Acknowledgements

Had Pheidippides, ancient epitome of the self sacrificing herald, died of exhaustion before he could utter his famous words “We have won!” in front of Athens elected archon, the message would have faded before its echoes had a chance to change history. Three little words deciding the outcome of a game of “all or nothing” much like a book’s publication sounds the author’s message to the world rather than let it fade away unheard.

Which brings to mind those whose criterion and diligence made that the message on the pages of this book doesn’t rest there forever, but got off to reach the minds of those concerned. And herewith go my heartfelt thanks to those at SpringerWienNewYork who dedicated their time and efforts to help my writing to overcome that threshold, in particular Mr. Stephen Soehnlen, Editor Natural Sciences, and Mr. Edwin W. Schwarz, Project Management.

Within my personal sphere my thanks go to my son in law, David Lench, for helping me with his professional knowledge and experience in hammering out my publishing contract with Springer; and likewise to all those who put up with my work related eccentricities and offered their support and input whenever asked for: My wife Gerda von Hebra and our daughter Renata von Hebra Lench, who both helped in reading proof pages and offered valuable comments on engaging and readability of my text. My sons Alexandre and Andre, and my grandchildren Daniel, Julie, and Ashley Lench; Melissa von Hebra; and Alexander and Andre von Hebra, whose patience used to be unduly strained by the priorities I extended to my work.

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And last but not least, I thank the country that became my new home for opening its vast markets and opportunities to my work and activities.
When Albert Einstein’s assistant alerted him that present year’s examination papers had the same questions as last year’s, Einstein responded: “True, but this year all answers are different.”

Likewise, this year’s measuring instruments might be different (and hopefully better) than last year’s, but the principles underlying their operation remain the same. You may set up an instrument by pressing buttons on its face plate, or click on virtual buttons popping up on your monitor; you may read the measured values on old fashioned dials, or from digital readouts. But the methods for obtaining those values are dictated by the immutable laws of nature. What changes are our ways of interpreting what those laws have to tell.

The concept of measurement brings us to the eternal question of the “appropriate” units of measure, which has split the world in two camps: Those based on the British Imperial System of Weights and Measures (what a complicated way of saying “ours”!), and the other side, the metric units, which were updated and unified a few decades ago into the International System of Weights and Measures.

It may surprise that both, the US customary system and the metric system, refer to the meter as the universal unit of length, but the truth of the matter is that the United States gave up on their proprietary standards of length and mass in 1893, and based their customary units on the meter standard bar and the kilogram standard mass. Following some minor corrections, our inch became exactly 25.4 millimeter (0.0254 meter), which makes the foot exactly 0.3048 meter. This yields the whole number relation of 5 inches = 127 millimeter.

The meter, originally intended as the ten millionth part of the meridian quadrant, lost this distinction when updated surveys revealed that distance as equal to 10,001,954.5 meter. But by then, the classical meter standard was already far too entrenched in commerce and industry worldwide as to allow for updates. And the latest definition of the meter, 1/299792458 of what a ray of light travels in vacuum in one second, has been derived so as to match the de facto length of the meter standard bar – not the other way round. Anyway, it would be hard to imagine that somebody out to check the accuracy of a caliper, micrometer, or gauge block, would do so by comparing his tools with the length of the meridian quadrant or the velocity of light, while NIST keeps all standard references at your fingertips, so to say.

1 the distance from the equator to the pole.
Metric units are taught in our schools because formulas and equations are more transparent with them than in our foot/pound system. And conversion is simple. At the gas station, you get 3.785 liter for the price of a gallon. And on the scale in the grocery store the pound stands for 0.454 kilogram. Better still, the kilowatt-hours of electricity in your monthly utility bills are the same in all systems of measure.

No big deal. But wait, and forgive me for warning that things get worse – read somewhat more complex – before they get better. The headache of native foot pound users is the metric unit of force. Accustomed as we are to the pound stepping in for mass and force as well, we find it strange that mass should come in kilogram, force however in newton (N). Blame the space age, that made the weight of one kilogram of mass only 1/6 kg on the moon and 0.40 kg on planet Mars. So the “honest pound” (as some of the anti-metrics call it), isn’t so honest anymore if you take it on a ride into space. What’s invariable is the mass, be it of the pound or the kilogram or any other quantity. The weight, actually the gravitational force on a piece of mass, is location dependent.

So, the International System of Weights and Measures changed from gravitation defined units to a unit of force built on inertia rather than the weight. The unit of newton is thus the inertial force of 1 kg of mass being accelerated by 1 meter per second squared. Under earthbound conditions, that means that 1 N = 1/9.80665 kilogram of force.

Whenever you look at the math in this book, remember that an input of mass in kilogram gets you force in newton. Also that pressure results in newton per square meter (called pascal or P), and not in psi, atmospheres, or mm Hg. So far, you needn’t worry about the rest. Much like you learn to drive a car by driving one rather than by brooding over instructions, familiarity with metric units will follow the lecture of this book pretty much by itself.

Metrology keeps our civilized world alive and kicking. Precise measurements make that the replacement parts for our cars always fit, that doorframes can be bought off the shelf, and that a five pound bag of sugar contains five pounds. Like a friendly genie, metrology has been around all the time to help – and yes, sometimes control – our lives. Let’s let the genie out of the bottle and contemplate her features!
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1 The measurement of length

The great Pyramid of Gizah towers over the Egyptian desert. In modern units, it is over 725 feet, or 230 meters tall. The Ancient Egyptians, though, used neither feet nor meters, but cubits – the length from the tip of a middle finger to the elbow. In terms of cubits, the Great Pyramid stands on a base of sides 439.80, 440.18, 440.06, and 440.00 cubits. How did they measure these distances? Suggestively, 439.82 = 140π. A wheel of one cubit diameter has a circumference of π cubits. Roll this 140 times, and you will have marked out the side of the pyramid. If the Egyptians used an early version of a perambulator or trundle wheel, their devices were accurate to 0.1%!

No wooden artifacts have been preserved from antiquity into our times, which may explain that we lack direct proof of an Egyptian wooden device for measuring distance. Hieroglyphs do show people using ropes with regularly spaced knots to measure. These ropes were conserved by rubbing them with a mixture of resin and beeswax. But attempts to measure a building the size of the pyramid with hemp ropes would have been plagued by the effects of the applied pull, changing air temperature and humidity. Copper bars would have shrunk in the cold of the desert nights and expanded in the heat of day.

Trundle wheel

The followers of Pharaoh’s use of a rolling disk was likely due to wood’s low thermal expansion, of 3 to $4 \times 10^{-6} \degree\text{C}$, about 1/3 that of steel. Trundle wheels similar to Fig. 1.1 have been in constant use ever since. Early in the eighteenth century, John Bennet\(^1\) used fine brass to craft trundle wheels with multiple scales in units of poles (equal to the rod, of 16.5 feet or 198 inches in length), furlongs (220 yards), and miles (5280 feet). The wheels had 30.51 inches diameter, which made their perimeter a straight 99 inches or half a pole, so that the device advanced by one pole for every two revolutions of the wheel.

In the clockmaker’s tradition, the dials of Bennet’s waywisers resemble clock faces, complete with large and small hand, and a third, still smaller hand on a separate scale, like the seconds dial on traditional pocket watches. This allowed for readouts in the British length units of that period.

Trundle wheels of up to six feet diameter were used in surveying because bigger wheels are insensitive to bumps and ditches. While small wheels measure the

\(^1\) British clock and instrument maker.
inner perimeter of a ditch they roll through, wheels which radius exceeds the
dwidth of the ditch bridge it from edge to edge and size its width. Eighteenth-cen-
tury trundle wheels, called Waywisers, whose structure resembled a lightweight
wheelbarrow, came from England and remained in use in the United States for
another one hundred years. In more recent times, simple trundle wheels are being
sold in hardware stores for a host of uses, such as pricing of fences and prelimi-
nary layouts of lots and buildings.

The familiar automotive odometer uses the principles of the trundle wheel, for
it picks up the revolutions of the vehicle’s wheels and, through reducing gears
of appropriate ratio, converts their count into miles traveled. For instance, a car
with properly inflated P185/75-14 tires, of 24.925 inches external diameter, drives
24.925\pi = 78.304 inches or 78.304/12 = 6.525 feet per turn of its wheels. With
5280 feet to the mile, that gets us 5280/6.525 \approx 809 revolutions per mile. There-
fore, a typical odometer, which readouts advance by one mile for every ten rev-
olutions of the instrument’s driveshaft, has to be actuated over a 10/809 = 1:80.9
gear reducer to read miles. Part of this reduction is provided by the typically 1:3
stepdown of the differential.

If you drive with low tire pressure, the odometer renders exaggerated mileage
readings, because the effective radius of the wheel, from hub to pavement, is be-
low standard and the wheel has to turn more often to cover a given distance.

The updated version of a trundle wheel (Fig. 1.1) typically employs a circular
disk of 5.730 inches diameter, which rolls over 5.730\pi = 18 inches per turn. Adding
an 18 teeth ratchet and counting the “clicks” would give rolling distances in
inches per click, but mechanical counters have since taken the place of Bennet’s
precision dials. Thus the trundle wheel has changed from Bennet’s analog devices
into a simple brand of today’s digital instruments.

Fig. 1.1. Trundle
wheel for length and
distance measurements
Chains and tape measures

The temperature sensitivity of metallic measuring tools might be the reason that their use spread no sooner than the invention of the thermometer and the availability of data on thermal expansion of metals. As the first thermometers, then called “thermoscopes,” turned up in the early sixteen hundreds, Aaron Rathborne’s personal “Decimal Chayn” was reported on in 1616.

The Rathborne chain of ten links, which added up to the length of one pole or 16.5 feet, was followed by Edmund Gunter’s 100-link chain of four poles (66 feet) overall length. The nineteenth-century “Engineer’s Chain” was made of one-foot links and measured fifty or one hundred feet overall. A modern Keuffel and Esser chain of this type is made from No. 12 gauge steel wire links, brazed shut, and carries a center spring hook for dividing the chain – if needed – into two identical halves.

In surveillance work, thermal expansion must be precalculated and taken into account. Where money is not an issue, Invar, an alloy of 36% nickel, 0.2% carbon and 63.8% iron, with its coefficient of expansion \(1.26 \times 10^{-6}\) almost ten times lower than that of steel, makes for tape measures that can be used – in most cases – without worrying about temperature.

Steel measuring bands were first fabricated in 1853 by James Chesterman (1792–1867) of Sheffield, England, and became the forerunners of present days pretensioned and springloaded steel tapes.

Distance measurement

Where tape measures become too short and trundle wheels too laborious, several types of instruments, from simple to sophisticated, are available for the job.

If high accuracy is not essential, a telescope with a crosshair scale in the eyepiece, along with a surveyor’s staff (also called “stadia”) will do. In Fig. 1.2, ten divisions on the telescope’s eyepiece scale coincide with one 10 cm long field on the staff, if posted 10 meters away. Move the staff to 20 meters, and the image of one shaded area will coincide with only 5 crosshair scale divisions. At 100 meters, scaling of staff and crosshair coincide. In short, the distance of the staff and the apparent size of its scales in the telescope are inversely proportional to each other.

Although this method lacks precision, it excels in simplicity. In a similar approach to measuring the distance to neighboring stars, Astronomers use the diameter of the orbit of Earth in ways of a staff. With 149.6 million kilometers from the Earth to the Sun, our planet’s position in the galaxy shifts by

\[ 2 \times 149.6 = 299.2 \text{ million kilometers in six months}, \]
causing an equivalent drift in the apparent positions of the stars. In 1838, Friedrich Wilhelm Bessel (1784–1846) was first in reliably measuring this motion, called parallax, on the star 61 Cygni in the constellation of Cygnus, the Swan. Though only few fixed stars locate close enough to show parallactic displacements, this method created a specific astronomic length-unit, the parsec, equal to the distance from where the radius of the orbit of Earth is seen one arcsecond wide. With \( 360 \times 60 \times 60 = 1,296,000 \) arcseconds to the full circle, the circumference of a circle with one parsec radius is \( 1,296,000 \times 149.6 \times 10^6 = 193.88 \times 10^{12} \) kilometers, which makes its radius equal to \( (193.88 \times 10^{12})/2\pi = 30.857 \times 10^{12} \) km. And with \( 9.460550 \times 10^{12} \) km to the light-year (ly), this leads to the conversion

\[
1 \text{ parsec} = \frac{30.857 \times 10^{12}}{9.460550 \times 10^{12}} = 3.26 \text{ ly}.
\]

The unit we got here seems enormous, and yet, no fixed star locates within the one parsec range. The Sun’s closest neighbor, Alpha Centauri on the southern celestial hemisphere, is 1.33 parsecs or 4.34 light-years away.

## Triangulation

The efforts of ancient Egyptians in re-appropriating the fertile land along the Nile every year after the waters of the river swept their landmarks away mark the first steps in the development of geometry and mathematics, which much later in history inspired generations of scientists in the Hellenistic age, such as Euclid, Archimedes, Eratosthenes, and Heron of Alexandria. The latter was first to come up with a formula for the area of a triangle based on the lengths of its sides.

Since the triangle is the building block of all other polygons, Heron’s formula can be used for multifaceted areas as well. For instance, a quadrilateral can be split into two triangles, the pentagon into three, the hexagon into four, and an \( n \)-sided polygon into \( n - 2 \) triangles. If you own a piece of land bordered by the sides \( a, b, d, \) and \( e \), you can find the square feet of your property by measuring the length of one of the diagonals, \( c \), and apply Heron’s formula to the resulting triangles \( a - b - c \) and \( d - e - c \). For a start, call the circumference of the first triangle \( 2s \), so that

\[
s = \frac{1}{2}(a + b + c),
\]

and use Heron’s formula for the area \( A \) of said triangle as follows:

\[
A = \sqrt{s(s-a)(s-b)(s-c)}.
\]

Repeat that process for the second triangle, add the two areas, and – voilà – you got the square feet of your four-sided land without buying a theodolite.

Although we remember Heron of Alexandria as a prolific writer on geometry and mechanics, including pneumatics, we aren’t even sure about his name. Some called him Heron, others Hero, and his date of birth has not been documented.
Historians place his lifetime between 250 BC and 150 BC. He might have been a Greek or an Egyptian with Greek education, but his mark on history remains, whatever his lifetime and nationality!

Modern times surveyors use an arbitrary baseline between two landmarks, A and B in Fig. 1.3, to describe the position of an object P by its plane coordinates, \( x \) and \( y \).

We have two distinct methods to determine an object’s position: **triangulation** and **trilateration**. Triangulation is defined as (take a deep breath) “measurement of the position of an isolated point in space accomplished by constructing a scalene triangle with a known base and known angles of the two adjacent legs.” In Fig. 1.3a, the coordinates \( x \) and \( y \) of point P are derived from the length of the baseline, \( a \), and the angles \( \alpha \) and \( \beta \), measured from points A and B to P. The geometry of the figure allows for direct deduction of the relations

\[
x \tan \alpha = (a - x) \tan \beta,
\]

which yields

\[
x = a \frac{\tan \beta}{\tan \alpha + \tan \beta} 
\tag{1.1}
\]

and likewise

\[
y = a \frac{\tan \alpha}{\tan \alpha + \tan \beta} 
\tag{1.2}
\]

Make A and B the milestones on a straight section of highway, and P the location for, say, a planned gas station, and you get \( x \) and \( y \) as the coordinates of P relative to the origin of the stretch of highway you selected as baseline.

If the baseline AB is drawn in the direction east-west, the geographical coordinates of the object P can be found by converting \( x \) and \( y \) into degrees of longitude and latitude and summing their values to longitude and latitude of point A. Keep in mind that for a place in North America, \( x \) and western longitude are counted in opposite directions, which makes the values of \( x \) negative.

The degree of *latitude* equals 60 nautical miles, which makes 1’ (minute of arc) of latitude equal to one nautical mile. In metric units, the degree is 111 km. These values are not exact; due to the oblate shape of the Earth, they vary slightly with the observer’s location.

By contrast, the degree of *longitude* equals that of latitude along the equator only, but shrinks toward the poles proportional to the cosine of the latitude of the observer’s location. Here again, this relation gains complexity if we consider the ellipsoidal shape of the globe, and reads for this case

\[
L = \cos \phi (111.320 + 0.373 \sin^2 \phi),
\]
where $L$ stands for the length of one degree of longitude in kilometers, and $\varphi$ for latitude.

Surveys for housing developments and other short-distance projects are usually conducted under the supposition of a flat Earth, and the Eqs. 1.1 and 1.2 apply. Farther reaching projects must account for the spherical shape of the globe and use the math of spherical trigonometry for the deduction of the equivalents of said equations. Continent wide measurements need to count in the oblate shape of the Earth, and for highest accuracy, even the local irregularities in the shape of the Earth’s surface. Such complexities turned up in the case of the French engineer and surveyor P. F. André Méchain, entrusted with measuring the length of the meridian quadrant. Méchain’s work was to create the natural basis of the metric length unit, the mètre, which later became the fundamental unit of the metric system, the meter. Although Méchain did his math correctly, his network of triangulations wouldn’t close at a single point because he apparently underestimated the magnitude of some deviations of the shape of the globe from an ideal ellipsoid.

The concept of triangulation reaches back into the late fifteen hundreds and apparently stems from the Danish astronomer Tycho Brahe. Since the telescope hadn’t yet been invented at Brahe’s times, all his observations were done with visors sliding along enormous quarter-circular scales. Nonetheless, his measurements of the positions of the planets on the sky were of such precision that they allowed for Johannes Kepler’s deduction of his laws on the motion of celestial objects.

**Theodolites**

Present-day instruments for measuring the angles $\alpha$ and $\beta$, called theodolites (or dioptra in older texts) (Fig. 1.4), rely on a sighting telescope with crosshairs in the
eyepiece, mounted in a U-shaped support frame. It can be rotated horizontally and tilted vertically. The angles of rotation and tilt are read through extra eyepieces, sometimes called microscopes, on graduated measuring circles with usually one minute of arc precision.

Before use, the instrument is set up and precisely leveled on a sturdy tripod. Some types of theodolites have a compass encased in their base, but the “magnetic declination” of the needle – an angular deviation from true North stemming from the different locations of magnetic and geographic poles – makes a compass a poor match for the accuracy of the Sun’s meridian transit. Presently, magnetic North locates in the area of Prince of Wales Island in the Arctic Archipelago north of Canada. However, its position changes over the years.

Updated models of the theodolite with optoelectronic encoders replacing the graduated measuring circles offer digital readouts with typically one arcsecond of accuracy. But all that gadgetry is hidden inside the telescope’s U-mount, which is why a classical instrument, with all its parts in the open, has been chosen for Fig. 1.4.

The invention of the theodolite is credited to Leonard Diggs of Kent for his 1571 description of such an instrument in his book Pantometria. But only the circular dividing machine, constructed in 1775 by Jesse Ramsden (1735–1800) made the crafting of scales for true precision-instruments possible.

In 1782, when British cartographers intended to catenate the locations of the Royal Observatory in Greenwich, England, and the Observatory in Paris, France, by triangulation, Jesse Ramsden was appointed to build a theodolite with the necessary accuracy. His instrument, nicknamed “The Great Theodolite,” now housed in the Greenwich Museum in England, weighs some 200 pounds and sports a three-foot diameter horizontal circle. But the two mightiest theodolites ever, also fitted with 36 inches wide scales and five scale reading microscopes, where built in the early eighteen hundreds for the “Great Trigonometric Survey” on British India. So heavy were those behemoths that it took twelve men to carry one around.

In 1843, with Andrew Scott Waugh in charge of the project, surveyors focused on the distant Himalayan peaks in the north of India. Hidden by clouds and haze most of the time, those peaks could rarely be viewed from the expedition’s point of observation down in the lowlands, some 100 miles distant. Nevertheless, Radanath Sikhdar, in charge of the trigonometric evaluation of the survey’s data, reported in 1852 the discovery of “the highest mountain in the world,” then designated Peak XV. Waugh himself renamed it four years later to Mount Everest after Sir George Everest, Waugh’s predecessor as chief surveyor.

While triangulation measures the angles of the lines of sight from two observers to the target, trilateration uses the distances \( b \) and \( c \) between observers and target (Fig. 1.3b). For this case, we derive

\[
b^2 = x^2 + y^2 \quad \text{and} \quad c^2 = (a - x)^2 + y^2
\]

\(2\) 29,028 feet high.
which yields
\[ x = \frac{1}{2a} (a^2 + b^2 - c^2) \]
and
\[ y = \sqrt{b^2 - x^2} \quad \text{or} \quad y = \frac{1}{2a} \sqrt{(2ab)^2 - (a^2 + b^2 - c^2)^2}. \]

**Optical distance meters**

The principles of triangulation and trilateration pop up in everyday items, such as the optical rangefinders we find in photographic cameras, where a miniature telescope (Fig. 1.5) shows the object’s reflections in a pair of face coated mirrors; one set at 45°, and the other pivotable around its 135° homing position. The former’s coating is semi-transparent, the other’s solely reflective. Through the eyepiece the viewer sees two distinct images, which merge into one when the adjustable mirror is rotated by \( \varphi = \alpha / 2 \) off its 135° base position. \( \alpha \) is the angle between the lines of sight from the object to each mirror and thus depends on how far the object is away. With \( a \) for the spacing of the mirrors, and \( D \) for the distance of the object, we get from Fig. 1.5

\[ \tan \alpha = \frac{a}{D} \quad \text{and} \quad \alpha = \arctan \frac{a}{D} \]

![Fig. 1.5. Rangefinder](image-url)
and figure the correct rotation angle of the mirror in degrees as

$$\varphi = 135 + \frac{\alpha}{2} = 135 + \frac{90}{\pi} \arctan \frac{\alpha}{D}.$$  

The circular unevenly spaced scale shown in Fig. 1.5, upper right, is derived from this equation.

With range finder cameras, you don’t have to physically read such a scale, as a cam governed drive mechanism transfers the angular displacement of the pivoting mirror to the spiral groove mount of the objective lens and moves it forth and backward into focus. Sharpness of the shot depends on how well the profile of the cam has been matched with the optical characteristics of the objective lens.

Correct focusing – manual or auto – is the basic and most important condition for shooting good pictures. The most expensive objective lens, if improperly focused, might be outperformed by its counterpart in a disposable camera. Few photographs from the era of plates and films match the sharpness of Anselm Adams’ classical landscapes, shot with a view camera from nearly a hundred years ago.

**Reflective distance meters**

Much like rangefinders, reflective distance meters too measure distance by triangulation. The reflection of a focused laser beam by the target is projected by a stationary objective lens onto a PSD\(^3\) image sensor. The position of the resulting point of light on the PSD changes with the instrument’s distance from the target, as can be seen in Fig. 1.6, where the light spot strikes the sensor farther down the further away the target is.

A gradually darkening light filter in front of the sensor is used to convert the light spot’s position into an electrical signal. Again in Fig. 1.6, the beam from target B goes through the thickest region of the filter, of highest opacity, while the beam from target C crosses the filter’s thinnest and therefore lowest opacity zone. As the PSD converts light intensity to voltage, the readout from the beam reflected by B will be much less than that from C.

---

3 position sensitive device.
If the location of target A has been selected for the light spot to centrally strike the image sensor, the instrument’s readout is set to zero and the distance of A becomes the “Instrument Constant.” Other positions, such as C and B, are counted from there up and down, as exemplified by the voltage outputs marked on each of the three differently set targets in Fig. 1.6.

If all that sounds too good to be true, it is. Making this principle into a usable instrument involves a series of highly complex design features, due to a number of factors, other than the target’s distance, are paramount for the voltage output of the PSD. They include the intensity of ambient light, the target’s reflectivity, and the losses of brilliance along the light path.

The effect of ambient light is eliminated by flashing the light source sequentially on and off. This makes its output an alternating voltage (AC), while the voltage stemming from ambient light is continuous (DC). Those two components are separated by a capacitor, which impedance $R_C = 1/2\pi f C$ is frequency dependent. $R_C$ is low for high frequency AC, but tends toward infinity for DC with $f = 0$.

Differences in the target’s reflectivity, which reach from 0.05 for black paper to 0.92 for fresh snow, with porcelain (0.75) and Stellite (0.62) in between, are dealt with by using a light-sensing semiconductor to convert a sample of the reflected light into a control voltage that sets the intensity of the light source inversely to the target’s reflectivity. This also takes care of distance contingent variations in the intensity of the reflected beam. A signal processor (let’s think of it as a chip) stores information on all those sources of error, and uses them to correct and linearize the output voltage accordingly.

Reflective distance sensors with ±0.001 inch precision are available in various ranges from 0.375 inches to 6 feet and more. Beyond simple distance checks, their applications include the alignment of CNC machine tools and MRI medical imaging devices; further position recognition, depth of hole and thickness measurements, checks on sag of beams and plates, and filling levels in tanks.

## Beam-modulation telemetry

Beam-modulation telemetry, also known as *tone ranging*, measures an object’s distance by sending an intensity-modulated light-beam toward the target and derive the time difference between emitted and reflected beam from their mutual phase shift. It is used in constructional surveys and for high-accuracy distance metering in general, but also in object recognition devices in warehousing and in collision avoidance systems for pilotless vehicles.

Some commercial instruments offer millimeter precision over the range of several kilometers, while short range high accuracy instruments are made to operate within 5 meters on diffusely reflecting (noncooperative) targets, and up to 20 meters if a mirror-like reflector (cooperative target) is being used.

The technique of deriving an object’s distance from the time difference be-

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4 computer numerical control.
between sending a signal and receiving its reflection is self evident. We estimate the distance of a thundercloud by dividing the time between seeing a bolt and hearing the thunder by the velocity of sound (341 m/s). Radar takes the same approach with radio waves, and the GPS satellite ranging system figures the distance between satellite and ground station from the time it takes radio signals to travel that distance. A technique hard to emulate “back home,” because electromagnetic waves, including light, propagate at such frightening speed$^5$. For instance, the time between triggering a flash and seeing its reflection from a 30 meter (ca. 100 feet) distant mirror would amount to 0.2 millionth of a second (0.2 $\mu$s) – obviously impossible to clock. But such minute time intervals can be detected by comparing them with the cycle time ($T$) of a rapidly flashing light source.

$^5 c = 300,000 \text{ km/s}$.

**Fig. 1.7.** Tone ranging distance meter