Chapter 2
Interaction of Low-Power Laser Radiation with Surfaces

Abstract Various interactions of low-power laser radiation with the surfaces are examined. We describe the applications of this radiation in rangefinders, LIDARs, holography, low-level laser therapy, laser interferometer gravitational-wave observatories, free-space optical communications, laser lighting displays, scanners for barcodes, laser discs, pointers, and printers, laser interferometry and surface velocimetry.

Keywords Low-power laser radiation · Laser rangefinders · Satellite laser ranging · Lunar laser ranging · LIDARs · Holography · Low-level laser therapy · Laser interferometer gravitational-wave observatories · Free-space optical communications · Laser lighting displays · Laser scanners for barcodes · Laser discs · Laser printers · Laser interferometry · Laser pointers · Laser surface velocimetry

We start our consideration of laser-surface interactions from the very low light intensities at which almost no impact occurs on the properties of surface. Those intensities comprise a broad range between 10^0 and 10^6 W cm^{-2}. At these levels of irradiation the only processes occurring during interaction of the light photons with the target surfaces are the reflection, scattering and absorption. The example of application of the reflective properties of surfaces is a laser rangefinder. The scattering of laser light is used in the laser lighting displays. Finally, the absorption of low power laser radiation found its application in low-level laser therapy. The low power lasers applications for the analysis of surface properties are not restricted to the abovementioned areas and include fingerprint detection, microscopy, interferometry, laser discs, laser printers, laser pointers, etc. In particular, laser mi-

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croscopy is a rapidly growing field that uses low power laser illumination sources in various forms of microscopy. For instance, laser microscopy focused on biological applications uses ultrashort pulse lasers, or femtosecond lasers, in a number of techniques labeled as nonlinear microscopy, saturation microscopy, and multiphoton fluorescence microscopy.

In this Chapter, we discuss some of these applications using low power and low-intense lasers.

2.1 Laser Rangefinders

A laser rangefinder is a device, which uses a laser pulse to determine the distance to an object. The most common form of laser rangefinder operates on the time of flight principle by sending a laser pulse in a narrow beam towards the object and measuring the time taken by the pulse to be reflected off the surface target and returned to the sender.

Despite the beam being narrow, it will eventually spread over long distances due to the divergence of the laser beam, as well as due to scintillation and beam wander effects, caused by the presence of air bubbles in the air acting as lenses. These atmospheric distortions coupled with the divergence of the laser itself and with transverse winds that serve to push the atmospheric heat bubbles laterally may combine to make it difficult to get an accurate reading of the distance of an object, say, beneath some trees or behind bushes, or even over long distances of more than 1 km in open and unobscured desert terrain.

The distance between point A and B is given by $d=ct/2$, where c is the speed of light in the atmosphere and t is the amount of time for the round-trip between A and B. With the speed of light known, and an accurate measurement of the time taken, the distance can be calculated. Many pulses are fired sequentially and the average response is most commonly used. This technique requires very accurate sub-nanosecond timing circuitry.

2.1.1 Applications of Laser Rangefinders

Rangefinders provide an exact distance to targets located beyond the distance of point-blank shooting to snipers and artillery. They can also be used for military reconciliation and engineering. Handheld military rangefinders operate at ranges of 2 km up to 10 km and are combined with binoculars or monoculars. When the rangefinder is equipped with a digital magnetic compass and inclinometer it is capable of providing magnetic azimuth, inclination, and height (length) of targets. Some rangefinders can also measure a target's speed in relation to the observer. Some rangefinders have cable or wireless interfaces to enable them to transfer their measurement data to other equipment like fire control computers.

Fig. 2.1 This LIDAR scanner may be used to scan buildings, rock formations, etc., to produce a 3D model. The LIDAR can aim its laser beam in a wide range: its head rotates horizontally, a mirror flips vertically. The laser beam is used to measure the distance to the first object on its path

The more powerful models of rangefinders measure distance up to 25 km and are normally installed either on a tripod or directly on a vehicle or gun platform. In the latter case the rangefinder module is integrated with on-board thermal, night vision and daytime observation equipment. The most advanced military rangefinders can be integrated with computers.

Laser rangefinders are used extensively in 3D object recognition, 3D object modeling, and a wide variety of computer vision-related fields. This technology constitutes the heart of the so-called time-of-flight 3D scanners. Laser rangefinders offer high-precision scanning abilities, with either single-face or 360-degree scanning modes.

Laser rangefinders used in computer vision applications often have depth resolutions of tenths of millimeters or less. This can be achieved by using triangulation or refraction measurement techniques as opposed to the time of flight techniques used in LIDAR (Fig. 2.1). The LIDAR scanner may be used to scan buildings, rock formations, etc., to produce a 3D model. More details on this technique are presented in the following section.

Special laser rangefinders are used in forestry. These devices have anti-leaf filters and work with reflectors. Laser beam reflects only from this reflector and so exact distance measurement is guaranteed. Laser rangefinders with anti-leaf filter are used for example for forest inventories. Laser rangefinders may be effectively

Fig. 2.2 Laser rangefinder (Bosch PLR 25)

used in various sports that require precision distance measurement, such as golf, hunting, and archery (Fig. 2.2). An important application is the use of laser rangefinder technology during the automation of stock management systems and production processes in steel industry.

Laser rangefinders are also used in several other industries like construction, renovation and real estate as an alternative to a tape measure. To measure a large object like a room with a tape measure, one would need another person to hold the tape at the far wall and a clear line straight across the room to stretch the tape. With a laser measuring tool, this same job can be completed by one operator with just a line of sight. Laser measuring tools typically include the ability to produce some simple calculations, such as the area or volume of a room, as well as switch between imperial and metric units.

The interesting and very important area of applications is the use of laser rangefinders in space, geodesy, earth science, and climate changes. In the following subsection, we address in details the applications of lasers to measure the distances to satellites.

2.1.2 Satellite Laser Ranging

In satellite laser ranging (SLR) a global network of observation stations measures the round trip time of flight of ultrashort pulses of light to satellites' surfaces equipped with retroreflectors. This provides instantaneous range measurements of millimeter level precision, which can be accumulated to provide accurate measurement of orbits and a host of important scientific data.

Satellite laser ranging is a proven technique with significant potential for important contributions to scientific studies of the Earth/Atmosphere/Oceans system. It is the most accurate technique currently available to determine the geocentric position of an Earth satellite, allowing for the precise calibration of radar altimeters

Fig. 2.3 The building where Laser Ranging System of the geodetic observatory Wettzell, Germany is installed. (Reproduced from [1] with permission from Elsevier)

and separation of long-term instrumentation drift from secular changes in ocean topography. SLR provides a unique capability for verification of the predictions of the theory of general relativity.

Its ability to measure the variations over time in the Earth's gravity field and to monitor motion of the station network with respect to the geocenter, together with the capability to monitor vertical motion in an absolute system, makes it unique for modeling and evaluating long-term climate change by: (a) providing a reference system for post-glacial rebound, sea level and ice volume change, (b) determining the temporal mavss redistribution of the solid Earth, ocean, and atmosphere system and (c) monitoring the response of the atmosphere to seasonal variations in solar heating.

SLR stations form an important part of the international network of space geodetic observatories, which include GPS (Global Positioning System, a US military and navigation system, which is now widely used for scientific and commercial purposes), DORIS (Doppler Orbitography and Radiopositioning Integrated by Sattelite), and PRARE (Precise Range and Range Rate Equipment, a German positioning equipment) systems [1]. On several critical missions, SLR has provided failsafe redundancy when other radiometric tracking systems have failed. The images of two SLR stations are presented in Figs. 2.3 and 2.4.

Laser ranging to a near-Earth satellite was first carried out by NASA in 1964 with the launch of the Beacon-B satellite. Since that time, ranging precision, spurred by scientific requirements, has improved by a factor of a thousand from a few meters to a few millimeters, and more satellites equipped with retroreflectors have been launched. The International Laser Ranging Service (ILRS) was formed in 1998 by the global SLR community to enhance geophysical and geodetic research activities, replacing the previous Satellite and Laser Ranging Subcommission. The map of SLR stations is shown in Fig. 2.5.

Presently, Satellite Laser Ranging and Lunar Laser Ranging use short-pulse lasers and state-of-the-art optical receivers and timing electronics to measure the two-way time of flight (and hence distance) from ground stations to retroreflector arrays on Earth orbiting satellites and the moon (Fig. 2.6). The laser stations are also used to measure one-way distance from the ground stations to remote optical receivers in

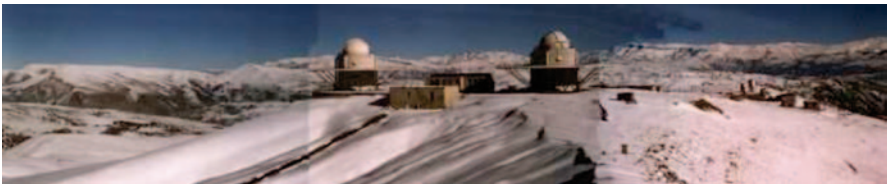

Fig. 2.4 The view of the SLR Maidanak, Uzbekistan placed on the altitude of 2.7 km. (Reproduced from [1] with permission from Elsevier)

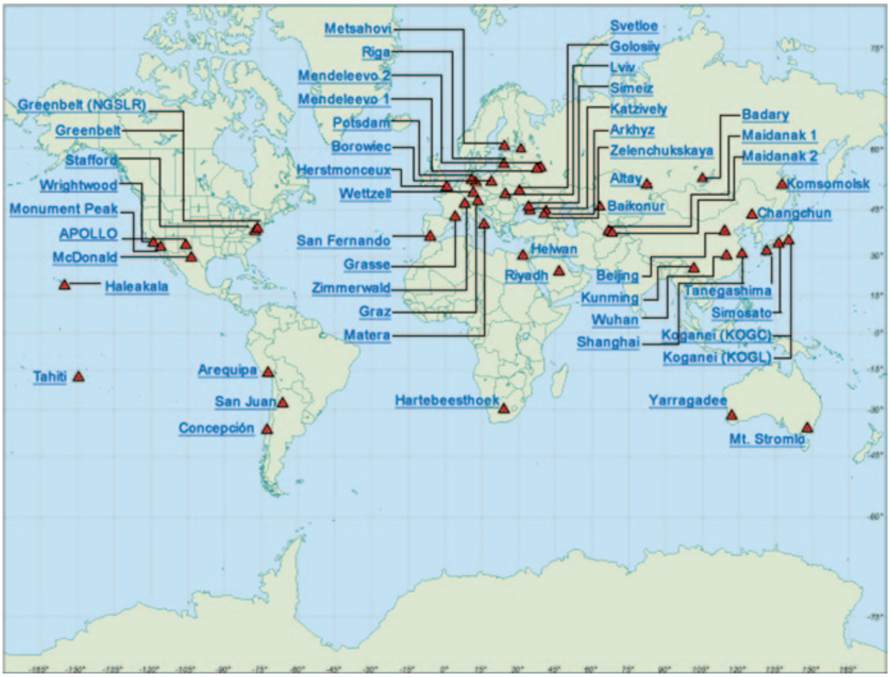

Fig. 2.5 Map of satellite laser ranging stations. (Reproduced from [1] with permission from Elsevier)

space and for very accurate time transfer. Currently, the accuracy of measurements of the distance between the Earth and Lunar Orbiter satellite reached 10 cm. Laser ranging activities organized under the ILRS, provide global satellite and lunar laser ranging data and their derived products to support geodetic, geophysical, and fundamental research activities as well as the maintenance of an accurate International Terrestrial Reference Frame. The service develops the necessary global standards/specifications and encourages international adherence to its conventions. The ILRS is one of the space geodetic services of the International Association of Geodesy and an entity within its Global Geodetic Observing System.

Several sets of retroreflectors were installed on the Earth's moon as part of the American Apollo and Soviet Lunokhod space programs. Some of these

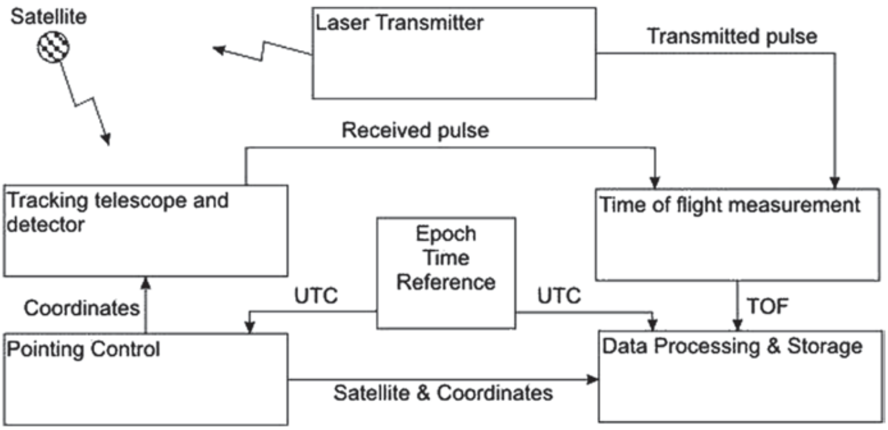

Fig. 2.6 Scheme of SLR equipment. (Reproduced from [1] with permission from Elsevier)

retroreflectors are also ranged on a regular basis, providing a highly accurate measurement of the dynamics of the Earth/Moon system. More details about these programs are given in the following subsection.

During the subsequent decades, the global satellite laser ranging network has evolved into a powerful source of data for studies of the solid Earth and its ocean and atmospheric systems. In addition, SLR provides precise orbit determination for spaceborne radar altimeter missions mapping the ocean surface (which are used to model global ocean circulation), for mapping volumetric changes in continental ice masses, and for land topography (Fig. 2.7). It provides a means for subnanosecond global time transfer, and a basis for special tests of the Theory of General Relativity.

SLR data has provided the standard, highly accurate model, which supports all precision orbit determination and provides the basis for studying temporal gravitational variations due to mass redistribution. The height of the geoid has been determined to less than ten centimeters. Also, SLR provides mm/year accurate determinations of tectonic drift station motion on a global scale in a geocentric reference frame. Combined with gravity models and decadal changes in Earth rotation, these results contribute to modeling of convection in the Earth's mantle by providing constraints on related Earth interior processes. As an example one can note the measurements of the velocity of the fiducial station in Hawaii using SLR (70 mm/year), which is closely matches the rate of the background geophysical model.

2.1.3 Lunar Laser Ranging

The ongoing Lunar Laser Ranging Experiment measures the distance between the Earth and the Moon using laser ranging. Lasers on Earth are aimed at retroreflectors planted on the Moon during the Apollo program, and the time for the reflected light to return is determined.

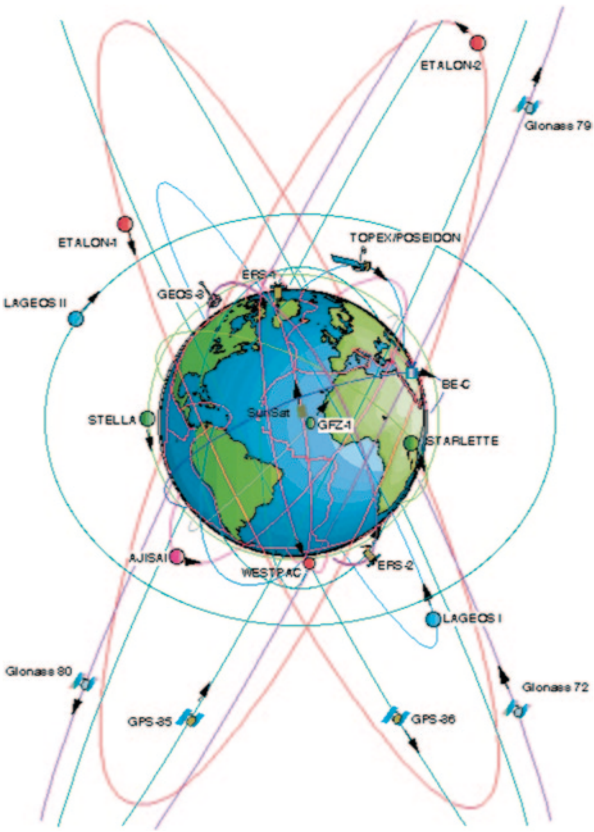

Fig. 2.7 A network of satellites used for SLR International System. (Reproduced from [1] with permission from Elsevier)

The first successful tests were carried out in 1962 when a team from the Massachusetts Institute of Technology succeeded in observing reflected laser pulses using a laser with a millisecond pulse length. Similar measurements were obtained later the same year by a Soviet team at the Crimean Astrophysical Observatory using a Q-switched ruby laser. Greater accuracy was achieved following the installation of a retroreflector array on July 21, 1969, by the crew of *Apollo 11*, while two more retroreflector arrays left by the *Apollo 14* and *Apollo 15* missions have also contributed to the experiment. Successful lunar laser range measurements to the retroreflectors were first reported by the 3.1 m telescope at Lick Observatory, Air Force Cambridge Research Laboratories Lunar Ranging Observatory in Arizona, the Pic du Midi Observatory in France, the Tokyo Astronomical Observatory, and McDonald Observatory in Texas.

The unmanned Soviet *Lunokhod 1* and *Lunokhod 2* rovers carried smaller arrays. Reflected signals were initially received from *Lunokhod 1*, but no return signals were detected after 1971 until a team from University of California rediscovered the array in April 2010 using images from NASA's Lunar Reconnaissance Orbiter. *Lunokhod 2's* array continues to return signals to Earth. The Lunokhod arrays suffer from decreased performance in direct sunlight, a factor, which was considered in the reflectors placed during the Apollo missions.

The *Apollo 15* array is three times the size of the arrays left by the two earlier *Apollo* missions. Its size made it the target of three-quarters of the sample measurements taken in the first 25 years of the experiment. Improvements in technology since then have resulted in greater use of the smaller arrays, by sites such as the Côte d'Azur Observatory in Grasse, France and the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) at the Apache Point Observatory in New Mexico.

The distance to the Moon is calculated using the abovementioned relation *Distance*= (*Speed of light ×Time taken for light to reflect*)/2. In actuality, the round-trip time of about 2½ s is affected by the relative motion of the Earth and the Moon, the rotation of the Earth, lunar libration, weather, polar motion, propagation delay through Earth's atmosphere, the motion of the observing station due to crustal motion and tides, velocity of light in various parts of air and relativistic effects. Nonetheless, the Earth-Moon distance has been measured with increasing accuracy for more than 35 years. The distance continually changes for a number of reasons, but averages about 384,467 km (238,897 miles).

At the Moon's surface, the beam is only about 6.5 km (4 miles) wide and scientists liken the task of aiming the beam to using a rifle to hit a moving dime 3 km (approximately 2 miles) away. The reflected light is too weak to be seen with the human eye: out of 10^{17} photons aimed at the reflector, only one will be received back on Earth every few seconds, even under good conditions. They can be identified as originating from the laser because the laser is highly monochromatic. This is one of the most precise distance measurements ever made, and is equivalent in accuracy to determining the distance between Los Angeles and New York to one hundredth of an inch. As of 2002 work is progressing on increasing the accuracy of the Earth-Moon measurements to near millimeter accuracy, though the performance of the reflectors continues to degrade with age.

Some of the findings of this long-term experiment are:

- The Moon is spiraling away from Earth at a rate of 3.8 cm per year. This rate has been described as anomalously high.
- The Moon probably has a liquid core of about 20 % of the Moon's radius.
- The universal force of gravity is very stable. The experiments have put an upper limit on the change in Newton's gravitational constant *G* of less than 1 part in 10^{11} since 1969.
- The likelihood of any "Nordtvedt effect" (a composition-dependent differential acceleration of the Moon and Earth towards the Sun) has been ruled out to high precision, strongly supporting the validity of the Strong Equivalence Principle.
- Einstein's theory of gravity (the general theory of relativity) predicts the Moon's orbit to within the accuracy of the laser ranging measurements.

The presence of reflectors on the Moon has been used to rebut claims that the Apollo landings were faked. For example, the APOLLO Collaboration photon pulse return graph has a pattern consistent with a retroreflector array near a known landing site.

2.2 Lidar

LIDAR (LIght Detection And Ranging) is an optical remote sensing technology that can measure the distance to, or other properties of, targets by illuminating the target with laser light and analyzing the backscattered light. LIDAR technology has applications in geoscience, archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing, atmospheric physics, airborne laser swath mapping (ALSM), laser altimetry, and contour mapping. The acronym LADAR (LAser Detection and Ranging) is often used in military contexts. The term “laser radar” is sometimes used, even though LIDAR does not employ microwaves or radio waves and therefore is not radar in the strict sense of the word.

LIDAR uses ultraviolet, visible, or near infrared light to image objects and can be used with a wide range of targets, including non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds and even single molecules [2]. A narrow laser beam can be used to map physical features with very high resolution.

LIDAR has been used extensively for atmospheric research and meteorology. Downward-looking LIDAR instruments fitted to aircraft and satellites are used for surveying and mapping—a recent example being the NASA Experimental Advanced Research LIDAR [3]. In addition LIDAR has been identified by NASA as a key technology for enabling autonomous precision safe landing of future robotic and crewed lunar landing vehicles [4].

Wavelengths from about 10 μm to the UV (250 nm) are used to illuminate the target. Typically light is reflected via backscattering. Different types of scattering are used for different LIDAR applications; most common are Rayleigh scattering, Mie scattering, Raman scattering, and fluorescence. Based on different kinds of backscattering, the LIDAR can be accordingly called Rayleigh LIDAR, Mie LIDAR, Raman LIDAR, Na/Fe/K Fluorescence LIDAR, and so on. Suitable combinations of wavelengths can allow for remote mapping of atmospheric contents by looking for wavelength-dependent changes in the intensity of the returned signal.

In general there are two kinds of LIDAR detection schema: “incoherent” or direct energy detection (which is principally an amplitude measurement) and coherent detection (which is best for Doppler, or phase sensitive measurements). Coherent systems generally use optical heterodyne detection, which, being more sensitive than direct detection, allows them to operate a much lower power but at the expense of more complex transceiver requirements.

In both coherent and incoherent LIDAR, there are two types of pulse models: micropulse LIDAR systems and high energy systems. Micropulse systems have developed as a result of the ever increasing amount of computer power available combined with advances in laser technology. They use considerably less energy in the laser, typically on the order of one microJoule, and are often “eye-safe,” meaning they can be used without safety precautions. High-power systems are common in atmospheric research, where they are widely used for measuring many atmospheric parameters: the height, layering and densities of clouds, cloud particle properties (extinction coefficient, backscatter coefficient, depolarization), temperature, pressure, wind, humidity, trace gas concentration (ozone, methane, nitrous oxide, etc.).

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