OPTICAL RADAR

LIDAR

Light detection and ranging (Lidar) is the optical analog of radar. Lidar systems employ intense beams of light, typically generated by lasers, and telescopes to receive the reflected light. The laser beams are either pulsed or modulated with radio frequency (RF) signals. Lidars are most commonly used to measure the composition and structure of the atmosphere. The very narrow beam width, narrow line width, and high modulation bandwidth of the laser make it possible to probe the atmosphere with exceptional sensitivity and resolution. When used to measure the range and velocity of hard targets, lidars are usually called laser ranging systems or laser radars.

For monostatic lidar systems, the laser beam is either projected through the receiving telescope or propagates parallel to the optical axis of the telescope (Fig. 1). The received signal levels depend on many factors including range to the target, power-aperture product of the lidar, and target scattering cross section or reflectivity. Depending on the application and range, telescope diameter varies from a few centimeters to several meters, and the average laser power varies from milliwatts to several tens of watts. Power-aperture products range from several tens of microwatts-square meter for laser theodolites and laser speed guns to almost 100 Wm^2 for powerful upper atmospheric lidars. If the lidar system is designed for ranging or altimetry, the receiver measures the round-trip propagation time of the laser pulse between the lidar and the target. The distance to the target is equal to $ct/2$, where c is the speed of light and t is the round-trip propagation time of the laser pulse. Precision timing is accomplished electronically by a device called the time interval unit. A beam splitter directs a small fraction (1%) of the transmitted laser beam to a photodetector. When illuminated by the transmitted laser pulse, the photodetector generates an electrical pulse which triggers (starts) a clock in the time interval unit. The laser pulse reflected by the target is collected by the receiving telescope and focused onto another, more sensitive photodetector, generating an electrical pulse that stops the clock. Then the elapsed time is transmitted to the range computer, which calculates the target distance. The optical filter and field stop in the telescope are designed to reduce interference and noise caused by other sources of light. The optical filter limits light transmission to the narrow wavelength range (color) of the laser, and the field stop limits the telescope's field of view to the region illuminated by the laser beam.

Ranging accuracy depends on many factors, including the laser pulse length, the received signal strength, and timing accuracy. The most sophisticated systems are used for ranging to retroreflector-equipped satellites and to the retroreflector arrays placed on the moon by the Apollo astronauts. Accuracies of a few centimeters are achieved routinely. Data from these measurements are used to monitor geophysical phenomena, such as continental drift, crustal dynamics, and the earth's rotational rate. Because of the extremely high accuracy required, a more sophisticated version of the range equation must be used which includes the effects of the additional propagation delay introduced by the earth's atmosphere. The first successful laser ranging measurements to satellites were conducted in 1964. In the early 1970s, the first

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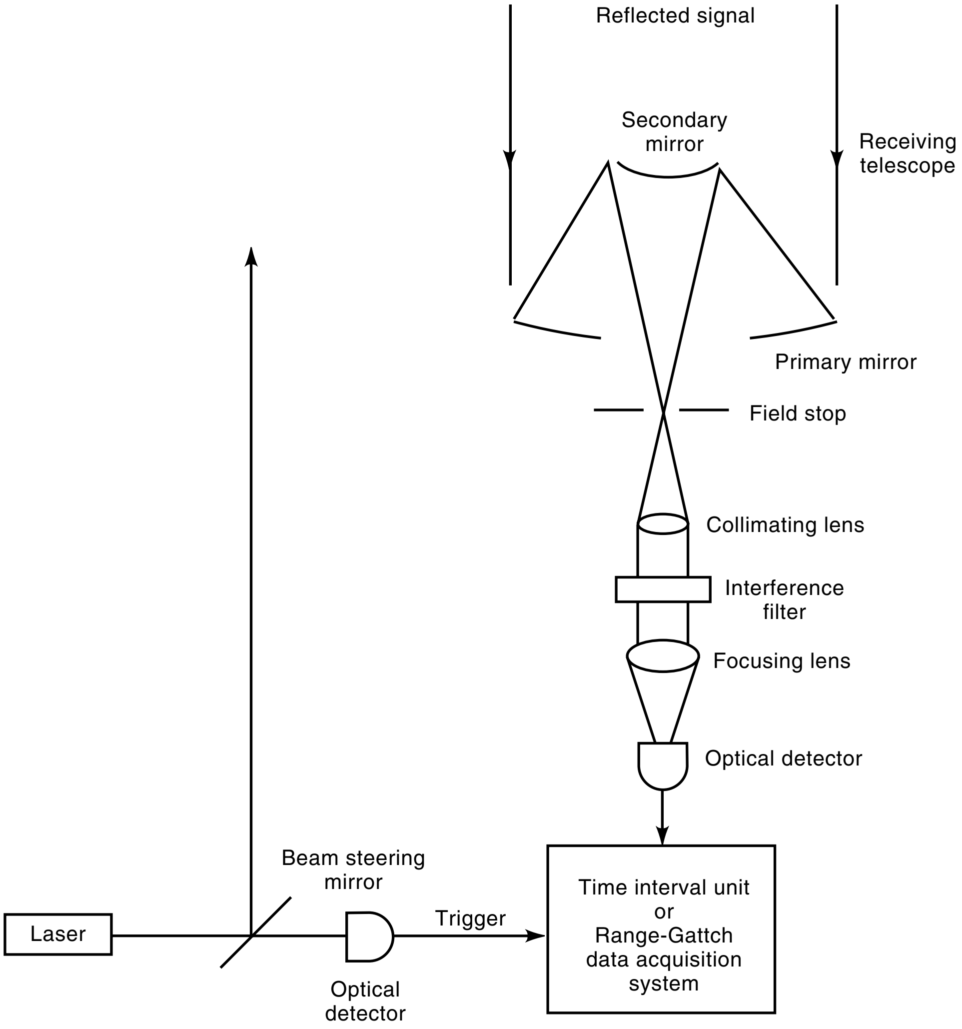

Figure 1. Block diagram of a typical monostatic system used for ranging or altimetry applications.

space-based laser altimeter was operated in lunar orbit from the Apollo 15, 16, and 17 command and service modules. The Mars Orbiter Laser Altimeter (MOLA) aboard the Mars Global Surveyor spacecraft began making precision measurements of the Martian topography on 15 September 1997. MOLA also records information on reflected pulse intensity and pulse width. Reflected intensity is related to surface albedo and composition. The pulse width is related to the roughness and slope of the terrain within the region illuminated by the laser beam.

Airborne laser altimeters provide maps of surface topography, coastal water depth, forest canopies, and sea ice distribution. For eye safety reasons, these systems employ laser power levels lower than those used for satellite ranging. Laser speed guns used by the police to monitor vehicle velocities, employ low-power diode lasers that are modulated by RF signals, such as sinusoids or pulse trains. The Doppler shift of the backscattered modulating waveform is measured by standard RF techniques and is used to compute line-of-sight velocity. Laser theodolites used for precision surveying, also employ RF modulated diode or gas lasers. The target is typically a cube corner retroreflector. The phase shift of the reflected signal is measured and used to compute distance. To obtain millimeter-level distance accuracies, it is necessary also to measure the atmospheric pressure and temperature along the propagation path to compensate for the additional delay (phase shift) introduced by the atmosphere. Except for the smaller telescopes (typically several centimeters in diameter) and lower laser powers (typically several milliwatts), the basic architecture of laser speed guns and laser theodolites is similar to that of the more sophisticated airborne and space-based altimeters.

The targets of atmospheric lidars are either suspended dust particles, aerosols, or gas molecules which are continuously distributed in the atmosphere along the propagation path of the laser beam. Atmospheric lidar systems are used to measure density profiles of the scatterers. Profiles are measured by pulsing the laser and then periodically sampling the detector output. The sampling process is called range gating. The signal level is proportional to the density of scatterers and inversely proportional to the square of the distance to the scattering volume. Because reflected signals from atmospheric aerosols and gas molecules are usually weak, many atmospheric lidars employ very sensitive photomultiplier tube detectors that operate in the photon-counting mode. The photomultiplier tube signal is processed by a pulse discriminator and range-gated counter. The pulse discriminator converts the low-level (few tenths of a volt) photomultiplier tube pulses generated by the individual detected photons to pulses that can be counted by conventional high-speed digital circuitry. The raw lidar data consists of a series of photon counts corresponding to consecutive range bins. The count in a given range bin is related to the number of scatterers in the corresponding volume illuminated by the laser pulse. In processing the photon count profile to yield the density profile of scatterers, other factors, such as the thickness of the scattering volume and the backscatter cross section, must also be taken into account. The thickness of the scattering volume is related to the laser pulse length and the receiver range gate length. The backscatter cross section is the effective cross-sectional area of the scatterer and depends on many factors, including scattering mechanism, optical wavelength, and optical properties of the scatterer. Only when the scatterer is large compared to the wavelength, which may be the case for cloud particles, does the physical size of the scatterer influence the value of the optical backscatter cross section.

Atmospheric lidars are classified according to the type of scattering mechanism exploited to make the measurement. Aerosol/cloud lidars measure scattering from dust, aerosols, and clouds. Ground-based observations with these systems have provided much of the data about the dispersion and global distribution of volcanic aerosols and about the life cycle and distribution of polar stratospheric clouds. Both phenomena occur in the altitude range between 10 km and 35 km (6 mi and 22 mi). Volcanic aerosols can have a significant influence on climate, and polar stratospheric clouds play a major role in the springtime depletion of ozone over both polar caps. The Lidar In-Space Technology Experiment (LITE) was the first spaceborne aerosol/cloud lidar. It flew aboard the shuttle Discovery in September 1994. LITE employed a Nd : YAG laser operating at three different wavelengths in the near infrared (1064 nm), visible (532 nm), and near ultraviolet (355 nm) and a one meter diameter telescope to measure aerosols, clouds, and even temperatures in the troposphere and lower stratosphere.

Rayleigh lidars are designed to measure the molecular (Rayleigh) scattered signal, which is proportional to atmospheric density. The atmospheric temperature profile is calculated from the density profile by using the ideal gas law and the hydrostatic equation. Density and temperature profiles at altitudes up to 100 km (60 mi) have been obtained with powerful ground-based systems employing lasers with tens of watts of power and telescopes of several meters diameter.

Differential absorption lidar (DIAL) is used to measure species concentrations in the lower atmosphere. DIAL systems employ two laser wavelengths, one tuned to an absorption line of the species of interest and the other tuned just off the absorption line. The signal received at the more strongly absorbed wavelength is weaker. By comparing the signal levels at the two wavelengths, a density profile of the species is calculated. A wide variety of important minor constituents in the lower atmosphere, including ozone and water vapor, are being studied by using DIAL systems.

Coherent or heterodyne detection Doppler lidars are used to measure tropospheric winds. The scattered laser pulse is Doppler-shifted in frequency in proportion to the line-of-sight velocity of the scatterer. The frequency shift is measured by combining the reflected signal with the transmitted laser beam, so that the electrical signal generated by the detector is at a frequency equal to the difference between the frequencies of the transmitted and reflected beams. The signal-processing electronics following the photodetector are similar to those used in Doppler radars. By scanning the lidar beam, the three-dimensional wind vector is measured. Mobile Doppler lidars have been used to map wind fields associated with a variety of atmospheric phenomena, such as frontal passages, downslope flows and gusts, and downbursts caused by severe thunderstorms.

Raman lidars measure the scattered signal at the Raman shifted wavelength. Because the Raman signal is very weak, measurements are usually restricted to the troposphere at altitudes below 10 km (6 mi). At these lower altitudes, however, Raman lidars have provided excellent measurements of atmospheric density, temperature, and water vapor concentration.

Resonance fluorescence lidars are used to measure the density, temperature, and velocity of specific molecular species, such as sodium, in the upper atmosphere between 80 km and 105 km (50 mi to 65 mi). The laser wavelength must be turned to the resonance absorption wavelength of the species of interest. When illuminated at the resonance wavelength by the lidar beam, the atoms fluoresce because some of the photons are resonantly absorbed and then reradiated. The resonant backscatter cross section is typically many orders of magnitude larger than the molecular backscatter cross section of the species. Meteoric ablation is the major source of sodium and the other metal layers in the upper atmosphere. Because these metallic species are excellent tracers of winds and temperature, resonance fluorescence lidars are used to study upper atmosphere chemistry and dynamics. More recently, astronomers have been experimenting with Na lidars to create artificial beacons (laser guide stars) in the upper atmosphere which can be used with adaptive imaging techniques to compensate for distortion caused by atmospheric turbulence. Adaptive telescopes equipped with Na guide stars are capable of producing images near the diffraction limit of the telescope. The resolution of these systems at near infrared and visible wavelengths can rival that of the Hubble Space Telescope.

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OPTICAL SIGNAL DETECTION. See INSPECTION IN SEMICONDUCTOR MANUFACTURING.

OPTICAL SIGNAL PROCESSING. See ACOUSTO-OPTICAL SIGNAL PROCESSING.

OPTICAL SYSTEMS. See PACKAGING OF OPTICAL COMPONENTS AND SYSTEMS.