J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

ALTIMETERS

Altitude for the purposes of this article, is the elevation of an object above a given level. (In astronomy, navigation, and surveying, altitude means the angular height of a celestial body above the plane of the horizon.) *Altimeters*, are instruments that measure altitude. Altimeters represent an advanced technology, finding diverse commercial and military applications ranging from air transport to space exploration. There are many companies (Table 1) offering wide range of altimeters and altimeter-related products.

There are three main types of altimeters:

(1) The pressure altimeter, which uses changes in the atmospheric pressure to infer altitudes.
(2) The radio detection and ranging (or *radar*) altimeter, which measures the time required for a continuous wave (*CW*) or pulse of radio energy to travel from an object in the atmosphere to the ground and back.
(3) The optical altimeter, based on laser optics, operating mainly on pulsed energy transmission, as in the case of laser radar (LIDAR).

Altimeters are usually associated with aircraft, but they are also used in geodesy and surveying, navigation weapon guidance systems, parachute jumping, mountaineering, and so on. The accuracy and the sophistication of the sensors and the associated electronics and computing power of altimeters depend on the measurement requirements. For example, in remote sensing applications, the selection of the sensors depends on the platform of the operation, as illustrated in Fig. 1.

Altimeters can be divided into two categories:

(1) Instruments that measure the altitude of an object above a fixed earth reference level (e.g., sea level)
(2) Instruments that measure the distance between an object and some earth reference

Instruments in the first category are of the barometric types that use the static air pressure at some altitude to infer height above a reference level. The second category is much broader and is based on the use of electromagnetic waves to determine altitudes. Some devices in this category are radar altimeters, laser altimeters, and the global positioning system (*GPS*s).

Barometric Altimeters

Barometric altimeters are based on the measurement of atmospheric pressure. The atmospheric pressure is compared with a reference pressure by a mechanism such as shown in Fig. 2. Over the years, many different mechanisms have been developed for barometric altitude measurements. However, they all rely on the use of a relation between air pressure and altitude.

Table 1. List of Manufacturers and Suppliers

Aeronautical Instrument & Radio Co.
234 Garibaldi Avenue
Lodi, NJ 07644
Tel: 973-473-0034
Fax: 973-473-8748

Aerospace Industries, Inc.
333 N. Broadway, Suite 3011-T
Jericho, NY 11753
Tel: 888-200-2681
Fax: 516-932-3307

A. I. R., Inc.
8401 Baseline Road
Boulder, CO 80303
Tel: 303-499-1701
Fax: 303-499-1767

Allen Osborne Associates, Inc.
756-T Lakefield Rd., Bldg. J
Westlake Village, CA 91361
Tel: 805-495-8420
Fax: 805-373-6067

AlliedSignal Inc.
101 Columbia Rd., Customer Operations
Morristown, NJ 07962
Tel: 800-707-4555
Fax: 602-365-3343

American Paulin System
1455-T Rocky Knolls Road
Cottonwood, AZ 86326
Tel: 520-634-0980

Atmospheric Instruments Research Inc.
8401 Baseline Rd., Dept. T
Boulder, CO 80303
Tel: 303-499-1701, Ext. 300
Fax: 303-499-1767

Azimuth Corp.
13-T Park Drive
Westford, MA 01886 3511
Tel: 978-692-8500
Fax: 978-692-8510

COSCO, Inc.
95 N. Lincoln St.
Denver, CO 80203
Tel: 800-372-6726
Fax: 303-777-3331

Garmin International, Inc.
1200-T E. 151st St.
Olathe, KS 66062
Tel: 913-397-8200
Fax: 913-397-8282

GEC-Marconi Hazeltine Corp.
164-T Totowa Road, P.O. Box 975
Wayne, NJ 07474-0975
Tel: 973-633-6000
Fax: 973-633-6431

Honeywell Inc.
P.O. Box 524
Minneapolis, MN 55440
Tel: 612-951-1000
Fax: 612-951-2294

Jewell Electrical Instruments
124 Joliette Street
Manchester, NH 03102
Tel: 603-669-6400
Fax: 603-669-5962

Landis & Staefa, Inc.
1000 Deerfield Pkwy.
Buffalo Grove, IL 60089
Tel: 847-215-1050
Fax: 847-215-9026

Laser Technology, Inc.
7070 S. Tucson Way, Dept. T
Englewood, CO 80112
Tel: 800-873-8916
Fax: 303-649-9710

Leica, Herbrugg
CH; 9435 Herbrugg
Switzerland
Tel: 41 (71) 70 33 84
Fax: 41 (71) 70 39 99

Magellan Corp.
960 Overland Court
San Dimas, CA 91773
Tel: 909-394-5000
Fax: 909-394-7050

Optech Inc.
100 Wildcat Road
North York, ON M3J3H4 Canada
Tel: 416-661-5904
Fax: 416-661-4168

Pathfinder Instruments
2075 Corte Del Nogal, Suite X
Carlsbad, CA 92009
Tel: 800-284-9698
Fax:760-438-3953

PLX, Inc.
40-T W. Jefryn Blvd.
Deer Park, NY 11729
Tel: 800-586-4190
Fax: 516-586-4196

Rockwell, Collins Commercial Avionics
400-T Collins Road N.E.
Cedar Rapids, IA 52498
Tel: 319-295-4085
Fax: 319-295-4777

Shelby Jones Co., Inc.
8800 West Chester Pike
Upper Darby, PA 19082 2619
Tel: 800-377-6060
Fax: 610-449-7010

Scientific Sales, Inc.
P.O. Box 6725-T
Lawrenceville, NJ 08648
Tel: 800-788-5666
Fax: 609-844-0466

Terra Tech, Inc.
P.O. Box 5547
Eugene, OR 97405 0547
Tel: 541-345-0597

UMA, Inc.
260 Main St.
Dayton, VA 22821
Tel: 703-879-2040
Fax: 703-879-2738

Watrous & Co., Inc.
Griffing Street, P.O. Box 996
Cutchogue, NY 11935 0996
Tel: 516-734-5504
Fax: 516-734-7931

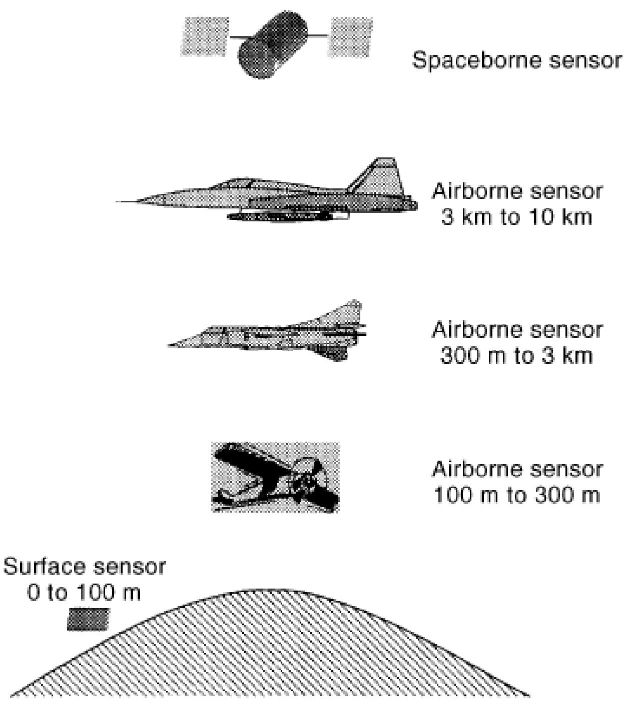

Fig. 1. Use of altimeters at various altitudes. Altimeters are designed to operate accurately at certain ranges. Developed in the recent years, the altimeters carried by the geostationary satellites offer very high accuracy.

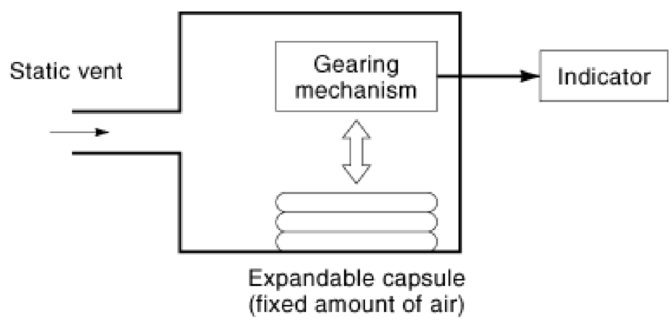

Fig. 2. A typical barometric altimeter. In this type a constant volume of air is trapped in the bellows. Depending on the air pressure in the chamber, the bellows changes its volume. The change in volume is scaled by a gearing mechanism connected to an analog indicator.

In most modern barometric altimeters, integrated circuit (*IC*) pressure transducers are used, as shown in Fig. 3. A wide variety of pressure transducers are available with different specifications, that are suitable for a large range of barometric altimeter applications. The performance of pressure transducers depends on the characteristics of the atmospheric pressure.

Principles of Operation and the Effect of Atmospheric Pressure. Certain assumptions are made to allow the altitude–pressure relationship to be simplified so that the altitude above sea level at any point in the earth's atmosphere can be related to air pressure by a single-valued function. The assumptions are often

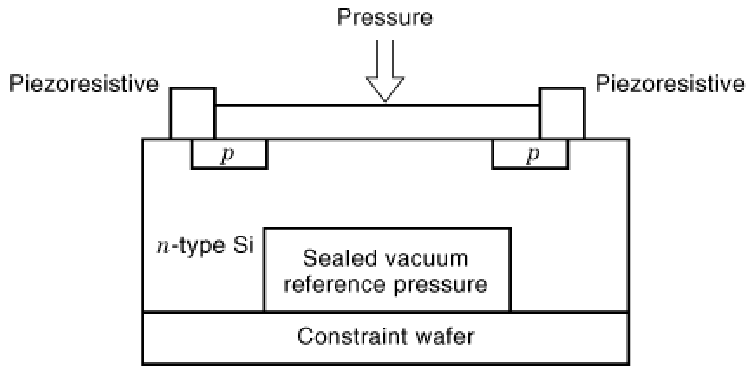

Fig. 3. A barometric altimeter based on piezoresistive integrated circuit. The characteristics of silicon allow construction of a thin diaphragm that can be deflected by an applied pressure, thus resulting in changes in resistance of the piezoresistive elements located on the diaphragm. The signal-processing and voltage regulation circuits are also integrated in the IC chip.

referred to as a *standard atmosphere* and are primarily concerned with the atmospheric conditions at sea level, chemical composition of the atmosphere, and atmospheric temperature distribution. These assumptions are based on a mixture of observations, measurements, and theories that are internationally accepted.

The concept of the standard atmosphere has a threefold purpose. First, it sets a reference for testing, design, and performance comparisons between instruments and the body carrying the altimeter, such as an aircraft, a balloon, or a parachute jumper. Second, it allows the derivation of the pressure–altitude relationship to be simplified both mathematically and physically within the altimeter. Finally, if all objects with altitude-measuring devices are set to the same reference, the vertical separation between these objects when they are in common airspace can be reliably inferred and safety can be increased. A summary of the International Standard Atmosphere (*ISA*) assumptions is as follows:

(1) The temperature at sea level, T_0, and the pressure at sea level, P_{s0}, are assumed to be constant at $T_0 =$ 288.15 K and $P_{s0} =$ 101,325 Pa (1013.25 mbar 29.92 in. Hg).

(2) The temperature decreases linearly with increasing height until a height known as the *tropopause* is reached, above which the temperature remains constant until the *stratopause* height is reached. The region below the tropopause is known as the *troposphere*. The law relating temperature T to altitude H to the tropopause height is given by

$$T = T_0 - LH \tag{1}$$

where L is the temperature decrease rate and is defined to be -6.5×10^{-3} K/m. At and above the tropopause (11,000 m), T remains constant at $T = T_T =$ 216.65 K (−56.5°C).

(3) The stratopause is defined to occur at 20,000 m. The region between the tropopause and the stratopause is known as the *stratosphere*.

(4) At heights above the stratopause the temperature starts to increase linearly with height; this region is known as the *chemosphere*. The temperature increase rate is defined to be 1.0×10^{-3} K/m. The chemosphere is defined to have a height limit of 32,004 m. The temperature in the chemosphere is given by

$$T = T_T + L(H - H_S) \tag{2}$$

where H_S is the height of the stratopause.

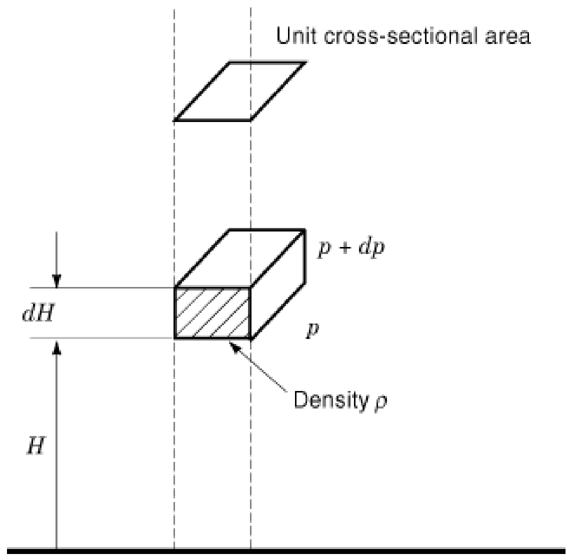

Fig. 4. Change in the atmospheric pressure due to air density. These changes in the air pressure can be related to altitude by using the gas laws.

Using these assumptions, the altitude versus static pressure relationship can now be derived by considering Fig. 4. A small change in pressure, dp, of air with density ρ, due to a small change in height, dH, can be found by equating the forces acting in the vertical plane on an elemental volume of air, so that

$$-dp = \rho g \, dH \tag{3}$$

where g is the gravitational acceleration. From the gas law,

$$p = \rho R_a T \tag{4}$$

where T is the air temperature (K) and R_a is the gas constant for a unit mass of dry air.

Combining Eqs. (1) and (2) through the variable ρ results in the following equation:

$$\frac{-dp}{p} = \frac{g}{R_a T} dH \tag{5}$$

The value of g, the gravitational acceleration is known to decrease with increasing distance from the center of the Earth. The equation governing this is

$$g = \frac{R^2}{(R+H)^2} g_0 \tag{6}$$

where R is the radius of Earth and g_0 is the gravitational acceleration at the surface of Earth, where its value is approximately equal to 9.807 m/s^2. This degradation of g, however, can be assumed to be insignificant in the evaluation of the pressure altitude. This additional assumption further simplifies the derivation.

The assumptions stated imply that the relation between the pressure altitude and the static pressure must be derived separately in three regions, namely the troposphere, stratosphere, and chemosphere. First, considering the troposphere, by substitution of Eq. (1) into Eq. (5), and integrating both sides to eliminate the dp and dH, we obtain

$$-\int_{P_{s0}}^{P_s} \frac{1}{p}\,dp = \frac{g_0}{R_a}\int_0^H \frac{1}{T_0 - LH}\,dH \qquad (7a)$$

where P_{s0} is the pressure at height $H = 0$ and P_s is the pressure at height H. Using the integration rule $(1/u)$ $du = \ln|u| + c$ and the equality $\ln A - \ln B = \ln(A/B)$, we have

$$\ln\frac{P_s}{P_{s0}} = \frac{g_0}{R_a L}\ln\frac{T_0 - LH}{T_0} \qquad (7b)$$

Solving for P_s gives

$$P_s = P_{s0}\left(1 - \frac{L}{T_0}H\right)^{g_0/LR_a} \qquad (8)$$

Similarly, for the two other regions of concern, their appropriate temperature equations, $T = T_T$ and Eq. (2) can be substituted into Eq. (5) and integrated.

Considering the constants implied in the ISA and additionally noting that R_a = 287.053 J/K·kg, the following equations are found to relate the static pressure to the pressure altitude H_p

(1) Troposphere (−914.4 m to 11,000 m):

$$P_s = 1013.25(1 - 2.25577\times10^{-5}H_p)^{5.255879}\,\text{mbar} \qquad (9)$$

(2) Stratosphere (11,000 m to 20,000 m):

$$P_s = 226.32e^{0.0001576885(H_p - 11{,}000)}\,\text{mbar} \qquad (10)$$

(3) Chemosphere (20,000 m to 32,004 m):

$$P_s = 54.7482[1 + 4.61574 \times10^{-6}(H_p - 20{,}000)]^{-34.163215}\,\text{mbar} \qquad (11)$$

It can be seen that these relationships are nonlinear. The nonlinearity can be observed graphically by plotting altitude on the horizontal axis against pressure as shown in Fig. 5.

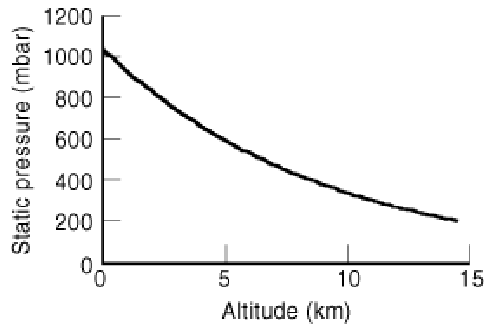

Fig. 5. Static pressure versus pressure altitude. The pressure changes in a nonlinear manner. Linearization techniques must be employed to measure and display altitudes by barometric methods.

Construction, Errors, and Use of Barometric Altimeters. A barometric altimeter must be able to display altitude linearly; therefore, a linearization, such as the gain adjustment, is necessary. The linearization is usually done by a calibratable mechanism to allow for variations in aneroid chambers. This mechanism introduces a gain that counters the nonlinear effects of pressure versus height, by means of nonlinear compression/expansion of the aneroid chamber. Gearing is also introduced, so that one revolution of the altimeter pointer is equivalent to a 330 m height displacement.

The linearizing part of the mechanism of an aneroid barometric altimeter is usually located at the center of the altimeter body. The temperature compensation is realized via a bimetallic strip, which alters its curvature as temperature increases. These features are necessary to compensate for the changes in the modulus of elasticity of the material that the aneroid chamber is made from. For example, if the sea-level temperature of an aneroid chamber were to decrease, its elasticity would increase. Since the chamber has a vacuum, it is in natural shape when fully expanded (i.e., at very low atmospheric pressure). If the chamber material becomes more elastic, it tries to resume its original shape. This results in the display of a height greater than the actual height. Since the atmospheric pressure decreases as the chamber is moved away from sea level, the extra height effect of the elasticity of the chamber increases as the altitude increases.

The static pressure port is placed on the back plate of the altimeter for use in a small aircraft. In modern aircraft this port is connected to a line that is in turn connected to either a Pitot tube or a static vent. The Pitot tube is often seen as a small probelike object pointed forward and located at the front of the aircraft to measure the airspeed. In altitude measurements, it fulfills the function of supplying a static pressure that is independent of the velocity of the aircraft.

It is important to note that Pitot tubes can introduce errors into altitude measurements. The tubes are mechanically designed to introduce minimum errors and also are positioned on the aircraft so that the attitude does not affect the airflow onto the tube. A badly designed or positioned Pitot tube can cause shock waves to occur at high air velocities and also cause extra air to be forced into the static measurement holes, thus increasing the pressure.

In an effort to attempt to alleviate some of the problems caused by Pitot tubes, the use of static vents has become common in modern aviation. They are designed to be mounted flush on the fuselage of an aircraft. In particular, these vents find extensive use in military applications where the removal of the probelike Pitot tube has improved stealth capabilities.

One problem common to all types of static-pressure-driven instruments is ice formation and water buildup inside the tubes or vents. To prevent ice formation, these tubes and vents have heating elements in them. Where there is ice, there can be water. Variations in pressure and temperature can cause water to condense in tubes and ports. In the interests of instrument functionality and minimization of errors, there must be provisions to check static lines for water and remove it.

A typical modern barometric altimeter is approximately 35 mm × 30 mm and has a liquid crystal display (*LCD*). It can also function as a barometer and can be set for the minimum and maximum altitudes, the absolute altitude, the speed of ascent and descent, the reduced and absolute air pressures, the weather forecast, and time and altitude alarms. Typically, the range of measurement of the barometric altimeter is −700 m to 10,000 m, and it updates information once every second. It has a pressure range from 600 mbar to 1100 mbar with ±0.5% accuracy and 0.1 mbar resolution. The altitude resolution is about 0.1 m. Altimeters with high precision find applications in geosciences, surveying, aviation, meteorology, recreation, and the laboratory.

Further Comments on Application of Barometric Altimeters in Aircraft. Barometric altimeters find extensive use in most modern aircraft as backup instruments. These altimeters are composed mechanically of sector gears, pinion, backlash springs, crankshafts, aneroid capsules, and pointers on a dial. A series of pointers on a graduated dial may be used to indicate altitude in hundreds, thousands, or tens of thousands of feet or meters. The barometric dial records the air pressure in millibars. Because atmospheric pressure is measured relative to sea-level, the pressure altimeter must be manually adjusted in order to compensate for variations in pressure caused by weather changes.

In aircraft, the barometric altimeters can be to set to show either altitude above sea level or altitude above an airfield once the height of the airfield above the sea level is known. If the pilot wishes to adjust the altimeter to display the height above sea level, the corrected sea-level pressure needs to be entered. When the corrected sea-level pressure is compared with the pressure at the airfield, the height of the airfield from sea level can be found. The sea-level pressure at that particular time must be known, however, because it may differ from the ISA assumption, indicating that the height of the airfield is higher or lower than what it actually is. Airfields continuously broadcast updated information on the pressure so that the pilot may correct the altimeter. The correct setting is called QNH, the adjusted sea-level pressure.

On the other hand, a pilot may wish to set the altimeter so that it displays the altitude above a particular airfield. To do this the pressure height of the airfield needs to be entered into the altimeter. Such pressures are denoted QFE and are given relative to the sea-level pressure. For example, an airfield 304.8 m above sea level, on a day where the sea level pressure is as per ISA (1013.25 mbar), has a QFE of 977.4 mbar. This value is calculated from Eq. (9). In summary, the barometric pressure knob is used to correct any variation in the sea-level pressure from the ISA assumed value of 1013.25 mbar.

Recalling the ISA assumptions, the temperature variations and air speed effects are ignored. However, these effects can be taken into account by the application of computers and suitable analog to digital converters (*ADC*s) to the real-time signals generated by the instruments. The computers use complex models to take into account many variables affecting the altitude measurements. This means that the computer-driven altitude display can be corrected in real time, so that the pilot has a very accurate altitude reading at all times.

Altimeters are prone to the following errors: (1) instrument errors due to manufacture, installation, maintenance, and so on, (2) instrument lag, and (3) position error due to placement of vents and blockage of the static vents by ice. In response, the availability of computers has prompted the development of advanced pressure-measuring devices, such as the vibrating pressure sensor and the solid-state capsule pressure sensor.

As illustrated in Fig. 6, vibrating sensors work on the principles of detecting change in the natural resonant frequency of a vibrating system within a cylinder as the air pressure changes. This means that the electrical output of this sensor, when amplified, will be a frequency that changes proportionally with the pressure it is exposed to. Modern ADCs can detect very small differences in output frequency due to density variations as well as the large frequency variations due to pressure changes. This type of setup, being enclosed, is very rugged and is in wide use today in commercial aircraft.

The second type of sensor, the capsule type, typically uses a vacuum chamber. The difference between these and the older aneroid chambers is in the materials from which the diaphragm is constructed. Typical materials are silicon, quartz, or ceramic compounds. These newer diaphragm materials are chemically engineered to

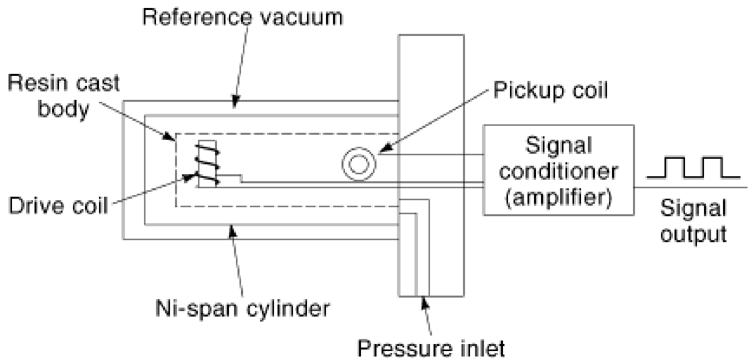

Fig. 6. Vibrating sensor barometric altimeter. The natural frequency of the vibrating element depends on the air pressure inside a cylinder chamber. The signal of natural vibration is picked up and processed to obtain the pressure, and hence the altitude of the mechanism above sea level.

have perfect mechanical properties in that they are very linear, do not suffer from hysteresis, and have a very stable modulus of elasticity.

The capsule-type transducers rely on two main methods. The first method involves the impregnation of the diaphragm with a Wheatstone bridge, thus allowing an excitation to be applied and a pressure-dependent voltage to appear at the output. This voltage varies due to the change in resistance of the impregnated resistors as the diaphragm flexes due to pressure, similarly to a resistive strain gauge. The second method is to form an area of metallization on the bottom side of the diaphragm and the bottom of the vacuum chamber. This creates a capacitor, and these sensors are highly sensitive to small variations in its capacitance. However, temperature variations and accelerations can severely affect both these types of sensors. Thus the temperature is measured near the device and fed into the ADC for correction. For the acceleration effect, ensuring that the device is mounted so that its axis of movement is orthogonal to the acceleration is sufficient compensation. It should be noted that these devices are designed to be minimally sensitive to gravitational effects.

It can be concluded that barometric altimeters are likely to continue to be used extensively in the near future to measure altitudes up to 15,000 m. Radar altimeters are expected to expand their role of providing accurate landing references, and low-altitude radar altimeters will continue to be used mainly for special-purpose military operations.

Radar (Radio) Altimetry

Radar and laser altimeters, also termed active ranging sensors, are based on the transmission of electromagnetic or optical energy directed at an object and the detection of the reflected energy from the object. The reflected energy is suitably processed to reveal information about the altitude as well as other parameters such as the atmospheric conditions, including pollution. Radar altimeters can provide height information at high altitudes, where barometric systems are not effective. They can also provide high-quality images, as illustrated in Fig. 7.

Aviation radar altimeters, which have been in use for many years, measure height above the ground or sea. They transmit either continuous waves (*CW*) or pulsed waves and normally operate in the 4.2 GHz to 4.4 GHz band to provide inputs to, for example, automatic landing systems or autostabilization systems for aircraft and helicopters. The basic operating principles of radio and radar altimeters are similar. The only difference is

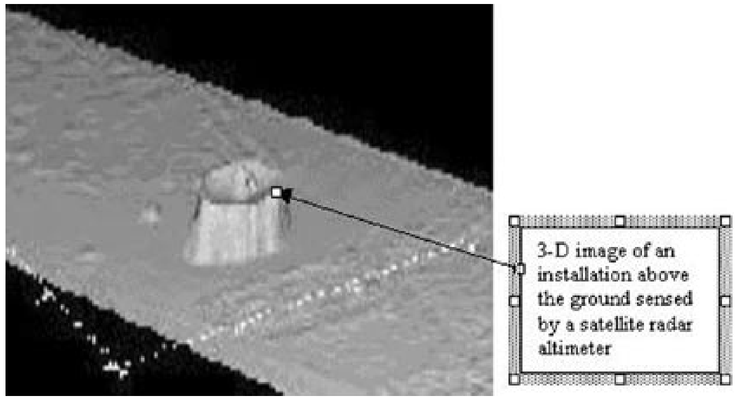

Fig. 7. A typical example of remote sensing. Active remote sensors transmit electromagnetic energy and pick up the return signals. By appropriate data processing three-dimensional images can be constructed.

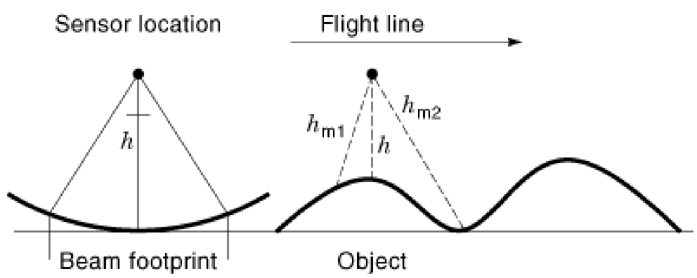

Fig. 8. Geometry of a pulse-limited radar altimeter. The pulse intersects the nearest point on the ground, and the illuminated disk spreads rapidly. This gives a maximum size for the footprint. The geometry of the beam-limited altimeter is similar.

that the term *radio altimeter* often refers to continuously modulated waves, whereas the term *radar altimeter* refers to pulsed waves, mainly used in aircraft, spacecraft, and satellites.

Radar Altimeters Used in Satellites. The radar altimeter is a single-frequency radar system that broadcasts a pulsed tone directly downward, as illustrated in Fig. 8. It has highly sensitive devices for signal detection and processing. A satellite altimeter is a nadir-pointing active microwave sensor designed to measure characteristics of the surface of the Earth. The time it takes for the reflected signal to be received directly is translated into the height above the terrain.

If a pulse is transmitted toward a target surface at an accurately measured time t_1, it reflects back to the source after a time t_2. The time difference $t_\mathrm{d} = t_1 - t_2$ is equal to the round trip distance to the reflecting surface divided by the propagation speed c. That is,

$$t_\mathrm{d} = 2h/c, \quad or \quad h = ct_\mathrm{d}/2 \tag{12}$$

The accuracy of the measured distance h can be expressed by

$$\Delta h = \Delta c \frac{t_\mathrm{d}}{2} + c\frac{\Delta t_\mathrm{d}}{2} \tag{13}$$

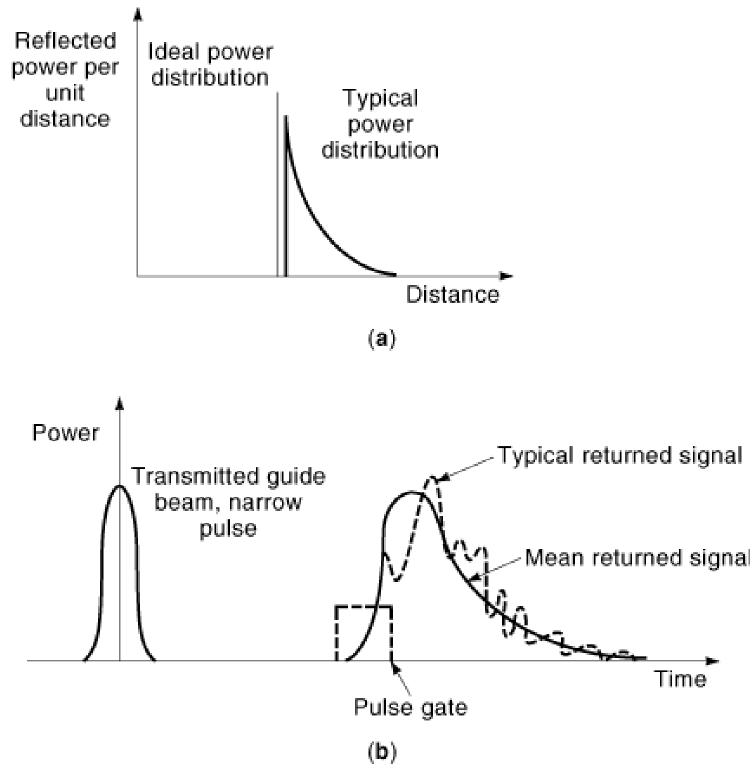

Fig. 9. Waveforms of returned pulses. (a) Ideal power distribution and typical power distribution of the returned signal. The distortion is due to imperfect mirroring of the signal back to the sensor. (b) Pulse shape of wide-beam, narrow-pulse altimeter.

Here, the time difference accuracy Δt_{d} depends mainly on the sharpness of the pulse, which is equal to

$$\Delta t = 1/B \tag{14}$$

where B is the signal bandwidth.

If the speed of the pulse is taken to be constant, the range resolution can be found from

$$\Delta h = c/2B \tag{15}$$

Higher accuracy is achieved by detailed analysis of the received signal; this is achieved by averaging a large number of echoes. Range errors can arise from pulse dispersion due to backscattering from the rough surface and to the propagation characteristics of the atmosphere. Consequently, the returned pulse is distorted and fading occurs, as illustrated in Fig. 9. The distortion in the waveform of the echo signal makes the altimeter signal less than perfect.

There are different types of radar altimeters, such as beam-limited altimeters, pulse-limited altimeters, synthetic aperture radar altimeters, imaging altimeters, and scanning altimeters. The operation principles of the altimeters are similar, but they vary in size of footprint, direction of the beam, and purpose of usage. The details in the differences of these altimeters are not given in this article, but interested readers can find further information in the references (e.g., Ref. 1).

In most modern radar altimeters, high measurement accuracy is required. This necessitates good information on the effect of the ionosphere and atmosphere as well as good understanding of the errors introduced by the sensor dynamics and signal-processing electronics. The signal-pressing electronics comprises many components such as oscillators, modulators, mixers, power amplifiers, filters, demodulators, digitizers, compressors, and computers. All these devices have to be of good quality and highly accurate. Judicious selection of all the discrete components and circuits is necessary for good conformity and matching.

The first satellite altimeter was tested in 1973, as parts of several Skylab missions conducted by the United States. At that time, a typical resolution was 1 m to 2 m; modern altimeters are capable of resolutions down to 2 cm (TOPEX/Poseidon). As an example, the discussion here focuses on one of the latest satellite altimeters, for the NASA TOPEX/Poseidon satellite used in oceanic applications.

The TOPEX/Poseidon mission, a joint mission between NASA and the Centre Nationale d'Etudes Spatiales (*CNES*), the French space agency, was designed to make high-precision measurements of the ocean surface possible. The application areas of this system are mainly for weather reports and predictions, in geodesy and geophysics. The TOPEX altimeter was the first dual-frequency satellite altimeter operating in space to perform these important measurements. The TOPEX used several methods for determining distance, such as the round trip time discussed previously, and the shape of the reflected pulse. In particular, the shape of the reflected pulse provided a wealth of information on wave height in the ocean and the sea-surface wind speeds.

The TOPEX altimeter uses a 13.6 GHz signal as its primary pulse, and a secondary frequency of 5.3 GHz. The use of two frequencies is helpful in removing the adverse effects of variations in the propagation speed of the pulse due to variations in the atmospheric conditions of the Earth.

NASA has built a self-calibration mechanism into the TOPEX altimeter. While over land, twice a day, the altimeter spends 5 min calibrating itself. The TOPEX is known to be extremely reliable and robust because of this self-calibration capability and due to its ability to compensate for ionospheric effects.

To obtain a high degree of precision, the satellite that carries TOPEX needs to know its exact position relative to points on Earth. The *GPS* helps the satellite to determine its position with a precision of about 2 cm. A laser Doppler system and a ground station are also used to verify this reading.

In recent years, another satellite system with importance for altitude measurements has been the Geosat follow-on meteorological–oceanographic satellite (*GFO METOC*). It is owned by the US Navy and is used for determining thermal fronts, eddies, ice edge locations, surface wind speeds, and wave heights.

The GFO and the *GPS* systems mentioned above are also used for position and altitude determinations, but their design is more elaborate than is needed for the accuracy of TOPEX. In these systems, an onboard water vapor detector is used to help correct ionospheric interference. Essentially, the GFO was a test to determine whether a low-cost, lightweight, and compact satellite could be used to provide the US Navy and its associated agencies with real-time ocean data. But the expectations for the GFO to replace TOPEX in a cost-effective manner have failed so far.

Spaceborne altimeters are primarily pulse-limited, and therefore they cannot deliver the required accuracy of surface height measurements over icy land. This is because the spreading and slope of the reflected pulse cause severe errors. In addition, during land height measurements, sudden changes in the slopes of the topography often result in a loss of tracking. Although techniques have been developed to improve the spatial resolution of radar altimeters for accurate elevation estimates over the terrain, most of them result in a significant increase in cost and complexity compared with a conventional altimeter.

In a typical noise-modulated radar altimeter, the principle of operation is based on the dependence of the cross-correlation function of the random modulation (Gaussian noise) on the finite correlator bandwidth, smoothing methods, extraneous noise disturbance, component characteristics, and changes in altitude during measurements.

Radio Altimeters. Like radar altimetry, radio altimetry is based on the use of electromagnetic (*EM*) waves to determine the distance between a reference point and an object that reflects the waves. Radio altimeters are used mostly in aircraft. Unlike radar altimetry, radio altimetry is based on continuous EM

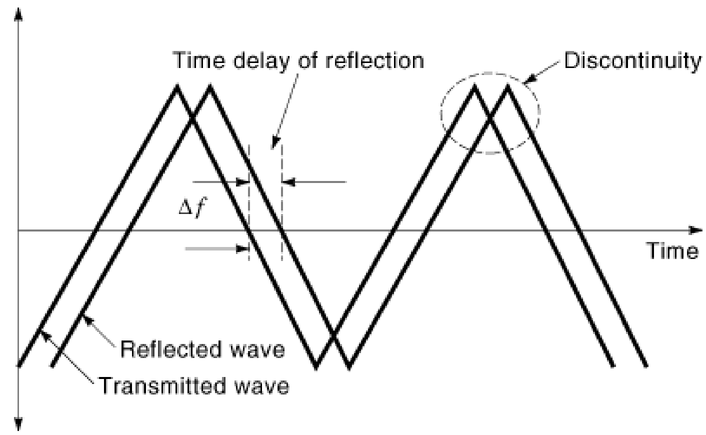

Fig. 10. The transmitted and received waveforms of a radio altimeter. The time difference between the transmitted waveform and the reflected wave from the target is an indication of the distance between the two objects.

waves. Generally, it uses a frequency-modulated (*FM*) carrier, whose frequency is varied at a constant rate. The carrier reaches the surface below and reflects back to the transmitter with a delay. The reflection appears as a time-shifted version of the transmitted signal; thus the phase shift can be made use of. This time difference equates to a frequency difference, which can easily be detected using a superheterodyne receiver. Figure 10, illustrates the time difference in the transmitted and received signals. A typical radio altimeter operates at about 4.3 GHz. A low-frequency (100 Hz) triangular waveform modulates the carrier over a range of about ±50 MHz.

All radio and radar altimeters have three basic components: one or two antennas, a transmitter receiver, and an indicator. The type of antenna varies, depending on where it is fixed on the aircraft (on a flat or skewed area under the fuselage). Antennas are designed specifically for each system, so changing the unit also involves changing the antenna. The transmitter–receiver is the core of the device. The indicator consists of an electronic digital display or a common analog display.

As mentioned before, frequency differences can be measured using a superheterodyne receiver. In the signal-processing section, the received signal is multiplied with the transmitted signal on an instantaneous basis. In this way, due to the superheterodyne principle, a sum and a difference frequency are created. A low-pass filter is used to remove the component containing the sum of the frequencies, leaving only the difference, as required for further processing. The difference frequency can then be applied to a signal processor for digital display, or perhaps to a frequency-to-voltage converter allowing the altitude to be displayed in analog form. This technique allows the display of instantaneous altitudes as well as changes in altitude.

It is important to note that in the determination of altitudes by radar altimeters the speed of an EM wave in air is assumed to be constant, 3×10^8 m/s. Although this assumption may be valid in some situations, the presence of water vapor in the atmosphere can affect the speed and introduce serious errors in the measurements. Apart from this common shortcoming of radio altimeters, specific altimeters have their own. For example, a conventional FM counter radio altimeter has the following shortcomings: (1) the step error can be severe, (2) an upper measurable limit is introduced by the spurious beat, and (3) there is a tendency to overcount due to unwanted far-distance propagation. The step errors can be reduced by the *modulation synchronous phase switching method*, using switching-type phase shifters placed at the transmitting (or receiving) antenna feeders. This results in an increase in the phase at every period of the frequency modulation. The upper limits and overcounting errors can be eliminated by the *frequency offset method*. In this method, the time-varying phase shifts are made at higher rates than the modulation repetitions.

Used in an aircraft, the radio altimeter measures its distance above the ground rather than above sea level. A cathode-ray tube indicates the time that a pulse of radio energy takes to travel from the aircraft to the ground and back to the aircraft. The altitude is equal to one-half the time multiplied by the speed of the pulse. Radio altimeters are used especially in automatic navigation and instrument landing systems (*ILS*s). They are also used in remote sensing applications for military intelligence gathering, mapping, and surveying.

Laser Altimeters

Laser altimeters are essentially a form of laser range-finding devices, and are used widely for accurate distance measurements. The operation principles are similar to those of radar altimeters in depending on the time difference between the transmitted and received signals. That is, the distance is measured by timing a light pulse traveling from a laser light emitter and back to a detector located in the vicinity of the transmitter.

Laser range finders are commonly used in land surveying. Airborne laser measurements can be used to directly measure topography, stream channel cross sections, gully cross sections, soil surface roughness, vegetation canopy heights, and vegetation cover and distributions. These laser measurements can be used for the estimation of forest biomass and volume, aerodynamic roughness, and leaf area indices. Airborne laser altimeters provide quick and accurate measurements for evaluating changes in land surface features and can be an additional and useful tool for remote sensing of watershed properties and water resources management.

In laser altimeter applications, three measurement techniques are used: (1) the interferometric method, which is extensively used in short distance measurements, up to 100 m in free air, (2) amplitude-modulated laser beam telemetry, suitable for distances from 100 m to 50 km, and (3) the pulsed laser radar method, for altitudes over 10 km. All these methods are based on the measurement of the propagation time of the laser pulse over the distance under investigation. Therefore, the evaluation of the true geometric distance depends on corrections for factors such as the air refractivity, the beam angles, and the signal processing techniques. Based on these principles, various type laser altimeters are available commercially, depending on the application requirements and the range of the altitudes. In extralong-range applications, optical radar altimeters, which are based on sending infrared pulses of about 5 ns duration, are found to be accurate.

Amplitude-Modulated Laser Beam Altimeters. Although interferometric methods for distance measurements are extensively used for short-distance applications, they are clearly not suitable for long-range distance measurements. For those a common method involves amplitude modulation of the laser beam. In this method the modulated beam is projected toward the target and the light returned from the target is collected by a telescope to be sent to a detector, as illustrated in Fig. 11. The phase of the amplitude modulation of the returning light is compared with that of the emitted light. The differences in the phases occur because of the time required for the light to travel to the target and back to the telescope. To describe the operations, an equation can be written in terms of intensities of transmitted beam $I(t)$ and the received beam $I(t - \tau)$

$$I(t) = \alpha I(t - \tau) \qquad (16)$$

where τ is the transit time, or propagation time delay, of the light beam, and α is the attenuation coefficient, which takes into account propagation efficiency and losses during transmission.

The transit time for the sinusoidal modulation, the geometric distances, and the refractive index of the spectral distribution of the light beam can be used to find the relationship between the phase shift Φ and the total path length L

$$\Phi = 2\pi n_g L/\lambda_v \qquad (17)$$

where n_g is the group index of refraction of air, and the λ_v is the wavelength in vacuum.

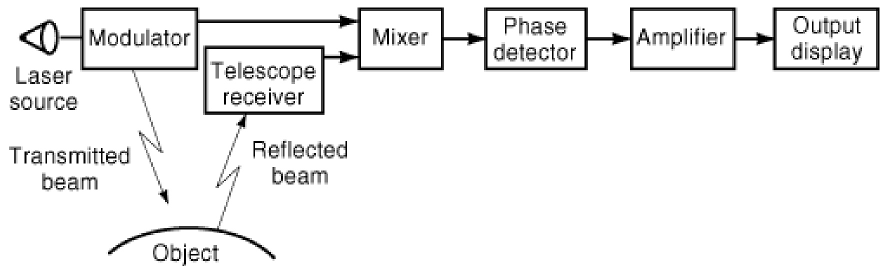

Fig. 11. A laser-beam-modulated altimeter. The phase difference between the transmitted and returned signals is measured. The phase comparison technique allows the evaluation of altitudes at high precision from distances of several hundred kilometers.

Pulsed Laser Radar. Another approach to laser-based altitude measurement is to make use of the round trip transit time for a very short pulse, as illustrated in Fig. 9b. Often the term LIDAR (light detection and ranging) is used, as an optical counterpart of "radar." Using lasers to measure altitude results in good accuracy and spatial resolution, but in doing so the advantage of all-weather capability of a microwave altimeter is lost. Such measurements can only be carried out in favorable atmospheric conditions.

Pulsed laser radars commonly use Q-switched laser switches with high peak power. The accuracy of the time measurement depends on the characteristics of the propagation medium and on the resolving capabilities of the photodetector and the timing system. In topographical applications, the statistical characteristics of the received signals for the short-pulse laser altimeters can directly be related to the statistics of the surface profile. In the signal analysis the effects of laser speckle, shot noise, and the surface profile of the ground target need to be considered carefully.

In pulsed radar applications, the altitude to be measured can be found from the expression

$$E_{\mathrm{R}} = \frac{E_0 A_{\mathrm{R}} \eta A_{\mathrm{T}} t^2}{\Omega_0 L^2 \Omega_{\mathrm{T}}} \qquad (18)$$

where E_0 is the transmitted pulse energy, A_{T} and A_{R} are the areas of the target and the received system, Ω_0 and Ω_{T} are the solid angles over which the emitted and reflected energy are spread, t is the atmospheric transmission time, η is the diffusion or reflection coefficient, and E_{R} is the received energy. This equation indicates that the energy follows an inverse square law. If the intensity of the returned signal is high, Eq. 18 can be used for altitude measurements. If it is low, various probability methods (e.g., the Poisson distribution) are used to estimate the number of photoelectrons.

Solid-state lasers can deliver pulses with time duration of typically 20 ns and peak power up to 1000 MW. Semiconductor laser diodes provide high efficiency pumping of solid state lasers with the promise of long-lived, reliable operation. In the next generation of laser altimeters, 100 W quasi-*CW* laser diode bars are likely to find applications. Even with the use of power laser equipment to generate the transmitted signals, the pulse intensity of the returned signals is very weak. To overcome this problem, highly sensitive photodiodes and photomultipliers are used for detection.

In this article, two different systems are discussed in order to explain the scope and the potential of practical laser altimeters. These altimeters are the shuttle laser altimeter (*SLA*) and the raster scanning airborne laser (RASCAL).

The first type, the SLA, is in its second generation of development. Constructed by NASA, this altimeter is used to determine the shape of land surfaces and vegetation canopies. At present, the accuracy of the SLA-2 is within ≈1.5 m (vertically) for each 100 m diameter footprint. The signal-processing component of the system is able to recognize the differences between the reflection from the soil surface and the reflections from other objects; hence the information can be separated and relief plots can be computed.

The mission objective was to compile a database of laser echo returns for every possible surface condition on Earth. The SLA-2 is constructed as an engineering experiment, and NASA is planning the introduction of a third-generation altimeter, the SLA-3. This instrument is planned to have an ultrahigh repetition rate, a smaller footprint than SLA-2, and the ability to penetrate vegetation canopies so that it can provide a contour of the surface under the canopy.

The operation of the SLA-2 is very complex, but it can be broken down into the following three major components: the laser transmitter (a Q-switched, diode-pumped Nd:YAG device, by McDonnell Douglas), the 38-cm diameter telescope antenna, and the altimeter receiver connected to a waveform digitizer. A variable gain amplifier is used to accommodate a greater range of return amplitudes of the returned signals, thus increasing the accuracy and the altitude range. The actual laser return pulse detection is performed via a silicon avalanche photodiode detector, which in turn is connected directly to the waveform digitizer.

The second altimeter is the RASCAL, also from NASA. The operational principle of the RASCAL is similar to that of the SLA, but the device is configured specifically to operate in aircraft. The RASCAL sensor was developed in 1995 at the Goddard Space Flight Center for airborne mapping of surface topography. The RASCAL is a second-generation laser altimeter with application to both Earth (airborne) and other planetary surface (space-based) topography determinations. It differs from earlier nadir-profiling laser altimeters by an increase in pulse repetition rate by two orders of magnitude and provision for a near-contiguous scan pattern. It was first operated in a NASA airborne remote sensing program station in California in September 1995, where its high spatial resolution (better than 2 m) in three-dimensional images of topography was demonstrated.

The complicated part of RASCAL is the need for accurate positioning of the laser relative to the aircraft and Earth. Through the use of the aircraft's *GPS* and inertial navigation system, the NASA team has, in its words, "brute forced" the solution to this problem and gained a reliable model for exact positioning information. The accuracy of this system has been described as "not as good as [it] should be," and there are plans to build a laser capable of 1 ns pulse width at 10 kHz to help correct this. The return-pulse energy sampling system is not at its optimum yet, either. By the use of the RASCAL, so far, postprocessed data have been used to re-create many footprints with diameters of 1 m, spaced approximately every 1.5 m in both directions in a pattern 100 m wide. An average accuracy of better than 20 cm with a precision of ± 5 cm is achievable.

A plot obtained from the RASCAL system data is shown Fig. 7. It showed up in postprocessing, when the analyzing team apparently did not realize that they had flown over a satellite tracking station. Though the desired accuracy is lacking, this typical plot shows the potential of the system.

Besides terrestrial applications, laser altimeters, LIDARs, and other ranging systems have been important parts of space missions to the moon, asteroids, and Mars; and more are planned and contemplated in the future exploration of the solar system. In 1997 the Mars Global Surveyor (*MGS*) entered into orbit around Mars. One of the four scientific instruments on the MGS is the Mars Orbiter Laser Altimeter (*MOLA*), which has started to map the topography of the planet with unprecedented accuracy. In 1999 the Near Earth Asteroid Rendezvous (*NEAR*) spacecraft, which carries the *NEAR* laser rangefinder (*NLR*), arrived at the asteroid Eros. The *NLR* was to study the shape and the dynamics of the body of Eros for a period of a year. The *MOLA* and the *NLR*, along with the Clementine laser altimeter that went to the moon in 1992, represent a new class of active remote sensing instruments for investigations of science in the solar system.

Global Positioning System (GPS)

The *GPS* was begun 1978 and completed in 1994 with 21 active and 3 spare satellites. The *GPS* allows users to determine their exact position, velocity, and time at any time of day, in any weather conditions, free of charge. In discussions of the *GPS*, it is convenient to break the system into three blocks or segments: the space segment, the user segment, and the control segment.

The Space Segment. The *GPS* satellites orbit the Earth at an approximate altitude of 20,000 km, and have an orbit period of 12 sidereal hours. The orbits have been arranged so that a user can have a direct line of sight to at least four satellites at all times at any place on the Earth.

Each satellite transmits a unique code, which is based on a pseudorandom sequence allocated before launching. Having received this code, the users can employ autocorrelation techniques to recover these sequences. Given an accurate time reference and the propagation time from the satellite to the receiver, the distance can be determined. If the distances from each satellite in sight and the locations of satellites are known, the relative position and thus the coordinates of the receiver can be calculated easily. For precise calculations, the clock references of the *GPS* satellites must be known exactly. The clocks on the satellites are known to be stable within 0.003 s per 1000 yr.

The satellites transmit signals at 1575.42 MHz and 1227.60 MHz; these two transmissions are known as the L1 and L2 signals. The L1 signal is described as being made up of a *precision* code (P) and a *coarse acquisition* code (C/A). The L2 contains only the P code, which when encrypted is called the Y code.

The User Segment. Users of the *GPS* often have hand-held *GPS* receivers. A receiver determines a pseudorange to work out the time that the signal takes to reach to the receiver. Performing this operation for more satellites in sight, the receiver can work out where the user is on the face of the Earth or above it.

The P code and C/A code are sometimes referred as the Precise Positioning Service (*PPS*) and the Standard Positioning Service (*SPS*) respectively. As these names would suggest, the *PPS* is more accurate than the *SPS*; this is due to a smaller bit period in the P code, The *PPS* has been withheld from public use, but is earmarked to be released for civilian use in the near future. A third frequency, which will give better accuracy, is planned to be released for the public. However, the Russian Global Navigation Satellite System (*GLONASS*) uses a single frequency, thus giving better accuracy for civilian use.

The Control Segment. The control segment consists of operators of the *GPS* network at a number of stations on Earth. The requirement of this segment is to maintain the *GPS* time, to monitor and control the satellite orbit positions, and to predict variations for compensation of any detected inaccuracies. The network has a master control station situated in Colorado Springs in the United States, and five additional monitoring stations. The positions of these stations are known precisely, and they are used to check and calibrate the *GPS*. The stations are distributed roughly along the equator and are geographically suitable for general system maintenance. At the moment, the number of stations is said not to be sufficient; however, more stations are being planned to allow the determination of precise orbital paths of the satellites.

Theory of Operation. The theory of operation of the *GPS* is too complicated for detailed treatment in this article. Here, a brief explanation will be given to provide a basic understanding of *GPS*-based altimeters, particularly concerning accuracy and errors.

The *GPS* makes use of the time of arrival. That is, the satellites send out signals that contain some information such as the exact time of signal transmission and satellite locations. Once received, the information in the signal can be processed to calculate the time taken for the signal to arrive from the satellite at the receiver. By repeating this operation with the information from at least four satellites, the latitude, longitude, and height of the user can be determined in reference to the satellites and thus, in turn, in reference to fixed points on Earth.

Each satellite transmits a binary phase shift-keyed sequence that is spread spectrally, by its pseudorandom code; this allows all of the satellites to transmit on the same L1 and L2 carriers. They all use the same bandwidths at 2.0463 MHz for the C/A codes and 20.98 MHz for the P codes. This is called *code division multiple access*, and it relies on the properties of pseudorandom codes to work.

Pseudorandom codes have the property of strong autocorrelation. This means that when a pseudorandom code is overlaid upon itself and correlated, the result will be slightly negative for all positions except an identical overlaying, in which the result becomes positive. A delay time is added to the internally generated pseudorandom code, to provide a positive, strong correlation with the received signal.

If the internal clock of the *GPS* receiver were exactly synchronized with the satellite's clock, the measured time delay would be representative of the actual physical distance between the satellite and the receiver. It is very unlikely, however, that the satellite and receiver clocks will be synchronized exactly. As a result, some differences in time, called *clock bias*, arise. The *GPS* receivers must determine the magnitude of the clock bias by taking delay times of the other satellites into consideration. This means that the measured delay times are the combination (physical distance)/(speed of light) + (clock bias) as explained above.

It is convenient to define a *pseudorange*, which is the delay time multiplied by the speed of light. This is a pseudodistance from the receiver to the satellite, with clock bias factored in. The actual process that the receiver executes can be summarized as follows:

(1) The receiver tracks four or more satellites and determines the delay time from each satellite.
(2) The receiver calculates all of the pseudoranges (i.e., multiplies the times by c).
(3) The receiver then corrects the pseudorange results for errors such as the satellite clock difference, the clock bias, the ionospheric effects, and time. The information sent by satellites, for the computation, is in the form of 50 bit/s frames superimposed on the C/A and P codes, called the NAV messages. It takes about 12.5 min to download 25 of the 1500 bit frames to the receiver. The precise position of the satellite, the clock time, and other relevant information is included in the NAV message. Due to the time required to download the message, the NAV message is defined to be valid for 4 h.
(4) When all of the pseudoranges have been corrected, the receiver performs a simultaneous solution of four equations with four unknowns. The four unknown quantities are the Cartesian coordinates x, y, z and the time.

Now that the receiver has solved the equations, the latitude, longitude, and altitude of the user can be calculated and displayed. The accuracy of these results depends on statistical analysis, and thus on the percentage of time of availability of satellites.

The *GPS* has a number of errors that need to be considered in altitude determinations. Some of these are the receiver clock error, the multipath error, and the ionospheric and tropospheric propagation errors.

As mentioned, the US Department of Defense (*DoD*) is planning to allow civilian users to use the *PPS* system instead of the *SPS*. This will give substantial improvement in accuracy of the position and altitude determinations, as shown in Table 2. In this table, the formal specified accuracies are shown in bold. The percentages 50%, 63%, and 95% are the probable fractions of time for the receiver to be located within the given distances of an exact position calculated statistically. For example, the measured vertical height of the receiver in the *SPS* system is within 140 m of the central value 95% of the time. This can be compared with 28 m for the *PPS* system. The distance error of 140 m is clearly too large to be useful in aircraft applications, at low altitudes, but may be acceptable at high altitudes.

A method of improving this accuracy is called *differential GPS* (*DGPS*), and it can help provide an *SPS* user with subcentimeter accuracy in many cases. The *DGPS* uses a ground station that is geodetically fixed (with exact latitude and longitude), and it continuously tracks all visible satellites. Given the precise location and altitude of the *DGPS* station, and that the satellites transmit their positions in the NAV message, the *DGPS* can apply corrections based on the measured delay times. By transmitting corrected information about the visible satellite positions to a *GPS* receiver via a radio channel, the computation at the receiver can be improved.

The *GPS* is a powerful tool for accurate determination of altitudes if one has access to a *PPS* system, and an altitude accuracy better than 100 m can be achieved even with the *SPS* system. Hand-held *GPS* receivers are now commonly available for a few hundred dollars in consumer retail outlets.

Table 2. Accuracy in GPS Systems

	Accuracy					
	50% of Time		63% of Time		95% of Time	
	PPS	SPS	PPS	SPS	PPS	SPS
Position (m):						
Horizontal	8	40	10.5	50	21	**100**
Vertical	9	47	14	70	28	140
Spherical	**16**	76	18	86	36	172
Velocity (x, y, z) (m/s)	0.07	—	**0.1**	—	0.2	—
Time (ns)	68	115	100	170	**100**	340

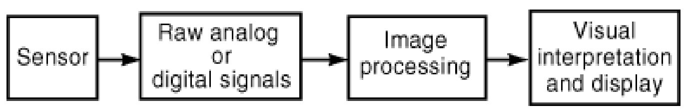

Fig. 12. Components of remote sensing for image processing. The sensed signals are stored and processed either online or offline.

Remote Sensing

Remote sensing is the science of detecting, measuring, and analyzing an object on the ground from a distance. It mainly comprises measurements of electromagnetic radiation from the ground, in the form of energy reflected by active sensors or emitted by passive sensors in various spectral ranges picked up by aircraft or satellites. Also, remote sensing may encompass aerial photography and similar methods whose results are generally displayed in the form of photographlike images. In aircraft applications, images from different flight paths can be combined to allow an interpreter to perceive features in three dimensions, and identify specific types of rock, soil, vegetation, and other entities, where they have distinctive reflectance values in different spectral regions of the electromagnetic radiation.

Remote sensing systems are made from distinct components as shown in Fig. 12. These components are: (1) an active or a passive remote sensor that employs detecting mechanisms to sense or scan the object, (2) a device for recording and imaging of the information received, and (3) the analysis and display system that makes the information useful. In some cases, analysis and display systems are combined and operate concurrently with the sensing system to process and display the data instantaneously. In other cases, the data are recorded and analyzed later. The displays are usually in the form of aerial photographs or television pictures.

An important feature of remote sensing is the identification of signatures, which is used to sense the desired objects against a complex background or surroundings. For example, it may be necessary to identify a particular mineral, crop blight, or type of air or water pollution. Signature, as applied to imagery, usually refers to visual characteristics that identify the subject and separate it from other similar objects.

Image formation is another important aspect of remote sensing. In this regard, there are two categories of systems: (1) imaging sensor systems, which can be subdivided into framing systems (e.g., aerial photographic cameras, vidicons) and scanning systems, (e.g., radar), and (2) nonimaging sensor systems, also known as spectral data systems (e.g., spectroradiometers, radar scatterometers).

Remote sensors may be surface-based and stationary or mobile, or airborne in aircraft, helicopters, or balloons; or carried aboard spacecraft, such as satellites, a Space Shuttle, or a space station. These bases are known as the sensor platforms. The resolution, or detail, with which a remote sensor can monitor a subject generally depends on the distance from the sensor platform to the object. Generally, remote sensors that employ the shortest wavelengths provide the best resolution. For example, microwave sensors, which operate at wavelengths longer than those of thermal infrared sensors, can be expected to have poorer resolution. However, the longer wavelengths have the best penetrating power. Microwaves, for example, can penetrate through clouds, whereas visible and infrared light do not. Therefore, microwave radar systems are often used to sense subjects that are not visible to optical-wavelength laser radar systems. Also, microwave systems can be used to penetrate vegetation for geologic mapping, to monitor snow depths, to indicate soil moisture, and so on.

Remote sensing finds many applications in military equipment; air transport; deep-space research; geography; environmental monitoring such as oceanography, hydrology, meteorology, and pollution control; monitoring snow depth and ice cover, flood control, hydroelectric generation, and water transport management; agriculture, and forestry; lightning and fire sensing; and so on. The geographical and geological applications include land-use and terrain mapping, geological mapping, and detection of mineral deposits. Oceanographic applications encompass monitoring of waves, currents, temperatures, salinity, turbidity, and other parameters and phenomena related to oceans and seas.

The technology of remote sensors varies from system to system, For example, in a typical infrared remote sensing system, the thermal infrared energy is detected by an optical–mechanical scanner. The detector is cooled by a liquid-nitrogen or liquid-helium jacket that encloses it, and a rotating mirror directs radiation coming from various directions onto the sensor. Infrared radiation permits mapping surface temperatures to a precision of less than a degree and thus shows the effects of phenomena that produce temperature variations, such as groundwater movements.

In another system, Landsat images are commonly used. They are produced with data obtained from a multispectral scanner carried aboard certain US Landsat satellites orbiting the earth at an altitude of about 900 km. Images covering an area of over 185 km^2 are available for virtually every part of the earth's surface. Scanner measurements are made in four spectral bands: green and red in the visible portion of the spectrum, and two infrared bands. The data are usually displayed by arbitrarily assigning different colors to the bands and then superimposing these to make representative images.

Topographic mapping of the earth, moon, and planets can be accomplished with high resolution and accuracy using satellite laser altimeters. These systems employ nanosecond laser pulses and microradian beam divergences to achieve submeter vertical range resolution from orbital altitudes of several hundred kilometers.

Conventional altimeters provide a topographic surface profile. In most cases the surface topography is required over an area. This can be achieved by multiple orbit traces displaced across the track by successive revolutions of an element making a large number of accurately positioned orbital passes. Often a multibeam or scanning beam altimeter is used to provide three-dimensional images. The corresponding geometry is illustrated in Fig. 13. The accurate performance of the altimeter depends on the effects of the target surface characteristics, spacecraft pointing jitter, and waveform digitizer characteristics. The ranging accuracy is critically dependent on the pointing accuracy and stability of the altimeter, especially over high-relief terrain where surface slopes are large. At typical orbital altitudes of several hundred kilometers, single-shot accuracy of a few centimeters can be achieved when the pointing jitter is on the order of 10 μrad or less.

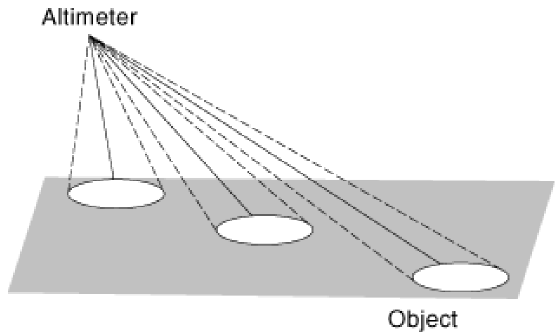

Fig. 13. The geometry of a scanning beam altimeter. The scanning is realized either electronically or mechanically. Processing of the returned signals from each scan gives accurate three-dimensional images.

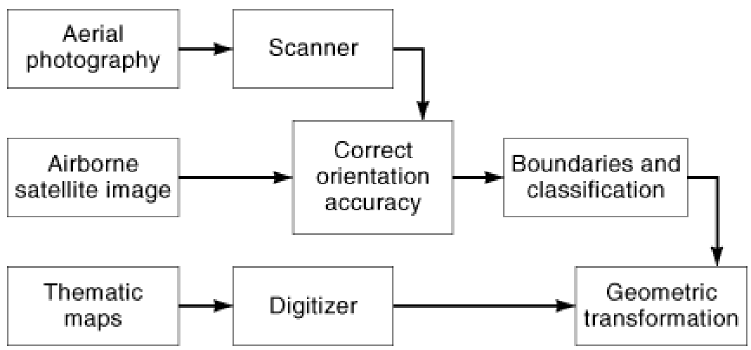

Fig. 14. Use of different methods in remote sensing. Several methods are combined electronically to give extremely accurate mapping. In this particular case aerial photography, airborne satellite images, and digitized thematic maps are combined.

Surface Height Measurement and Height Accuracy

Surface height measurement is an important concept associated with altimeter technology. In general, height measurement has many applications, ranging from the microscopic scale of measuring step heights in wafers in integrated circuits and height measurements of machined metal surfaces, to the very large scales of ice formation on the earth's surface and wave heights in the oceans. Consequently the instrumentation suitable for these measurements ranges from microscopes and interferometers to *GPS* and satellite radar.

In large-scale applications, there are many methods to determine heights on land. These are: (1) spirit leveling (most accurate but slow), (2) measuring vertical angles and distances (accurate and faster), (3) measuring differences in atmospheric pressure, (4) using photographic techniques such as aerial surveying, and (5) using radar and satellite systems. The last two techniques are accurate but require expensive and sophisticated equipment, as discussed earlier. Often, more than one technique is employed to obtain accurate geographical information, as illustrated in Fig. 14.

In spirit leveling, a horizontal telescope fitted with crosshairs, rotating around a vertical axis on a tripod, is used to adjust a bubble, which is exactly centered. The reading on a graduated vertical staff is observed through the telescope. If such staffs are placed on successive ground points, and the telescope is truly leveled, the difference between the readings at the crosshairs will equal that between the heights of the points. By moving the level and the staffs alternately along a path or road and repeating this procedure, differences in height can be measured accurately over long horizontal distances. In some stringent surveys, the error may be kept to less than a centimeter over a distance of 100 km.

For faster work in hilly areas, where lower accuracy is usually acceptable, trigonometric height determination is employed, using a theodolite to measure vertical angles and measuring or calculating the distances by triangulation. To increase precision, the observations are made simultaneously in both directions so that aerial refraction is eliminated.

The third method of height determination depends on measurements of atmospheric pressure differences with a sensitive aneroid barometer, which can respond to pressure differences small enough to correspond to 0.3 m to 0.6 m in height. To obtain reliable results it is necessary to use a reference barometer, as the air pressure changes constantly. An alternative to the barometer for the pressure measurements is the use of an apparatus for measuring the boiling point of a liquid, since the boiling temperature depends on the atmospheric pressure.

A relatively new method of surface height measurement is the use of satellite and radar systems. The analysis of the signals received simultaneously from several satellites gives heights as accurately as positions. Heights determined in this way are useful in previously unmapped areas as a check on results obtained by faster relative methods, but they are not accurate enough for mapping developed areas or for engineering projects. For example, absolute and relative height measurements with the differential *GPS* systems are accurate to about 30 m, whereas in photogrammetric surveys subcentimeter accuracy can be achieved over a wide area, typically 5 km^2.

Another application of the satellite systems is in the oceans, to measure the sea level, since the surface of the sea acts as a reflector for radar waves. The accuracy of the measurements depends on how precisely the satellite orbit is known, and on the reduction of dynamic effects on the sea surface such as semidiurnal and diurnal tides.

A typical application of altimeters is in aircraft to determine their height above the surface. Radar systems are often used for geometric height estimation of civil and military aircraft. A typical system consists of a standard altimeter backed up with secondary surveillance radar (*SSR*) operating on mode S coupled to an omnidirectional antenna fixed under the airplane. The geometric height is derived by various methods, such as the trilateration method, and the systematic errors are compensated for by deriving the profile of the effect on height measurements of the bias in range measurements. Various curve-fitting techniques are used, which estimate both the geometric height and any nonzero systematic errors.

High single point precision and high point density can be obtained by airborne laser altimetry, using *GPS* positioning and INS attitude determination. However, these methods are subject to various error sources, which include (1) internal laser sensor errors, (2) *GPS* and *INS* errors, (3) atmospheric effects, (4) terrain roughness, reflectivity, and slope, (5) presence, height, and type of vegetation, and (6) integration and synchronization of laser, *GPS*, and *INS*. When well calibrated, laser altimeters can give subcentimeter accuracy. However, the accuracy may be very sensitive to terrain type, terrain coverage, and filters used to remove undesired objects, such as buildings and trees. In particular, pointing accuracy, which depends on the pointing jitter of the scanning mirror and *INS* attitude determination, is a main error source, especially over high-relief terrain.

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