Fritz Deumlich
Surveying Instruments

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Surveying Instruments

Fritz Deumlich

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Preface

Surveying instruments are the "tools" of surveyors, engineers and geodesists. Solid knowledge of their design, function and operation enable them to select and to effectively utilize and handle the proper instrument for their measurements. It is therefore indispensible for them to study surveying instruments.

Like many of my colleagues involved in teaching surveying. I have been painfully aware of the need for a comprehensive treatment in the English language. Although certain common instrument types are adequately covered in a number of books, these are generally written for different purposes, and thus do not offer the deep understanding of the instruments, which is needed if one is to fully comprehend the factors behind certain field procedures and measuring accuracies.

Having appreciated Prof. *Deumlich's* book as information source and reference, and having occasionally translated the odd section to a graduate student. I whole-heartedly agreed to translate the new edition when approached by the publisher.

Prof. *Deumlich's* book was first published in 1957 and has been thoroughly revised and updated in 1963, 1967, 1972 and 1974. This new 7th edition provides up-to-date and complete information on surveying instrumentation on a wordwide scale. After short remarks on purpose and classification of surveying instruments, and a sketch of their historical development, emphasis is placed on the design of surveying instruments, standardization as well as further developments and the treatment of instruments. As a basis for subsequent sections, optical elements and spirit levels are discussed.

Presently produced instruments are covered in detail, starting with instruments for horizontal angles. For instruments like compasses or rectangle prisms, the coverage reflects their practical importance, while the theodolite as most important instrument of this category receives prime treatment. The most modern developments in automation for circle readings are high-lighted. This section is rounded out by presentations of gyroinstruments, optical precision plummets, and alignments, especially the ones using laser.

Although simple instruments are mentioned, levelling instruments are central to the section on instruments for measuring elevations and elevation differences. The different types of automatic levels and their design receive special attention. When dealing with instruments to measure vertical angles, the respective device of the theodolite is prosented, especially the development of the automatic height index. An overview of instruments for barometric levelling as used in remote areas is also given.

In view of modern developments regarding instruments to measure distances, the treatment of mechanical and optical instruments has been shortened as to provide better coverage to electronic distance meters, which are the most modern and efficient instruments for that purpose.

The closing section deals with the various types of stadia- and tacheometer instruments. Here again, the treatment of optical instruments has been shortened in favour of electronic tacheometers which presently represent the most "complete" surveying instruments.

Although many instruments are listed, the emphasis is placed on instrument types and design concepts rather than particular units. Similarly, methods of instrument testing are not intended to be rigidly adhered to like book recipes, but rather as guides to inspire the user. Some instruments, which conceivably could have been treated in the historical section, are included because they are in practical use.

Numerous instructive illustrations simplify studying of the book. Tables with technical data of instruments produced in countries all over the world provide a complete overview for the respective instrument type.

In recognition of Prof. *Deumlich's* accomplishments I have tried to retain his style and form of presentation as much as possible. Without distracting from the main topics, this provides the reader with the additional advantage of discovering—quasi between the lines—European approaches to surveying problems thus offering alternatives to his own way of thinking. Lie may—in places—find an unfamiliar term, e.g. angular units in "gons" as well as in the familiar "degrees", or "metres" instead of "feet", but then again, he has to cope with this in practice as well.

With its comprehensive treatment of all surveying instruments, this book should be welcomed by the surveying community and serve as a reference for professionals and para professionals, as well as a text for students. It is my privilege to have been able to make a small contribution to the English speaking surveying profession in helping to make this book available.

On behalf of Prof. *Deumlich*, I would like to thank all the companies, agencies and colleagues who have contributed to this book by generously supporting him with materials, illustrations and advise.

Fredericton

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Contents

Introduction

I. Purpose and Classification of Surveying Instruments

Good knowledge of surveying instruments enables the professional surveyor to select the most suitable instrument for his measurements, to operate it correctly and to utilize it efficiently. This requires not only sufficient theoretical knowledge of structure and function of the instruments, but also practical experience in handling and use.

The surveying instruments discussed here are used for surveying of terrain or objects with the aid of selected points for numerical or cartographic representation. According to their purpose, different types of instruments are being distinguished.

For the determination of the horizontal projection of points, instruments are used which measure directions or horizontal distances. Furthermore, instruments to determine the position of a point along the plumbline are available.

For the determination of heights, instruments to measure elevations and elevation differences are utilized.

In many cases position and height of points are needed. Tacheometric instruments are then used for simultaneous determination of both.

The characteristics mentioned indicate the main purpose for the instruments. Points which are referred to a horizontal plane can be determined via orthogonal or polar coordinates. The necessary distance measurement can be done directly or indirectly (e.g. optically or electronically).

The main sections of this book are arranged according to these groups. This arrangement based on purpose is further subdivided according to the capabilities of the instruments. Low accuracy instruments are simple and are used for simple technical measurements, e.g. on construction sites.

Instruments of medium and high precision are used for triangulation, traversing and levelling, to densify control nets, and for engineering surveys.

Precision instruments are required for astro-geodetic measurements like azimuth, latitude and time determinations, for triangulation and 1st and 2nd order levelling, as well as occasionally for engineering surveys.

Every instrument designed to measure some quantity has errors which affect the results. In order to obtain results free of the influences of instrument errors, one can deal with it as follows:

a) the error is adjusted at the instrument such that its influence can be considered negligible for a specific purpose of the measurement.

b) one can select a surveying method which yields results free of the influence of the instrument error.

c) the magnitude of the instrument error is determined and its influence is compensated by some corrections.

Depending on the required accuracy one or more of these possibilities can be used. The modern instruments are usually produced with such high precision that adjustments are seldom needed.

II. History of Surveying Instruments

The oldest surveying instruments served to determine distance when erecting shelter, diverting water, staking fields and determining their area. The construction of roads, canals, and buildings of art as well as developing war geometry indicate the use of more complete instruments, while later surveys for mapping and the origins of geodetic measurements point to further improvements. While the oldest instruments (for distances, plumb bob, set

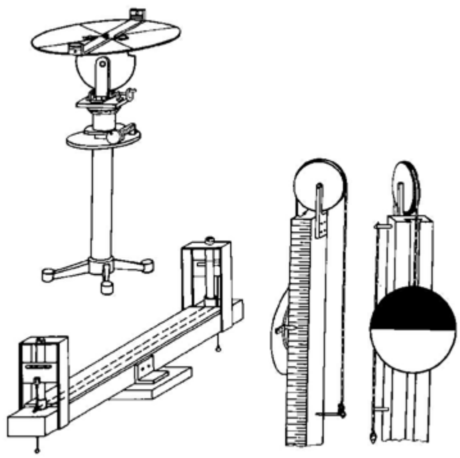


Figure 1 Dioptra (dioptra on tripod; sighting ruler for levelling; 4 yard long hydrostatic level; shifting rod for dioptra)

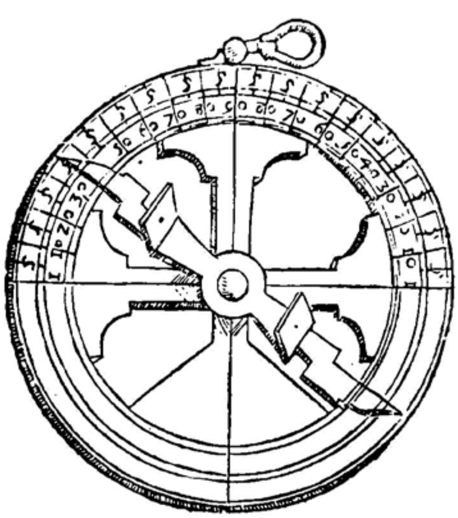


Figure 2 Astrolabe

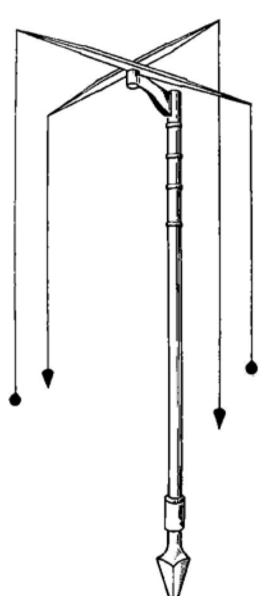


Figure 3 Reconstruction of a Groma from Pompeji

square) are of surveying origin, others, especially instruments to measure angles, were taken from the field of astronomy.

Early surveying instruments have been established in Sumaria, Babylonia, Chaldea, Egypt, China and India. Around 3000 B.C. rulers, measuring ropes and rods were known in Babylonia and Egypt. Similar instruments were used in China around 1100 B.C. Plumb bob and spirit level were utilized by the Sumarians, Egyptians and Chinese. The set square was known to the Egyptians, the magnetic compass to the Chinese. The accuracy of surveys at that time was quite high, for instance for levelling in Egypt ± 8 cm/200 m. The knowledge of the Asiatic and Egyptian people was enhanced by the Greeks. The scientists of these times were often not only distinguished mathematicians or surveyors, but also excellent mechanics and designers. Around 560 B.C. *Anaximander* introduced in Greece, the "Gnomon" (shadow square) which probably was already known to Babylonians and Egyptians. It was used by *Meton* around 440 B.C. to determine the north direction and around 200 B.C. by *Erathostenes* to determine the circumference of the earth. Around 100 B.C. *Heron* from Alexandria wrote his volume "about the Dioptra", collecting material from his predecessors as well as expanding it himself. For nearly 2000 years, this book remained the best text on practical surveying. The dioptra served as cross staff with diopter ruler (figure 1). Its main part was a simple water levelling device consisting of a U-shaped pipe which could be rotated around a vertical axis. The appropriate levelling rod had a movable target. *Heron* also mentioned the design of an automatic distance meter, which determines the distances from revolutions of a wheel.

Ptolemäus was the first to describe the quadrant as used for astronomical observations. Its name was derived from a quarter circle (radius up to 3 m) plotted on a plate. For vertical angles the Ptolemäus rulers, (approx. 150 B.C.) made from tangent – and chord rulers was used until the Middle Ages. The Greek scientist *Hipparch* is considered to be the inventor of the astrolabe (approx. 150 B.C.), a circular disc of 10 to 20 cm diameter with degree graduation hanging on a small ring (figure 2). This forerunner of the theodolite was originally an astronomical device.

Although the Romans added little to the Hellenistic instruments, they spread the Greco-Roman knowledge to Central Europe. Besides measuring rods for distances, the surveyor's cross "Groma" was the most important instrument of the Roman land surveyors, the Agrimensores. The groma is a cross fastened eccentrically on a wooden staff with plumb bobs (later diopters) for aiming (figure 3). *Vitruvius* (approx. 15 B.C.) mentiones besides the Dioptra the Chorobates (figure 4), which is an approximately 2 meter long spirit level and was probably known to the Greeks. He also mentions carts with counters for distance measurements. Large distances were also determined by pacing. Pace counters (Bematists), whose paces were "calibrated" could be found in most army units.

In Europe, scientific development was hindered for thousand years by the church. The Arabs, however, who penetrated into France, had a high level of astronomic-geodetic knowledge. They took over the geometric knowledge from the Greeks and had astrolabes divided to 5 minutes of arc. Usbeke *Biruni* (973–1048) designed the prototype of a circle graduation machine. After the Arab Empire collapsed, the knowledge continued in the Schools of Baghdad, France and Spain and influenced the Europe of the Middle Ages, which previously only had contact with the remains of Roman land surveying.

Geographic discoveries, the expansion of shipping and world wide trading connected with it, increased the demand for maps and geodetic data. Growing productivity led to an uplift for arts and science. The new physical findings also influenced the development of surveying instruments. Even towards the end of the Middle Ages, instruments known for ages, perhaps slightly improved, were still used in Europe, e.g. measuring strings and rods for distances, cross staffs with diopters for staking right angles, horizontal straight edges and open water levelling devices for elevations as well as astrolabes and quadrants for angles. Around 1300, the Jacob staff (figure 5), a device for indirect distance – and angular measurement appeared and was first described by the Arab *Levi ben Gerson* (1288–1344). Here the parallactic angle was obtained by moving a lateral rod along the main rod until its ends appeared to coincide with the end points of the line to be measured. Then the angle was read on the graduation of the main rod.

Leonardo da Vinci (1452–1529) designed carts with distance meters, even a pace counter. The French doctor *Fernel* (1497–1558) measured distances with a measuring wheel attached to his coach for geodetic degree measure-

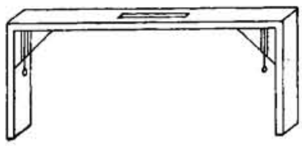


Figure 4 Chorobates (Reconstruction)

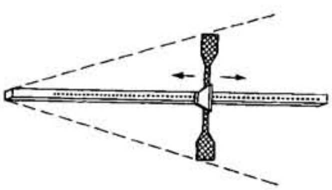


Figure 5 Jacob staff

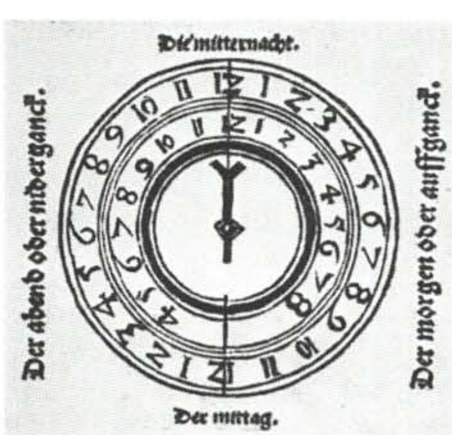
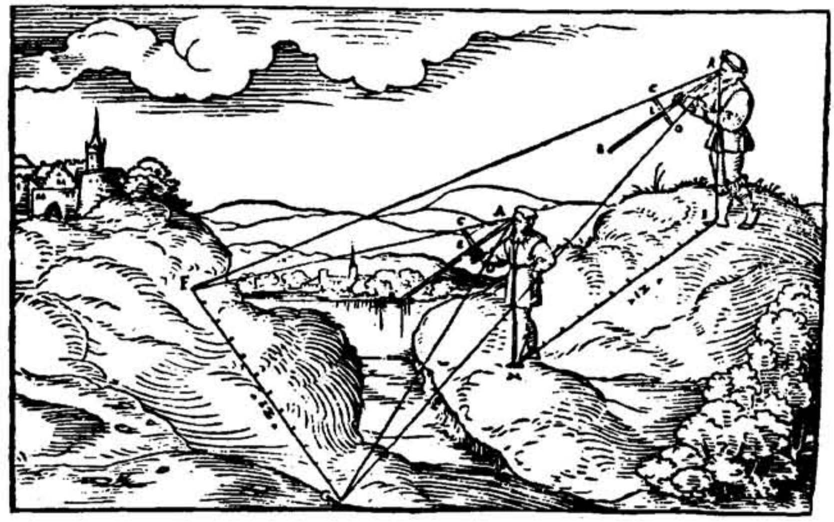


Figure 6 Compass of *Rülein* (1505)

ments in 1525. One geographic degree represented 17,024 revolutions. He used a quadrant to determine the latitude. Mapping of the countries created a boom for the builders of cart-distance meters. Directions were usually measured with a compass.



Such compasses were specially designed for surveying purposes, and most likely came from China to the Arabs. It is a fact, that Chinese ships were equipped with magnetic compasses 100 years prior to their use in the Western World. In 1187 the Scotch monk *Alexander Neckham* mentions a compass. *Petrus Peregrimus*, probably of Norman origin, who in 1269 was suited up with the Duke of Anjou, first described the wet and dry compasses. In these times the housing was made from boxtree wood (figure 6) from which its name in several languages is derived (e.g. German "Bussole" or French "Boussole"). In Italy the versatile *Leonardo da Vinci* sketched around 1500 a compass in a circular housing. In 1650 the compass theodolite was developed, and in 1812 the mechanic *Schmalcalder* invented the prism compass which carries his name.

Around 1530 the surveyor's chain, the predecessor of the tape, was first utilized in the Netherlands. Around 1550 tripods appeared, and around 1600 devices to measure horizontal angles were developed from astrolabes (figure 7). The Englishman *Digges* described such a device in 1552 and used for the first time the term theodolite. The universal instrument by *Josua Habermel*, a device based on the theodolite principle with compass was built in 1576 in Germany.

It is believed that the Dutch astronomer *Gemma Frisius* (1508–1555) invented the plane table. It became wider known through the German professor *Johann Praetorius* (1537–1616). Instead of an alidade, a diopter ruler (figure 8) was used in that period. Important inventions lead to significant improvements of surveying instruments at the beginning of the 17th century. The construction of the first telescope in 1608 is attributed to the Dutch eye glass maker *Hans Lipperhey* (1560–1619). Apparently, the Italian physicist and mathematician *Galileo Galilei* (1564–1642) heard of it and build in 1609 an improved version of the same telescope, which is called Dutch or Galilei telescope. It did not gain much significance in surveying, since it cannot be fitted with a cross hair. In 1611 *Johannes Kepler* (1571 to 1630) presented the lens arrangement for the astronomic or Kepler telescope, which was first built by the Suabian Jesuit Father *Christoph Scheiner* (1575–1650). The terrestrial telescope with inverted lens also comes from *Kepler* in 1611.

Generini introduced around 1630, the aiming telescope with ocular diopter. The English astronomer *William Gascoigne* (1620–1644), who in 1640 invented the screw micrometer, fitted cross hairs into the focal plane of the telescope of his height quadrant. After these improvements, the aiming telescope slowly started to displace the up to then dominant diopter devices. In 1670 for instance, the French astronomer *Picard* (1620–1682) used a quadrant for his degree measurements, whose telescope had crosshairs for aiming (figure 9).

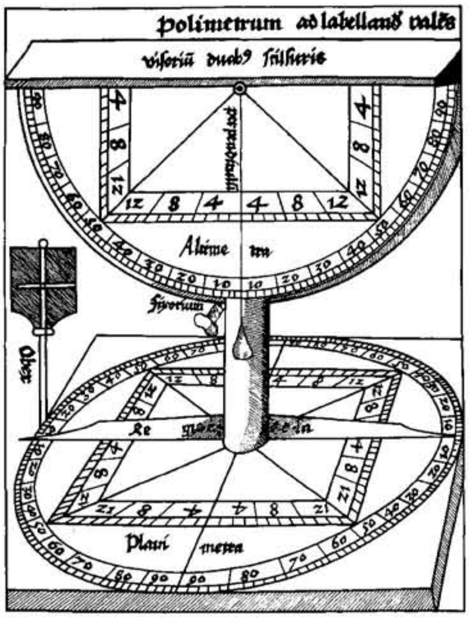


Figure 7 Polimetrum—the first European fore-runner of the theodolite (1512)

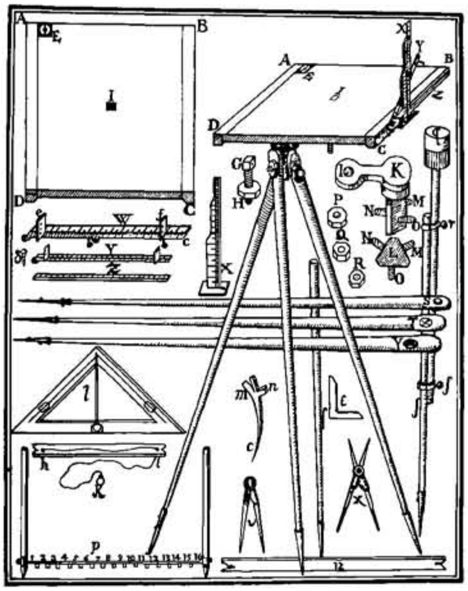


Figure 8 Plane table equipment designed by *Praetorius*

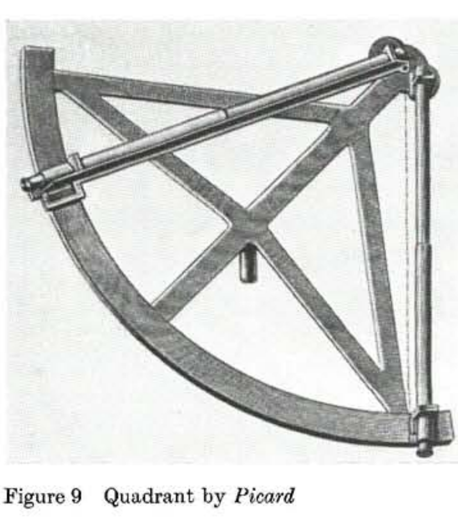


Figure 9 Quadrant by *Picard*

For astronomical purposes *Tobias Mayer* (1723–1762), Professor and director of the observatory in Göttingen, did not use real threads in micrometers but instead drew lines on glass in 1748. The mechanic and instrument builder *Georg Friedrich Brander* (1713–1783) from Augsburg scribed with diamonds fine lines into the glass.

Magnification of the telescopes built in the 17th century was small (9 to 30 times). With the invention of the achromatic objective lens in 1729 by the English lawyer *Moor Hall* (1704–1771) and its introduction by *John Dollond* in 1758 as well as improvements in glass techniques by *Louis Guinand* and *Fraunhofer*, further improvements were possible. *Josef Fraunhofer* (1787–1826) put the production of optical instruments onto a scientific base. Instead of the experimentations of the tradesmen, he utilized optical calculations. He also was a pioneer in the precise mechanical production of instruments. The Italian Major *Ignazio Porro* (1801–1875) became known for his inverted prism systems (1850), the Porro telescope (1823), his self reducing tacheometer (1858) and others.

The oldest aid to refine readings is probably the principle of transverse graduation, used around 1300 by *Levi ben Gerson* and by the Danish astronomer *Tycho Brahe* (1546–1601) for his quadrant. In 1542 the Portuguese *Pedro Nuñez* (1492–1577) suggested a reading device for a quadrant. Each of 46 concentric circles was divided into $(n - 1)$ parts of the previous one so that the radius as index in any position nearly coincided with a gradual mark of one of the circles. The "vernier" principle, which is still used was invented by the mathematician *Clavius* in 1593. However, he used the device for setting out and not for measuring angles and distances. Later the Dutch *Peter Werner* (*Pierre Vernier*, 1580–1637) used in 1631 the "vernier" in its presently used form.

In 1629 *G. Branca* developed in Rome the hydrostatic level. However, it took until 1849 when *Geiger* from Stuttgart utilized rubber hoses, that it gained practical importance. This hydrostatic level superseeded the earlier levelling device with U-pipe and water, even though the latter was developed as a hand held instrument by *Bolz* and by *Kahle* in the middle of the 19th century.

In order to level the line of sight of his telescope used for trigonometric height measurements, *Picard* used in 1674 a pendulum with 1.30 m length. Already the Romans had used a pendulum for levelling purposes, and so did *Huygens*. The development of levels as well as all other devices for levelling of geodetic instruments was significantly influenced by the invention of the tubular bubble in 1662 by the Parisian mechanic *Thévenot* (1620–1692). *Mallet's* reports (Paris, 1702) indicate, that the levels of that time already were equipped with eyepiece slide, tilting screw and adjustment devices. In Germany, the tubular bubble was first mentioned by *L. Christoph Sturm* in 1715.

Only towards the end of the 18th century it reached a practically suitable shape. *Amsler-Laffon* built in 1857 the first level with a reversible bubble. The tilting screw was named after the Karlsruhe fine mechanic *Sickler* (figure 10). In 1770, *Johann Mayer* of Göttingen invented the bull's eye level used for approximate levelling of instruments. In 1904 *Mollenkopf* produced the whole body of the level bubble of glass to avoid evaporation of the liquid.

The English mechanic *John Sisson* built in 1730 the first theodolite. Up to the end of the 18th century it was improved in England by *James Short*, *Adams*, and especially by *Jesse Ramsden* (1735–1800), who invented a microscope with screw micrometers for circle readings as well as in 1783 an eye piece, named after him.

The Dutch physicist *Christian Huygens* (1629–1695) had designed an eyepiece in 1684. From the Ramsden eyepiece the mechanic *Kellner* from Wetzlar developed in 1849 a three-lens eyepiece. In the 20th century, eyepieces with large apparent field of view appeared.

In 1763 *Ramsden* built the first circle graduation machine in England. A predecessor of this machine was produced by *Hidley* in 1760 in York. In 1684 *Hooke* had introduced a semi automatic method of circle graduation. In 1803 *Reichenbach* built a circle graduation machine based on the copy method whose principle is still in use today. Towards the end of the 19th century *Heyde* introduced the globoid spiral.

In 1785 the French astronomer *Borda* (1733–1799) introduced a new axial system. *Reichenbach* (1804), with his repetition theodolite, utilized another one (figure 11), and the mechanic *Repsold* from Hamburg used yet another one around 1830. In order to achieve forced centering, *Breithaupt* utilized

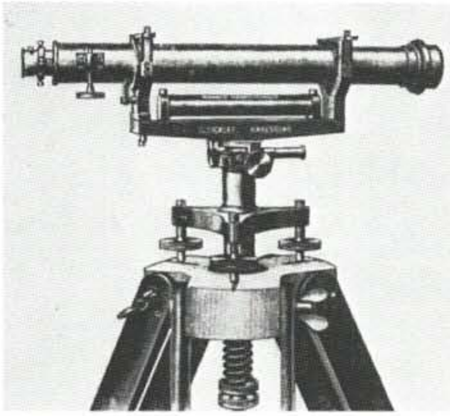


Figure 10 Level (19th century)

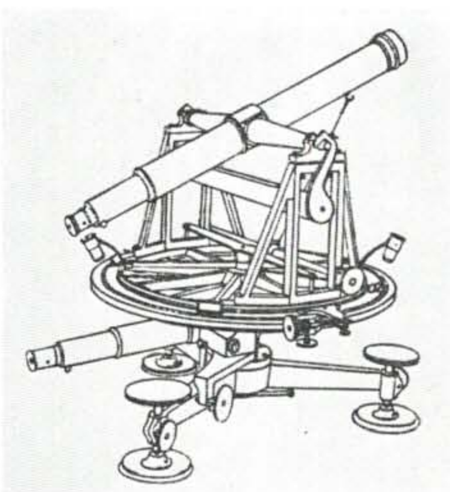


Figure 11 Reichenbach's precision theodolite (with circle diameter of 12 Parisian inches)

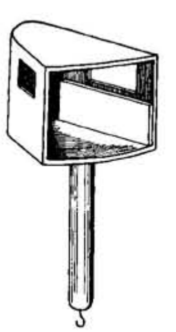


Figure 12 Optical Square

in 1840 a socket arrangement and *Hildebrand* in 1876 the Freiberg sphere. Only after World War I, forced centering started to be used in surveying practice, especially for precise traversing in urban areas.
Hildebrand published in 1878 – based on *Nagel's* notes from 1873 – the first optical plumbing instrument with a central telescope. Since approximately 1960, optical precision plummets are produced, and used primarily in construction surveys.
Around 1740, the London mechanic *Adams* (1720–1773) built an optical square (figure 12), while the double optical square was described in 1844 by *Berlin*. The three sided right angle prism, discovered in 1851 by the Munich Professor *Bauernfeind* eventually superseded the mirror instruments. *Prandtl* introduced in 1890 the pentagon prism, mentioned by *Goulier* in 1864, into the surveying field. Since 1924, the totally reflecting prism, mentioned in 1812 by the English physicist *Wollaston* (1766–1828) is used in two prism squares.
The mercury barometer, used for barometric levelling was invented in 1638 by *Galilei* and *Torricelli*, and practically used by *Pascal* ten years later. Through improvements, especially by the French physicist *Gay-Lussac*, the siphon barometer was created around 1800. In 1847, the French *Lucien Vidi* (1805–1866) invented the aneroid barometer, which now is mainly used in the field. Probably it was first built by *Naudet* and later perfected by *Bourdon*.
Geminiano Montanari carried out the first optical distance measurements in 1674 in Italy using 12 to 15 parallel and equidistant crosshairs in his telescope. The steam engine producer *James Watt* built in 1771 an optical distance meter with two horizontal and one vertical crosshair. The optician *William Green* described in 1778 a similar one. From 1812 on however, optical distance measurements gained widespread use, starting with cadastral surveys in Bavaria by *Georg von Reichenbach* (1771–1826) who in 1810 added stadia hairs to his alidade.
In 1823 *Porro* moved the vertex of the parallactic angle into the vertical axis with the aid of placing a positive lens into the optical path. From 1839 on he calls his instruments tacheometer and thus introduces the term tacheometry. The increasing demand for topographic maps and plans for design and construction of extended structures, such as railroads and canals, contributed to the distribution of optical distance meters, especially in Italy, France, Germany and Austria.
In 1800 the engineer-Colonel *Hogrewe* invented in Hannover the tangent screw which he used as clinometer when levelling. *Stampfer* introduced in 1839 in Austria the chord screw for optical distance measurement, which is based on the tangent principle. This tangent principle which is used for screw distance meters led to tangent – and contact tacheometers. With these instruments horizontal distances and elevation differences could automatically be obtained with the aid of reduction devices rather than by subsequent calculations. The French *Sanguet* constructed in 1866 the first contact tacheometer with vertical scale (figure 13) which sold to several thousand in France, Italy and Switzerland. In *Charnot's* tacheometer (1889) the contact device was horizontal. In 1898 the Max Hildebrand Company in Freiberg produced an instrument with horizontal scale according to *Vogler's* design. Further known are the instruments by *Doergens* (1900) and the one designed by the French engineer *Balu* in 1912 which was produced by Kern, Aarau. In France, contact tacheometer are still used and produced. *Eckhold's* omnimeter (1868), a tangent tacheometer with horizontal scale was widely spread in England and her colonies. In Hungary and England the tangent tacheometer designed by *Szepessy*, produced by Süss, Budapest was used in practice. A further development of this graduation in the field of view (by *Bors*) was used by MOM, Budapest in 1956 for their alidade MF, while in 1954 Filotecnica Salmoiraghi in Milano produced the tangent tacheometer Tari.

At about the same time as the contact tacheometers, shift – or projection tacheometers appeared, which are especially suitable for plane table work. Its predecessor of this type was already built by *G. F. Brander* in 1780. In 1865, the surveyor *Kiefer* from Cologne suggested the construction of a shift tacheometer, and Breithaupt built it in 1873. The best known one is the Tachygraphometer by *Wagner*, using a tilted rod built in 1867 by Fennel in Kassel and known as Wagner-Fennel shift tacheometer (figure 14). In 1873 Ertel in Munich built *Kreuter's* design. *Peaucellier* and *Wagner* designed in France a shift tacheometer as alidade with a circular plotting table, called Homolograph. In 1878 Kraft & Son, Vienna produced *Stern's* tacheo-

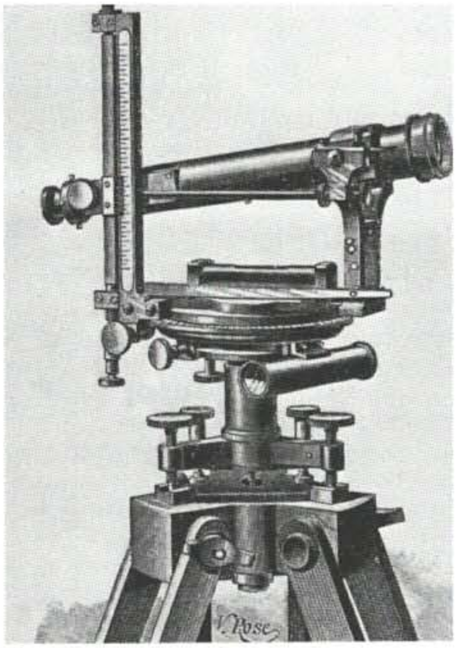


Figure 13 Contact tacheometer by *Sanguet*

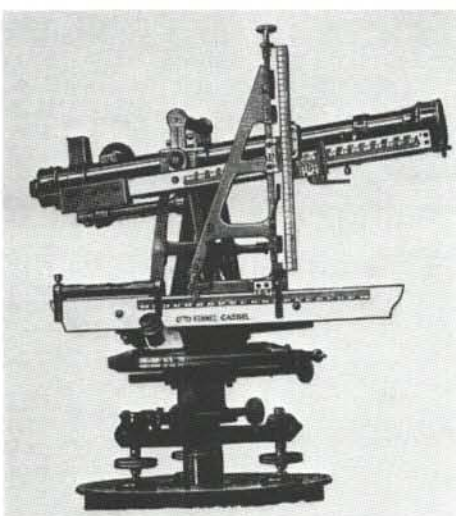


Figure 14 Shift tacheometer by *Wagner-Fennel*

meter with a vertical rod. *Puller* introduced a new projection principle with vertical rod, which was utilized in an instrument built by Breithaupt, Kassel in 1901 and used until about 1930.
A diagram tacheometer as alidade with computation sector according to *Soldati* was produced in 1900 in Italy by Salmoiraghi. An instrument of this type is the tacheometer with Ewing-Esdaile-curve drum built by Hilger & Watts, London in 1954, based on an invention by *J. A. Ewing*, Australia (figure 15).

Figure 15 Ewing distance- and height meter attached to Watts theodolite

In 1878 the Austrian forester *A. Tichy* developed logarithmic tacheometry. His first instrument with an eye piece micrometer was built by *Starke*, Vienna in 1884, another with an optical part in 1890 by *Ott*. This method became interesting again in 1955 with the Lotakeil (logarithmic tacheometer wedge) by Carl Zeiss, Jena, did however, not make an impact (figure 16). Several ideas to obtain automatic reduction by changing the focal length (*Porro* 1858) or the distance between the crosshairs (*Jeffcott* 1912 with Cooke, Troughton & Simms, London; *G. Heyde* 1934) have not gained practical acceptance. Only recently the monitoring device could be produced with the required accuracy of 1 μm (DK-RV by *Conzett* and *Hinden* 1955, and Kl-RA 1963, both produced by Kern, Aarau).
The optical monitoring of the crosshair separation gained great importance. The basis for the development of diagram tacheometers was the plan of the Italian engineers *Roncagli* and *Urbani* in 1890 to use two pairs of distance lines instead of fixed crosshairs in the tacheometer. These line pairs were to be edged into a glassplate located horizontally in the image plane of the telescope and which could be shifted normal to the line of sight (figure 17).
Professor *von Hammer* (1858–1925) from Stuttgart developed with this a diagram with distance curve and added a two branch height curve. Instead of the straight zeroline, *Fennel* used a circular arc as base line for the diagram. He produced in 1900 the first diagram tacheometers, utilizing the principle of the "anallactic telescope" according to *Porro* (figure 18). Subsequently, newer improved models of the Hammer-Fennel-Tacheometer appeared.
This Hammer-Fennel principle was further developed by Carl Zeiss, Jena with the Dahlta, based on a patent of the Norwegian *Dahl* (prototype 1932, in series 1942). A principle reported by the Swiss Canton surveyor *Leemann* in 1930 was realized with an alidade in 1936, the tacheometer DKR in 1939, the DKRM in 1946, and the alidade RK all produced by Kern, Aarau in 1951.
In 1953, the Fennel Company presented the Fenta with undivided field of view. Other further developments are the RDS from Wild, Heerbrugg (1951), the alidade RKl (1962), the TA-Dl from MOM, Budapest with *Bességh's* diagram (1959), the TA-2 from the Soviet Union (1959) and the RTa4 from

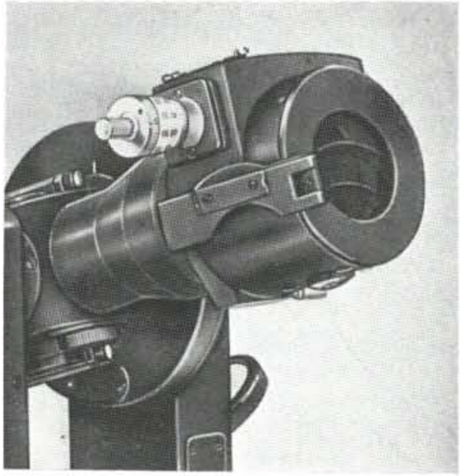


Figure 16 Lotakeil

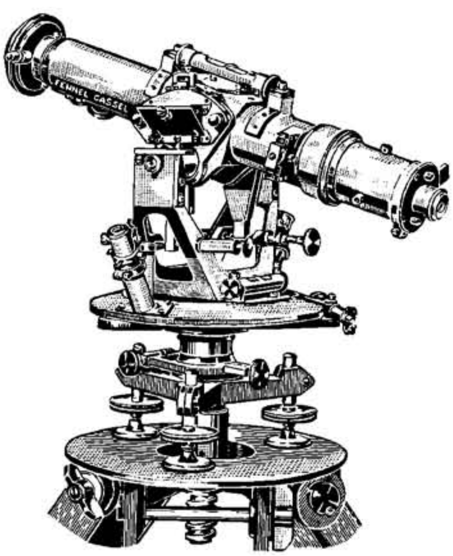


Figure 18 The first Hammer-Fennel tacheometer

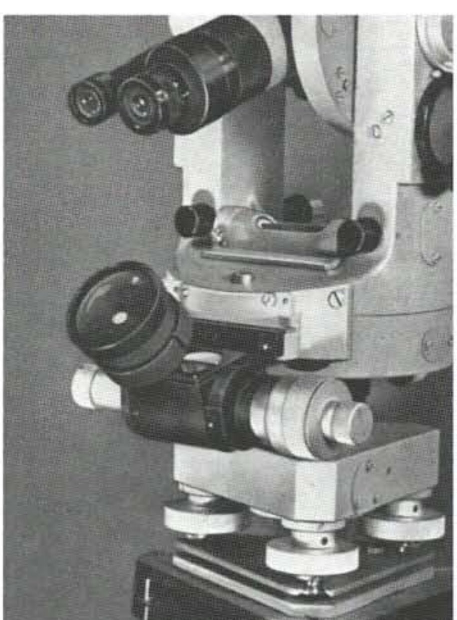


Figure 19 Tangent Screw at the Zeiss IV theodolite (about 1930)

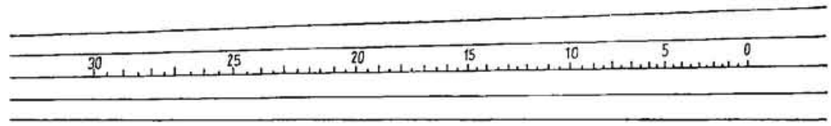


Figure 17 Stadia hairs by *Roncagli* and *Urbani*

Carl Zeiss, Oberkochen (1967). Since 1904 the diagrams are used accordingly for self reducing alidades.

Towards the end of the 19th century numerous range finders appeared. Their base was at the station, thus requiring no rod at the target. *Brander* built in 1781 a one station range finder with mirrors at the ends of a cross pipe. The images created by two objectives are made to coincide in the field of view of the common eyepiece, and onto a vertical line (coincidence telemeter). In 1790, *Ramsden* presented a half-image range finder. Since 1888 the English company Barr & Stroud builds half image range finders. Later Carl Zeiss, Jena, and C. P. Goerz, Berlin-Friedenau built them too.

The first stereo range finder (stereo telemeter) originated from *Pulfrich* (1858–1927) at Carl Zeiss, Jena in 1899 according to a patent by *Grousilliers* (1893). These range finders gained only little importance in surveying. Even the stereotachygraphs, especially designed for surveying purposes by *Hugershoff* in 1931/32 and produced by Heyde in Dresden could not gain practical acceptance. Only the teletop, built since 1937 by Carl Zeiss, Jena according to *Eppenstein's* design, is still being produced. Other range finders for surveying purposes are produced by Breithaupt & Son, Kassel (Todis, 1952), Wild, Heerbrugg (TM 10, 1959), Hilger & Watts, London, and Works of the Soviet Union (DWT, 1965).

Since about 1880, wooden subtense bars were used. In 1906, *Pulfrich* at Carl Zeiss, Jena used for the first time a subtense bar made of a steel pipe, in connection with a phototheodolite with tangent screw (figure 19). Optical distance measurement with subtense bar gained importance after the production of Pulfrich's distance measuring theodolite (1921) and the invar subtense bar (1923) at Carl Zeiss, Jena, and a 2 m invar subtense bar together with a one second theodolite which is the present standard equipment from Wild, Heerbrugg built since 1969.

Development has been at a rapid pace. In former times the various instrument types were large and heavy and therefore awkward for use and transportation, the telescope was very long, the rough circle reading had to be refined by special methods (figure 20).

In the last decades it was the aim of the instrument manufacturers to make the instruments more handy, smaller and lighter. Furthermore, the reading accuracy had to be increased to fully utilize the optics. Circle readings should be simple and fast, possibly right near the eye piece of the telescope, and both horizontal and vertical circles should be visible at the same time. Sensitive instrument parts should be protected against damage, dust, and humidity.

The Swiss *Heinrich Wild* (1877–1951), who in 1908 as collaborator of Carl Zeiss, Jena introduced interior focussing, earned great merit in modernizing surveying instruments. While the first levels with interior focussing had a positive focussing lens, *Wild* switched later to the negative lens as presently used, and thus could reduce the length of the telescope. He also designed cylindrical axes, split level bubbles, plane parallel micrometer and invar rod – all integral parts of modern surveying instruments. The parallel plate micrometer can be traced to *Clausen* (1841), and *Porro* used it already in 1854 for the micrometer microscopes of his theodolites. In 1918 *Wild* discovered the optical coincidence micrometer with parallel plates, and in 1922 Carl Zeiss, Jena produced the first optical theodolite (Th I) with the above mentioned modernizations (figure 21). Also of importance are the graduated glass circles, which for the first time were used in theodolites produced in series. In 1884 glass circles were built into a mining theodolite by *Josef* and *Jan Frič*, Prague. In 1936, *Smakula* at Carl Zeiss, Jena was successful in improving optical glass by vaporization of a film in vacuum, which significantly reduces the light loss in optical systems, caused by reflection. Similar methods of improving optical glass were invented at other places at around the same time.

The following inventions contributed to simplifying circle readings: in 1879 *Hensoldt* reported on the scale microscope; in 1912 Fennel introduced the vernier microscope, Breithaupt utilized in 1925 *Heckmann's* combination

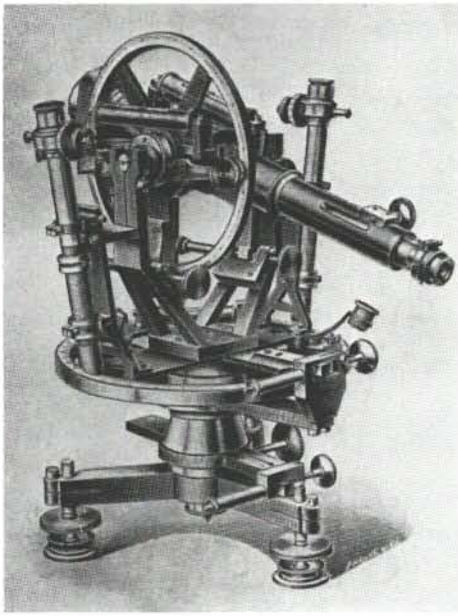


Figure 20 Theodolite with screw microscope (ɐbout 1900)

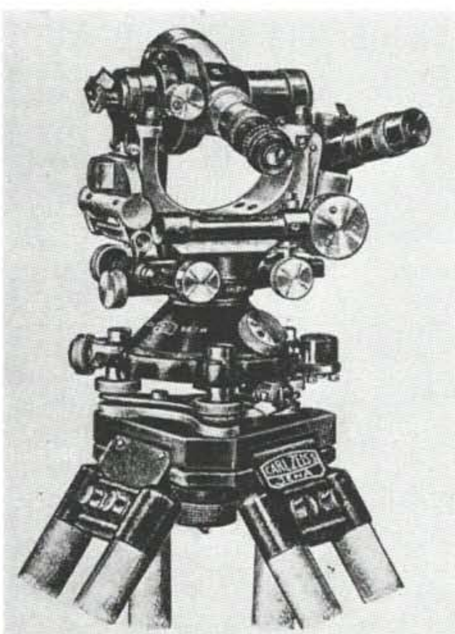


Figure 21 Th I—the first optical theodolite

microscope which is similar to it, and in 1920 Fennel introduced to plane glass microscope. Until 1964 Askania, Berlin equipped a microtheodolite with an inclined scale micrometer based on transverse graduation.

Further novelties from *H. Wild* reached practical importance with the DK-theodolites of Kern, Aarau, with levelling knobs instead of foot screws and ball bearing axes, disktype guidance surfaces (1937), and the mirror telescope which was used for the first time in surveying instruments in the DKM-3 (1939). Only for astronomical purposes, mirror telescopes had been used prior to that. Other types are mentioned by *Maxutow* in 1941 (utilized partly in the Russian TT 2/6), and the mirror telescope in *Cassegrain's* (1682) arrangement as computed by *H. Köhler* and utilized in the Theo 010 (figure 22) of Carl Zeiss, Jena.

Based on a suggestion by *Gigas*, the Askania Company added in 1942 to its 27 cm triangulation theodolite a device for photographic registration of the readings, in order to better take advantage of the most suitable measuring conditions. This later became the precision theodolite Tpr. Since 1950, Wild Heerbrugg produces the theodolite T3, and Carl Zeiss JENA the Theo 002 with photographic registration. Theodolite attachments for electro-optical rather than visual registration of illuminated targets ("electric eye", Askania, 1958) have not yet gained practical acceptance (figure 23).

In 1886 *Sanguet* invented a distance meter with an optical wedge in front of the whole objective lens. Two crosshair readings, with and without the wedge had to be taken. The Englishmen *A. Barr* and *W. Stroud* used in 1889 a wedge, which can be shifted inside the telescope (mentioned in 1777 ' y *Maskelyne*), and in 1890 a prism that can be snapped in front of the objective lens of the telescope. The American *Richards* used a measuring wedge in 1890 in connection with a vertical rod. From 1910 on *Oltay* produced in Budapest distance meters with a wedge in front of the whole objective lens, whose models were built in 1915 and 1922 by Süss, Budapest. Wild's design from 1921, features an attachment which can be fixed onto the objective lens of the theodolite, containing two achromatic glass wedges, operating in opposite directions and covering half of the lens each, as well as a parallel plate micrometer. A suggestion by the Swiss *Engi* in 1923 to place tacheometer and rod at the station and a pair of wedges with constant deflection at the target, was not picked up. On order to eliminate personal errors, Kern, Aarau placed the wedge attachment in the central strip of the objective lens, as suggested by *Aregger*. This arrangement is still common. Hildebrand, Freiberg produced in 1928 a theodolite attachment with Aregger-Wedge. At Fennel's distance meter, model 1929, the wedge covered the bottom half. Since 1931, Zeiss, Jena has been producing the wedge attachment "Dimess" with the *Aregger* arrangement (figure 24). Since 1942, Kern, Aarau produces the DM-M with parallel plate, and Wild, Heerbrugg a similar type wedge since 1949.

Uhink's design for Breithaupt & Son, Kassel (1929), using two mirror prisms in front of the telescope objective was no practical success, neither were the plumbing staff distance meter Lodis (1930) and Kipplodis (1932) by *Gröne*, both produced by Carl Zeiss, Jena (figure 25).

According to the literature, the French *Lugeol* was the first one in 1859 to utilize the heliometer principle, as described by *Bouguer* in 1752, for measuring terrestrial distances. *Belizyn*, in Russia used it in 1954 for the theodolite attachment DNB-2 to measure the varying parallactic angle to a fixed base. Also in Russia, *Greim* and *Tschurilowski* utilized wedges that can be shifted. In the Russian differential distance meters (1969), the parallactic angle is created with the aid of a lens compensator.

In the third decade of this century, the practical use of double image tacheometers started. These were predominantly equipped with rotational wedges (1777) according to *Bošković* (1711–1787).

In 1924 a prototype of these instruments was the product of the cooperation of the Swiss land surveyor *R. Bosshardt* (1884–1967) with Carl Zeiss, Jena (figure 26). Heyde, Dresden built in 1930 a three image tacheometer designed by *Hugershoff* with vertical rod and simultaneous reduction to horizontal distance. This instrument was no success, neither was one designed by *Barot* and produced by Wild, Heerbrugg in 1935. In this case, the interval is measured with a parallel plate, which is rotated by the amount of the angle of telescope inclination, via cog-wheels, and thus reduces the micrometer range. In 1947, Kern, Aarau introduced the DK-RT, and Wild, Heerbrugg in 1950 the RDH, which in addition provides elevation differences. In 1954 the reducing wedge attachment DR was built in series at Kern, Aarau, and in 1960 Carl Zeiss, Jena introduced the BRT 006 which has the base at the sta-

Figure 22 Theo 010 with mirror telescope

Figure 24 Wedge attachment Dimess

Figure 25 Plumbing staff distance meter "Kipplodis"

Figure 23 Electric eye on top of Askania theodolite

tion. In 1961, the DAR-100 for vertical rod with a wedge pendulum in front of the objective lens appeared in Russia.

Among the suggestions, which did not gain practical success are attempts by *Nestler* (1912) and the Swiss *Werffeli* to use the vernier principle for horizontal rods with wedge type graduation, as built in 1919 by Kern, Aarau, and the idea of the Dutch *Dieperink* (1920) to improve the measuring accuracy for distance measurements with stadia hairs, as well as in levelling by using a rod with transverse graduation. *Heckmann's* precision distance meter built by Breithaupt (1933) with a vertical, and a 1 : 10 inclined stadia hair for reading a horizontal rod with transverse graduations (figure 27) did also not become popular. Carl Zeiss, Jena accepted *Candidos'* suggestion in 1966 to refine the rod reading with small plate attachments.

In recent years, mechanization and automation of observation and evaluation processes for surveying instruments involves electronics as well as precision mechanics and optics.

For a long time, attempts have been made to automatically level the line of sight. The pendulum telescope of the Mining Academy in Clausthal built in 1790 is supposed to provide a standard deviation of 10 mm per kilometre. In 1878 *Couturier* designed a reflecting level with a cardanically suspended vertical telescope, which serves also as pendulum. The levelling errors of these pendulum instruments were however too large as to compete with spirit levels. Around the turn of the century the French *Claude* and *Drien-*

Figure 26 First Boßhardt-Zeiss reduction tacheometer

Figure 27 Rod graduations by *Heckmann*

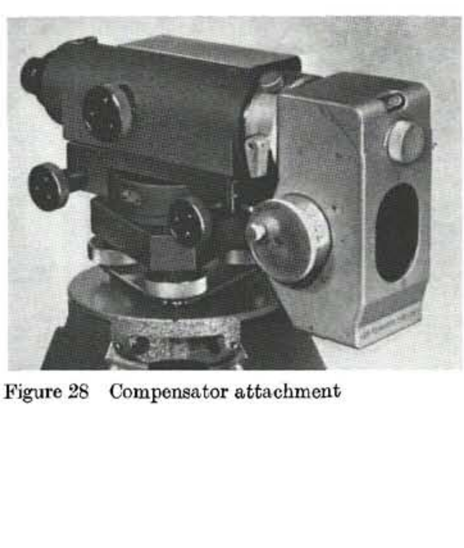


Figure 28 Compensator attachment

court designed an instrument which is levelled by autocollimation with a mercury horizon and a pentagon prism. *H. Wild* at Zeiss, Jena also attempted to include a mercury horizon into the optical train of a level in 1923. *Heckmann* suggested in 1932 an instrument where the level bubble, reflected into the field of view, serves to determine the correction for an inclined line of sight. In U.S.S.R., a compensation level was built in series in 1938. *Drodofsky* utilized in 1940 at Carl Zeiss, Jena the bubble of a 30″ bull's eye level as lens element in the optical train. The Italian *Bonechi* patented in 1940 a liquid compensation for levelling. At Carl Zeiss, Oberkochen a level was designed in 1946 where the image of half the bubble arc of a focus-bubble was used instead of a crosshair to determine the line of sight (when using a focus-bubble, its radius corresponds to the focal length of the objective lens).

The self levelling level with bubble compensator, developed by *Stodolkjewich* in U.S.S.R. in 1946 was the first to be used in practice. In 1950, the Ni 2 from Carl Zeiss, Oberkochen started a new epoch, because this instrument contains a mechanical compensator instead of a tubular bubble. Since then, 70,000 levels of this design have been produced, and numerous other automatic levels appeared on the market. They simplify and speed up the work, and have partly replaced the spirit levels.

The types of compensators used vary significantly. Besides pendulum arrangements with mirrors, even the Abat wedge (1777), a glass wedge with a variable refraction angle, is used. Compensator attachments which make it possible to use spirit levels like automatic ones (1960 Feinmess, Dresden (figure 28) and Askania, Berlin) were hardly used.

Occasionally, theodolites are also built without tubular bubble; the principle of automatic levelling of the line of sight is then applied to the reading of the vertical circle. Askania, Berlin produced in 1956 the first theodolites with automatic vertical index, although the Th 3 from Carl Zeiss, Oberkochen had utilized the end of the level bubble as automatic vertical index in 1953.

In 1852 the French physicist *Foucault* discovered that a gyro with two degrees of freedom will point towards North (figure 29). In 1908, the gyrocompass which is based on this principle, was introduced into marine navigation. *M. Schuler* build in 1921 the first surveying gyro, which however, could not cope with rough transportation conditions because of its sensitivity. In 1949, a surveying gyro, named meridian pointer, was applied by the Mining Academy Clausthal for the first time underground. Similar use is reported from U.S.S.R. in 1950. There gyrotheodolites were equipped with autocollimation telescopes around 1952–54. In 1960, Fennel & Sons, Kassel produced the first gyro theodolite KT 1 in series. Since 1963 gyros are also constructed as attachments for theodolites.

In 1905 *Bykow* presented the first suggestion for fully automated height measuring instruments in Russia. *Leontowski* designed in 1915 a cart with four wheels whose instrumentation plotted the profile of the path of the cart. Since 1947 fully automatic height meters installed in automobiles or trailers are used in the United States and in Russia.

After invar was discovered in 1897 by the French *Benoit* and *Guillaume*, invar wires were produced in 1898, and the Jäderin method became popular. In the following years, many baselines for triangulation were measured in this manner. More recently, measurements with long invar—or steel tapes have become quite common.

A new step in the development started with the use of electromagnetic waves for distance measurements. The Finn *Väisälä* presented in 1923 a method for highest precision distance measurement with the aid of light interference. Since then it is used to calibrate invar wires and to measure test bases. In 1945 the Shoran method was introduced in the United States for surveying purposes by *Aslakson*. After it was tested, the Hiran method followed in 1950, which developed into the Shiran approach by 1965. In 1936 the first electro-optical distance meter was built in U.S.S.R. at the Governmental Optical Institute (GOI). This instrument type reached practical importance with *Bergstrand's* Geodimeter, built by AGA in Stockholm in 1948 (figure 30). In 1957 the South African *Wadley* presented the Tellurometer (figure 31), a distance meter operating with micro waves, which quickly became widely used in surveying and geodesy. In 1968 electro-optical distance meters using lasers were presented with a range of 30 km in daylight—"Quartz" (U.S.S.R.) and AGA Geodimeter 8. In 1968, the first instrument with a GaAs-diode for close range (up to 3 km) was built in series. It was the Wild DI 10, a light instrument of small dimensions. Attached to a theodolite, this becomes an EDM tacheometer. The Electronic

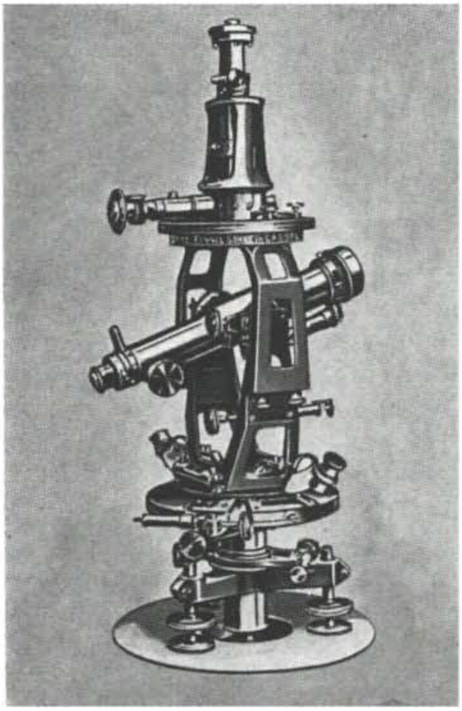


Figure 29 Declinatorium-fore-runner of the gyrotheodolite (2nd of the 19th century)

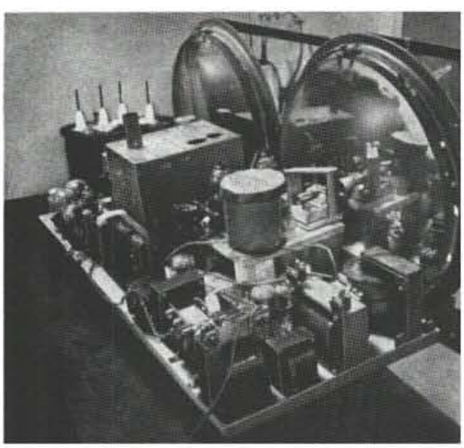


Figure 30 First geodimeter (1948)

Figure 31 Tellurometer MRA 1 (1957)

Distance Measurements (EDM) have laed to significant economic benefits and high accuracy for planimetric nets as well as topographic and engineering surveys.
Progress in mechanizing and automation led to the construction of code theodolites and – tacheometers (1963 Fennel, Kassel; 1965 Kern, Aarau).
The observations were directly registered on film in a code which, after processing, was evaluated with photoelectric sensors which transferred the results onto punched tape. A further step in the development is the digital theodolite Digigon, designed in 1965 by Breithaupt & Son, Kassel. Graduated circle and optical reading device are replaced by incremental encoders. The angles are presently digitally. Only a prototype was produced.
With the development of electro optical distance meters for close range and the possibility to detect angles sufficiently accurate by code or incremental methods and store them electronically, self registering electronic tacheometers the–at present–most complete instruments could be designed. In 1968, Carl Zeiss, Oberkochen introduced the Reg Elta 14, the first such instrument built in series. In 1977, Hewlett-Packard, United States presented with the HP 3820 A a new generation of EDM with laserdiode and microcomputer.

III. Manufacturers of Surveying Instruments

In the course of time companies were formed in various countries which are primarily involved in the production of surveying instruments.
In 1846, *Carl Zeiss* (1816–1888) founded in Jena a company, whose successor in Jena, the VEB Carl Zeiss Jena is the leader in the precision mechanical-optical-electronic industry of the German Democratic Republic. Since 1909 it has a separate division for surveying instruments. *Gotthelf Studer* founded in 1791 a workshop in Freiberg, which was continued by *Friedrich Lingke*. In 1873 *Max Hildebrand* joined the company, which obtained his name, but was changed to VEB Freiberger Präzisionsmechanik in 1950. In 1872 the Gustav Heyde Company originated in Dresden and is now named VEB Feinmess Dresden. In 1762 the company F. W. Breithaupt and Son was founded in Kassel. In 1802 *Georg von Reichenbach* opened a mechanical-optical institute in Munich, which was continued by *Ertel* and to which, among others *Soldner*, *Utzschneider* and *Fraunhofer* were associated (since 1935 "Ertel-Werk für Feinmechanik"). In 1848 Dennert and Pape was founded in Hamburg-Altona, and in 1851 Otto Fennel, Kassel. In 1871 the company of Carl Bamberg, later Askania Werke, was founded, and in 1946 Carl Zeiss, Oberkochen/Württemberg started production. Theis Gmbh & Co., Breidenbach/FRG (wich comtinues the production of Fennel-instruments), Pentax, Hamburg, and G. Nestle KG, Dornstetten are also mentioned.
In Switzerland surveying instruments are produced by Kern & Co. AG in Aarau (founded 1819), and by Wild Heerbrugg AG (founded 1921). Altimeters are made by Revue Thommen AG, Waldenburg (founded 1936), and levels also by Visomat AG, Rümlang.
In Austria, Gebr. Müller GmbH, Innsbruck produced surveying instruments a few years ago.
Up until 1917, surveying instruments were produced in Russia primarily by Schwabe in Moscow. This company became Geofizika in the U.S.S.R. In 1929 Aerogeopribor (later Aerogeoinstrument, since 1960 EOMS) was formed, and in 1938 the Charkow Works for Mining Instruments. At present the factories of the Main Administration Geodesy and Cartography of the Council of Ministers of U.S.S.R. produce approximately 25,000 theodolites and 35,000 levels per year.
In Hungary, *Ferdinand Süss* founded in 1876 a company for optical instruments, today called MOM = Magyar Optikai Murek or Hungarian Optical Works.
In the Č.S.S.R., Meopta, Prague – since 1945 the successor of the Srb and Stys Company, founded 1923 – produced surveying instruments until 1965.
In Poland and Bulgaria, surveying instruments are produced by the Polish Optical Works (PZO = Polskie Zaklady optyczne), respectively RPGP, Sofia (founded 1962.)
With Filotechnica Salmoiraghi, Milano (founded 1865 by *Porro*) and Officine Galileo, Florence (founded 1866) Italy has well known producers of surveying instruments.
The two largest French companies for optics and precision mechanics, ESSEL and SOPELEM, combined their production in 1955 as SLOM (Société d'Optique, Précision, Electronique et Mécanique), a Division of the Essilor group. Furthermore, the companies Chasselon, Cachau (Seine) and Coppin, Paris should be mentioned.
In Great Britain, surveying instruments are produced by Vickers Ltd., Vickers Instruments, York (formerly Cooke, Troughton and Simms, founded 1922, dating back to 1686), Rank Precisions Industries Ltd., England, of which Watts (founded 1856) is a part and W. F. Stanley and Co., London (founded 1853).
Svenska Aktiebolaget Gasaccumulator (AGA), Stockholm Lidingö (founded 1904) produces EDM equipment in Sweden.
The production of surveying equipment in the U.S.A. takes place at Berger and Sons Inc., Boston, Brunson Instrument Comp., Kansas City, Dietzgen Corp., Chicago, Ill., W. & L. E. Gurley and Co., Troy, N.Y. (founded 1845), Keuffel & Esser Comp., Morristown, N.J. (founded 1867), Lietz Comp., South San Francisco (founded 1882) and Path Instr. Intern., New York.
In Japan there are Fuji Surveying Instr. Co., Ltd., Tokyo (founded 1929), Sokkisha Ltd., Tokyo (founded 1920), Tokyo Optical Co. (Topcon, founded 1932) and Nippon Kogaku (NIKON, founded 1917).
India has the National Instruments and Ophthalmic Glass in Calcutta (founded 1830).
The People's Republic of China has government factories for surveying equipment.

Electronic Distance Meters and tacheometers are produced by Tellurometer Ltd., belonging to the Plessey International Group in South Africa, U.K., U.S.A., Canada and Australia, by Cubic Int. Ltd., Hewlett-Packard L.S.E. and Precision Int. Inc., Tullahoma (U.S.A.).
Among the producers or industrial groups, connections and sales arrangements to compliment their own offerings are common. In foreign countries sales companies are formed. More recently, instruments are also often produced under licence from or for other companies. The influence of electronics has also led to connection with companies of that type.

IV. Standardization

The technical development has led to a steadily increasing number of technical terms, dimensions, materials and products. This rather uneconomical multitude caused efforts towards standarization in Germany as early as the middle of the 19th century.
Under standards in this context should be understood: unification regarding the quality of tools and products (Quality standards, markings with information on dimensions, materials and surface characteristics), production-, test- and other methods (method standards). Unification related to the amount of work are referred to as effort norms.
In the G.D.R., for instance TGL regulations have been delcared as state standards (TGL are technical norm, quality regulations and delivery conditions). A state standard is a legal standard for the area of the G.D.R. and has to be recognized by the Bureau of Standardization, Mensuration and Merchandize Control (ASMW) as well as entered into the Central Register of the G.D.R.
Therefore the DIN as presented by the German Institute for Norms (Deutsches Institut für Normung e.V. (DIN) in the Federal Republic are no standards according to the above definition, since their use is only recommended.
National standards of other states are for instance the State Union Norm (GOST) in the U.S.S.R., ČSN in the Č.S.S.R., PN in the People's Republic of Poland, BS in England, NP in Portugal, NS in Norway, SIS in Sweden, IS in India, NF in France, UNI in Italy, NGN in the Netherlands, ASTM and ASA in the U.S.A. The efforts to unify national standards and to arrive at new international standards led in 1928 to the constitution of the International Organization for Standardization (IS), so named since 1946.

V. Further Developments

There are two main possibilities for further improvements of surveying instruments, namely: Improvements of present instruments by purposefully utilizing known building elements, or the development of completely new instruments and methods.
Ideas and suggestions which are worth consideration will not all be suitable. The practical use is the main criterion. Here the novelty has to prove itself and to obtain confirmation of its suitability.
H. Wild wrote in 1939 about the aim of novelties in the design of surveying instruments:
"The new instrument designs shall not lead to a reduction of the given tolerances, e.g. the permissible error of the measuring results, because claims in this regard are in part already exaggerated. Rather they should make it possible to obtain these results in a simpler manner, in less time, and with less effort. It should also not be necessary anymore, that the user has to adjust the instrument prior to measuring, because we have known methods for a long time, which permit simple elimination of possible instrument errors."
The new instruments therefore, should simplify the work and enable better performances. Furthermore, accuracy and economy have to be considered. Accuracy should not be exaggerated. Finally, the stability of the instruments should be improved, their optics refined and more robust types produced. This would make the instruments less sensitive for external influences. In recent years, more efforts are directed to mechanize and automate the working procedures, and to make them objective.
The industry strives to deliver the best instruments. The professional surveyor has to strive to master these highly developed instruments and to utilize them purposefully.

VI. Operation and Care of Surveying Instruments

Surveying instruments are only then completely effective, if they are carefully and conscientiously treated as well as professionally operated. The directions which are included should not only be read but also be followed. More than ever, this holds true for EDM instruments and other surveying equipment with electronic parts.
If the methods match the characteristics of the instruments, then they are effectively utilized.

Instrument Storage

Figure 32 Instrument container

Surveying instruments should be stored inside their respective container (figure 32) in dust free rooms without large temperature changes. In humid climate, they have to be removed from the tightly sealed containers so that the air can circulate freely around them.
In large collections, instruments and equipment are usually registered in a card file. It is expedient to prepare an instrument passport. It contains producer, type, description and technical data as well as a record on the calibration results.
In extremely cold areas the instrument should not be taken into a heated shelter as long as it is needed for measurements, but rather remain exposed to the outside temperature at some protected location. This prevents vapour formation on the optical and interior elements of the instrument when work is being resumed.
When storing a compass for a longer period of time, the position of the unlocked needle should be checked in order to maintain its magnetic characteristics.

Instrument Inspection and Checks

Instruments should be carefully inspected and checked for their suitability for a specific task before they are issued from the storage area. Furthermore, it should be checked whether the auxiliary equipment in the container is complete and operational.
At the beginning of each field season, the instruments should be tested and, when needed, adjusted according to the directions provided. It is recommended to repeat this test after completion of the field work, or after extended work interruptions or long distance transportation. In this manner, work stoppage due to faulty equipment can be prevented.
Instruments should only be adjusted when it is really necessary and only according to directions. When tightening adjustment screws, care has to be taken as to not create stresses.

Transport of Instruments

Before transporting instruments, one should first check whether the clamps are evenly tightened and then close the container and perhaps lock it. The keys have to be kept at a safe place.
When lifting or moving in vehicles, jerky movements should be avoided and shocks dampened.
It is best to hold the container with instrument upright on ones lap, possibly wrapped in a soft blanket. For longer transportation on land–sea–or air the container with the instrument is placed inside a padded crate (figure 33). During transport the crate has to stand upright. When using pack animals, the instrument is fastened upright, usually hanging. Generally the instruments are to be protected against fall, shock and heavy vibrations.
Rods are to be transported in their crates. In any case they have to be packed like instruments so they are not exposed to sudden blows.
When walking, the pointed ends of tripods, range poles etc. have to be kept in view. Rods should not be touched at their graduation, and protected from heavy blows. This is especially important for invar rods.

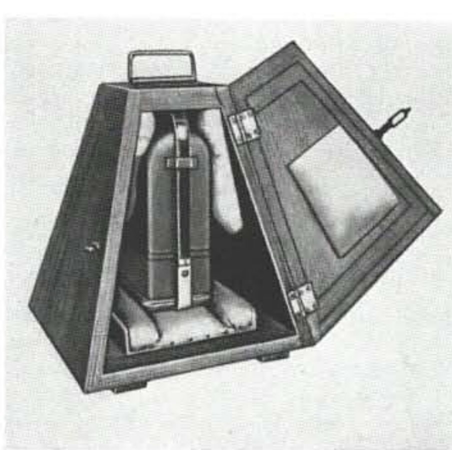


Figure 33 Padded transport crate

Setting-up of Instruments

At the survey location, warning signs and -flags should be erected, and industrial safety rules have to be observed. It is of advantage to have the back of the rods and the tripods painted in bright colour, such as red and white.
The tripod is to be set up solidly and in such a way that its legs are not in the way when observing certain directions. The tripod legs should be ex-

Figure 34 Position of instrument inside the container

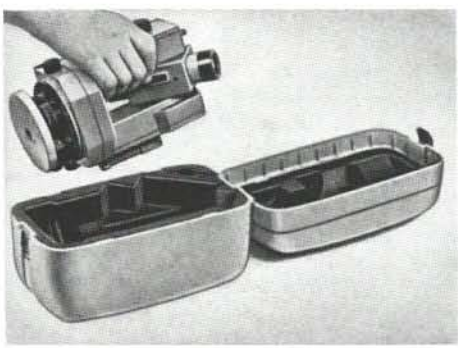


Figure 35 Packing and unpacking of an instrument

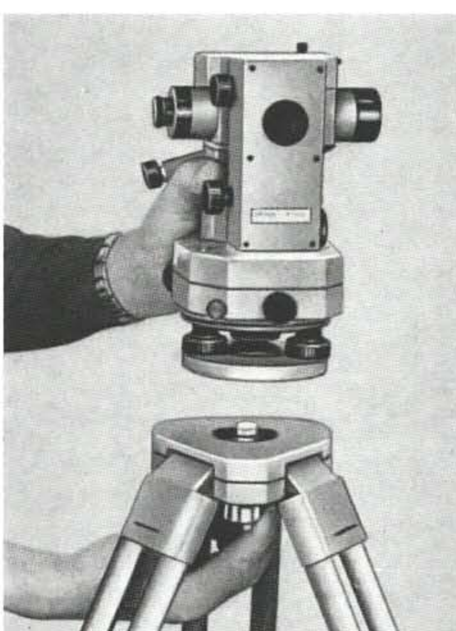


Figure 36 Placing the instrument onto the tripod

tended such that the observations can be made with ease. Their pointed ends have to be firmly pressed into the ground. One should also watch that the top of the tripod is approximately level and, for angular and distance measurements, is centered above the station.
When unpacking an instrument one should note its arrangement within the container (figure 34). A figure showing the arrangement of the various parts when properly packed should be inside the container. In any case, the given directions should be followed. Prior to unpacking, all clamps should be loosened. Then theodolites and tacheometers are lifted at the right standard – never on the side which houses the index bubble! – levels at the tribach (figure 35).
The instrument is then placed on the tripod and fastened to the tripod head while still being held with one hand. An instrument may never stand loosely on the tripod. Only after it is fastened, the hand can be taken away (figure 36). For centering and levelling, the fastening screw is to be loosened somewhat to reduce the pressure on the thread of the foot screws. It will be tightened again afterwards.
If the instrument temperature differs significantly from the field temperature, the instrument has to be left on the tripod until its temperature conforms. For 10 K temperature difference this requires about 5 minutes.

Care of the Instrument during Measurements

The instrument and the whole tripod are to be protected from direct sunlight and rain with an umbrella (figure 37). If work is interrupted due to rain, the instrument has to be protected with a cover. Drops of water should be blotted with a soft clean rag. Optical parts may not be touched with fingers. Dust should be carefully removed with a soft hair brush to the edge and then with a dust- and spot free soft cloth or soft chamois. Other dirt should be removed with hygroscopical cotton, never with liquid.
Whenever work stops, the instruments are to be protected against rain or dust with a hood or other cover. Prior to measuring, instruments with graduated circles should be rotated several times around both vertical and horizontal axes, so that the lubrication in the bearings is distributed. When measuring, touch only the solid parts of the instruments, never the eyepiece.
Stress on the instrument should be avoided. Clamps should be tightened slowly and evenly. When measuring horizontal directions, the vertical clamp does not need to be tightened. Finite fine motions should only be operated clockwise, so that the part is moved by the screws and not the spring, thus avoiding back lash.
When connecting upper and lower theodolite part with a repetition clamp of the *Mahler* type, one should press vertically on the clamp and counteract this movement with a fingertip. If the clamp is not needed, it should remain open.
Bends in tapes, caused for instance by vehicles driving have to be avoided. When rolling up the tape extra loops cannot be tolerated. Invar wires have to be protected from shock and reeled carefully. Their metal parts have to be cleaned daily with a soft rag and then rubbed with acid free grease. Prior to measuring, the grease has to be removed again.
Even though the human eye is not directly endangered when working with laser instruments, because of their low power (construction laser up to 5 mW, laser diodes), one should never look directly into a laser beam. If the laser beam is directed through a telescope, one should not look into the eyepiece as long as the laser is operating. If necessary, protective eye glasses should

Figure 37 Field umbrella

be worn. The laser should be screened off as much as possible, and never be without supervision when running.
When using instruments with mercury, one has to be extremely careful. Especially inside closed rooms, mercury should not be spilled. If this should happen, mercury drops can be lifted with copper sticks and then treated with sulfur for chemical bonding.

Instrument Transport between Stations

The observer should transport the instrument from one station to the next. If the distance is only a few hundred metres, the instrument can remain on the tripod. One has to check however, whether the fastening screw and the instrument clamps are tightened. For the reduction tacheometer Redta, however the side clamp has to be opened.
Then each hand holds one tripod leg, while the 3rd one hangs over the shoulder (figure 38), so that the vertical axis remains vertical.
Horizontal rods for optical distance meters are turned to vertical, but remain on their support. If needed the braces are loosened.

Figure 38 Transporting the instrument between stations

Care of Instruments after the Measurements

Before packing of the instrument, its clamps should be loosened. Once the instrument is correctly in the container, they are tightened evenly.
The pointed ends of tripods and rangepoles are to be cleaned with rag, brush or bushel of grass.
Tapes which have gotten wet have to be dried with a cloth, and then greased lightly with acid free oil or fat. If there are rust spots, do not use sand or sand paper but wood ash soaked with kerosene.
Instruments that got wet have to be unpacked at home and left out until they are completely dry. Occasionally the producer supplies with the instrument a little bag of Silicon-gel (highly hydroscopic grains of amorphous quartz). The grains are blue when dry and pink when saturated. Since they absorb water from the air, the instrument container has to be closed except when packing or unpacking. Pink grains can be regenerated when placing them directly on a heatable plate and heating it above the boiling temperature (check with a water drop: hiss-test). If the temperature is too high, the grains crack. The now blue grains are placed again into their bag after they are cooled down.
The tripod head, and the threads of the foot screws and the fastening screw should be kept clean and lightly oiled.
The bottom parts of rods have to remain free of dirt and dust and should be greased lightly.
After completion of the field season, the instruments should be thoroughly inspected. Damages are to be fixed by the mechanic.

1. Optical Equipment and Level Bubbles

1.1. Optical Equipment

1.1.1. Fundamentals of Optics

Geometric Optics and Wave Optics

Most surveying instruments are optical instruments whose operation is based on different characteristics of light. More and more, electronic parts are used.

Natural light is composed of electro magnetic waves starting from the light source; it penetrates straight into all directions with the same velocity depending on the matter. The direction of the energy flow of light is called light ray, the total amount of light rays is known as bundle of rays.

In vacuum the light velocity is 3×10^{10} cm/s. In air it is only slightly less, but in other matter much slower, e.g. 2×10^{10} cm/s in glass. In geodesy the velocity of electro-magnetic waves in vacuum is used as 299,792.458 km/s.

Optics is the science of light. Wave optics considers the wave characteristics of light. It is used to describe phenomena occuring with light energy, such as diffraction, interference, polarization and others. Geometric optics or ray optics is concerned with the path of rays in optical systems. With the aid of light rays the operation principle of optical systems can be presented much easier than with wave optics.

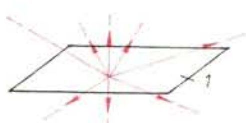


Figure 39 Diffuse reflection
1 rough surface

Figure 40 Directional reflection

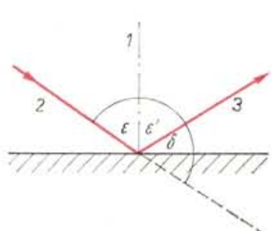


Figure 41 Mirror reflection
1 incident normal; *2* incident ray; reflected ray

Laws of Geometric Optics

Reflection. If a bundle of light rays hits the boundary surface between two media, part of the light is thrown back (reflected), while the rest is refracted into the other medium.

Diffuse reflection (reflected rays into all directions) can be observed on rough surfaces (figures 39), while directional reflection (rays are reflected into one direction) occurs on polished bodies (figure 40). The intensity of the reflected light is always less than that of the incoming light, partly because of partial penetration into the other medium, partly because of some diffuse reflection. The intensity loss depends on the incident angle, on the intensity and on the characteristics of the reflecting surface.

The law of reflection (figure 41) states: Incoming ray, normal to the reflecting surface and reflected ray lie in one plane. The incident angle ε equals the reflection angle ε'.

Refraction. If a light ray passes from one medium to another, e.g. air to glass (figure 42a) or glass to air (figure 42b), its direction of the ray is reversible.

When passing from an optically thinner medium (air) to a denser one (glass), the incident ray is refracted towards the normal. In reverse direction it is refracted away from the normal (figure 42). In the first case $\varepsilon > \varepsilon'$ in the second $\varepsilon < \varepsilon'$. Again, incident ray, normal and refracted ray span one plane.

Light rays passing from air into another transparent body are refracted the more, the larger the inclination to the boundary surface. At the point of entry into the denser medium, the velocity of propagation of the light is instantaneously reduced. The ratio between light velocities c_L in air and

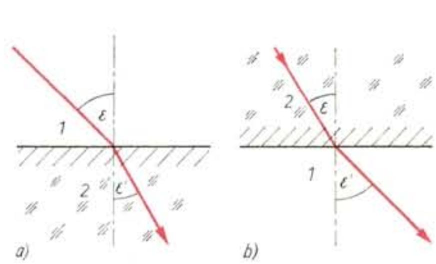


Figure 42 Refraction of a ray when passing (a) from air to glass, resp. (b) from glass to air
1 air; *2* glass

c_M in the medium represents the refractive ratio $n_{L,M}$. It corresponds to the ratio of the sines of the incident and refraction angles. This ratio remains constant for two particular media.

$$n_{L,M} = \frac{c_L}{c_M} = \frac{\sin \varepsilon}{\sin \varepsilon'} = \text{const.} \tag{1}$$

The refractive ratio referred to vacuum is called the refractive index n:

$$\frac{\sin \varepsilon_0}{\sin \varepsilon} = n \tag{2}$$

The refractive index of air at 20°C is 1.00028. Optical glass types have refractive indexes ranging between 1.47 and 1.92, e.g. light crown glass has 1.5153, while heavy flint glass has 1.7515.
With the same angle of incidence ε_0 the refraction angle ε' results for a medium with n' as refractive index, because $\sin \varepsilon_0/\sin \varepsilon' = n'$.
Dividing this with equation (2) one obtains after rearranging

$$n \sin \varepsilon = n' \sin \varepsilon' = \text{const.} \tag{3}$$

This is the law of refraction, discovered around 1618 by the Dutch *Snellius* (1581–1626). It states that the product between refractive index and the sine of the refraction angle remains constant. If refractive index and incident – or refraction angle are known, the unknown angle can be computed.
For ray tracing in optical instruments the refractive indices of air – practically equal to 1 – and glass – approximately 1.5 – are mainly needed. When passing from air to glass (figure 42a), $\sin \varepsilon/\sin \varepsilon' = 3/2$, and reversed (figure 42b) $\sin \varepsilon/\sin \varepsilon' = 2/3$. According to equation (3) the refraction angle of light ray passing from air to glass at 50 gon from the normal is:

$$\sin \varepsilon' = \sin 50 \text{ gon} \times 2/3 = 0.707 \times 2/3;\ \varepsilon' \approx 31 \text{ gon}$$

For a ray passing from glass at 25 gon to the normal, the refraction angle is:

$$\sin \varepsilon' = \sin 25 \text{ gon} \times 3/2 = 0.383 \times 3/2;\ \varepsilon' \approx 39 \text{ gon}$$

The ray tracing can be done by simple graphical means (figure 43). Here, a light ray falls at E onto the plane surface of the refracting body. Two circles are drawn around E, whose radii correspond to the ratio of refractive indices, e.g. air–glass as 3 : 2. The incident ray intersects the arc with r_1, at P. The intersection of a parallel to the surface normal at P with the arc of r_2 is point P'. The straight line connecting P' and E represents the ray after refraction. The following proves the validity of this graphical approach:

$$\sin \varepsilon : \sin \varepsilon' = \frac{a}{r_1} : \frac{a}{r_2} = r_2 : r_1 = \frac{3}{2}$$

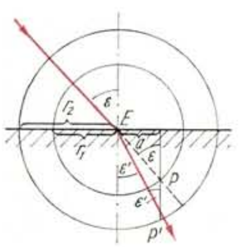


Figure 43 Graphical determination of refraction

The ray tracing from the optically denser medium to the thinner one (glass to air) can be performed graphically in a similar manner.
If a light ray falls perpendicularly onto the boundary between two media, its direction will not change (figure 44).

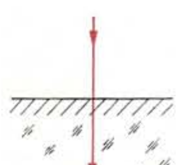


Figure 44 A ray hitting a boundary surface orthogonally

Total Reflection. According to the law of reflection the values $\sin \varepsilon \cdot n/n'$ and $\sin \varepsilon' \cdot n'/n$ cannot become larger than 1 because $\sin \varepsilon$ and $\sin \varepsilon'$ cannot exceed 1.
When light passes from the optically denser glass into the optically thinner air it is split at the boundary into a refracted part ($E_1 S'$ in figure 45) and a reflected part ($E_1 S'_1$). At an incident angle of ε_2 in glass, the refracted ray ($E_2 S_2$) passes along the boundary surface. The refraction angle is 100 gon, therefore $\sin \varepsilon_2' = 1$. According to equation (3) the limiting angle ε_2 can be computed from $\sin \varepsilon_2 = 1/n$. With $n = 1.47$ ε_2 becomes about 48 gon while with $n = 1.92$ it becomes approximately 35 gon.
If the incident angle is larger than ε_2, e.g. ε_3, then no light can pass into the optically thinner medium. The ray is totally reflected. Total reflection therefore occurs, when a light ray in an optically denser medium hits the boundary surface to a thinner medium at an indicence angle larger than the limiting angle.

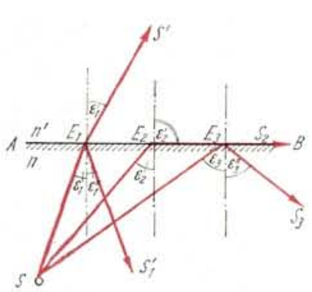


Figure 45 Refraction and total reflection

Application of the Laws of Geometric Optics to Mirrors and Prisms

Plane Mirrors. Mirrors are bodies with an optically reflecting surface. They may be made of material that can or cannot be penetrated by light. Light rays falling from a point L onto a plane mirror under various incident angles are reflected according to the law of reflection (figure 46).

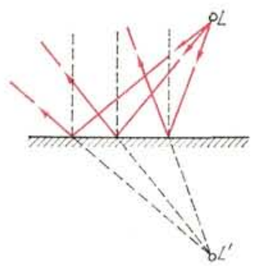


Figure 46 Generation of an image with a plane mirror

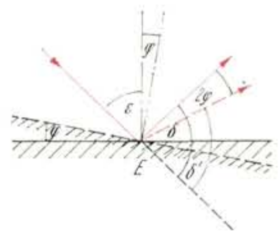


Figure 47 Propagation of rays when rotating a mirror

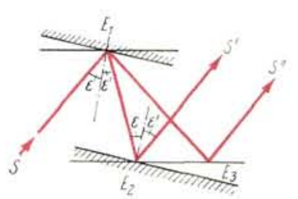


Figure 48 Propagation of rays when rotating two parallel mirrors

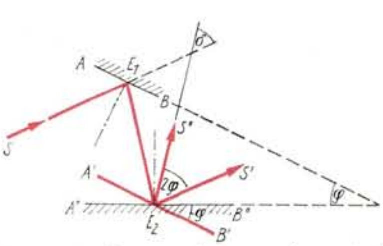


Figure 49 Propagation rays when rotating one of two parallel mirrors

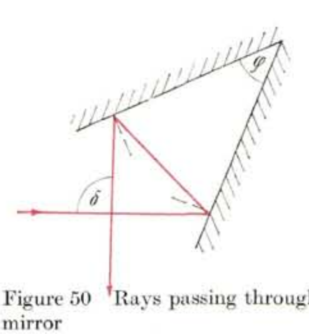


Figure 50 Rays passing through an angle mirror

Since the reflecting angle always equals the corresponding incident angle, the rays diverge after reflection. The rays which hit the eye of an observer appear to originate at the point L' behind the mirror. The image of the light point L appears to be there. The image L' is a virtual image of L. It does not exist in reality and therefore cannot be captured on a screen. The line LL' is normal to the mirror surface. The virtual image is exactly the same distance behind the mirror as the object is in front of it.

The mirror image of a surface or body consists of the mirror images of its points and is mirror reversed.

The direction of this mirror reversal depends on the position of both mirror and observer. With a vertical mirror, a horizontal reveral (left–right) is obtained, while a horizontal mirror creates a vertical reversal (top–bottom).

A light ray hitting a mirror under an angle ε (figure 47) is reflected such, that angular deflection from its original direction is

$$\delta = 200\,\text{gon} - 2\varepsilon \tag{4}$$

If one rotates the mirror around point E by a random angle φ, then the reflected ray is diverted by

$$\delta' = 200\,\text{gon} - 2(\varepsilon + \varphi)$$

$(\varepsilon + \varphi)$ is the incident angle for the rotated mirror. With this one gets (figure 47)

$$\delta - \delta' = 200\,\text{gon} - 2\varepsilon - [200\,\text{gon} - 2(\varepsilon + \varphi)] = 2\varphi \tag{5}$$

Therefore when turning the mirror by an angle φ the reflected ray is deflected by 2φ. This characteristic of the plane mirror is utilized in some magnetic instruments (declinators and compasses) as well as compensator levels.

A light ray who is reflected on two parallel mirrors retains its direction but is shifted (figure 48). The direction is even retained if both mirrors are rotated by the same amount in the same sense. Only the amount of the parallel shift changes (from E_2S' to E_3S''). If however, only one of the mirrors is rotated, then the reflected ray is deflected by twice the amount of the angle between the mirrors. The ray passing in direction E_2S' (figure 49) is rotated into the position $A''B''$. According to equation (4) it is deflected by the angle $S''E_2S' = 2\varphi$. The rotation angle φ equals the angle between the two mirrors.

Therefore

$$\delta = 2\varphi \tag{6}$$

The angle of deflection δ is thus independent of the angle of incidence at the first mirror. This is utilized in the mirror sextant.

An angle-mirror consists of two mirrors at an angle φ (figure 50). In surveying, angle mirrors with $\varphi = 50$ gon are used, which according to equation (6) results in $\delta = 100$ gon.

With this arrangement the following is achieved:

1. The incoming ray is deflected by 100 gon after two reflections, and
2. the image remains stationary when turning the instrument.

This holds true for all mirror combinations which have an even number of reflecting surfaces.

Figure 50 can also be used for another proof:

$$\begin{aligned}(100\,\text{gon} - \alpha) + (100\,\text{gon} - \beta) + \varphi &= 200\,\text{gon}\\ \alpha + \beta &= \varphi\\ \delta &= 2\alpha + 2\beta\\ \delta &= 2\varphi\end{aligned}$$

A light ray between two parallel mirrors and two reflections on each mirror is again shifted while retaining its original direction (figure 51). If the first mirror is rotated by an angle φ, the twice reflected ray on each mirror is deflected by 4φ from its original direction. This characteristic is utilized in compensation levels.

Curved Mirrors. The laws of plane mirrors also hold for small elements of curved surfaces, e.g. concave and convex mirrors. In this case, the normal to the curved surface provides the reference.

The optical axis or primary axis is defined as the straight line connecting the centre of curvature and the centre of the mirror, as given by the vertex

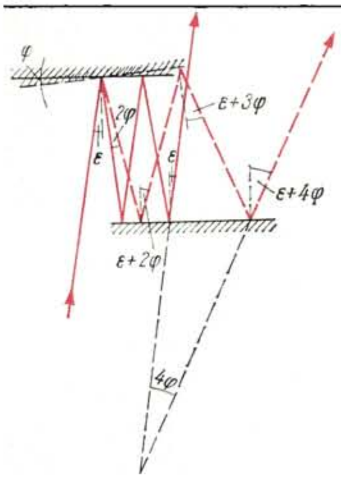


Figure 51 Double reflection

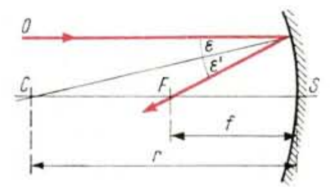


Figure 52 Spherical concave mirror

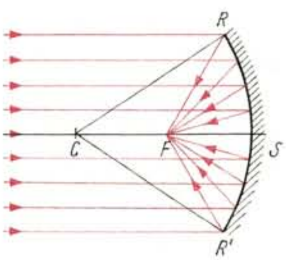


Figure 53 Effect of a spherical concave mirror

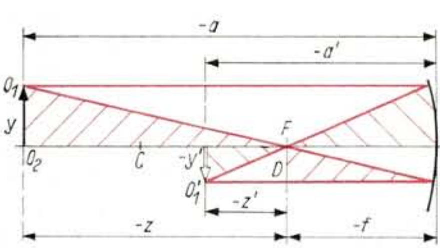


Figure 54 Graphical tracing of an image using a spherical concave mirror

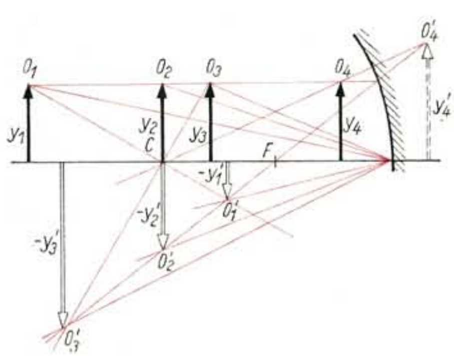


Figure 55 Image locations for different object locations, when using a spherical concave mirror

S (figure 52). The angle RCR' from the centre of curvature to the mirror edges is referred to as field angle (figure 53).
If a ray OE parallel to the primary axis hits a parabolic mirror, it is reflected to the point F ($\varepsilon = \varepsilon'$). This also holds as a first approximation for spherical mirrors with small field angle (figure 52).
The rays parallel to the axis converge into the focal point F. All rays passing through the focal point will be parallel to the optical axis after reflection at a concave mirror. For a spherical concave mirror the focal point is located half way between C and S. The distance f between focal point and vertex is called focal length. If the radius of curvature of the mirror is r, then

$$f = \frac{r}{2} \tag{7}$$

For larger field angles the rays parallel to the axis will not converge to a point any more. The points of intersection of neighbouring rays form a focal area which is pointed at the focal point. When intersected with a plane containing the mirror axis, this focal surface provides a rather oddly shaped line called catakaustic.
In order to graphically display the image of a point O_1, who is not located on the primary axis of the spherical mirror (figure 54), one first has to determine the focal point halfway between C and S. Then the image point O_1' is obtained at the intersection of the axis-parallel ray $O_1 E_1$ after reflection through the focal point and the focal ray O_1FE_2 or with a ray passing through C (figure 55), which is reflected into itself. $SO_2 = -a = -z - f$ is the object distance while $SO_2' = -a' = -z' - f$ denotes the image distance. z and z' are the distances to the focal points of the object – resp. image point.
From $FD = -y'$ and the similarity of the triangles O_1O_2F and FDE_2 the relationship $-y'/y = -f/-z$ follows. For small y values the triangles FE_1S and $FO_1'O_2'$ are approximately similar, then $-y'/y = -z'/-f$.
Combining the two equations results in Newton's Imaging Equation for concave mirrors.

$$z \times z' = f^2 \tag{8}$$

With $z = a - f$ and $z' = a' - f$ equation (8) which is referred to the focal point, can be transformed to the lens equation which in this case is referred to the vertex.

$$\frac{1}{a} + \frac{1}{a'} = \frac{1}{f} \tag{9}$$

Depending on the distance of the object y from the mirror, the image y' can be real and reversed or virtual and upright.
From figure 55 the following can be derived:

1. Real upright objects outside twice the focal length of a concave mirror result in real, reversed and reduced images located between single and double the focal length.
2. Real upright objects at twice the focal length of a concave mirror result in real reversed images of equal size at double the focal length.
3. Real upright objects between single and double focal length of a concave mirror result in real, reversed and enlarged images beyond the double focal length.
4. Real upright objects within one focal length of a concave mirror result in virtual enlarged images.

For spherical convex mirrors, where the outside of the sphere is the reflecting surface, the same imaging equations (8) and (9) hold true. Focal point and focal length are virtual. Real upright objects when reflected by a convex mirror result in virtual, upright and reduced images within one virtual focal length (figure 56).
Although curved mirrors have been utilized in astronomic telescopes for more than 300 years, they only appeared within the last decades in surveying as elements of mirror telescopes.

Parallel Plate. A transparent body bounded by two plane parallel surfaces is called a (plane)parallel plate (figure 57). A light ray entering from air the upper surface under an angle ε_1 is refracted towards the normal at an angle ε_1'. It continues on a straight path and hits the glass-air surface at an angle ε_2. Due to the parallelity of the two surfaces, ε_1' equals ε_2. When entering the air, the ray is refracted away from the normal. Since ε_1' equals ε_2, ε_1

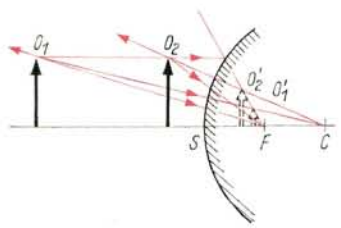


Figure 56 Image positions for a spherical convex mirror

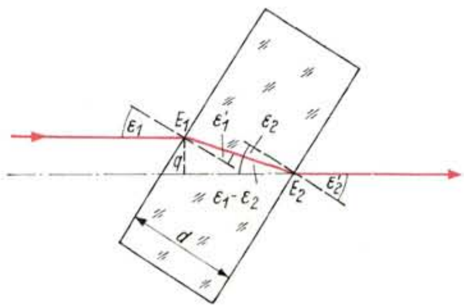


Figure 57 Rays passing through a plane parallel plate

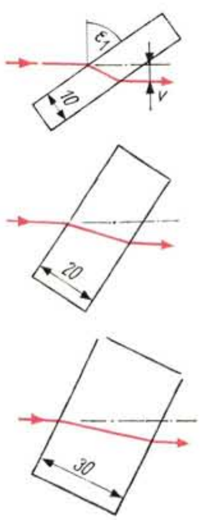


Figure 58 Shift of rays by 5 mm caused by plane parallel plates of various thicknesses

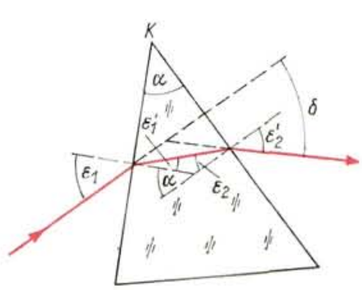


Figure 59 Deflection of rays passing through a prism

equals ε_2'. Therefore, when penetrating a parallel plate a lightray is shifted parallel. The amount of the parallel shift q is $q = E_1E_2 \times \sin(\varepsilon_1 - \varepsilon_2)$. With $E_1E_2 = d/\cos\varepsilon_1$ and $\varepsilon_1' = \varepsilon_2$ one gets

$$q = \frac{d \sin(\varepsilon_1 - \varepsilon_2)}{\cos \varepsilon_2} \tag{10}$$

where $\sin\varepsilon_2 = \sin\varepsilon_1/n$, according to equation (1). The approximate formula

$$q \approx \frac{n-1}{n} d \tan \varepsilon_1 \tag{11}$$

derived from equation (10) and used by *H. Wild* is sufficiently accurate for practical purposes.
The parallel shift q depends on the thickness d of the glass plate, the incident angle ε_1 and the refractive index n of the glass. In order to shift a horizontal ray by 5 mm, parallel plates of 10, 20 and 30 mm thickness have to be rotated by the following angles from their vertical starting position according to equation (11) (figure 58):

q	d	n	ε_1
5 mm	10 mm	1.52	61.8 gon
5 mm	20 mm	1.52	40.2 gon
5 mm	30 mm	1.52	28.9 gon

For surveying instruments, parallel plates are used for reading of graduations by measuring small intervals, e.g. parallel plate micrometers at levels and optical micrometers at theodolites.

Prism (*Glass Wedge*). An optical prism is a body of transparent material with at least two boundary surfaces. The plane perpendicular to the reflecting edge K (figure 59) is called primary section, and the angle within this primary section is called prism angle. A glass wedge is a prism with a small prism angle.
A light ray falling onto the prism in the plane of the primary section is deflected after two reflections by the angle δ away from the reflecting edge. The amount of the deflection depends on the refractive index n, the material of the prism as well as the prism angle and the incident angle ε_1. According to figure 59

$$\delta = \varepsilon_1 - \varepsilon_1' + \varepsilon_2' - \varepsilon_2 \text{ and } \alpha = \varepsilon_1' + \varepsilon_2 \tag{12}$$

Thus the deflection becomes

$$\delta = \varepsilon_1 + \varepsilon_2' - \alpha \tag{13}$$

According to the law of refraction the following holds with n being the refractive index of glass

$$\sin\varepsilon_1 = n \sin\varepsilon_1' \tag{14a}$$

$$n \sin\varepsilon_2 = \sin\varepsilon_2' \tag{14b}$$

With $\varepsilon_2 = \alpha - \varepsilon_1'$ from equation (12) and $\varepsilon_2' = \delta + \alpha - \varepsilon_1$ from equation (13), equation (14b) becomes

$$n \cdot \sin(\alpha - \varepsilon_1') = \sin(\delta + \alpha - \varepsilon_1) = \sin[(\delta + \alpha) - \varepsilon_1].$$

Since α and δ are small angles for a wedge, the sine can be replaced by the arc and the cosine by one. With this as well as equation (3) and $n\alpha \cos\varepsilon_1' = (\delta + \alpha)\cos\varepsilon_1$ one gets

$$\delta = \left(\frac{n \cos\varepsilon_1'}{\cos\varepsilon_1} - 1\right)\alpha \tag{15}$$

Therefore if the prism angle α, the refractive index n of the wedge material, and the incident angle ε_1 are known, the deflection δ can be computed according to equations (14a) and (15). If in addition the incident angle ε_1 is small, one obtains the approximate formula

$$\delta \approx (n - 1)\alpha \tag{16}$$

with $\cos\varepsilon_1'/\cos\varepsilon \approx 1$, which can be used for incident angles up to ± 1 gon.
The biprism (figure 60) is a combination of two glass wedges with equal prism angles. At the left side two lightly inclined refracting surfaces meet at

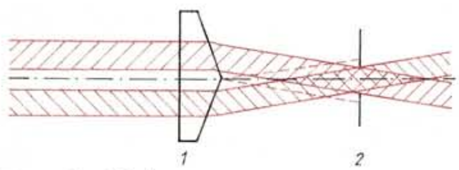


Figure 60 Biprism
1 biprism; *2* diaphragm

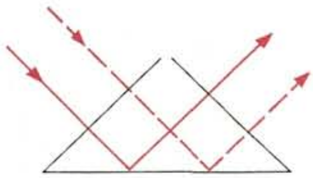


Figure 61 Deflection of rays by 100 gon when passing through a rectangle prism with equal sides

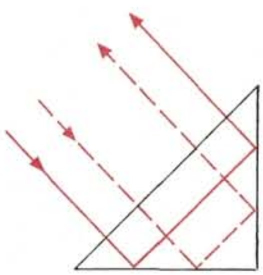


Figure 62 Deflection of rays by 200 gon when passing through a rectangle prism with equal sides

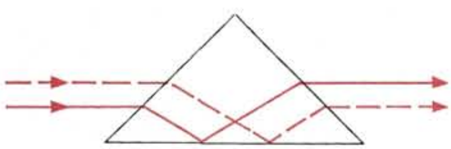


Figure 63 Reverse prism

a carefully machined edge, while the right reflecting surface is plane. Combined with a converging lens, a crossed path of rays can be generated which results in two images shifted against each other.
Among others, the glass wedge is used in optical micrometers and double image distance meters, while the biprism is used in the latter.

Reflection Prism. Reflection prisms (total reflecting prisms) are prisms with several polished plane surfaces where total reflection is used for the deflection of the light ray. Prisms have the following advantages over mirrors:

1. The angle between reflecting surfaces is fixed.
2. The reflecting surfaces are not subjected to wear.
3. The images are clear and bright.
4. With a prism, several reflections of a ray can be obtained.
5. Prisms can easily be fastened and built into instruments.

A prism with an even number of reflecting surfaces gives a straight image, one with an odd number, a reversed image like with a plane mirror.
If the incident angle is smaller than the boundary angle than the reflecting surface has to be silver coated which has the disadvantage of light loss.
A rectangle prism with equal sides is used to deflect a light ray by 100 gon (reflection at the hypothenusis, figure 61), or by 200 gon (reflection at the sides, figure 62) and to reverse the image (reverse prism, also called Dove- or Amici prism, figure 63). Prisms as in figures 61 and 62 are used for inclined sights and for circle readings.
The rectangular prism with equal sides and silver coded hypothenuses is used as angular prism (figure 64). If a light ray passing in a plane normal to the side edges, hits the edge AB, it is refracted at E_1, reflected at E_2 and again refracted at E_3. The deflection of the ray from its original direction is as follows:
The sum of angles in the quadrilateral E_1AE_3D is

$$(100\text{ gon} - \varepsilon_1) + 100\text{ gon} + (100\text{ gon} - \varepsilon_3') + (200\text{ gon} - \delta) = 400\text{ gon}.$$

Therefore $\delta = 100\text{ gon} - (\varepsilon_1 + \varepsilon_3')$

Since $\varepsilon_1' = \varepsilon_3$ and $\varepsilon_1 = \varepsilon_3'$, δ becomes $100\text{ gon} - 2\varepsilon_1$.

Thus the amount of δ depends on the incident angle. If the prism is rotated around an axis normal to its cross-sectional plane, the image moves. It should be noted, that only one reflection occurs.
If the ray hits the side close to the 100 gon edge (figure 65), it is refracted at E_1, totally reflected at E_2, reflected at E_3 and refracted at E_4. The deflection δ from its original direction is as follows:
The sum of angles in triangle CE_3E_4 amounts to

$$(100\text{ gon} - \varepsilon_3) + (100\text{ gon} - \varepsilon_4) + 50\text{ gon} = 200\text{ gon}$$

therefore $\varepsilon_3 = 50\text{ gon} - \varepsilon_4$.

From triangle CE_2E_3 it is apparent that $\varepsilon_3 + \varepsilon_1' = 50$ gon, therefore $\varepsilon_4 = \varepsilon_1'$ and $\varepsilon_4' = \varepsilon_1$.
Triangle DE_4F supplies $\delta + (100\text{ gon} - \varepsilon_4') + \varepsilon_1 = 200$ gon. With $\varepsilon_1 = \varepsilon_4'$, δ becomes 100 gon.
This proof can also be found by simple considerations: Since AC and BC enclose an angle of 50 gon, and the ray is twice reflected on each surface like in an angle-mirror, the direction E_3E_4 is deflected by 100 gon from E_1E_2. Since the sides of ε_4 and ε_1 are normal to each other, $\varepsilon_1' = \varepsilon_4$. This equality of the angles in glass, commands equality of the incident angles $\varepsilon_1 = \varepsilon_4'$. This means that the ray entering the prism at E_1 and exiting at E_4 forms a 100 gon angle.
The deflection angle δ is independent of the incidence angle ε_1. If the prism is rotated around an axis normal to its cross sectional plane, the image remains static.

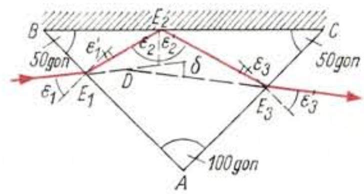


Figure 64 Movable image from a triangle prism

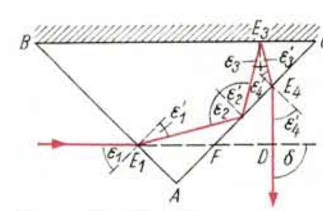


Figure 65 Fixed image from a triangle prism

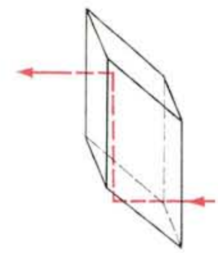


Figure 66 Rhomb-prism

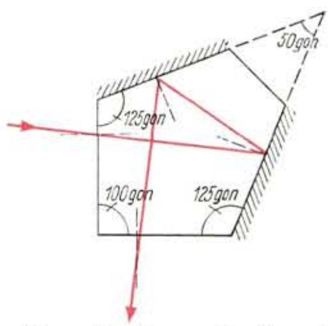


Figure 67 Ray passing through pentagon prism

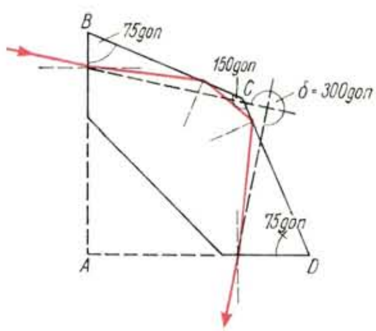


Figure 68 Ray passing through Wollaston prism

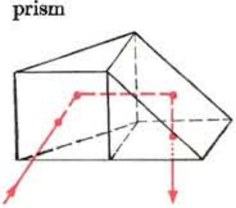


Figure 69 Sphenoid

It should be noted that two reflections take place in this case.
Therefore one has to distinguish two types of images with a triangle prism: Moving images, which wander by rotation of the prism around its vertical plane, and images which remain stationary when rotating the prism. Only the latter are of interest for practical purposes.
With a rhomb prism the light ray can be shifted by the length of its side without directional change (figure 66). It is used for graduated circle readings and others.
The pentagon prism (figure 67) has a quadrilateral cross-section symmetrical to one of its diagonals. It acts like an angle mirror whose mirror surfaces enclose an angle of 50 gon. It thus deflects the ray by 100 gon from its original direction, independent from the incident angle on the prism surface. The pointed prism edge is cut off, which results in its handy form as pentagon prism. Since total reflection does not occur, the reflecting sides are mirror cowated.
The Wollaston prism (figure 68) acts like an angle mirror whose reflecting sides *BC* and *CD* enclose an angle of 150 gon and therefore deflect the ray by 300 gon, according to equation (5). The complementing angle amounts again to 100 gon. For this prism the reflecting surfaces need not to be coated. The rectangular edge is usually cut off, so that it becomes another five sided prism. The pentagon- and Wollaston prisms are utilized as rectangle prisms.
A combination of two rectangular prisms with equal sides, called sphenoid (figure 69) causes a light ray to be not only shifted sideways but also deflected by 100 gon, because of one total reflection in each prism. Sphenoids are used for instance with a combination of other prisms for split bubble readings of a spirit bubble.
Porro's reversal systems serve to reverse images. The first Porro system (figure 70a) which is mainly used in prism field glasses and surveying instruments, consists of two rectangular prisms with equal sides. It can also be used to create an upright and correct image with an astronomical telescope. The second Porro system (figure 70b) is a combination of three rectangle prisms and is used in compensator levels.
Roof prisms serve to simultaneously obtain ray deflection by 100 gon and image reversal. If one of the reflecting surfaces is replaced by a roof edge, triangle-, pentagon- or Wollaston prisms can be made into roof prisms. In surveying instruments, primarily the *Amici* roof prism (figure 71) is utilized, which is a triangle prism with roof edge at its hypothenusis. A ray passing through the prism is twice refracted (at entrance and exit, with usually 0 gon incidence- and refraction angles) and twice totally reflected (at the roof surfaces). The roof prism is used for graduated circle readings and compensator levels.
A triple mirror prism has three prism surfaces normal to each other, thus forming a corner is space (figure 72). Any ray coming from the outside is totally reflected at all three surfaces and returns parallel to the incident direction and symmetrically to the central ray. When turning the triple mirror around any axis the direction of the returned ray will not change.
Triple mirror prisms are used with EDM instruments to return the light from the reflector station.

Lenses

A lens is a body of transparent material, mainly glass, which is bounded by at least one spherical surface. The other surface may be plane or spherical.
A lens can be considered to consist of numerous prisms with the outside ones having a larger reflective angle than the centre ones. By steadily increasing the number of the prisms which become progressively smaller the

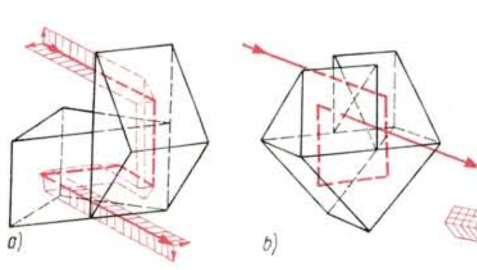


Figure 70 Porro's first (a) and second (b) reversal systems

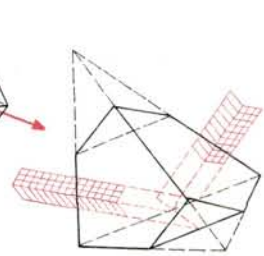


Figure 71 Roof prism by *Amici*

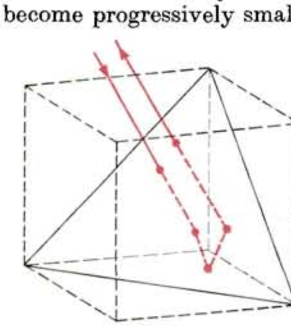


Figure 72 Triple mirror prism

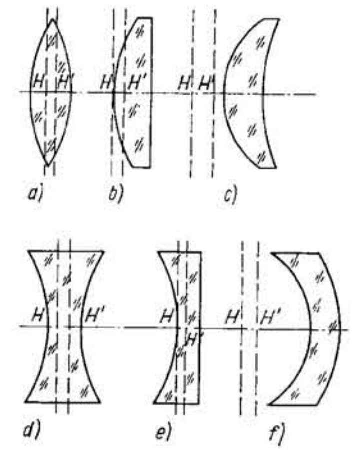


Figure 73 Different lens types:
a) bi-convex; b) plane-convex; c) concave-convex (collecting meniscus); d) bi-concave; e) plane-concave; f) convex-concave (dispersing meniscus)

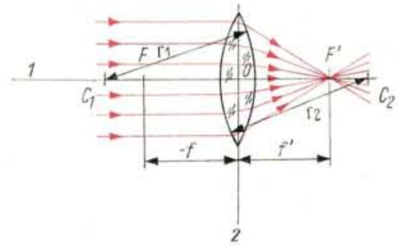


Figure 74 Collecting lens
1 optical axis; *2* central plane

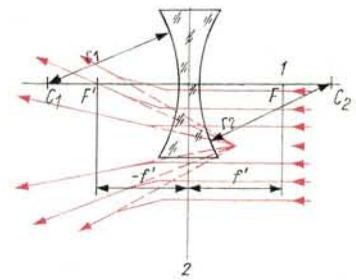


Figure 75 Dispersing lens
1 optical axis; *2* central plane

spherical lens surface is finally obtained. Depending whether the lenses are thicker at the centre or edge, one distinguishes between collecting or dispersing lenses (figure 73). The line connecting the two centres of curvature C_1 and C_2 represents the optical axis of the lens, with r_1 and r_2 being the radii of curvature (figure 74).
Collecting lenses cause convergency of parallel rays (figure 74), dispersing lenses divergency (figure 75). Rays entering the lens parallel and near the optical axis intersect after exiting at the focal point. For the collecting lens, this occurs directly (figure 74), for the dispersing lens virturally at the backwards extension (figure 75). The back focal point F' (image focal point) represents the image of an infinitely distant object point located on the axis (in figure 74 a real image, in figure 75 a virtual one).
Similarly the front focal point F (object focal point) is the axis point who is imaged at infinity.
The distances of the focal points from the central plane of the lens (the thickness of thin lenses can be neglected for most practical purposes) are the image focal length f' and the object focal length f. For thin lenses f and f' can be considered as equal.
A parallel bundle of rays entering the lens inclined to the optical axis converges to a point in the respective focal plane (figure 76). The focal planes are perpendicular to the optical axis and contain the respective focal point.
A ray passing through the centre of a thin lens will not change direction, except for a slight parallel shift.
Mirror lenses are a special form of lenses with one surface mirror coated. Thus refracting and reflecting effects occur simultaneously and supplement each other.

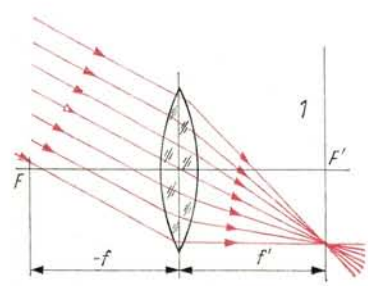


Figure 76 Parallel bundle of rays, inclined to the optical axis
1 focal plane

Imaging with Lenses and Lens Systems

Imaging with Thin Single Lenses. A light ray parallel to the lens axis originating at the object point O_1 passes after refraction through the image focal point of the lens (figure 77). A ray passing through the object focal point is parallel to the lens axis after refraction. The point of intersection is also common for all other rays. In the figure, this point is the image of the arrow head, while y' is the image of the object y.

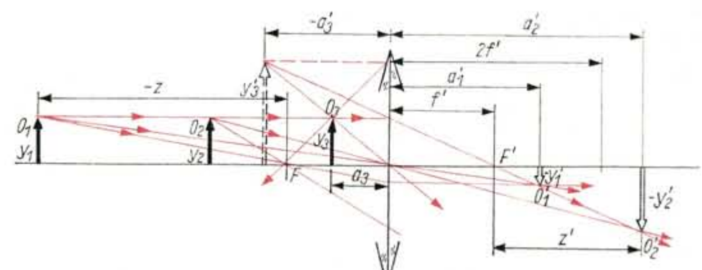


Figure 77 Positions of object and image when imaged with a collecting lens

For the graphical construction of this image point one can also use the ray which passes unchanged through the centre of the lens together with one of these fundamental rays.
Like for the curved mirror, three cases of object location have to be distinguished for imaging which result in different image, locations and sizes.

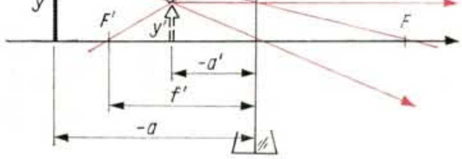


Figure 78 Graphical tracing of an image for a dispersing lens

1. If the object y_1 is located beyond twice the focal length in object space ($a > 2f$), a real, reversed and reduced image located between one and two focal lengths in the image space is obtained.