, instruments such as the geometric square and various graduated circles and semicircles 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. It was described in the appendix by Martin Waldseemüller, a Rhineland topographer and cartographer, who made the device in the same year. Waldseemüller called his instrument the *polimetrum*.



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. The etymology of the word is unknown. The first part of the New Latin *theo-delitus* might stem from the Greek *θεῖσθαι*, "to behold or look attentively upon" or *θεῖν* "to run", 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", or *δολιχός* "long", or *δοῦλος* "slave", or an unattested Neolatin compound combining *ὁδός* "way" and *λίτος* "plain". It has been also suggested that *-delitus* is a variation of the Latin supine *deletus*, in the sense of "crossed out".

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]. 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". Even as late as the 19<sup>th</sup> century, the instrument for measuring horizontal angles only was called a *simple theodolite* and the altazimuth instrument, the *plain theodolite*.

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.

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.

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. 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. 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. It was used by the U.S. Navy to take the first precision surveys of American harbors on the Atlantic and

Gulf coasts. With continuing refinements, the instrument steadily evolved into the modern theodolite used by surveyors today.

### ***Operation in surveying***



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).

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.

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***

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.

## Chapter 11

# Total Station & Surveyor's Wheel

## Total Station



Archaeological survey using a Leica TPS1100 total station on an Iron Age dwelling in Ytterby, Sweden.

A **total station** is an electronic/optical instrument used in modern surveying. The total station is an electronic theodolite (transit) integrated with an electronic distance meter (EDM) to read slope distances from the instrument to a particular point.

Robotic total stations allow the operator to control the instrument from a distance via remote control. This eliminates the need for an assistant staff member as the operator holds the reflector and controls the total station from the observed point.

## **Technology**

### **Coordinate Measurement**

Coordinates of an unknown point relative to a known coordinate can be determined using the total station as long as a direct line of sight can be established between the two points. Angles and distances are measured from the total station to points under survey, and the coordinates (X, Y, and Z or northing, easting and elevation) of surveyed points relative to the total station position are calculated using trigonometry and triangulation. To determine an absolute location a Total Station requires line of sight observations and must be set up over a known point or with line of sight to 2 or more points with known location.

For this reason, some total stations also have a Global Navigation Satellite System interface which do not require a direct line of sight to determine coordinates. However, GNSS measurements may require longer occupation periods and offer relatively poor accuracy in the vertical axis.

### **Angle measurement**

Most modern total station instruments measure angles by means of electro-optical scanning of extremely precise digital bar-codes etched on rotating glass cylinders or discs within the instrument. The best quality total stations are capable of measuring angles to 0.5 arc-second. Inexpensive "construction grade" total stations can generally measure angles to 5 or 10 arc-seconds.

### **Distance Measurement**

Measurement of distance is accomplished with a modulated microwave or infrared carrier signal, generated by a small solid-state emitter within the instrument's optical path, and reflected by a prism reflector or the object under survey. The modulation pattern in the returning signal is read and interpreted by the computer in the total station. The distance is determined by emitting and receiving multiple frequencies, and determining the integer number of wavelengths to the target for each frequency. Most total stations use purpose-built glass corner cube prism reflectors for the EDM signal. A typical total station can measure distances with an accuracy of about 1.5 millimetres (0.0049 ft) + 2 parts per million over a distance of up to 1,500 metres (4,900 ft).

Reflectorless total stations can measure distances to any object that is reasonably light in color, to a few hundred meters.

### **Data processing**

Some models include internal electronic data storage to record distance, horizontal angle, and vertical angle measured, while other models are equipped to write these measurements to an external data collector, such as a hand-held computer.

When data is downloaded from a total station onto a computer, application software can be used to compute results and generate a map of the surveyed area.

## ***Applications***

Total stations are mainly used by land surveyors. They are also used by archaeologists to record excavations and by police, crime scene investigators, private accident reconstructionists and insurance companies to take measurements of scenes.

## **Mining**

Total stations are the primary survey instrument used in mining surveying.

A total station is used to record the absolute location of the tunnel walls (stopes), ceilings (backs), and floors as the drifts of an underground mine are driven. The recorded data is then downloaded into a CAD program, and compared to the designed layout of the tunnel.

The survey party installs control stations at regular intervals. These are small steel plugs installed in pairs in holes drilled into walls or the back. For wall stations, two plugs are installed in opposite walls, forming a line perpendicular to the drift. For back stations, two plugs are installed in the back, forming a line parallel to the drift.

A set of plugs can be used to locate the total station set up in a drift or tunnel by processing measurements to the plugs by intersection and resection.

## ***Instrument manufacturers***

- F. W. Breithaupt & Sohn
- Fennel (today: Geo-Fennel)
- Hilti
- Leica Geosystems
  - Kern & Co. AG (until 1992, today Leica Geosystems)
  - Wild Heerbrugg AG (historical). The company was incorporated into Leica Geosystems in 1990
- Miller, Innsbruck (until ca. 1990)
- Nikon
- Sokkia
- Topcon
- Trimble Navigation Ltd.
  - Carl Zeiss (historical), today part of Trimble Navigations Ltd.
  - Geodimeter (historical), today part of Trimble Navigations Ltd.
  - Spectra Precision, today part of Trimble, although still manufactured under its own brand.

# Surveyor's Wheel



Surveyor's wheel

A **surveyor's wheel**, also called a **clickwheel**, **hodometer**, **waywiser**, **trundle wheel**, **measuring wheel**, or **perambulator** is a device for measuring distance.

## ***Origin***

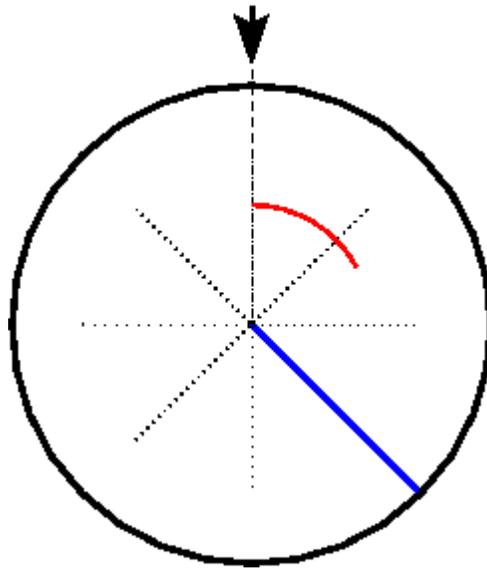
The origins of the surveyor's wheel are connected to the origins of the odometer. While the latter is derived to measure distances travelled by a vehicle, the former is specialized to measure distances. Much of the material on the earliest stages in the development of the odometer are adequately covered in odometer.

In the 17<sup>th</sup> century, the surveyor's wheel was re-introduced and used to measure distances. A single wheel is attached to a handle and the device can be pushed or pulled along by a person walking. Early devices were made of wood and may have an iron rim to provide strength. The wheels themselves would be made in the same manner as wagon wheels and often by the same makers. The measuring devices would be made by makers of scientific instruments and the device and handles would be attached to the wheel by them. The device to read the distance travelled would be mounted either near the hub of the wheel or at the top of the handle.

In some cases, double-wheel odometers were constructed.

Modern surveyor's wheels are constructed primarily of aluminium, with solid or pneumatic tires on the wheel. Some can fold for transport or storage.

## How the surveyor's wheel works



A diagram of a surveyor's wheel taking a measurement.

The surveyor's wheel is marked in fractional increments of revolution from a reference position and its current position can be represented as  $\frac{a}{b}$  of a revolution from this reference, where  $a$  and  $b$  are integers. In the figure on the right, the blue line is the reference starting point. As the wheel turned during measurement, it is shown the wheel sweeps out an angle of  $\frac{3}{4}\pi$  radians or  $\frac{3}{8}$  turns. In this situation, the fraction,  $\frac{3}{8}$ , would be the relevant  $\frac{a}{b}$  ratio. The usefulness of this ratio becomes clear after further consideration of the equation for the arc length of a circle.

This equation is

$$s = \theta r,$$

where  $s$  is the arc length,  $\theta$  is the angle, in radians, of the circle swept through and  $r$  is the radius of the circle. Now, substitute into the arc length equation the conversion from radians to revolutions to obtain the form,

$$s = \frac{a}{b} 2\pi r.$$

The equation for the circumference of a circle,  $C = 2\pi r$ , can clearly be seen and simplifying gives,

$$s = \frac{a}{b}C$$

Thus showing that the base unit of measurement of the surveyor's wheel is determined only by the circumference of the wheel attached.

### ***Usage of the surveyor's wheel***

Each revolution of the wheel measures a specific distance, such as a yard, metre or half-rod. Thus counting revolutions with a mechanical device attached to the wheel measures the distance directly.

Surveyor's wheels will provide a measure of good accuracy on a smooth surface, such as pavement. On rough terrain, wheel slippage and bouncing can reduce the accuracy. Soft sandy or muddy soil can also affect the rolling of the wheel. As well, obstacles in the way of the path may have to be accounted for separately. Good surveyors will keep track of any circumstance on the path that can influence the accuracy of the distance measured and either measure that portion with an alternative, such as a surveyor's tape or measuring tape, or make a reasonable estimate of the correction to apply.

Surveyor's wheels are used primarily for lower accuracy surveys. They are often used by road maintenance or underground utility workers and by farmers for fast measures over distances too inconvenient to measure with a surveyor's tape.

The surveyor's wheel measures the distance along a surface, whereas in normal land surveying, distances between points are usually measured horizontally with vertical measurements indicated in differences in elevation. Thus conventionally surveyed distances will be less than those measured by a surveyor's wheel.

## Chapter 12

# Plumb-Bob & Graphometer

## Plumb-Bob



A plumb-bob

A **plumb-bob** or a **plummet** is a weight, usually with a pointed tip on the bottom, that is suspended from a string and used as a vertical reference line, or **plumb-line**.

The instrument has been used since at least the time of ancient Egypt to ensure that constructions are "plumb", or vertical. It is also used in surveying to establish the nadir with respect to gravity of a point in space. They are used with a variety of instruments

(including levels, theodolites, and steel tapes) to set the instrument exactly over a fixed survey marker, or to transcribe positions onto the ground for placing a marker.

### ***Etymology***

The "plumb" in "plumb-bob" comes from the fact that such tools were originally made of lead (Latin *plumbum*, probably through French *plomb*). The adjective "plumb" developed by extension.

### ***Use***

Up until the modern age, on most tall structures, plumb-bobs were used to provide vertical datum lines for the building measurements. A section of the scaffolding would hold a plumb line that was centered over a datum mark on the floor. As the building proceeded upwards the plumb line would also be taken higher, still centered on the datum. Many cathedral spires, domes and towers still have brass datum marks inlaid into their floors, that signify the center of the structure above.



Plumb-bob with scale as an inclinometer

Although a plumb-bob and line alone can only determine a vertical, if mounted on a suitable scale the instrument may also be used as an inclinometer to measure angles to the vertical.

The early skyscrapers used heavy plumb-bobs hung on wire in their elevator shafts. The weight would hang in a container of oil to dampen any swinging movement, functioning as a shock absorber.

### **Determining center of gravity of an irregular shape**

Students of figure drawing will also make use of a plumb line to find the vertical axis through the center of gravity of their subject and lay it down on paper as a point of reference. The device used may be purpose-made plumb lines, or simply makeshift devices made from a piece of string and a weighted object, such as a metal washer. This plumb line is important for lining up anatomical geometries and visualizing the subject's center of balance.

## **Graphometer**



Butterfield compass graphometer



A German graphometer in Göttingen, Stadtmuseum. The instrument is on its side. At the back, the socket for a Jacob's staff can be seen.

The **graphometer** or **semicircle** is a surveying instrument used for angle measurements. It consists of a semicircular limb divided into 180 degrees and sometimes subdivided into minutes. The limb is subtended by the diameter with two sights at its ends. In the middle of the diameter a "box and needle" (a compass) is fixed. On the same middle the alidade with two other sights is fitted. The device is mounted on a staff via a ball and socket joint. In effect the device is a half-circumferentor. For convenience, sometimes another half-circle from 180 to 360 degrees may be graduated in another line on the limb.

The form was introduced in Philippe Danfrie's, *Déclaration de l'usage du graphomètre* (Paris, 1597) and the term "graphometer" was popular with French geodesists. The preferable English-language terms were semicircle or semicircumferentors. Some 19th-century graphometers had telescopic rather than open sights.

## Usage

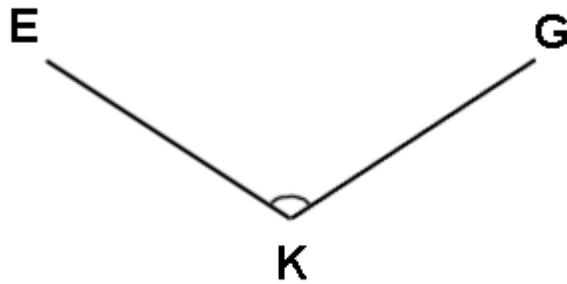
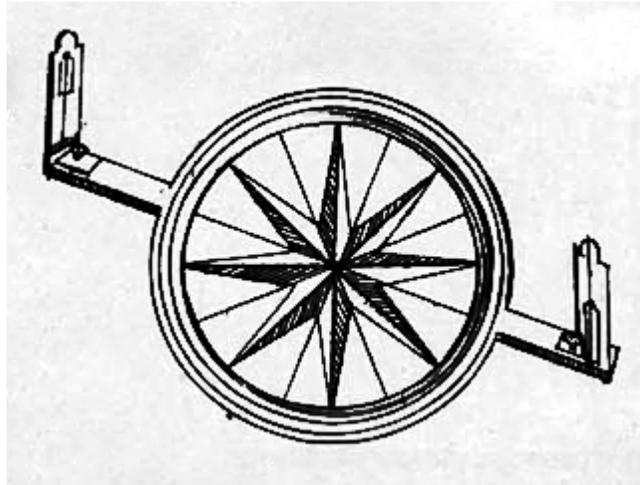


Figure 1: Angle EKG

To measure an angle, say, EKG, place the diameter middle C at the angle apex K using the plummet at point C of the instrument. Align the diameter with leg KE of the angle using the sights at the ends of the diameter. Align the alidade with the leg KG using another pair of sights, and read the angle off the limb as marked by the alidade. Further uses of the graphometer are the same as those of the circumferentor.

## Chapter 13

# Circumferentor



Drawing of a circumferentor from the *Cyclopaedia*



Circumferentor with gunter's chain at Campus Martius Museum in Marietta, Ohio

A **circumferentor**, or **surveyor's compass**, is an instrument used in surveying to measure horizontal angles, now superseded by the theodolite.

It consists of a brass circle and an index, all of one piece. On the circle is a card, or compass, divided into 360 degrees; the meridian line of which is in the middle of the breadth of the index. On the circumference of the circle is a brass ring, which, with another ring fitted with glass, make a kind of box for the needle, which is suspended on a rivet in the center of the circle. On each extreme of the index is a sight. The whole apparatus is mounted on a staff, with a ball-and-socket joint for easy rotation.

Circumferentors were made throughout Europe, including England, France, Italy, and Holland. By the early 19th century, Europeans preferred theodolites to circumferentors. However, in America, and other wooded or uncleared areas, the circumferentor was still in common use.

## Usage

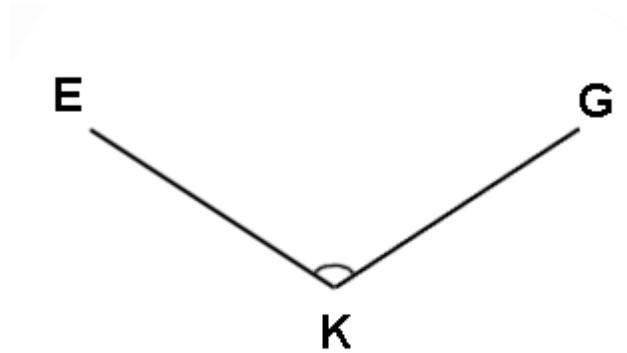


Figure 1: Angle EKG

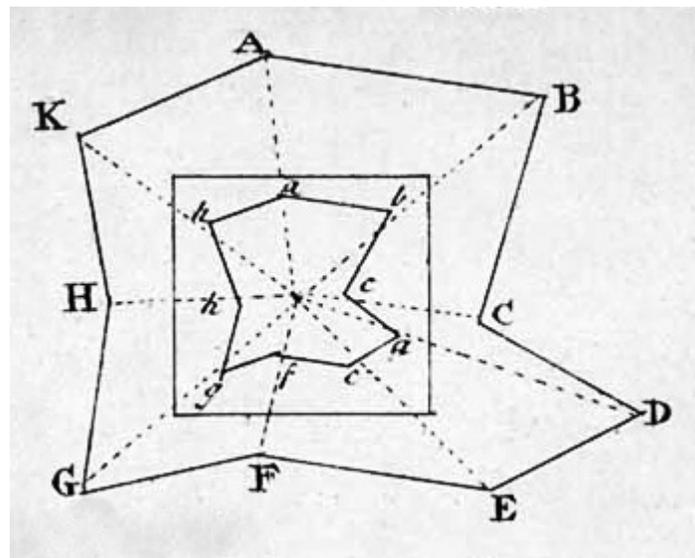


Figure 2: Region ABCDEFGHK

## Measuring angles

To measure an angle with a circumferentor, such as angle EKG (Figure 1), place the instrument at K, with the fleur-de-lis in the card towards you. Then direct the sights, until through them you see E; and note the degree pointed at by the south end of the needle, such as  $296^\circ$ . Then, turn the instrument around, with the fleur-de-lis still towards you, and direct the sights to G; note the degree at which the south end of the needle point, such as  $182^\circ$ . Finally, subtract the lesser number, 182, from the greater,  $296^\circ$ ; the remainder,  $114^\circ$ , is the number of degrees in the angle EKG.

If the remainder is more than 180 degrees, it must be subtracted from 360 degrees.

## Surveying a region

To take the plot of a field, forest, park, etc, with a circumferentor, consider region ABCDEFGHK in Figure 2, an area to be surveyed.

1. Placing the instrument at A, the fleur-de-lis towards you, direct the sights to B; where suppose the south end of the needle cuts  $191^\circ$ ; and the ditch, wall, or hedge, measuring with a Gunter's chain, contains 10 chains, 75 links.
2. Placing the instrument at B, direct the sights as before to C; the south end of the needle, *e.g.* will cut  $279^\circ$ ; and the line BC contains 6 chains and 83 links.

Then move the instrument to C; turn the sights to measure D, and measure CD as before. In the same manner, proceed to D, E, F, G, H, and lastly to K; still noting the degrees of every bearing, or angle, and the distances of every side. This will result in a table of the following form:

<b>Station</b>	<b>Degrees</b>	<b>Min.</b>	<b>Chains</b>	<b>Link</b>
----------------	----------------	-------------	---------------	-------------

A	191	00	10	75
---	-----	----	----	----

B	297	00	6	83
---	-----	----	---	----

C	216	30	7	82
---	-----	----	---	----

etc.

From this table, the field is to be plotted, or protracted.

## ***Surveyor's double prism***



Double prism as used in surveying.

It's a device to measure right angles, a double pentaprism (two pentaprisms stacked on top of each other) and a plumb-bob are used to stake out right angles, e.g. on a construction site.

## Chapter 14

# Tape Correction (Surveying)

In surveying, **tape correction(s)** refer(s) to specific mathematical technique(s) used to apply corrections into a taping operation. Tape correction is applied to systematic or instrument errors or combination of both.

### ***Correction due to incorrect tape length***

Manufacturers of measuring tapes do not usually guarantee their tape products, and standardization requires additional processes. On the other hand, nominal length of tapes were often due to physical imperfections like manufacture, stretching or wear. Constant use of tapes tend it to become worn, kinked or sometimes improperly repaired when breaks occur.

The correction due to tape length was given by:

$$CL = ML \pm Corr \times \frac{ML}{NL}$$

Where:

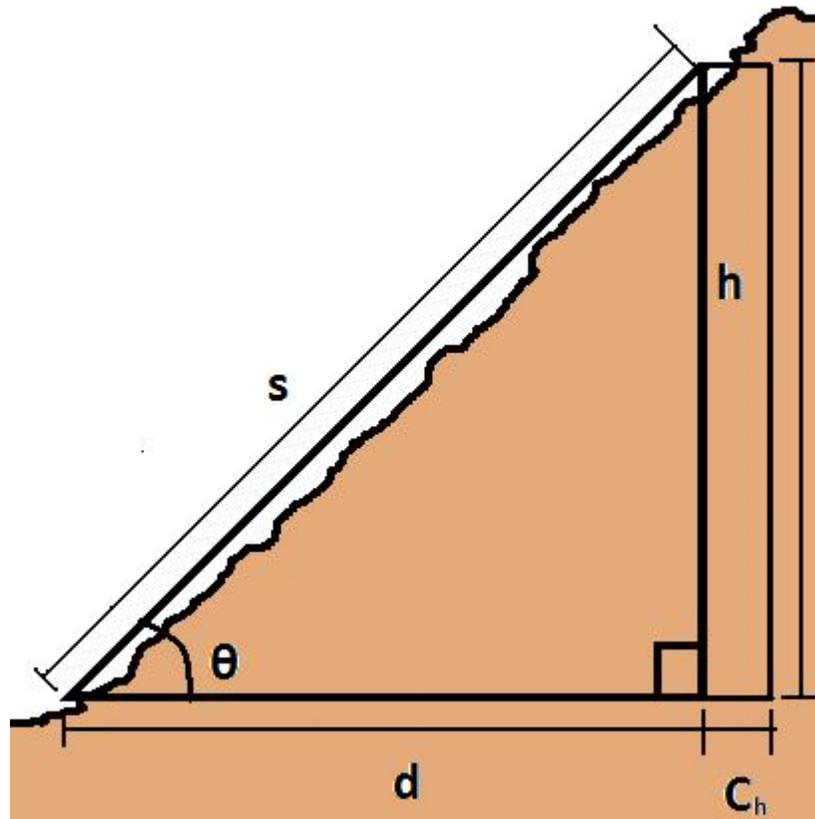
**CL** is the corrected length of the line to be measured or laid out;

**ML** is the measured length or length to be laid out;

**NL** is the nominal length of the tape as specified by its mark.

Note that incorrect tape length introduces systematic error that must be calibrated periodically.

## Correction due to slope



Correction due to slope.  $C_h$  is the correction of height due to slope,  $\theta$  is the angle formed by the slope line oriented from the horizontal ground,  $s$  is the measured slope distance between two points on the slope line,  $h$  is the height of the slope.

When distances are measured along the slope, then the equivalent horizontal distance may correspondingly be determined by applying an approximate slope correction.

When applying corrections due to slope, it is necessary to determine the slope orientation of the length to be measured. (Refer to the figure on the other side) Thus,

- For gentle slopes,  $m < 20\%$

$$C_h = \frac{h^2}{2s}$$

- For steep slopes,  $20\% \leq m \leq 30\%$

$$C_h = \frac{h^2}{2s} + \frac{h^4}{8s^3}$$

- For very steep slopes,  $m > 30\%$

$$C_h = s(1 - \cos\theta)$$

Where:

$C_h$  is the correction of height due to slope;  
 $\theta$  is the angle formed by the slope line oriented from the horizontal ground;  
 $s$  is the measured slope distance between two points on the slope line.

The obtained correction  $C_h$  is subtracted from  $s$  to obtain the corrected tape length of the horizontal distance between two points on the slope line:

$$d = s - C_h$$

### ***Correction due to temperature***

When measuring or laying out distances, there is always a change in temperature especially when the taping operation requires time to do so. Usually, to avoid circumstances where there is an introduced error due to temperature, tapes were standardized as a response to such factor.

The correction of the tape length due to change in temperature is given by:

$$C_f = C \cdot L(T - T_s)$$

Where:

$C_f$  is the correction to be applied to the tape due to temperature;  
 $T$  is the observed temperature or average observed temperature at the time of measurement;  
 $T_s$  is the temperature at which the tape was standardized;  
 $C$  is the coefficient of thermal expansion of the tape;  
 $L$  is the length of the tape or length of the line measured.

Usually, for common tape measurements, the tape used is a steel tape. Therefore, the coefficient of thermal expansion  $C$  is equal to 0.0000116 per degree Celsius. It means that the tape stretched by 0.0000116 units for every rise of one degree Celsius temperature.

### ***Correction due to tension***

Tension usually introduces error when the tape is pulled at a force that causes the tape to stretch to a certain length. Correspondingly, it will stretch less than its standard length when an insufficient pull is applied making the tape too short.

The tape stretches in an elastic manner (up until it reaches its elastic limit where it will deform permanently, essentially ruining the tape). The correction due to tension is given by:

$$C_p = \frac{(P_m - P_s)L}{AE}$$

Where:

$C_p$  is the total elongation in tape length due to pull; or the correction to be applied due to incorrect pull applied on the tape; meters;

$P_m$  is the pull applied on the tape during measurement; kilograms;

$P_s$  is the pull applied on the tape during standardization; kilograms;

$A$  is the cross-sectional area of the tape; square centimeters;

$E$  is the modulus of elasticity of the tape material; kilogram per square centimeters;

$L$  is the measured or erroneous length of the line; meters

The value for  $A$  is given by:

$$A = \frac{W}{(L)(U_w)}$$

Where:

$W$  is the total weight of the tape; kilograms;

$U_w$  is the unit weight of the tape; kilogram per cubic centimeter.

In steel tapes, the value for  $U_w$  is given by  $7.866 \times 10^{-3} \text{kg/cm}^3$ .

### **Correction due to sag**

When a tape is not supported along its length it will sag, forming a catenary between supports. The correction due to sag must be calculated for each unsupported stretch separately and is given by:

$$C_s = \frac{\omega^2 L^3}{24P^2}$$

Where:

$C_s$  is the correction applied to the tape due to sag; meters;

$\omega$  is the weight of the tape per unit length; kilogram per meters;

**L** is the interval length between two supports or unsupported lengths of the tape; meters;

**P** is the tension or pull applied to the tape that causes it to sag; kilogram.

Note that the weight of the tape per unit length is equal to the actual weight of the tape divided by the length of the tape:

$$\omega = \frac{W}{L}$$

and

$$W = \omega L$$

Therefore, we can rewrite the formula for correction due to sag by:

$$C_s = \frac{W^2 L}{24P^2}$$

Chapter 15

# Survey Marker



Closeup of a Geodetic Survey marker



This USGS survey marker is designed to be a standard nail to be used by the USGS to mark high-watermarks, set reference points, set bench marks, set reference marks, and turning points for levels. This nail is designed to be recovered (re-found) at a later date without any question that the nail was set by the USGS.

**Survey markers**, also called **survey marks**, and sometimes **geodetic marks**, are objects placed to mark key survey points on the Earth's surface. They are used in geodetic and land surveying. Informally, such marks are referred to as benchmarks, although strictly speaking the term "benchmark" is reserved for marks that indicate elevation. Horizontal position markers used for triangulation are also known as trig points or **triangulation stations**.



A common type of marker for a triangulation station. The triangle at its center indicates that it is a "station mark."



A reference mark disk for the main station shown above. This is one of six such marks for this station.

All sorts of different objects, ranging from the familiar brass disks to liquor bottles, clay pots, and rock cairns, have been used over the years as survey markers. Some truly monumental markers have been used to designate **tripoints**, or the meeting points of three or more countries. In the 19th Century, these marks were often drill holes in rock ledges, crosses or triangles chiseled in rock, or copper or brass bolts sunk into bedrock. Today, the most common survey marks are cast metal disks (with stamped legends on their face) set in rock ledges, sunken into the tops of concrete pillars, or affixed to the tops of pipes that have been sunk into the ground. These marks are intended to be permanent, and disturbing them is generally prohibited by federal and state law.

These marks were often placed as part of triangulation surveys, measurement efforts that moved systematically across states or regions, establishing the angles and distances between various points. Such surveys laid the basis for map-making in the United States and across the world.

Geodetic survey markers were often set in groups. For example, in triangulation surveys, the primary point identified was called the **triangulation station**, or the "main station". It was often marked by a "station disk", a brass disk with a triangle inscribed on its surface and an impressed mark that indicated the precise point over which a surveyor's plumb bob should be dropped to assure a precise location over it. A triangulation station was often surrounded by several (usually three) **reference marks**, each of which bore an arrow that pointed back towards the main station. These reference marks made it easier for later visitors to "recover" (or re-find) the primary ("station") mark. Reference marks also made it possible to replace (or reset) a station mark that had been disturbed or destroyed.

Some old station marks were buried several feet down (to protect them from being struck by plows). Occasionally, these buried marks had surface marks set directly above them.

In the U.S., survey marks that meet certain standards for accuracy are part of a national database that is maintained by the National Geodetic Survey (**NGS**). Each station mark in the database has a **PID** (Permanent IDentifier), a unique 6-character code that can be used to call up a **datasheet** describing that station. The NGS has a web-based form that can be used to access any datasheet, if the station's PID is known. Alternatively, datasheets can be called up by station name.

A typical datasheet has either the precise or the estimated coordinates. Precise coordinates are called "**adjusted**" and result from precise surveys. Estimated coordinates are termed "**scaled**" and have usually been set by locating the point on a map and reading off its latitude and longitude. Scaled coordinates can be as much as several thousand feet distant from the true positions of their marks. In the U.S., some survey markers have the latitude and longitude of the station mark, a listing of any reference marks (with their distance and bearing **from** the station mark), and a narrative (which is updated over the years) describing other reference features (e.g., buildings, roadways, trees, or fire hydrants) and the distance and/or direction of these features from the marks, and giving a history of past efforts to recover (or re-find) these marks (including any resets of the marks, or evidence of their damage or destruction).

Current best practice for stability of new survey markers is to use a punch mark stamped in the top of a metal rod driven deep into the ground, surrounded by a grease filled sleeve, and covered with a hinged cap set in concrete.

Survey markers are now often used to set up a GPS receiver antenna in a known position for use in Differential GPS surveying.

## Chapter 16

# Triangulation

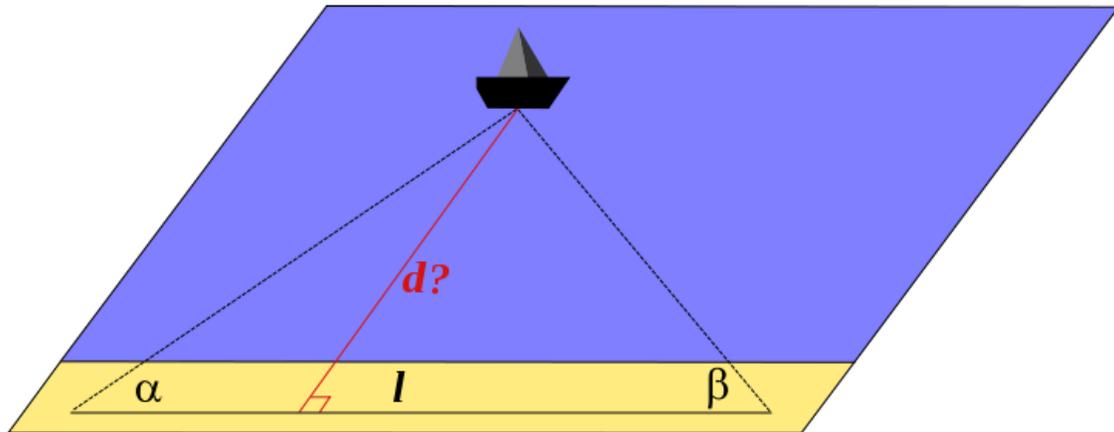
In trigonometry and geometry, **triangulation** is the process of determining the location of a point by measuring *angles* to it from known points at either end of a fixed baseline, rather than measuring distances to the point directly (trilateration). The point can then be fixed as the third point of a triangle with one known side and two known angles.

Triangulation can also refer to the accurate surveying of systems of very large triangles, called **triangulation networks**. This followed from the work of Willebrord Snell in 1615–17, who showed how a point could be located from the angles subtended from *three* known points, but measured at the new unknown point rather than the previously fixed points, a problem called resectioning. Surveying error is minimized if a mesh of triangles at the largest appropriate scale is established first. Points inside the triangles can all then be accurately located with reference to it. Such triangulation methods were used for accurate large-scale land surveying until the rise of global navigation satellite systems in the 1980s.

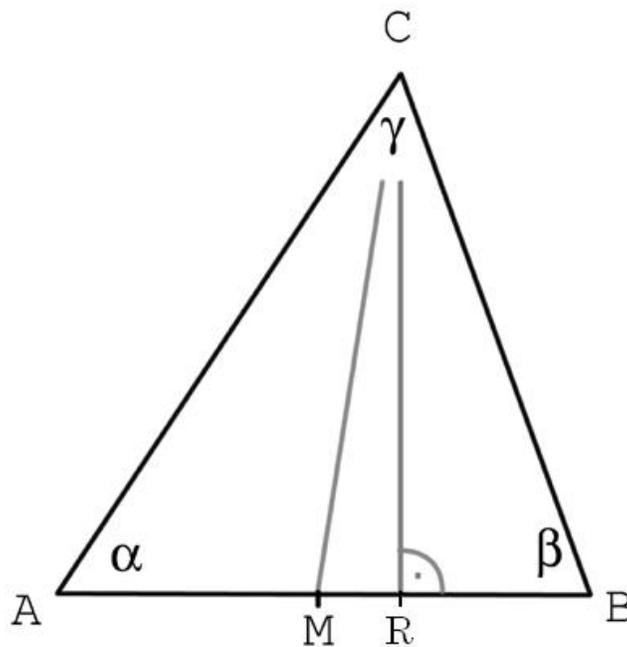
### ***Applications***

Optical 3d measuring systems use this principle as well in order to determine the spatial dimensions and the geometry of an item. Basically, the configuration consists of two sensors observing the item. One of the sensors is typically a digital camera device, and the other one can also be a camera or a light projector. The projection centers of the sensors and the considered point on the object's surface define a (spatial) triangle. Within this triangle, the distance between the sensors is the base  $b$  and must be known. By determining the angles between the projection rays of the sensors and the basis, the intersection point, and thus the 3d coordinate, is calculated from the triangular relations.

## Distance to a point by measuring two fixed angles



Triangulation can be used to calculate the coordinates and distance from the shore to the ship. The observer at  $A$  measures the angle  $\alpha$  between the shore and the ship, and the observer at  $B$  does likewise for  $\beta$ . With the length  $l$  or the coordinates of  $A$  and  $B$  known, then the law of sines can be applied to find the coordinates of the ship at  $C$  and the distance  $d$ .



The coordinates and distance to a point can be found by calculating the length of one side of a triangle, given measurements of angles and sides of the triangle formed by that point and two other known reference points.

The following formulas apply in flat or Euclidean geometry. They become inaccurate if distances become appreciable compared to the curvature of the Earth, but can be replaced with more complicated results derived using spherical trigonometry.

## Calculation

$$\ell = \frac{d}{\tan \alpha} + \frac{d}{\tan \beta}$$

Therefore

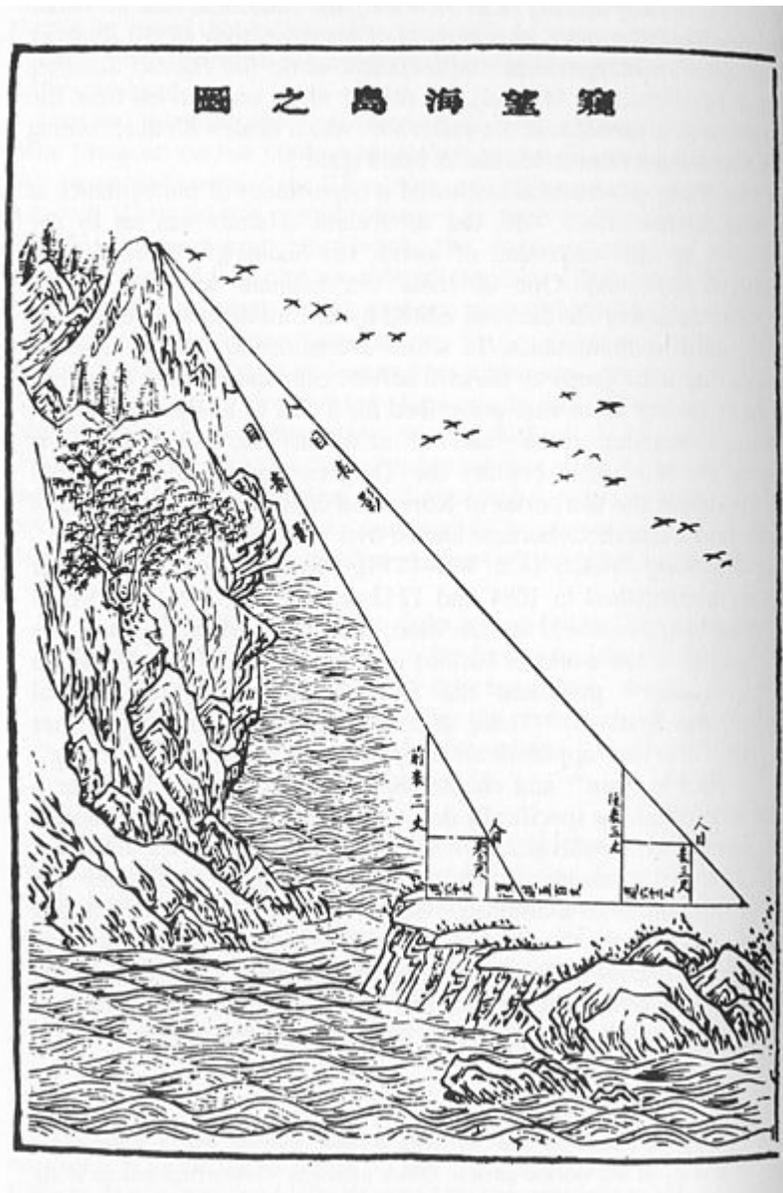
$$d = \ell / \left( \frac{1}{\tan \alpha} + \frac{1}{\tan \beta} \right)$$

Using the trigonometric identities  $\tan \alpha = \sin \alpha / \cos \alpha$  and  $\sin(\alpha + \beta) = \sin \alpha \cos \beta + \cos \alpha \sin \beta$ , this is equivalent to:

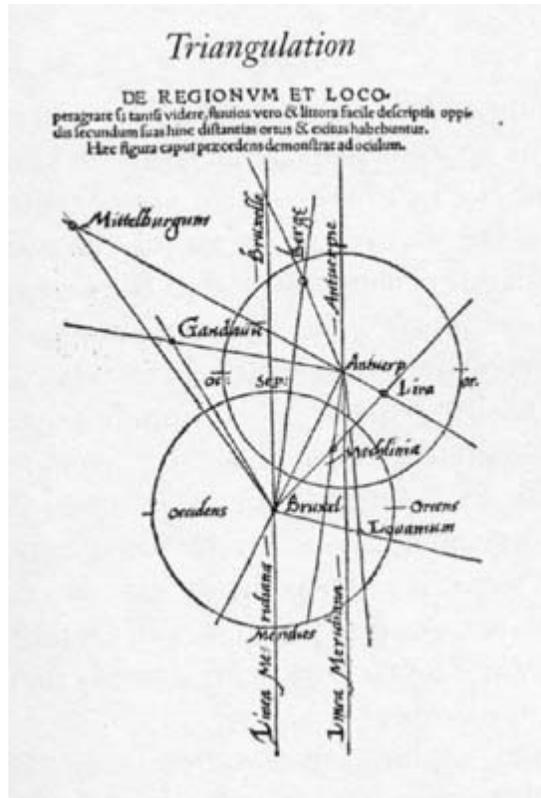
$$d = \frac{\ell \sin \alpha \sin \beta}{\sin(\alpha + \beta)}$$

From this, it is easy to determine the distance of the unknown point from either observation point, its north/south and east/west offsets from the observation point, and finally its full coordinates.

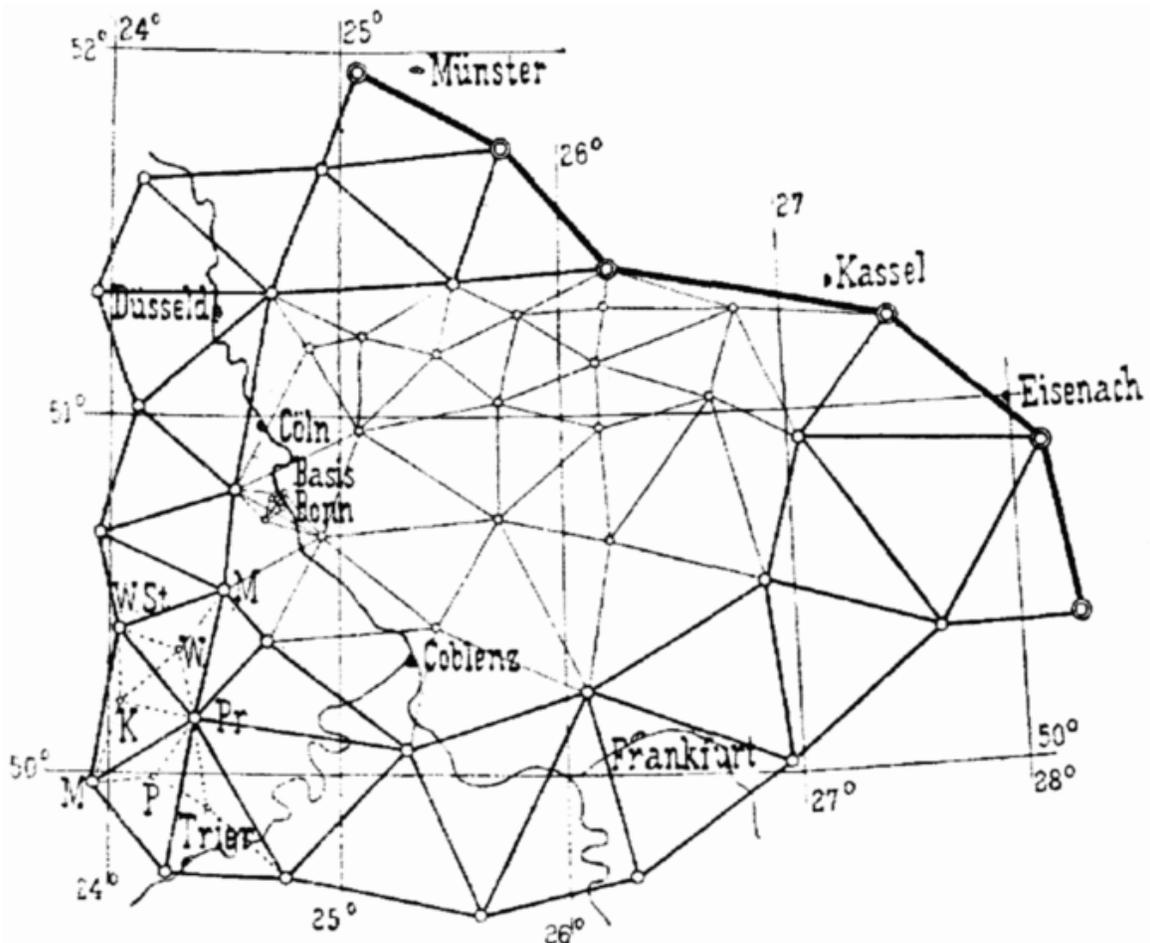
**History**



Liu Hui (c. 263), How to measure the height of a sea island. Illustration from an edition of 1726



Gemma Frisius's 1533 proposal to use triangulation for mapmaking



**Fig. 4. Die rheinish-hessische Kette und das nieder-rheinische Dreiecksnetz.**

Nineteenth-century triangulation network for the triangulation of Rhineland-Hesse

Triangulation today is used for many purposes, including surveying, navigation, metrology, astrometry, binocular vision, model rocketry and gun direction of weapons.

The use of triangles to estimate distances goes back to antiquity. In the 6th century BC the Greek philosopher Thales is recorded as using similar triangles to estimate the height of the pyramids by measuring the length of their shadows at the moment when his own shadow was equal to his height; and to have estimated the distances to ships at sea as seen from a cliff top, by measuring the horizontal distance traversed by the line-of-sight for a known fall, and scaling up to the height of the whole cliff. Such techniques would have been familiar to the ancient Egyptians. Problem 57 of the Rhind papyrus, a thousand years earlier, defines the *seqt* or *seked* as the ratio of the run to the rise of a slope, *i.e.* the reciprocal of gradients as measured today. The slopes and angles were measured using a sighting rod that the Greeks called a *dioptra*, the forerunner of the Arabic alidade. A detailed contemporary collection of constructions for the determination of lengths from a distance using this instrument is known, the *Dioptra* of Hero of Alexandria (c. 10–70

AD), which survived in Arabic translation; but the knowledge became lost in Europe. In China, Pei Xiu (224–271) identified "measuring right angles and acute angles" as the fifth of his six principles for accurate map-making, necessary to accurately establish distances; while Liu Hui (c. 263) gives a version of the calculation above, for measuring perpendicular distances to inaccessible places.

In the field, triangulation methods were apparently not used by the Roman specialist land surveyors, the *agromensores*; but were introduced into medieval Spain through Arabic treatises on the astrolabe, such as that by Ibn al-Saffar (d. 1035). Abu Rayhan Biruni (d. 1048) also introduced triangulation techniques to measure the size of the Earth and the distances between various places. Simplified Roman techniques then seem to have co-existed with more sophisticated techniques used by professional surveyors. But it was rare for such methods to be translated into Latin (a manual on Geometry, the eleventh century *Geometria incerti auctoris* is a rare exception), and such techniques appear to have percolated only slowly into the rest of Europe. Increased awareness and use of such techniques in Spain may be attested by the medieval Jacob's staff, used specifically for measuring angles, which dates from about 1300; and the appearance of accurately surveyed coastlines in the Portolan charts, the earliest of which that survives is dated 1296.

### **Gemma Frisius and triangulation for mapmaking**

On land, the Dutch cartographer Gemma Frisius proposed using triangulation to accurately position far-away places for map-making in his 1533 pamphlet *Libellus de Locorum describendorum ratione* (*Booklet concerning a way of describing places*), which he bound in as an appendix in a new edition of Peter Apian's best-selling 1524 *Cosmographica*. This became very influential, and the technique spread across Germany, Austria and the Netherlands. The astronomer Tycho Brahe applied the method in Scandinavia, completing a detailed triangulation in 1579 of the island of Hven, where his observatory was based, with reference to key landmarks on both sides of the Øresund, producing an estate plan of the island in 1584. In England Frisius's method was included in the growing number of books on surveying which appeared from the middle of the century onwards, including William Cunningham's *Cosmographical Glasse* (1559), Valentine Leigh's *Treatise of Measuring All Kinds of Lands* (1562), William Bourne's *Rules of Navigation* (1571), Thomas Digges's *Geometrical Practise named Pantometria* (1571), and John Norden's *Surveyor's Dialogue* (1607). It has been suggested that Christopher Saxton may have used rough-and-ready triangulation to place features in his county maps of the 1570s; but others suppose that, having obtained rough bearings to features from key vantage points, he may have estimated the distances to them simply by guesswork.

### **Willebrord Snell and modern triangulation networks**

The modern systematic use of triangulation networks stems from the work of the Dutch mathematician Willebrord Snell, who in 1615 surveyed the distance from Alkmaar to Bergen op Zoom, approximately 70 miles (110 kilometres), using a chain of quadrangles

containing 33 triangles in all. The two towns were separated by one degree on the meridian, so from his measurement he was able to calculate a value for the circumference of the earth – a feat celebrated in the title of his book *Eratosthenes Batavus (The Dutch Eratosthenes)*, published in 1617. Snell calculated how the planar formulae could be corrected to allow for the curvature of the earth. He also showed how to resection, or calculate, the position of a point inside a triangle using the angles cast between the vertices at the unknown point. These could be measured much more accurately than bearings of the vertices, which depended on a compass. This established the key idea of surveying a large-scale primary network of control points first, and then locating secondary subsidiary points later, within that primary network.

Snell's methods were taken up by Jean Picard who in 1669–70 surveyed one degree of latitude along the Paris Meridian using a chain of thirteen triangles stretching north from Paris to the clocktower of Sourdon, near Amiens. Thanks to improvements in instruments and accuracy, Picard's is rated as the first reasonably accurate measurement of the radius of the earth. Over the next century this work was extended most notably by the Cassini family: between 1683 and 1718 Jean-Dominique Cassini and his son Jacques Cassini surveyed the whole of the Paris meridian from Dunkirk to Perpignan; and between 1733 and 1740 Jacques and his son César Cassini undertook the first triangulation of the whole country, including a re-surveying of the meridian arc, leading to the publication in 1745 of the first map of France constructed on rigorous principles.

Triangulation methods were by now well established for local mapmaking, but it was only towards the end of the 18th century that other countries began to establish detailed triangulation network surveys to map whole countries. The Principal Triangulation of Great Britain was begun by the Ordnance Survey in 1783, though not completed until 1853; and the Great Trigonometric Survey of India, which ultimately named and mapped Mount Everest and the other Himalayan peaks, was begun in 1801. For the Napoleonic French state, the French triangulation was extended by Jean Joseph Tranchot into the German Rhineland from 1801, subsequently completed after 1815 by the Prussian general Karl von Müffling. Meanwhile, the famous mathematician Carl Friedrich Gauss was entrusted from 1821 to 1825 with the triangulation of the kingdom of Hanover, for which he developed the method of least squares to find the best fit solution for problems of large systems of simultaneous equations given more real-world measurements than unknowns.

Today, large-scale triangulation networks for positioning have largely been superseded by the Global navigation satellite systems established since the 1980s. But many of the control points for the earlier surveys still survive as valued historical features in the landscape, such as the concrete triangulation pillars set up for retriangulation of Great Britain (1936–1962), or the triangulation points set up for the Struve Geodetic Arc (1816–1855), now scheduled as a UNESCO World Heritage Site.