3 Theodolites

A theodolite is a surveying instrument used for precise angular measurement in both horizontal and vertical planes. Theodolites are commonly used for land surveying, route surveying, construction surveying, and in the engineering industry.

3.1 HISTORICAL PROTOTYPES OF MODERN THEODOLITES

We can consider Heron of Alexandria’s dioptra (first century BC) as the modern theodolite prototype. Prior to Heron’s invention, ancient scientists applied primitive goniometrical instruments in astronomy and building. In astronomy, mainly vertical angles were measured, and only horizontal angles were measured in building. Heron’s merit is invention of a universal goniometrical instrument (Figure 3.1).

FIGURE 3.1 Heron’s dioptra.
He also worked out methods for practical use of the instrument. Applying those methods people could carry out joining of water supply tunnels that they dug up from opposite sides of a mountain!

Over time goniometrical instruments eventually became equipped with a compass for orientation, a tubular level, and a Kepler telescope. In that time, the Kepler telescope could only provide external focusing. That meant the need to remove the ocular along the optical axis of the telescope. The term “theodolite” was introduced by Leonard Digges in the fourteenth century, but it only referred to an instrument that measured horizontal angles. The next significant step was the fitting of the theodolite with a telescope, made in 1725 by Jonathan Sisson. By the end of the nineteenth century the instrument looked like what we see in Figure 3.2. At that point the theodolite had metallic circles (limbs). Measuring was fulfilled by the means of two diametrically opposite microscopes. Therefore, eccentricity of the circles’ influence was minimized. Presence of three or four lifting screws at the tribrach was the main feature. A precise tubular level was often placed on the Kepler telescope. The compass was an important instrument for orientation and was usually placed between the

![Theodolite with metallic circles (limbs).](image-url)
Theodolites standards. Fastening and focusing screws were separated, which may be present in modern elementary theodolites.

3.2 OPTICAL THEODOLITE

In the 1920s, leading surveying instrument manufacturers started using glass limbs in their theodolites. Nevertheless, metallic limbs were still applied in theodolites until the 1960s. About the same time with the glass limb-style theodolites appearance, another type of theodolite with an internal focusing telescope appeared. Instead of the compass, a tubular level was set up between the standards. The compass was moved onto the standard and it became demountable. The separate microscopes were replaced with the common one, and its ocular was set next to the telescope ocular. Also, an optical plummet was added. Replacement of the separate tubular level at the vertical circle with an optical and mechanical compensator was the last improvement of optical theodolites. The most advanced theodolites have coaxial fastening and focusing screws, instead of separate ones. The last improvements of the optical theodolites were carried out in the 1990s. An up-to-date optical theodolite is shown in Figure 3.3. Current surveying instrument manufacturers have stopped developing

![Diagram of Optical Theodolite]

**FIGURE 3.3** Optical theodolite.
and releasing optical theodolites. However, some manufactures still make them available, mainly under licenses (Table 3.1).

### 3.3 ELECTRONIC THEODOLITE

At the peak of their development optical theodolites became reliable, compact, light, and ergonomic, but reading out the values remained tiring and hardly available for automatic registration. Some attempts were made to automate data registration in field conditions by taking photos of the limb parts at the moment of reading out. Then the film was processed in the lab and went into automatic counters. In the 1970s character recognition technology was poorly developed, so the values on the limbs were encoded with the help of white and black stripes. There is no doubt that the technologies of today would allow reading out the limb characters’ image much more easily, but at that time people had to deal with various constraints. Thus, the first coded limbs on theodolites appeared. As electronic and microprocessor technology has progressed, it has become possible to fulfill the coded limb image processing technique in the theodolite. Such theodolites are called electronic theodolites. Nowadays, surveying instrument manufacturers produce them. An electronic theodolite has much in common with optical models (Figure 3.4).

The telescope, tribrach, optical plummet, focusing and fastening screws, and axes systems mainly remained unchanged. The measuring microscope disappeared due to lack of need. The digital display console with control keys appeared. Now there is a battery module at the right standard. The accuracy of many models released ranges from 2″ to 20″. Two-second accuracy theodolites have electronic monoaxial inclination compensators. Some of them even have a dual-axis compensator and a laser plummet. Five-second accuracy electronic theodolites usually include a monoaxial compensator. Some electronic theodolites are equipped with a laser pointer. Those of this type are called laser theodolites.
3.4 BASIC OPERATION PRINCIPLE OF A THEODOLITE

The main principle of every theodolite operation is a selected basic axial configuration according to certain requirements.

3.4.1 BASIC AXES OF A THEODOLITE

Optical and electronic theodolites have an identical geometric and kinematical scheme (Figure 3.5). This consists of vertical and horizontal rotation axes and the collimation axis. The vertical axis is the instrument rotation axis. The horizontal axis is the telescope rotation axis. The vertical rotation axis is provided with the horizontal measuring circle. The horizontal rotation axis is provided with the vertical measuring circle. These circles are often called limbs. The collimation axis is the line that connects the center of the telescope objective with the reticle’s crosshairs.

3.4.1.1 Theodolite Vertical Axis

The vertical axis must be set into the plumb position at the beginning of a measurement. This is carried out by the means of the foot screws on the tribrach and using a tubular level as an indicator (Figure 3.6). Next we rotate the instrument and place the tubular level parallel to the line connecting foot screw 1 with foot screw 2. Then we set the bubble into the center of the tubular level turning foot screws 1 and 2. Next we turn the instrument at 90° around its vertical axis and again center the bubble by the means of foot screw 3. Then we turn the instrument 180° to check adjustment of the tubular level.

FIGURE 3.4 Electronic theodolite.
If the bubble on the tubular level moves from the center, set it halfway back to the center by the means of leveling screw 3. Now we correct the other halfway by the means of the adjusting screw. We need to be sure that the bubble is in the center by rotating the instrument at 180°. If not, repeat the adjustment. We need to repeat checking and adjusting until the bubble is in the center at any instrument position.

FIGURE 3.5 Basic axes of a theodolite.

FIGURE 3.6 Tubular level adjusting.
Theodolites

The tubular level scale division ranges from 20″ to 60″ per 2 mm depending on the theodolite’s precision. This allows us to establish the vertical axis accuracy from 10″ to 20″. This is enough for low-precision theodolites. Moderate- and high-precision theodolites have monoaxial and dual-axial compensators for the instrument’s vertical inclination for correct readings of vertical and horizontal angles.

It is an important requirement for the vertical axis to remain highly stable. When the instrument is new there is usually little worry about this, even with low-precision theodolites. However, after a shock or unskilled repair the tight vertical axis may develop some gaps or internal dents made by the bearing balls. The first sign of a problem is usually inadequate tubular level reactions during adjustment. In order to verify this malfunction we should direct our theodolite to a very clear target at a distance of about 10 m. Beforehand, we should set the instrument very carefully to the vertical position using a tubular level. Then, we unfasten the horizontal circle clamping screw and rotate the instrument several times to one direction and contrariwise. Before changing the rotation direction we should make sure that the horizontal line of the reticle and the target coincide. In the case of visible noncoincidence at any change of direction, and also attended with the bubble deviation, this indicates vertical axis instability. The problem is resolved by changing out the axial pair in a specialized workshop.

3.4.1.2 Theodolite Horizontal Axis

The horizontal axis must be perpendicular to the vertical. The horizontal axis is called the telescope rotation axis. The vertical axis is referred to as the instrument rotation axis. The horizontal axis nonperpendicularity to the vertical one is called the horizontal axis inclination.

Inclination of the horizontal axis $\iota$ distorts the horizontal circle reading out results at the value $\upsilon$:

$$\upsilon = \iota \cdot \tan \beta,$$

(3.1)

where $\beta$ is the angle of telescope inclination (the vertical circle reading out).

The horizontal axis inclinations influence upon horizontal angle measurement values can be minimized by carrying out measurement at two circular positions (Figure 3.7).

One of the bushes of the horizontal axis can be slightly removed to regulate the axis inclination. The adjusting bush is placed in the standard that is without the vertical circle. Usually this is the right standard of the theodolite. Some manufacturers provide the option of regulation during the theodolite usage, while others rule out any access and set the bush with epoxy glue. Three commonly used types of a regulated bush fixations are in Figures 3.8 through 3.10.

The first type of fastening is the handiest. It is applied in Nikon, Trimble, Spectra Precision, and Pentax instruments. Adjustment is fulfilled by the means of two screws that have conical tips. Before adjusting, the flange fastening screws are slightly loosened. We need to remove the battery and open the rubber plugs to reach these screws.

The regulating screws may also be covered with rubber plugs. While rotating the adjusting screws in any direction we can rotate the bearing flange at a slight angle around the pin. The horizontal axis is slightly removed at height. After adjusting we should tighten the fastening screws.
FIGURE 3.7 Theodolite positions.

FIGURE 3.8 Units for Nikon theodolite horizontal axis inclination adjustment.

FIGURE 3.9 Units for Topcon theodolite horizontal axis inclination adjustment.
Theodolites

The second type is often applied in Topcon instruments. The main difference of this type is the lack of a pin. One of the lateral fastening screws is used as the pin. It is not loosened before adjusting. Another difference is that the adjusting screws are rotated in the same direction. The adjusting screws have spherical tips.

The third type is often applied in low-precision theodolites. The horizontal axis removal is fulfilled by rotating the eccentric bearing flange by means of the adjusting screws.

If a theodolite has no horizontal axis inclination adjusting unit, then we can make slight adjustments via the fastening screws on the vertical axis flange.

These screws are placed between the theodolite standards and protected with a cover or rubber plugs. Adjusting is fulfilled by means of lateral fastening screws (Figure 3.11). We can do it only by tightening one of the screws at the required side,

**FIGURE 3.10** Units for Geo-Fennel theodolite horizontal axis inclination adjustment.

**FIGURE 3.11** The alternative method for elimination of theodolite horizontal axis inclination.
and never loosening the opposite screw. This method is not very efficient because after adjusting we should adjust the compensator.

Next we make a fundamental equipment assessment of the theodolite axes perpendicularity. We can examine this in two ways. The first way is shown in Figure 3.12. Set up the theodolite on the tripod at the distance of 2.6 m from the wall. A thin wire with a weight is suspended from the top of the wall. In order to remove oscillations of the wire, the weight is put into a can with oil.

The wire thickness should be about 0.1 mm. Its angular size is 5″ at the distance of 3 m from the theodolite objective. We can use the horizontal theodolite circle or the reticle bisector to measure small angles. The reticle bisector angular size depends on the theodolites precision and can be equal to 20″, 30″, 40″, or 60″.

The second method uses a mark and a ruler, graduated in millimeters. The mark is placed at the top of the wall. The ruler is placed horizontally at the bottom. The angular size of 1 mm division at the same distance of 3 m is about 50″. This is sufficient enough for low- and moderate-precision theodolites adjustment.

We test the horizontal axis inclination in the following way. Direct the telescope to the upper ending of the wire (or to the mark) at one of the circle positions. Then unfasten the vertical clamp and direct the telescope to the lower ending of the wire (or to the ruler). The vertical line of the reticle may coincide slightly with the center of the wire. This is natural because some inclination of the vertical axis may occur. Then we find out the deviation by the means of the reticle bisector or the horizontal circle of the theodolite. If we apply the second method, we should do the ruler reading. Then we turn the theodolite to another position and direct it again to the upper target. Again we direct it to the lower target. The vertical direction deviation from the lower target at both positions of the theodolite should not be more than 10″ for
moderate- and high-precision theodolites. The 30′ difference is allowable for low-precision theodolites. In case we try the second way, the rulers’ read out difference should not exceed 0.2 mm (0.6 mm for low-precision theodolites). If the limits are exceeded, we should correct the horizontal axis inclination with the aid of accommodation described earlier or the vertical axis flange fastening screws.

### 3.4.1.3 Theodolite Collimation Axis

The collimation axis of the telescope should be perpendicular to the horizontal axis of the theodolite. Nonperpendicularity of these axes is called collimation error \( C \) and influences the horizontal angle read out value \( \epsilon \) like this:

\[
\epsilon = \frac{C}{\cos \beta}
\]

where \( \beta \) is the angle of telescope inclination.

The collimation error’s influence on horizontal angle readings could be excluded the following way. The horizontal angle's measurements are fulfilled at two positions of the theodolite and then the result is averaged. Surely we should take into account the 180° difference between two positions at the same direction. The double collimation error is the angular read out difference from 180° at the same direction for both positions of the theodolite. The collimation error should not exceed 10′ for high-precision theodolites. It need to be less than 20′ for moderate-precision theodolites and not exceed 60′ for low-precision theodolites. In case it exceeds these values we should adjust the instrument with of the horizontal adjusting screws on the reticle (see Figure 3.13).

Before collimation error corrections, we should be sure that reticle inclination has not occurred. It is convenient to use a suspended vertical wire (see Figure 3.12). First, we should properly set the vertical axis of the theodolite into the vertical position. In case the wire image does not coincide with the vertical line of the reticle, we should slightly loosen the ocular flange’s fastening screws and turn the flange at the required angle. Then we tighten the screws. There is another suggested method for reticle inclination adjustment. We start by superposing the reticle vertical line with the target. Then we remove the target image to the lower edge of the reticle by means

![FIGURE 3.13 Reticle adjusting screws.](image)
of the vertical tangent screw. In the case that the image removes more than the size line thickness, adjusting is needed.

The collimation axis of the telescope should be horizontal when the vertical circle read out is equal to zero. In order to meet this requirement, we should measure the vertical angle at two positions of the theodolite. The total sum of these readings must be $360^\circ$ if the theodolite has an ordinary full scale (from $0^\circ$ to $360^\circ$) of the vertical circle. Some low-precision theodolites have an inclination scale of $\pm90^\circ$ instead of the full scale. In this case, sightings of the same target should have angles of inclination at both positions of the theodolites and must be equal but have opposite signs. The difference of the sum from $360^\circ$ ($0^\circ$ for the instruments with the inclination scale) divided in two is called the vertical circle index error. In order to correct it we should correct the vertical circle read out by means of the vertical tangent screw. Then we superpose the horizontal line of the reticle to the target with the help of the vertical adjusting screws (see Figure 3.13). We suggest correcting only slight vertical index errors with the help of these screws. If the vertical index value is several minutes, the reticle’s horizontal removal or inclination could appear. The horizontal removal of the reticle changes the collimation error value that must be corrected. The vertical index adjustment of low-precision theodolites can be fulfilled only adjusting the reticle screws.

Optical theodolites equipped with an inclination compensator of the vertical axis usually have options for regulating the vertical index via compensator adjustments. All electronic theodolites have special programs to calculate the vertical index error. Users are advised to use the correcting program instead of using the vertical adjusting screws of the reticle. The program is usually initiated by a simultaneous keypress combination (which is specific for every manufacturer and described in their manuals) or entering a special menu. Then we usually point at the target twice from different theodolite positions. After each sighting we should press the Enter key. After the second input the vertical index error correction is fulfilled automatically. Electronic theodolites without a compensator are adjusted in such a way without any troubles. A more complicated adjustment is needed for electronic theodolites with a compensator.

If an electronic theodolite experiences an impact, software-based vertical index adjustments may be incorrect. This occurs due to compensator shift after the shock. In order to verify the vertical index position we should put the telescope into the horizontal position by setting the vertical circle read out equal to $90^\circ$ (or $0^\circ$). Then we test it like a usual optical level with the leveling rods.

### 3.5 MAIN PARTS OF A THEODOLITE

#### 3.5.1 MEASURING SYSTEM OF A THEODOLITE

##### 3.5.1.1 Measuring System of an Optical Theodolite

An optical theodolite measuring system consists of horizontal and vertical glass limbs, plus reading units. Optical theodolites glass transparent limbs have circular scales graduating from $10'$ to $1^\circ$. Degree divisions are added with Arabic figures. The optical theodolite reading device is a microscope furnished with an index or scale micrometer.

The measuring system of an elementary contemporary optical theodolite is shown in Figure 3.14. The outside light illuminates the vertical limb through the
Theodolites

matte window. Then the light goes through the right-angled prism of the vertical channel and comes to the transparent horizontal limb. The horizontal and vertical scale images do not overlap each other and are parallel if adjustment is correct. Then the images enter the horizontal microscope. As a matter of fact, it is common for both vertical and horizontal channels. This is why after the horizontal channel image adjustment we must confirm the vertical channel image. The optical scheme of this kind is called consecutive. Having gone through the microscope, the circles’ images enter the right-angled prism, which sends the images to the mask. The microscope mask is like the telescope reticle. It has two separate transparent windows for the vertical and horizontal channels. Various types of microscopes have different windows. Elementary microscopes have index-marked windows (see Figure 3.15). The microscopes of moderate precision theodolites have scaled windows.

The vertical and horizontal circles’ images superposed with the mask enter the pentaprism and then the microscope’s ocular.

3.5.1.2 Measuring System of an Electronic Theodolite

Electronic theodolites limbs are covered with a nontransparent coating that has code gaps on it. They may have regular intervals (incremental solution) and irregular ones (barcode solution). A five-photodiode matrix is used as a reader in incremental solution. The CCD (charge-coupled device) line is applied as a reader in barcode solution.
An electronic theodolite incremental measuring system is a sort of accumulative measuring system. Before measuring they are forcibly zeroed. While measuring the incremental system accumulates small parts of the measured quantity. A classic example of these units is a clock. An ordinary clock is an incremental quantity irreversible system to measure time. A photoelectronic incremental irreversible system for distance measuring is in the top part of Figure 3.16.

The source of light (light-emitting diode) is formed into a narrow beam with a condenser lens and a mask that has a slit. A slit grid is set in front of the photodetector. At the moment the slit grid moves, sinusoidal modulation of light occurs at the photodetector input. Monochannel irreversible solutions are seldom used. In the bottom part of Figure 3.16 there are two channels, which is necessary to provide reversibility. Since distance is able to increase or, on the contrary decrease, in practice only a dual-channel reversible system is used to measure distance. The sensor has two slits shifted one relative to the other at a one-fourth period phase of the grid step. There are also two photodetectors. When the grid moves to one direction a sinusoidal signal at one of the photodiodes output advances the signal at the output of the other photodiode. When the grid moves in the reverse direction the signals sequence is opposite.

Angular measuring incremental systems are based upon the same principle. The slit grid is set circle-wise, and the angle is identified as the distance passed by the slit mask around the circle. There are several tenths of slits on the mask to increase signals at the photodiodes outputs. The mask slits are distributed at the same step as the grid spacing around the limb.

An incremental measuring system of an electronic theodolite is in Figure 3.17. The incremental limb scale is a regular sequence of equal dark and transparent stripes. The angular interval between them is from 1′ to 2′. The limb also has a short barcode strip for zeroing. There is an immovable mask at a very small distance (from 5 to 10 mkm) from the scales (Figure 3.18).

There is a light source at one side of the limb and a five-photodiode matrix at another one. The mask is made nontransparent, but it has five transparent stencils. One of them has a barcode strip identical to that the limb has. When we rotate the limb once their complete superposition occurs, and the zero photodiode generates a short impulse. The other four stencils consist of sequences of transparent stripes with
Theodolites

Irreversible incremental sensor

FIGURE 3.16 Incremental measuring principle.

Reversible incremental sensor

FIGURE 3.17 Incremental measuring system.
the same periods as on the limb. However, these stencils are shifted at one-fourth of the period from each other. While rotating the limb, four sinusoidal signals are generated at the corresponding photodiodes’ outputs. The phase shift of these signals is 90°. Further, these signals are processed by the means of two units: a reverse counter and an interpolator. Before entering the reverse counter, the sinusoidal signals are transformed into impulse ones. Further, the pairs of 90° phase shift signals are analyzed. While rotating the limb at one direction, the first pair of impulses advances the second pair of impulses. When we change the direction of the limb rotation, the impulse sequence is changed too. These impulses enter the trigger, which is sensitive to changes of these signals’ sequences at its inputs. The trigger is switched over at every change of the limb rotation direction. The trigger controls a reverse impulse counter. The impulse sequence from one of four channels enters the counter input. The data accumulated by the reverse counter is equal to the current angular value. The value discreteness is from 1′ to 2′. More exact angular value can be attained by the means of the interpolator. It carries out preliminary analog processing of the sinusoidal signals and then they enter an analog-to-digital converter. The preliminary analog-digital processing is necessary to minimize the constant signal drift. This is why 180° phase shift signals are processed in pairs. Data from both the reverse counter and the analog-to-digital converter enter the theodolite microprocessor. Using the data the microprocessor calculates the angular value to within 1″.

The incremental angular measuring system was most widespread 10–20 years ago. At that time all leading manufacturers, except Leica, created electronic theodolites on this principle. Nowadays, this principle is slowly excluded by more advanced absolute methods. Today only a quarter of electronic theodolites made use incremental sensors.

The absolute method is based on the fact that any position of a limb corresponds to an appointed angular value. Optical theodolite measuring systems are similar to absolute systems. Electronic theodolites have absolute code limbs (Figure 3.19).

There are several types of limb coding. In the past there were multitrack code limbs in angular measuring surveying instruments. Because of CCD line technology
development, nowadays only barcode solutions are used in absolute electronic theo-
odolites. Such a limb has an infinite barcode stripe circumferentially spaced. An
absolute angular sensor consists of a light-emitting diode and the CCD line where
the barcode stripe images are projected. The CCD signal is processed the same way
as it was described in Chapter 2 about digital levels. The only difference is that a
digital rod is coded in linear values, whereas a barcode limb is coded in angular val-
ues. This is the same way we find out the exact part of the angular value according
to the phase shift of the barcode support grid. This is how we find millimeters and their
fractions in a digital level. There are several systems of limb coding. Usually they
are unified by every manufacturer. For example, Topcon applies the same phase-
measuring method to code leveling rods and their theodolites limbs. Other leading
manufacturers use their technical groundwork both in digital theodolites and levels.

3.5.1.3 Influence of Wrong Limb Position on Angular
Measuring System Accuracy

Theodolite measuring system errors may occur because of wrong positions for either
the limbs or sensors. The errors occur if the center of the limb scale is not on the axis
of rotation and also if the limb plane is inclined to this axis (Figure 3.20). Such errors
are called limb eccentricity and limb tilting.

*Limb eccentricity* is one of the main reasons for theodolites measurement errors,
and it can hardly be corrected. Let us analyze the eccentricity formula:

\[
\beta = \left( \frac{l}{r} \right) \rho'' \sin \alpha
\]  

(3.3)

where \(\beta\) is the eccentricity influence on the angular read out, \(l\) is the linear com-
ponent of eccentricity, \(r\) is the limb radius, \(\rho''\) equals 206265 '', and \(\alpha\) is the angular
component of eccentricity.

We take a typical limb of an 80 mm diameter and then superpose it with the
axis of rotation. Usually the superposition accuracy is from 1 to 2 mkm. According

FIGURE 3.19 Barcode measuring system.
to this formula we evaluate the maximal value angular error as from 5″ to 10″!
Now we realize that we need not only high accuracy of theodolite adjustment, but also the highest quality of axial systems and bearings. The eccentricity influence could be minimized methodically by measuring the angle at two positions of the theodolite (see Figure 3.7). Two diametrically opposed sensors are set in high- and moderate-precision electronic theodolites to minimize this error. Some of leading manufacturers apply mathematical correction methods in electronic theodolites. After assemblage, the instrument is tested on an angle-measuring stand. According to testing, angular and linear components of this error are determined. Then they are written into the permanent storage of the microprocessor, which calculates eccentricity correction data and inserts them into every angular reading out.

In optical theodolites significant values of limb eccentricities may be visible. We could see limb images shifting about the mask edges while rotating the theodolite. It is advised to test limb eccentricity influence in the lab. In the center of a room with a stable floor we set up our tested theodolite. In order to test the horizontal circle eccentricity, we put from six to twelve marks at the same angular interval on the walls of the room. The marks must be set up at the same horizontal line and it is advisable that they be at the same distance from the theodolite. Then we carry out angular measurements pointing to these marks at both positions of the theodolite. Now we calculate collimating errors of every direction. Then we draw a diagram illustrating collimation error dependence of the horizontal limb position (Figure 3.21).

The diagram has a sinusoidal configuration, especially when errors are significant. The diagram amplitude should not exceed an acceptable collimating error for definite rating of a theodolites precision.

If we do not have the opportunity to distribute the marks evenly along the horizontal line, we may place only four or three marks distributed evenly within the angle of about 100°. Then we outline the tribrach position on the tripod base with a
pointed pencil. The next step is to measure the angles pointing to the marks at two theodolite positions. Then carefully unfasten the fastening screw of the tripod base and turn the theodolite at an angle of 120°. Then we superpose the tribrach with the contour on the tripod base and secure the tripod fastening screw. If we are testing an electronic incremental theodolite, we should not power it off during the test. Now fulfill the measurements again by pointing to the marks at two positions of the theodolite. Again we rearrange the instrument at 120° and fulfill the same measurements pointing to the marks. In this manner, we have from nine to twelve directions to test the horizontal circle eccentricity.

The vertical circle eccentricity test is less difficult. We should test out the eccentricity influence only during the operating range of the vertical circle ±30°. Three marks will do. One of them is set near to the horizontal line and two others are placed on the operating range edges. One of the marks is placed at the angle of 30° above the horizontal line and the other at the same angle below the horizontal line. The vertical angular measurements are carried out at two positions of the theodolite pointing to these marks. Then we calculate the zero positions (vertical indexes) for three vertical directions. If the zero positions are the same, eccentricity does not exist. If eccentricity exists, the zero position should not exceed the utmost limits for theodolites of this type of accuracy.

Limb inclination has very little geometrical influence on angular reads. Even an inclination of several minutes does not influence the result. Nevertheless, the limb inclination value must be less than one angular minute because of the following reasons. In an optical theodolite, modification of the distance between the microscope and the limb may be the reason for the limb image defocusing at various sections. In an electronic theodolite, this change of distance may have resulted in the sensor’s malfunction because of the signal changing level. The limb inclination is especially
unsafe for incremental electronic theodolites. The incremental sensor mask is usually set up at the distance of 10 mkm from the limb; that is why the limb inclination may have led to the mask and the limb coming in contact with each other. In this case they may be destroyed.

It is known that theodolites produced by leading manufacturers have properly setup limbs. Collisions seldom occur while using the theodolites, for their horizontal circles are properly protected and have strong axes. Meanwhile, the vertical limb may have changed its position in case of physical shock. The telescope is especially sensitive to impacts. Any time a theodolite is dropped we should test the limbs eccentricities.

### 3.5.2 Vertical Index Compensator of a Theodolite

#### 3.5.2.1 Vertical Index Compensator of an Optical Theodolite

Moderate precision optical theodolites have a more complicated optical scheme of the vertical channel because of existence of the compensator’s vertical circle index (Figure 3.22).

Compensation is carried out the following way. A parallel glass plate suspended on elastic strips is set between the vertical circle microscope and a mask. The suspension scheme is similar to a level compensator with a reverse pendulum. It is balanced by adjusting weights located at the upper part of the compensator pendulum. When the theodolite vertical axis is inclined along the longitudinal direction $x$ the parallel plate glass rotates around its axis keeping its previous balanced state. During this rotation, the vertical limb image is shifted about the mask scale at the required compensation value. At the moment of theodolite vertical axis inclination, the transversal direction $y$ of compensation does not occur. Therefore, when using optical theodolites it is necessary to closely watch the bubble position in the tubular level. In a moderate precision theodolite the level is always set in a transversal position.

![Vertical index compensator of an optical theodolite](image_url)
3.5.2.2 Vertical Index Compensator of an Electronic Theodolite

Compensators in electronic theodolites fulfill the same function that they do in optical theodolites, that is, they minimize influence of the vertical axis inclination upon the measurement results. Nevertheless, this problem in an electronic theodolite is solved in different manner than in their optical counterparts. An optical theodolite compensator changes the beam’s motion in the optical readout unit. The beam’s motion depends on the vertical axis inclination.

In electronic theodolites, the compensator is an independent device that measures slight angular inclinations of the vertical axis. Data from the compensator enters the microprocessor of the theodolite. It is up to us what to do with the data. We are able to give instructions to the microprocessor to take the data into account of angular measuring results. We can switch off the compensator or put the data into the display for estimating the instruments inclination. There are electronic theodolites that do not have a tubular level. In this case, we can use an electronic level to set the vertical axis into the plumb line. The theodolite preliminary setting is carried out with the circular level. The inclination along the direction $x$ mostly influences the measurement results. The direction is parallel to the plane of rotation of the telescope. The vertical axis inclination to the $x$ direction directly influences the vertical angle measurement result. The $y$ direction is perpendicular to the $x$ direction. So we can see from Equation 2.1 that the vertical axis inclination along the $y$ direction has less of an influence on the measurement results. That is why dual-axial compensators are usually applied in a total station and seldom in a theodolite.

A monoaxial compensator is applied in electronic theodolites where accuracy is $5''$ and above (Table 3.2). Unfortunately, some manufacturers do not set up compensators into $5''$ accuracy theodolites. This seems to show that it does not concern leading manufacturers. For instance, even Leica sets up dual-axial compensators into $9''$ accuracy theodolites.

Now we will look at a typical monoaxial compensator that is set up in most electronic theodolites (Figure 3.23).

The compensator’s main component is a tubular fluidal level whose external side has some metallic contacts. They are used as variable capacitor plates. Operation of such a tubular capacitor leveling cell was mentioned in Chapter 2. We should point out that the compensator in an electronic theodolite must meet higher requirements. We know that the length of the bubble in a tubular level depends on temperature. Tubular levels with vials whose sensitivities are from $20''$ per $2$ mm to $30''$ per $2$ mm are used in theodolites. Precision of the compensator provided with such tubular levels is about several seconds. This kind of precision in the whole operating range may be achieved only by taking into account temperature correction. That is why an electronic temperature sensor is set next to the vial. Data from the sensor enters directly into the theodolite microprocessor.

Any capacitor measurement system is very sensitive to electrical induction. That is why the compensator vial is protected with a metallic electrostatic screen.

On the bottom of the compensator bracket there are two holes to fasten it to the internal side of the theodolite standard. If we need to adjust the compensator, we should slightly loosen the fastening screws into these holes. Through gentle tapping
### TABLE 3.2
Up-to-Date Electronic Theodolites Provided with Monoaxial Compensators (or No Compensator)

<table>
<thead>
<tr>
<th>Model</th>
<th>Angle Measure Accuracy (°)</th>
<th>Magnification (n×)</th>
<th>Compensator Working Range (±n')</th>
<th>Tubular Level Accuracy (n''/2 m)</th>
<th>Minimal Focusing Range (m)</th>
<th>Manufacturer</th>
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<tr>
<td>DT202</td>
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<td>30</td>
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<td>1.35</td>
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<tr>
<td>ET-02</td>
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<td>BOIF</td>
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<td>40</td>
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<td>40</td>
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<td>Topcon</td>
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<td>—</td>
<td>60</td>
<td>0.9</td>
<td>Topcon</td>
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<td>Nikon</td>
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<td>BOIF</td>
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<td>30</td>
<td>—</td>
<td>30</td>
<td>1.3</td>
<td>BOIF</td>
</tr>
</tbody>
</table>

* — no compensator.

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we can incline the compensator along the $x$ direction until the tubular level axis is perpendicular to the vertical axis of rotation of the instrument. Afterward, the fastening screws should be tightened. As usual this kind of adjustment is initially set by the manufacturer, and if the theodolite is not disturbed, then the manufacturer adjustment will be sufficient during the service life.

As a rule, periodic electronic adjustments will suffice. Every electronic theodolite has special software for detecting the vertical circle zero position. The software is usually combined with an electronic level-adjusting program. Sometimes the electronic level-adjusting program is a detached point in the theodolite menu. More often, dual-axial compensators have such a program solution. All of these programs are available for users.

In case a theodolite has gone through a strong impact it is suggested to test the compensator. We must do this even if the theodolite correctly carries out program adjustment. During the test we should determine the compensator operating range and linearity of its work. We start by placing the theodolite at several meters from the wall so that one of the foot screws is directed to the wall. Now we set the vertical axis into the plumb position using the tubular level. Then we set the telescope horizontally, rotating it until the vertical angle reading out is equal to $0^\circ$ or $90^\circ$. Then we look up the compensator’s operating range in the technical specifications of the theodolite. It usually is $3'$. Then we mark three index lines on the wall. One of them is horizontal, and other two are $3'$ above and below the horizontal line correspondingly. Marking of these lines is fulfilled with the help of the vertical angle readout. The stand is now ready. Then we point the theodolite to the horizontal index line on the wall. Now we will turn the foot screw of the tribrach and superpose the horizontal line of the reticle with the upper index line on the wall. This way we incline the theodolite vertical axis at the $3'$ level. Then write down the vertical angle value. Ideally it must be equal to $3'$. The allowable difference is $\pm 3''$ for high-precision theodolites and it is $\pm 5''$ for moderate-precision theodolites. We test the compensator the same way inclining it in the opposite direction. At this point we superpose the reticle with the lower index line by the means the foot screw. If the deviations exceed the aforementioned values but are still the same at opposite inclinations, we can arrive at the conclusion of a nonrelevant scale factor.

If these deviations are asymmetrical that means the compensator shifted. The compensator position correction should be completed at a specialized workshop.

If you are well experienced in adjusting surveying instruments, you could try to adjust a monoaxial compensator by yourself. We would use the same stand. First, we set the vertical axis into the plumb position. Then we loosen the compensator slightly from the fastening screws. Then we put the telescope into the horizontal position and point to the horizontal index line on the wall. Now carefully turn the foot screw until the vertical angle readout stops changing. We mark this position on the wall. For the next step, we turn the foot screw to the opposite direction and mark the opposite point at which the compensator ceases operation.

Now we find the middle between these two points with a graduated millimeter ruler. Next we rotate the telescope and superpose the reticle with the middle. The vertical circle readout will now be different than $90^\circ 00'00''$. With light tapping on the compensator bracket, we try to get the readout close to $90^\circ 00'00''$. Twenty-second
accuracy will do. We should not tap heavily, as the fragile vial of the level might crack. Now let us carefully tighten the compensator fastening screws. Afterward, we must complete the adjustment with the help of the compensator software and carry out the tests again.

Electronic theodolites with dual-axial compensators are seldom used. Some examples of this type are listed in Table 3.3. One of the best known dual-axial compensators is shown in Figure 3.24. It has often been used in total stations from leading manufacturers and is also set up in the Sokkia electronic theodolites. The main component of this compensator is a precise circular level. Its bottom is made of smooth optical glass. The source of light is set up below. Beams freely go through the bubble center of the circular level. The beams that reach the bubble edges are reflected and dispersed. Those beams that have passed through the bubble go up past the vial freely with minimal deflection to the center. If we set up a screen above the level, we can then see the annular shadow moving during the circular level’s inclination. If we set up a four-photodiode matrix instead of the screen, we can watch the bubble’s movement analyzing the photodiodes’ signals. These photodiodes

<table>
<thead>
<tr>
<th>Model</th>
<th>Angle Measure Accuracy (°)</th>
<th>Magnification (n×)</th>
<th>Compensator Working Range (±n’)</th>
<th>Tubular Level Accuracy (n”/2 m)</th>
<th>Minimal Focusing Range (m)</th>
<th>Manufacturer</th>
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<tbody>
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<td>43</td>
<td>2</td>
<td>—</td>
<td>0.6</td>
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<tr>
<td>DT210</td>
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<td>3</td>
<td>30</td>
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<td>Sokkia</td>
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<tr>
<td>DT510</td>
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<td>30</td>
<td>3</td>
<td>40</td>
<td>0.9</td>
<td>Sokkia</td>
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<td>2T5E</td>
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<td>30</td>
<td>1</td>
<td>UOMZ</td>
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<tr>
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<td>4</td>
<td>—</td>
<td>—</td>
<td>1.3</td>
<td>Leica Geosystems</td>
</tr>
<tr>
<td>Builder T109</td>
<td>9</td>
<td>4</td>
<td>—</td>
<td>—</td>
<td>1.3</td>
<td>Leica Geosystems</td>
</tr>
</tbody>
</table>

**FIGURE 3.24** Dual-axes electronic compensator arrangement applied by Sokkia.
Theodolites

are set up on the electronic board together with amplifiers and a temperature sensor. The microprocessor applies these signals to calculate the bubble position. The bubble position information is available in either a graphic or digital form.

A dual-axial compensator is set up in the same location at a monoaxial unit, via the two fastening screws. It is adjusted along the \( x \) direction the same way as a monoaxial compensator. In order to adjust the compensator along the \( y \) direction, we turn the compensator case around its axis relative to the fastening bracket. Once the adjustment along the \( y \) direction is complete, the compensator is fixed with the help of the stopper screws.

Dual-axial compensator testing is very similar to monoaxial testing. Separate testing of both directions is carried out. The \( x \) direction testing is just like the monoaxial compensator testing. The \( y \) direction testing is also related, but the inclination angles are set in a different manner. First, we incline the theodolite along the \( x \) direction by rotating the foot screw and target the reticle to the index lines. Then we turn the theodolite at 90° and switch the display into electronic level mode. We can see the angular value of inclination along the \( y \) direction. We then switch the display into angle measuring mode and turn the theodolite 180°. Now we note the value of the inclination angle along the \( y \) direction. Then we correct the compensator along the \( y \) direction the way we did along the \( x \) direction. Of course, afterward we must finalize adjustment with the help of the compensator software and carry out the tests again.

A dual-axial compensator solution from Leica is shown in Figure 3.25.

---

**FIGURE 3.25** Dual-axes electronic compensator arrangement applied by Leica.
A leak proof vessel filled with silicone oil is used as a sensitive element in the compensator. The oil is used because oscillations subside quickly in it. The vessel has a transparent bottom. The upper surface of the oil has a mirror for the rays of light falling on the surface at an acute angle. LED emission is directed to an optical mask (Figure 3.26) that forms the image of orthogonal and inclined stripes. The image is turned with the mirror and goes through half of the objective. Then the image of stripes goes through the sensitive element and returns to the half of the objective that sends the image to the linear CCD.

There is an electronic signal at the CCD output (the lower part of Figure 3.26). The distance from the zero pixel to the central group of exposed pixels provides information about the $x$ direction's incline. The interval between two groups of inclined lines provides the information about the incline of the $y$ direction.

Other developers also use a vessel filled with silicone oil in their compensators. The solution brought forward by Trimble is shown in Figure 3.27. A narrow beam...
Theodolites come from an LED to the prism that rotates it to the vessel bottom. There is a lens window in the vessel bottom. The light beam is reflected from the oil’s surface. Then the beam hits to the image matrix. A similar type is used in camcorders. There is a light spot on the sensitive area of the image matrix. A video signal comes from the matrix output to the image microprocessor that calculates the $x$ and $y$ coordinate of the light spot energetic center.

In the newest designs Sokkia applies the same structure for a dual-axes compensator (Figure 3.28). Their main difference consists in using a square mask that consists of two crossing orthogonal barcodes. The mask image moves around the sensitive area of the image matrix as a result of the oil surface incline change. The image microprocessor calculates image movement along both the $x$ axis and the $y$ axis. Typical programs are applied for barcode image processing.

Compensators that have a vessel filled with silicone oil and an image matrix (or the linear CCD) are more stable than those with a tubular (or circular) fluidal level. Also they have a wide operating range and better linearity. This is why they usually do not require mechanical adjusting. Periodically a program adjustment of the compensators is necessary with the purpose of reassigning their zero pixels.

### 3.5.3 Theodolite Telescope

Modern surveying instrument telescopes are often based on Kepler telescope principles. The story about its development and its optical scheme is in Chapter 2. In theodolites, 20 to 40 times magnification telescopes are used. This kind of magnification is necessary because the naked eye has angular resolution of about 30′,
meanwhile required sighting accuracy in surveying is $2''$ and above. We know that Kepler telescope magnification is described as

$$M = \frac{f_o}{f_e}$$

(3.4)

where $f_o$ is the objective focal distance and $f_e$ is the ocular focal distance.

There are some technological limits in the choice of ocular focal distance. It is difficult to make a short-focus ocular with acceptable geometrical distortions. That is why focus oculars of less than 10 mm are seldom applied in surveying instrument telescopes. If we insert this value in Equation 3.4 we will see that at 30 times telescope magnification its length is equal to 300 mm. Previous surveying instrument telescopes were quite large and long.

Nowadays surveying instrument objectives consist of two parts. There is a front objective and a focusing lens (see Figure 3.29).

Dual-lens optical systems have equivalent focal distance:

$$F = \frac{f_o f_F}{f_o + f_F - l}$$

(3.5)

where $f_o$ is front objective focal distance, $f_F$ is the focusing lens focal distance (if the lens is negative the minus sign “−” appears), and $l$ is the distance between the front objective lens and the focusing lens.

When we analyze the formula we see that the equivalent focal distance $F$ is longer than the focal distance for the front objective lens $f_o$. That means that in order to get the required telescope magnification, we must apply a shorter focal front objective lens and then add a negative lens that is set at the distance $l$ following the front lens. Thus, the negative lens is applied for focusing. The total length of the telescope depends on the front objective lens’s focal distance. Dual-component objective appliances allow us to shorten the telescope length by a rough factor of 2.

Modern telescope objectives may consist of three components. Telescopes of this kind are applied in surveying levels. Theodolites only have dual-component

![FIGURE 3.29 Dual-component objective.](image-url)
Theodolites

objectives. Getting the direct image in theodolites is fulfilled the same way as with surveying levels. Optical schemes for converting reversed images into direct ones are described in Chapter 2. Abbe or Porro prisms are used for this goal (their full names are Abbe-Koefin or Porro-Abbe prisms).

Nowadays, in the majority of theodolites that have direct imaging, Abbe prism-type telescopes are applied (Figure 3.30).

This category of telescope consists of three main parts. These are the telescope’s main body with the objective front lens, a focusing system, and the ocular element. The main body of the telescope also has axle journals, which are not present in the figure. The objective of the theodolites usually has two or three lenses. Some of them consist of pairs of lenses that are joined together.

A theodolite focusing system consists of the focusing lens in a frame and a focusing knob. A cylindrical frame of the focusing lens has precise bearing slides allowing it to move along the optical axis of the telescope. The frame also has a cogged ledge connected with threading at the internal side of the focusing knob. As we rotate the focusing knob, the cogged ledge slides along the thread, causing the focusing lens to move.

A theodolite’s ocular element consists of an ocular, a reticle, and an inverting prism. The ocular is placed into a frame, which can be moved within several millimeters along the telescope’s optical axis by rotating the frame along the thread. Its movement is necessary for the reticle image individual focusing. The ocular consists of several lenses stuck together in pairs.

The reticle consists of two adhered round glass plates. The internal side of one of these plates has some crossed lines, whose thickness is 2 to 4 mkm. A two-plate solution is applied to protect the reticle from dust. The reticle is put into a frame, which can move along two directions by means of four adjusting screws. The direction of movement is perpendicular to the telescope’s optical axis.

Reticle adjusting units are of the pushing or pulling type. The pulling type is more popular now because in the pushing type reticles can be destroyed with excessive tightening of the adjusting screws.

The inverting prism is associated with the ocular part in that it is usually set on top of it. As mentioned earlier, besides the Abbe prism, an inverting Porro prism may

FIGURE 3.30 Theodolite telescope with Abbe prism.
also be used in theodolites (Figure 3.31). The Porro prism is quite often applied in
total stations, however only Nikon uses it in theodolites. Telescopes fitted out with a
Porro prism are a bit shorter than those equipped with Abbe prisms. The Porro prism
solution brings about the removal of the ocular axis relative to the objective axis.

Laser theodolites allow target visualization while fulfilling the layout. A direct
image telescope with a built-in laser module is the primary component of a contem-
porary laser-type theodolite (Figure 3.32). Laser and sighting channels are separated
by a splitting prism. This prism consists of two attached one-half fractions of a glass
cube. The internal side of one of these fractions has a monochromatic mirror cover-
ing. It reflects only laser spectrum beams, otherwise it is transparent for optical beams
in the visible range. The splitting prism is located between the focusing lens and Porro
(or Abbe) prism. That is why image and laser spot focusing occur simultaneously.

The source of light from the laser module is placed at the same distance from
the objective as the reticle. Therefore, at the moment the telescope is pointed to
the target, it is illuminated by the focused laser spot. Unfortunately, the part of the
laser light reflected from the objective lenses goes through the splitting prism and
illuminates the target with a red aureole. In order to eliminate this effect, we sug-
gest setting a protective red spectral filter onto the ocular at the moment the laser is
switched on. The removable spectral filter is available in the complete theodolite set.

The most well-known laser theodolites are listed in Table 3.4.

Theodolite telescope with a laser pointer.
The integral part of any theodolite is its targeting unit. A separated targeting and clamping screws solution was applied in the earliest theodolites and continued to be used for a long time. Such a solution is also applied in many contemporary optical theodolites. Nowadays, all low-precision optical theodolites have such a targeting system (Figure 3.33).

The most recently developed theodolites have more ergonomic coaxial targeting solutions. This is mainly in reference to high- and moderate-precision theodolites. Even some of these theodolites have a separated screws system. These are usually theodolites that are produced under license. Up-to-date electronic theodolites are released with coaxial screws only. Their horizontal targeting solutions have the same operating principle. The coaxial screw arrangement as shown in Figure 3.34 and is typical for Sokkia and Pentax theodolites. Topcon and Nikon instruments also have

### TABLE 3.4
Up-to-Date Electronic Laser Theodolites

<table>
<thead>
<tr>
<th>Model</th>
<th>Class of Accuracy</th>
<th>Value of Accuracy (&quot;)</th>
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<td>9</td>
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</tbody>
</table>

![FIGURE 3.33](Targeting unit provided with separated screws.)
similar coaxial screws. Topcon and Nikon solutions have a thin targeting screw that is set in the inside of the clamping screw.

Leica theodolites have so-called infinite screws (Figure 3.35). Here you can see the targeting unit arrangement for the theodolite horizontal axis. A worm gear is used for accurate sighting. In order to establish preliminary aiming, we should make some effort to turn the theodolite getting over the wavy spring braking force. A good aspect of the solution is faster targeting. As far as the efforts made to turn the theodolite are considerable, the foot screws and the tripod stability must meet high requirements (Figure 3.36).

If the error quantity from 10” to 60” errors occur while measuring horizontal angles, we should check the leveling screws and the tripod. As needed, we should adjust them. Surely they must be checked while using any theodolite; however, it is the theodolites with infinite targeting screws that are especially sensitive to these errors.
Theodolites

3.5.5 THEODOLITE PLUMMETS

In order to set the theodolite exactly over the point of reference, in modern times we apply built-in optical and laser plummets. The optical plummet is the Kepler telescope provided with an internal focusing lens (Figure 3.37). The direct image is achieved by the right-angled roof prism that also directs the plummet optical axis vertical down. The bush of the theodolite’s vertical axis is hollow. The plummet optical system’s magnification is usually about three times. The telescope reticle is superposed with the theodolite vertical axis with four adjusting screws.

The superposed accuracy of the theodolite’s vertical axis, with the plummet axis, is assessed the following way (see Figure 3.38). We place the tripod with the
theodolite on a plane surface and mark point $A$ by means of the plummet. At this time we do not pay attention to the position of the bubbles. Then we turn the theodolite to $180^\circ$ and mark point $B$. If we split the distance $AB$, we get point $C$, which is found on the theodolite’s vertical axis. Then we should superpose the reticle with point $C$ by adjusting the reticle screws. Again, we now rotate the instrument to $180^\circ$
Theodolites

and check whether the reticle is removed from point C. If so, we should complete the adjusting steps once more.

Optical plummets of this kind can be easily converted for laser use (Figure 3.39). Manufacturers install a laser module instead of the reticle and the ocular. Checking and adjustment are carried out in the same manner that the optical plummet is tested. In this case, the adjusting screws remove the laser module case and not the reticle.

These days, optical plummets are mainly built into the theodolites and seldom are on the tribrach. Optical plummets that are built into tribrachs are more typical for low precision theodolites. It is difficult to adjust a plummet that has been built into the tribrach. It is often advised to adjust the plummet by placing the theodolite sideways onto a table edge, and then turning the tribrach itself to 180°. The points are marked on a paperboard set up at 1.5 m distance. We do not advise this sort of adjustment for a theodolite, as it is difficult to fasten it properly at the edge of the table. We risk dropping the instrument. It would be better to use some other accessories such as a prism reflector holder or an angle measuring mark.

We can also adjust this plummet by the means of tribrach removal at 120°. We put the theodolite on the tripod and then properly set the horizontal aspect. Then we outline the contour of the tribrach on the tripod base. Now we mark a point according to the plummet reticle on the paperboard, which is placed under the tripod. Now we slightly loosen the fastening screw and turn the tribrach to 120°. Then we accurately superpose the tribrach with its contour on the tripod base. Again, we set the horizontal aspect of the theodolite and mark the second point on the paperboard. We use this same procedure to get the third point. Afterward, we find the triangle’s center and superpose the reticle with it by fine-tuning the adjusting screws.

Laser plummets built into a theodolite’s vertical axis are considered to be the most current and accurate (Figure 3.40). Here we see that it is very well protected and does not demand adjustment. Coincidence between the theodolite’s vertical axis and the laser beam are guaranteed by the manufacturer.
BIBLIOGRAPHY