8 Laser Ranging

8.1 Introduction

In laser distance measurements to satellites (Satellite Laser Ranging, SLR) the time of flight of a laser pulse as it travels between a ground station and a satellite is observed. A short laser pulse is generated in the ground station, and is transmitted through an optical system to the satellite. A part of the outgoing laser pulse is used to start an electronic time interval counter (user clock). The target satellite carries appropriate retro-reflectors. The reflected pulse is received at the ground station, detected, amplified, analyzed, and used to stop the electronic counter (Fig. 8.1). The two-way travel time of the signal is derived from the two readings of the user clock, and is scaled into the distance, $d$, with the signal propagation velocity, $c$ (cf. (4.8)). The basic observation equation is hence very simple:

$$d = \frac{\Delta t}{2} c. \quad (8.1)$$

It is evident that satellite laser ranging is a two-way ranging method [4.2.2]. The main components of the ground equipment are

- a generator and transmitter of the laser pulses, including the optical system and mounting,
- a detector and analyser for the return pulses, including the receiver telescope, and
- a time-of-flight measurement unit.

In addition, some sub-components are required for pointing and control of the complete laser-tracking system, and for relation of the observation epochs to universal time.
The space segment consists of suitable satellites equipped with retro-reflectors.

The development of pulsed laser-systems for the tracking of artificial satellites started in the USA as early as 1961/62. The first satellite to carry laser-reflectors, BEACON EXPLORER-B (BE-B), was launched into an orbit of about 1000 km altitude and 80° inclination on October 9, 1964. The first successful signal returns were obtained in 1965 and yielded an accuracy of a few meters (Vonbun, 1977a).

In subsequent years progress has been very fast, the accuracy of range measurements being improved from several meters to a few centimeters (see Fig. 8.2). Satellite laser ranging systems have been developed, configured, and deployed at many places around the world, in some cases as in-house developments from working groups in the observatories. In 2002, about 40 systems were operating worldwide (ILRS, 2002).

The achievable range accuracy is strongly correlated with the length and resolution of the laser pulses. The simple relation is (cf. Fig. 8.5, p. 413) that

$$1 \text{ nanosecond (ns)} \equiv 15 \text{ cm}. \quad (8.2)$$

Usually, the laser systems were assigned to one of the following groups (generations), according to their concept and accuracy level:

**First generation**, pulse lengths of 10 to 40 ns, corresponding to 1 to 6 m in range accuracy; mostly ruby laser with Q-switch [8.3].

**Second generation**, pulse lengths of 2 to 5 ns, corresponding to 30 to 100 cm; application of sophisticated pulse analysis methods [8.4].

**Third generation**, pulse lengths of 0.1 to 0.2 ns (100 to 200 picoseconds), corresponding to 1 to 3 cm; mostly mode-locked Nd:YAG laser [8.3]; single photon detection capability.

A new generation of laser-systems is currently being developed with the capability of 1 to 3 mm range accuracy, low eye-safe energy and a high grade of autonomous tracking (Degnan, 2000), see [8.3.4]. Systems of the first and second generation have nearly disappeared from the field of scientific applications. The increase of accuracy over three decades was about three orders of magnitude (Fig. 8.2).

New and broad fields of application have been and are evolving with the increasing accuracy of the measuring systems. With an accuracy range of ±1 cm or better, considerable contributions can be made to the establishment of reference frames, to geodynamics, to the determination of precise satellite orbits and to the modeling of Earth’s gravity field [8.5].

Laser distance measurements are among the most accurate observation techniques in satellite geodesy, which is why they will be continuously used in the long-term
solution of important tasks in geoscience. This remains true in spite of the increasing efficiency of microwave techniques like GPS and DORIS. The eminent advantages of the satellite laser ranging technique are, among others, the

- very high accuracy potential, in particular because of the favorable propagation properties of light,
- longevity of satellites without active elements,
- long time series of observations and derived parameters,
- determination of absolute (geocentric) coordinates, in particular absolute heights,
- independent control of other geodetic space techniques, and
- backup for active orbit determination systems like PRARE, DORIS, GPS.

Possible disadvantages are:

- strong dependence on suitable weather conditions,
- high costs in building and maintaining the ground segment,
- inhomogeneous data distribution compared to GPS, DORIS, or VLBI,
- no or limited mobility of the ground segment, and hence only limited operational capability.

For further reading on technical questions see the proceedings volumes of the *International Workshop on Laser Ranging Instrumentation* (e.g. Schlüter et al. (1999); ILRS (2001)). The application of SLR in geodesy and geodynamics is widely discussed in the geodetic literature, in proceedings of the IAG (e.g. Schwarz (ed.) (2000)), in scientific journals like the *Journal of Geophysical Research* or the *Journal of Geodesy*, and in the reports of the *International Laser Ranging Service* (ILRS), see [8.5.1]. A short introduction is also given in Degnan, Pavlis (1994).

### 8.2 Satellites Equipped with Laser Reflectors

Laser ranging is only possible to satellites equipped with appropriate reflectors. The incoming laser light must be sent back in exactly the same direction from which it comes. Such types of reflectors are also called *retro-reflectors*; they are mostly made from glass prisms. A retro-reflector can be created by cutting an evenly sized pyramid from the corner of a cube. This is why they are often named *corner cube reflectors* (Henriksen, 1977).

In order to attain the desired accuracy, reflectors have to be carefully designed for the particular satellite geometry and orbital height; in particular, the energy balance has to be adjusted. The reflector must be sufficiently large to reflect enough energy. In most cases several single reflectors with a diameter of 2 to 4 cm are assembled in certain arrays, to achieve the necessary energy level. The alignment of the individual reflector requires extreme care in order to avoid pulse deformations caused by signal superposition.

The signal path within the cube corner must be known. If the reflectors cannot be arranged symmetrically with respect to the spacecraft’s center of mass, for instance for multiple-purpose satellites, the geometrical relationship between the individual reflector and the satellite’s center of mass is required [8.4].
Reflectors are passive devices and can be fitted easily enough as additional components on a given satellite. This is why a fairly large number of space vehicles carry an array of laser-reflectors. Table 8.1 gives an overview of a selection of satellites carrying laser ranging targets. The total number by 2002 amounts to about 70. In

<table>
<thead>
<tr>
<th>Satellite Name</th>
<th>Launch [year]</th>
<th>Altitude [km]</th>
<th>Inclination [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEACON-B</td>
<td>1964</td>
<td>890</td>
<td>80</td>
</tr>
<tr>
<td>BEACON-C</td>
<td>1965</td>
<td>930</td>
<td>41</td>
</tr>
<tr>
<td>GEOS-1</td>
<td>1965</td>
<td>1120</td>
<td>40</td>
</tr>
<tr>
<td>DIADEME-1C</td>
<td>1967</td>
<td>540</td>
<td>40</td>
</tr>
<tr>
<td>DIADEME-1D</td>
<td>1967</td>
<td>580</td>
<td>40</td>
</tr>
<tr>
<td>GEOS-2</td>
<td>1968</td>
<td>1080</td>
<td>106</td>
</tr>
<tr>
<td>STARLETTE</td>
<td>1975</td>
<td>810</td>
<td>50</td>
</tr>
<tr>
<td>GEOS-3</td>
<td>1975</td>
<td>840</td>
<td>115</td>
</tr>
<tr>
<td>LAGEOS-1</td>
<td>1976</td>
<td>5850</td>
<td>110</td>
</tr>
<tr>
<td>SEASAT</td>
<td>1978</td>
<td>800</td>
<td>108</td>
</tr>
<tr>
<td>ASIJAI</td>
<td>1986</td>
<td>1480</td>
<td>50</td>
</tr>
<tr>
<td>ETALON-1</td>
<td>1989</td>
<td>19100</td>
<td>65</td>
</tr>
<tr>
<td>ETALON-2</td>
<td>1989</td>
<td>19100</td>
<td>65</td>
</tr>
<tr>
<td>GLONASS-40...</td>
<td>1989–2001</td>
<td>19140</td>
<td>65</td>
</tr>
<tr>
<td>ERS-1</td>
<td>1991</td>
<td>780</td>
<td>99</td>
</tr>
<tr>
<td>TOPEX/POSEIDON</td>
<td>1992</td>
<td>1350</td>
<td>66</td>
</tr>
<tr>
<td>LAGEOS-2</td>
<td>1992</td>
<td>5630</td>
<td>53</td>
</tr>
<tr>
<td>STELLA</td>
<td>1993</td>
<td>810</td>
<td>99</td>
</tr>
<tr>
<td>GPS 35</td>
<td>1993</td>
<td>20100</td>
<td>54</td>
</tr>
<tr>
<td>GPS 36</td>
<td>1994</td>
<td>20100</td>
<td>55</td>
</tr>
<tr>
<td>ERS-2</td>
<td>1995</td>
<td>800</td>
<td>99</td>
</tr>
<tr>
<td>GFZ-1</td>
<td>1995</td>
<td>400</td>
<td>52</td>
</tr>
<tr>
<td>TIPS</td>
<td>1996</td>
<td>1020</td>
<td>63</td>
</tr>
<tr>
<td>GFO-1</td>
<td>1998</td>
<td>800</td>
<td>108</td>
</tr>
<tr>
<td>WESTPAC</td>
<td>1998</td>
<td>830</td>
<td>98</td>
</tr>
<tr>
<td>SUNSAT</td>
<td>1999</td>
<td>400</td>
<td>93</td>
</tr>
<tr>
<td>CHAMP</td>
<td>2000</td>
<td>430–470</td>
<td>87</td>
</tr>
<tr>
<td>STARSHINE-3</td>
<td>2001</td>
<td>470</td>
<td>67</td>
</tr>
<tr>
<td>JASON</td>
<td>2001</td>
<td>1340</td>
<td>66</td>
</tr>
<tr>
<td>METEOR 3M</td>
<td>2001</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>REFLECTOR</td>
<td>2001</td>
<td>1020</td>
<td>100</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>2002</td>
<td>800</td>
<td>98</td>
</tr>
<tr>
<td>GRACE A</td>
<td>2002</td>
<td>480–500</td>
<td>89</td>
</tr>
<tr>
<td>GRACE B</td>
<td>2002</td>
<td>480–500</td>
<td>89</td>
</tr>
<tr>
<td>ICESAT</td>
<td>2003</td>
<td>600</td>
<td>94</td>
</tr>
</tbody>
</table>
most cases, the SLR technique is applied to provide precise orbital information for the particular satellite mission (e.g. for altimeter satellites [9] or for gravity field missions [10]). Today, in most cases where precise orbits are required, space vehicles are fitted with a reflector array as a back-up system.

Some satellites have been launched with the sole objective of serving as precise targets in their orbits. These space vehicles have been optimized in design and orbital parameters. Dedicated laser satellites of this type are STARLETTE, STELLA, LAGEOS-1/2, AJISAI, ETALON-1/2, GFZ-1 and WESTPAC. They are described below in more detail.

**STARLETTE** was launched by the French Space Agency CNES (Centre National d’Etudes Spatiales) on February 6, 1975 with the following characteristic data (CNES, 1975):

- perigee height 805 km,
- apogee height 1108 km,
- orbit inclination 49.8 degrees,
- period of perigee \( \sim 110 \) days,
- nodal period \( \sim 91 \) days,
- diameter 24 cm,
- mass 47.295 kg, and
- retro-reflecor 60, diameter 33 mm.

STARLETTE was the first satellite to be designed with minimized surface forces in order to allow highly precise laser ranging. The core consists of Uranium 238 with a density of 18.7 [g/cm³], formed as an icosahedron with 20 triangular planes. Each triangle carries a spherical aluminum cap with three integrated retro-reflectors.

Due to the extremely favorable area/mass ratio the disturbing forces (drag and solar radiation pressure [3.2.3]) are minimized, and can be precisely modeled. This is why gravitational forces, acting on low orbiting satellites, can be separated and well analyzed. The main fields of application are the determination and analysis of [8.5]

- ocean tides and body tides (main purpose),
- Earth’s gravity field,
- geocentric station coordinates,
- polar motion, Earth rotation, and
- tidal friction.

Because of its rather low orbit, STARLETTE is particularly suitable for the study of solid Earth tides and related elasticity models of the Earth [8.5.6].

A virtually identical twin satellite, named **STELLA**, was launched into a sun-synchronous orbit on September 26, 1993. The orbital parameters are:

- inclination 98.6 degrees,
- height 800 km,
- quasi circular orbit.

As with STARLETTE, the main objectives are: a contribution to the gravity field, in particular tuning the field for sun-synchronous Earth observing satellites such as SPOT, ERS and others; a contribution to the modeling of non-gravitational forces; and
8.2 Satellites Equipped with Laser Reflectors

for modeling the Earth and ocean tides. The anticipated lifetime of STARLETTE and STELLA is several centuries.

*LAGEOS-1* was launched by the American Space Agency NASA on May 4, 1976; and *LAGEOS-2* as a joint U.S.-Italian project on October 22, 1992. The orbital characteristics are:

<table>
<thead>
<tr>
<th></th>
<th>LAGEOS-1</th>
<th>LAGEOS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perigee height</td>
<td>5860 km</td>
<td>5620 km</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>109.84 degrees</td>
<td>52.64 degrees</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0045</td>
<td>0.0135</td>
</tr>
<tr>
<td>Period</td>
<td>225 minutes</td>
<td>223 minutes</td>
</tr>
<tr>
<td>Diameter</td>
<td>60 cm</td>
<td>60 cm</td>
</tr>
<tr>
<td>Shape</td>
<td>sphere</td>
<td>sphere</td>
</tr>
<tr>
<td>Mass</td>
<td>411 kg</td>
<td>405 kg</td>
</tr>
<tr>
<td>Reflectors</td>
<td>426 corner cubes</td>
<td>426 corner cubes</td>
</tr>
</tbody>
</table>

The design goals of LAGEOS were, as for STARLETTE, to minimize surface forces, and to create a precise relationship between the satellite’s center of gravity and the individual reflectors. Due to its greater altitude, the LAGEOS orbit is less sensitive to atmospheric drag and short wavelength terms of Earth’s gravity field than is the STARLETTE orbit. The retro-reflectors are incorporated into an aluminum sphere surrounding a cylindric brass core (Fig. 8.3). 422 silicon reflectors serve for the pulse range measurements. Four additional germanium reflectors were designed for range rate observations with optical Doppler measurements. The name LAGEOS stands for *Laser Geodynamics Satellite* (originally “Laser Geodetic Satellite”), and thus indicates the main fields of application [8.5]:

- installation and maintenance of a precise geodetic reference frame,
- determination of tectonic plate motion and regional crustal movements,
- determination of Earth orientation parameters (polar motion, Earth rotation),
- study of Earth’s gravity field.

The lifetime of the LAGEOS satellites is estimated to be several millions of years. This is why a steel plaque, indicating continental drift, was added to the first spacecraft as a “message to the future”.

The Japanese *Experimental Geodetic Satellite* (EGS), also named AJISAI, was launched on August 12, 1986 into a circular orbit of 1500 km altitude and 50° inclination (cf. [4.3.2]). The orbital period is 1.93 hours, the rotation period of perigee 142.53 days, and the nodal period 117.53 days. The spherical satellite has a diameter
of 214 cm, a mass of 685 kg, and carries 120 laser reflector assemblies. The area/mass ratio is hence less favorable than for STARLETTE and LAGEOS. The satellite can be used for laser range and photographic direction measurements. The original goal was to determine the location of isolated islands and to adjust the geodetic network of Japan (Komaki et al., 1985). In the meantime, tracking of AJISAI has contributed considerably to the improvement of gravity field models and the geodetic reference frame (Torrence, 1999).

In January and May 1989 the former Soviet Union launched two spherical satellites, named ETALON-1 and ETALON-2, each time together with two GLONASS satellites into rather high orbits. The characteristic parameters are:

- altitude: 19 120 km,
- eccentricity: 0.00068,
- orbit inclination: 65 degrees,
- diameter of sphere: 1.294 m,
- mass: 1 415 kg,
- period: 675 minutes, and
- reflector arrays: 306, each with 14 corner cubes.

Of the reflectors, six are made of germanium for possible future infrared interferometric measurements, and they are placed symmetrically.

The original objective of the ETALON mission was to determine solar radiation pressure for the orbit control of GLONASS satellites (Anodina, Prilepin, 1989). Because of the high orbital altitude, the ETALON satellites, together with LAGEOS, form the basis of a high-accuracy global reference coordinate frame. Further significant contributions are expected to the modeling of the low order gravitational field parameters, to the determination of the geocentric gravitational constant \(GM\) and station positions, and to the estimation of Earth orientation parameters.

Two particular dedicated laser tracking satellite are GFZ-1 and WESTPAC-1. GFZ stands for GeoForschungsZentrum Potsdam. The small spherical satellite with a diameter of 21.5 cm and a mass of 20.6 kg (Fig. 8.4) carried 60 retro-reflectors and was jettisoned from the Russian MIR space station on April 19, 1995, into a low (400 km) nearly circular Earth orbit of 51.6 degrees inclination. From this initial altitude it was to decay naturally with a predicted lifetime of 3.5 to 5 years. On June 23rd 1999 it burned up after nearly 24,000 orbits. The last observation placed GFZ-1 at an altitude of 230 km.

The mission objectives of GFZ-1 were to determine variations in rotational characteristics of the Earth and to recover high resolution parameters of the gravity field.
Through the changing orbital height during the satellite’s lifetime it was possible to estimate a wide variety of higher order gravity coefficients [8.5.3].

**WESTPAC-1** stands for **Western Pacific Laser Tracking Network Satellite**. The satellite is of a similar size to GFZ-1, and was launched on July 10, 1998, into a sun-synchronous circular orbit of 835 km altitude and 98 degrees inclination. The satellite has a diameter of 24 cm, a mass of 23 kg and carries 60 corner cube reflectors. WESTPAC-1 was designed in particular to provide a high ranging accuracy. The specific features are a center-of-mass correction within 0.5 mm accuracy and that only a single corner-cube will reflect at any shot.

In total, at the end of the year 2002, eight dedicated laser-satellites are in orbit. The tracking characteristics are quite different allowing multi-satellite ranging for appropriate tracking systems [8.3]. Table 8.2 shows some characteristic features of the most important dedicated targets.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mean altitude</th>
<th>Maximum pass duration</th>
<th>Signal flight time Min./Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>STARLETTE/STELLA</td>
<td>810 km</td>
<td>10 min.</td>
<td>6/14 ms</td>
</tr>
<tr>
<td>AJISAI</td>
<td>1,490 km</td>
<td>15 min.</td>
<td>10/20 ms</td>
</tr>
<tr>
<td>LAGEOS-1, -2</td>
<td>5,999 km</td>
<td>50 min.</td>
<td>40/57 ms</td>
</tr>
<tr>
<td>ETALON-1, -2</td>
<td>19,100 km</td>
<td>330 min.</td>
<td>127/150 ms</td>
</tr>
</tbody>
</table>

### 8.3 Laser Ranging Systems and Components

#### 8.3.1 Laser Oscillators

The most important component of a laser ranging system is the laser-oscillator. The artificial word **LASER** (Light Amplification by Stimulated Emission of Radiation) denotes a configuration for the coherent amplification of electromagnetic oscillations in the (optical) spectral domain through induced emission. In an optical resonator, the electromagnetic wave interacts with excited material.

Besides the coherence, (i.e. the fixed phase coupling between the individual beams providing monochromatic light), two more properties of the laser are exploited in satellite geodesy. These are the high degree of collimation of the beam, and the high power density. Hence, very high-energy, sharply defined, pulses can be transported over large distances.

In satellite geodesy two types of solid state pulsed lasers are widely used, the ruby laser and the Neodymium-YAG laser. The SLR systems of the first and second generation are almost exclusively equipped with ruby lasers, whereas the third generation systems mostly use the Nd:YAG laser.
Ruby is the classic material of solid state lasers. Ruby is a crystal, absorbing green and blue-violet light, and emitting sharp red spectral lines at 694.3 nm. By changing the resonator quality and opening the resonator at the predefined maximum of energy absorption, single laser pulses can be generated with a pulse width of about 10 to 50 nanoseconds and a peak power of 1 GigaWatt. The process is controlled by the so-called Q-switch (Q stands for quality). With a special arrangement of the Q-switch inside the resonator it becomes possible to reduce the pulse width to 2–5 ns. This is, however, the upper limit of performance for a ruby laser.

Another way of generating short pulses is the coupling of longitudinal resonator oscillations, the so-called modes, through active modulators, producing a defined sequence of short, high energy pulses. In particular, the Neodymium-YAG laser (YAG = Yttrium-Aluminium-Garnet) is suited for the mode-coupling. This technique makes a reduction of the pulse width to 100 to 200 picoseconds possible. It also requires less pumping energy, and hence provides a better system performance and a higher pulse repetition rate. Finally, the frequency is doubled and, with a wavelength of 530 nm (green) instead of 1060 nm (infrared), produces better conditions for the reception of return pulses.

Modern developments are directed toward eyesafe lasers, i.e. lasers with low power and high repetition rate (see [8.3.4]). For an overview of the current status in satellite laser ranging technology see the proceedings of the biannual International Workshop on Laser Ranging, e.g. Schlüter et al. (1999); ILRS (2001).

8.3.2 Other System Components

(a) Telescope Mount
The transmitter component must be able to follow moving targets. This is possible with a mounting that permits changes in azimuth and elevation. It is advisable to fit the receiver to the same mounting, or to integrate the transmitter and receiver telescopes.

For first generation systems the laser apparatus was usually also mounted on the pointing assembly. Third generation lasers are rather sensitive and hence need a well controlled environment. Stationary systems are usually kept on a rigid bench in a particular clean-room near the pointing assembly. The laser pulses are directed via a series of prisms or optical conductors to the transmission telescope. It is necessary to point the telescope with sufficient accuracy to the satellite. For first generation systems, tracking was often controlled visually with the help of a guidance telescope. The pointing control of third generation systems usually works automatically, with computer control, based on pre-computed ephemerides, so-called IRVs (Inter-Range Vector, see [8.5.1]). This is also required because of the ability to make daytime observations.

During the satellite pass, corrections are derived from a comparison between the pre-determined and actual satellite positions. In order to achieve a high return rate, even for distant satellites, a pointing accuracy of ±1" is aimed for, which is quite a demanding requirement for guidance and control. The divergence of the outgoing laser beam can usually be adapted to different satellite ranges, and for tracing the
8.3 Laser Ranging Systems and Components

A fast switch between different satellites, following a priority list, is essential for participation in international projects [8.5.1].

(b) Receiver elements, signal detection package

The laser pulse energy per unit area decreases with the square of the distance, and in addition the signal is attenuated in the atmosphere. This is the reason why very little energy comes back to the ground system after travelling to and from the satellite, in spite of the high initial energy and the strong beam focussing. Very powerful receiver systems are hence required, especially for distant satellites.

The receiver unit consists of optical and electronic components. Reflector telescopes (mirrors) or refractor telescopes (lenses) can be used as optical receivers. In most cases preference is given to a reflector because of its better capacity for weak luminosities. The geometrical quality of the signals is of minor interest. A filter of very low bandwidth is used ($\Delta \lambda \sim 1 \text{ nm}$) in the frequency domain of the laser light, in order to minimize the influence of disturbing light.

The signal detection package usually contains a photomultiplier with an extremely short rise time and high resolution. To avoid the reception of disturbing signals, the element is only activated for a very short pre-determined time interval $\Delta t$ (0.1 to 10 $\mu$s). The rise time should not be larger than 100 to 300 ps, and the necessary amplification is about $10^5$. Third generation laser systems work on the basis of single photon detection. Some new developments use microchannel plate photomultipliers (MCP) for amplification and a so-called streak-camera to collect the echo photons (Riepl, 1998).

(c) Impulse analysis

The transmitted laser pulse has a well defined form as is shown in Fig. 8.5 (a), in which the energy distribution is traced along the direction of the signal propagation. $H_1$ and $H_2$ denote the level where the impulse reaches half of the amplitude. The distance between $H_1$ and $H_2$ is called pulse length or pulse half width. The epoch of transmission, $t_a$, referred to the pulse center, can be easily determined by triggering techniques if the half-length of the known or measured pulse length, $l_1$, is added to the trigger signal, $H_1$.

![Figure 8.5](image)

Figure 8.5. Shape of the transmitted (a) and received (b) pulse signal in satellite laser ranging

The shape of the return signal is deformed because of several disturbing influences (Fig. 8.5 (b)). Amongst these are atmospheric disturbances, superposition caused by
signal reflection at different retro-cubes, and relative motion between transmitter and reflector. A careful pulse-analysis is required to determine the pulse center.

For modern systems, working on the basis of single photon-electron detection, no pulse analysis is possible. In these cases the single photon-electrons have to be identified and analyzed with very fast detectors. Current techniques use, for example, SPAD (Single Photon Avalanche Diode) techniques (Prochazka et al., 1999).

Instead of using a single pulse, techniques have been developed to use a train of 5 to 10 short pulses (about 50 ps length) at a fixed interval of a few nanoseconds. From this train an electro-optical shutter passes about half the pulses, the so-called semitrain, containing 3 to 5 pulses (Paunonen, 1999), see also Hamal, Prochazka (1989). This method increases the precision and decreases the single pulse energy.

(d) **Time Base**
The signal travel time is measured by a propagation timer, which is controlled by an extremely accurate clock. Electronic counters are used with a resolution of about 10 ps. The counters are controlled by atomic clocks with high long-term and short-term stability, in particular rubidium and cesium standards, or hydrogen masers [2.2.5]. Atomic clocks also define the station system time which is needed for determination of the observation epochs. Regular comparisons with international time scales (UTC) are required, and can be easily realized via an appropriate GPS receiver with an accuracy level of better than 20 ns [7.6.2.9].

(e) **System Computer**
A suitable computer is required, with the related software, for the pre-calculation of satellite ephemerides and pointing elements, the guidance and control of the instrument mounting, the control of the whole system, calibration and control of system parameters, data analysis, data control and data transfer. In modern systems, multi-tasking and network processors with real-time capability, as well as remote control, are required.

(f) **Aircraft Detector**
In some areas with dense air traffic, and near airports, it may be required to make provisions against an airplane passing through the laser beam. An optical or radar airplane detection system can be deployed that automatically interrupts the laser operation. Because of the low energy of modern laser ranging systems (eye safe operation), the requirement for installing airplane detection devices is now less stringent.

### 8.3.3 Currently Available Fixed and Transportable Laser Systems

In 2002 about 40 systems were used worldwide for laser ranging to satellites. Most of them now belong to the third generation or are new developments. The majority has the capability of ranging to high satellites such as ETALON, GLONASS and GPS, while only three or four systems can reach the Moon. Most systems installed are stationary, although the number of transportable systems is increasing. A current overview of systems contributing to global geodesy and geodynamics [8.5] is given in
the documents of the *International Laser Ranging Service* (ILRS) [8.5.1]. Many of the older systems have been replaced or upgraded in recent years (Husson, 1999).

Table 8.3 gives an overview on the system data of two modern laser ranging systems, the *Wettzell Laser Ranging System* (WLRS), operating in the fundamental station Wettzell, Germany [12.5], and the MOBLAS-7, operating at the *Goddard Geophysical Astronomical Observatory* (GGAO) in Greenbelt, Md. USA.

**Table 8.3. System data of two laser ranging systems**

<table>
<thead>
<tr>
<th>System</th>
<th>WLRS</th>
<th>MOBLAS-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>75 cm mirror</td>
<td>76 cm mirror</td>
</tr>
<tr>
<td>Mount</td>
<td>Alt/Az</td>
<td>Alt/Az</td>
</tr>
<tr>
<td>Lasertype</td>
<td>Nd:YAG</td>
<td>Nd:YAG</td>
</tr>
<tr>
<td>Laserfrequency</td>
<td>532 nm</td>
<td>532 nm</td>
</tr>
<tr>
<td>Operating mode</td>
<td>single pulse 532nm (100ps, 180 mJ)</td>
<td>single pulse 532nm (100ps, 180 mJ)</td>
</tr>
<tr>
<td></td>
<td>single pulse 1064 nm (100 ps, 360 mJ)</td>
<td>(200ps,100 mJ) pulse semitrain (4-8 pulses, 300 mJ)</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>1 to 10 Hz</td>
<td>1, 5, 10 Hz</td>
</tr>
<tr>
<td>Receiver</td>
<td>Photomultiplier, Avalanche diode, Microchannel plate photomultiplier</td>
<td>Photomultiplier Microchannel plate photomultiplier</td>
</tr>
<tr>
<td></td>
<td>Streak camera</td>
<td>Streak camera</td>
</tr>
<tr>
<td>Observation range</td>
<td>satellites and Moon</td>
<td>high satellites</td>
</tr>
</tbody>
</table>

The global geographical distribution of laser systems (see Fig. 8.13, p. 432) reflects national capabilities and interests, and is often not very suitable for the analysis of regional and local geodynamical phenomena. To allow more flexible applications, in particular in the determination of crustal motion [8.5.1][12.4.1], transportable systems of the newest laser technology are being developed. Some of them have already been widely used in recent years, for example in the Mediterranean area (MEDLAS project [8.5.4]) and in the NASA *Crustal Dynamics Program* [12.4.1]. The systems have a modular construction and can be transported with containers in regular airplanes. They work with quite low energy and with single photon detection. Typically, mobile systems occupy sites for periods of 2–3 months, and then require several days for relocation. Examples of current transportable systems are:

- FTRLS-1 (France),
- TLRS (Germany),
- TROS (China),
- MTLRS-1 (Germany), and
- MTLRS-2 (Netherlands).

Table 8.4 gives some system data. All systems work with the single photon technique and allow daylight operation.
### Table 8.4. System data of transportable laser ranging systems

<table>
<thead>
<tr>
<th>System</th>
<th>MTLRS-1/2</th>
<th>FTLRS</th>
<th>TLRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>40 cm</td>
<td>13 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>500 kg</td>
<td>300 kg</td>
<td>1700 kg incl. cart</td>
</tr>
<tr>
<td>Laser</td>
<td>Nd:YAP 539 nm</td>
<td>Nd:YAG 1064 nm</td>
<td>Titan Sapphire 427/854 nm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>10 mJ</td>
<td>100 mJ</td>
<td>30 mJ</td>
</tr>
<tr>
<td>Pulse length</td>
<td>200 ps</td>
<td>100 ps</td>
<td>80 ps</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Time base</td>
<td>cesium</td>
<td>rubidium, GPS controlled</td>
<td>2 cesium, 2 hydrogen maser</td>
</tr>
<tr>
<td>Range</td>
<td>6000 km</td>
<td>6000 km</td>
<td>36000 km</td>
</tr>
</tbody>
</table>

The Modular Transportable Laser Ranging Systems, MTLRS-1 and MTLRS-2, have been operated successfully since 1984 for about 15 years, mainly in the Mediterranean for international geodynamic projects (e.g. WEGENER/MEDLAS). The slight difference of wavelength, as compared with the Nd:YAG laser, comes from the use of a different laser active material, named Nd:YAP (YAP: Yttrium OrthoAluminate, a crystal of the mineral type Perovskite). The normal point [8.4.2] accuracy is about 1 to 2 cm.

The French Transportable Laser Ranging Station, FTRLS (Pierron et al., 1999), was developed by French organizations and entered its operational phase in 1996. The system is highly mobile, weighing only 300 kg, in 8 containers. The system can reach satellites at LAGEOS height. Its main objective is the installation of low cost laser stations in remote areas for research in geodynamics and the calibration of altimeter satellites [9.3.3].

The TIGO Laser Ranging System, TLRS, is designed to measure ranges to satellites with an accuracy better than 1 cm simultaneously at two wavelengths. The tracking range is from low orbit satellites at about 300 km altitude up to geostationary satellites (36000 km). TIGO stands for Transportable Integrated Geodetic Observatory. Besides the SLR module, TIGO includes a VLBI module [11.1], GPS, GLONASS and DORIS receivers, a time-keeping laboratory and a superconducting gravity meter (Schlüter et al., 2000). The installation of TIGO at a particular site is always anticipated for a duration of several years. Since 2002 TIGO has been operating in Concepción, Chile [12.5.2].

### 8.3.4 Trends in SLR System Developments

Some of the main development trends are toward the following characteristics:
- short pulse width, down to 50 picoseconds or even less; pulse trains;
- high repetition rate (10 Hz); low output signal strength,
single photon detection; exploitation of quantum-statistic properties; faster electronics; improved photodetectors such as single photon avalanche diode or microchannel plate; streak cameras,
- eyesafe systems, i.e. low energy (150 µJ) and high repetition rate (2 KHz),
- fully automatic operation, remote control, 24-hour operation,
- reduced station construction, operating and maintenance costs,
- higher mobility through low-weight optics,
- real-time data processing and data transfer,
- software-oriented systems, hence higher flexibility,
- multiple satellite tracking capability,
- low error budget (~1 mm),
- two-color ranging, and
- epoch synchronization down to 10 ns (corresponding to 0.1 mm).

NASA is developing a modern SLR system meeting most of these requirements under the name SLR2000. SLR2000 is an autonomous, eyesafe, single photon-counting satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm (Degnan, 2000). The system is designed to provide 24-hour tracking coverage. It is planned to build more than 10 systems with a replication cost of $1M per system. The main features are:
- Q-switched Nd:YAG microlaser, frequency-doubled, 532 nm,
- 130 µJ of energy, 2 KHz repetition rate,
- high-speed quadrant microchannel plate photomultiplier,
- high-speed high resolution event timer,
- arcsecond precision tracking mount,
- shelter and protective dome,
- CCD camera for guidance control and focussing, and
- daylight tracking capability to GPS.
Potential upgrades are to a two-color system as well as adapting the SLR2000 for interplanetary ranging through the use of transponders.

The ILRS [8.5.1] has established System Performance Standards in order to evaluate SLR systems. The performance guidelines are divided into three categories (data quantity, data quality and operational compliance). A high performance SLR system should fulfill the following criteria for

**yearly data quantity:**
- 1000 Low Earth Satellite (LEO) passes,
- 400 LAGEOS-1,2 passes, and
- 100 high satellite passes;

**data quality:**
- 1 cm LAGEOS normal point precision,
- 2 cm short term range bias stability (standard deviation of the pass by pass biases), and
- 1 cm long term bias stability (standard deviation of the monthly biases for 8 of the last 12 months);

**operational compliance:**
- data delivery within 24 hours,
- specific ILRS normal point data format, and
- site and system information form.

About one third of the approximately 40 SLR stations operating worldwide at the end of 2002 fulfill the System Performance Standards. For current details see the ILRS Annual Reports.

### 8.4 Corrections, Data Processing and Accuracy

#### 8.4.1 Extended Ranging Equation

In order to describe the measuring process it is necessary to introduce additional parameters and corrections into the simple basic observation equation (8.1). Following Fig. 8.8 (Aardoom et al., 1982) we find for the most important components that

\[
d = \frac{1}{2}c\Delta t + \Delta d_0 + \Delta d_S + \Delta d_b + \Delta d_r + \eta,
\]

(8.3)

with

- \(\Delta d_0\) eccentricity correction on the ground,
- \(\Delta d_S\) eccentricity correction at the satellite,
- \(\Delta d_b\) signal delay in the ground system,
- \(\Delta t\) measured flight-time of the laser pulse between the start and the stop signal,
- \(\Delta d_r\) refraction correction, and
- \(\eta\) remaining systematic and random observation errors.
As a general rule, geometrical and physical corrections should be applied with one order of magnitude accuracy higher than the corresponding resolution of the observables. This means, for third generation satellite laser ranging systems, that the corrections are required with an accuracy of 2 to 3 mm. For the current development of laser systems (toward the 1 mm level of observation accuracy), corrections and biases should accordingly be modeled with submillimeter accuracy.

(a) **Time measurement, Δt**

Two aspects have to be distinguished. Firstly, the measured ranges must be tied to universal time, UTC, because of satellite motion relative to Earth. An accuracy of ±100 ns (corresponding to a satellite motion of 1 mm) is completely sufficient for most purposes and does not constitute any problem for modern techniques of time keeping or time transfer [2.2.5]. Secondly, the flight time of pulses, Δt, has to be measured. The time-tagging of the start and stop events is affected by uncertainties in the signal identification. The quality of these measurements constitutes one of the most critical accuracy limitations in the whole error budget. The desired resolution is a few picoseconds.

(b) **Eccentricity corrections, Δd₀, Δdₛ**

Generally the intersection, 0, of the vertical axis with the horizontal axis is used as the reference point in the ranging system. The position of 0 has to be connected with 1 mm-accuracy or better to the station marker, L. The stability of 0 must be controlled. The eccentricities are also needed for local ties between collocated sites of differing space techniques like SLR, VLBI and GPS.

The geometrical relationship between the center of mass, S, of a satellite and the optical center, R, of a single cube corner reflector, the so-called *center-of-mass correction* (CoM), has to be established for all usable satellites. This can be done with high accuracy for the spherical satellites such as LAGEOS, STARLETTE and AJISAI. The situation is more difficult for irregularly shaped satellites (e.g. altimeter satellites). A careful pre-launch calibration is of eminent importance. If return signals come from
several cube corner reflectors it is necessary to analyze the impulse response functions. The CoM corrections may vary by several millimeters between single photon systems and microchannel plate photomultipliers (MCP) (ILRS, 2000). A careful design of the retro-reflector array (e.g. for WESTPAC-1) ensures that only a single corner-cube will reflect any shot.

(c) Propagation correction, $\Delta d_r$

Laser impulses experience a delay in the atmosphere. It is not possible to measure the atmospheric state parameters along the total path; therefore atmospheric models are used which are supported by measured atmospheric data at the laser site. In the frequency domain, applied for laser light, the atmospheric refraction can be modeled reliably for elevations above 10°. The correction is fairly insensitive to water vapor content. The total refraction delay (see [2.3.3.2]) for some elevations is:

- Zenith direction $\sim 2.5$ m,
- 20° elevation $\sim 7.3$ m,
- 10° elevation $\sim 14$ m.

For satellite laser ranging the formulation of Marini and Murray is commonly used and recommended in the IERS conventions (McCarthy, 2000). The formula has been tested by comparisons with ray-tracing radio-sonde profiles. The correction to the one-way range is

$$\Delta d_r = \frac{f(\lambda)}{f(\varphi, H)} \cdot \frac{A + B \sin E}{\sin E + \frac{B/(A+B)}{E+0.01}},$$  \hspace{1cm} (8.4)

where

- $A = 0.002357 P_0 + 0.000141 e_0$,
- $B = (1.084 \times 10^{-8}) P_0 T_0 K + (4.734 \times 10^{-8}) P_0^2 \frac{2}{T_0 (3 - 1/K)}$,
- $K = 1.163 - 0.00968 \cos 2 \varphi - 0.00104 T_0 + 0.00001435 P_0$,

and

- $\Delta d_r$ range correction (meters),
- $E$ true elevation of satellite (degrees),
- $P_0$ atmospheric pressure at the laser site (in $10^{-1}$ kPa, equivalent to millibars),
- $T_0$ atmospheric temperature at the laser site (degrees Kelvin),
- $e_0$ water vapor pressure at the laser site (in $10^{-1}$ kPa, equivalent to millibars),
- $f(\lambda)$ laser frequency parameter ($\lambda$ = wavelength in micrometers), and
- $f(\varphi, H)$ laser site function.

The laser frequency parameter is

$$f(\lambda) = 0.9650 + \frac{0.0164}{\lambda^2} + \frac{0.000228}{\lambda^4}.$$
The laser site function is

\[ f(\varphi, H) = 1 - 0.0026 \cos 2\varphi - 0.00031H, \]

where \( \varphi \) is the latitude and \( H \) is the station height in kilometers.

The currently recommended model of Marini and Murray is believed to be uncertain by up to 1 cm in the zenith delay term and up to several cm at low elevations. Improved models and mapping functions are under discussion, see e.g. Mendes et al. (2001). Modeling of the propagation correction can be improved with two-color ranging because the troposphere is a dispersive medium for wavelengths in the optical domain [2.3.1.2]. Two pulses at different wavelengths have to be sent out, and the differential times of arrival have to be measured with picosecond precision. Developments of this challenging method are underway. Successful test measurements with streak-camera based systems have been reported (Bianco et al., 1999).

(d) Delay correction, \( \Delta d_b \)
The geometric reference point, 0, within the laser ranging system does not necessarily correspond to the electrical zero point of the measurements. This can be interpreted as a systematic time delay with a superposed uncertainty, the laser jitter (Fig. 8.9). The laser delay is determined by calibration. Older systems are calibrated with respect to a known terrestrial target, \( Z \). For modern instruments the calibration is performed inside the laser system.

![Figure 8.9. Laser delay and laser jitter](image)

A considerable contribution to a delayed range measurement comes from internal detector properties and is related to the intensity of the detected light pulse. For single photon operation the delay is constant and can be calibrated. Single photon sensors are hence capable of millimeter range precision. However, when the return energy exceeds the single photon level, time walk effects are introduced and have to be compensated for (Kirchner et al., 1999).

The term \( \eta \) contains unmodeled residual effects, such as instabilities in the ranging system. For more detailed discussions on accuracy and corrections see e.g. the
proceedings of the biannual *International Workshop on Laser Ranging*, e.g. Schlüter et al. (1999); ILRS (2001).

The most effective method of testing a satellite laser ranging system is by parallel observation with another system at the same site (*collocation test*).

### 8.4.2 Data Control, Data Compression, and Normal Points

The observed raw data are controlled in a filtering and data compression process in order to

- detect and eliminate gross errors (blunders),
- evaluate the accuracy of the observations, and
- reduce the amount of data for subsequent processing.

Gross errors may arise, in particular, during day-time observations, if spurious return signals are acquired. The quality of the single observations can be assessed through comparison of the individual measurements with a curve smoothed through all observations. Data compression is necessary, because modern SLR systems with pulse repetition rates of 10 Hz may produce several thousand data points per satellite pass. These data are highly correlated because of instrumental and meteorological effects. For subsequent investigations, only one representative range mean is required for each time interval of about one or a few minutes.

Data control and data compression can be achieved operationally within one multi-step process. Several methods have been proposed; in the interest of international cooperation, however, the procedure recommended at the “Herstmonceux Laser Workshop” in 1984 (Gaignebet (ed.), 1985) is mostly used, and has since been discussed and updated (e.g. Sinclair, 1999).

In the first step, the observed ranges, $d_0$, are compared with computed reference ranges, $d_p$ (predictions), and a series of residuals, $d_r$, is generated (Fig. 8.10):

$$d_r = d_0 - d_p. \quad (8.5)$$

The reference ranges can be obtained from all available observations, be they short arc or long arc approximations of the observed orbit [3.3.3.3]. This procedure demands a rather large computational effort; high precision predictions are required with a best available estimate for a time bias. The predicted range must include the refraction delay. Data with gross differences (outliers) are eliminated using an adequate range window.

In the second step a suitable trend function, $f(p)$, is fitted to the residuals, $d_r$, either using a set of orbital parameters (preferable) or a polynomial, e.g. Chebyshev polynomials [3.3.3.2]. Care has to be taken not to introduce spurious high frequency signals by fitting a high order polynomial. The deviations after the fit,

$$f_r = d_r - f(p), \quad (8.6)$$

are analyzed for any remaining outliers, using a 3 σ-criterion. This approximation procedure can be repeated iteratively. For systems that detect the first photo-electron a 2.5 σ criterion can be of advantage (Sinclair, 1999).
In the third step, the observed trajectory is divided into fixed intervals, so-called bins, starting from 0$^h$ UTC. The proposed interval sizes for various satellites are for example:

- GPS, GLONASS: 300 seconds,
- LAGEOS-1,2: 120 seconds,
- STARLETTE, STELLA: 30 seconds,
- ERS-1/2: 15 seconds, and
- GRACE: 5 seconds.

In each interval, $i$, a mean value of all deviations, $\bar{f}_{ri}$, is formed and added to the trend function at the center of the interval. This point, $NP_i$ (Fig. 8.10), is called the normal point, and represents all single observations of the particular interval. The observation, $d_{0i}$, with the fit residual, $f_{ri}$, nearest to the mean epoch of the accepted fit residuals in bin $i$, leads to the normal point range, $d_{NP_i}$:

$$d_{NP_i} = d_{0i} - (f_{ri} - \bar{f}_{ri}).$$  \hspace{1cm} (8.7)

The discrepancies between the single residuals, $f_r$, with respect to the mean, $\bar{f}_r$, are used to determine the observation noise of the single distance measurement. The precision of the mean laser range in the normal point (8.7) is used as the characteristic measure of the internal accuracy of the laser ranging equipment. It is called the normal point precision, and is about ±1 to 2 cm for the third generation SLR configurations. For modern systems, like the SLR 2000, a normal point precision better than 3 mm is expected (Degnan, 2000). Systematic effects are not included; they have to be estimated in the subsequent adjustment model.

Summarizing, the following aspects have to be emphasized when forming normal points:

- the essential information of the raw measurements is maintained,
- outliers are eliminated from the data,
— the remaining correlation between normal points is insignificant, and
— the observation noise is removed.

Normal points are also referred to as “quick-look data” because they are generated very shortly after the satellite pass and can be used, together with equivalent data from other stations, for rapid orbit prediction. Today, normal point data are the primary product of SLR stations. They have, in most cases, replaced the full-rate data.

8.5 Applications of Satellite Laser Ranging

Due to the very high accuracy potential of laser range observations to satellites a broad field of applications in geodesy and geodynamics opened early on. Fig. 8.11 gives an overview of the development related to the achievable accuracy. The main fields of application are in:

- Gravity field and satellite orbits [8.5.3]: precise determination of low degree and order coefficients; tailored Earth models for particular satellite orbits; precise orbit determination (POD);
- Positions, position changes and reference frames [8.5.4]: absolute geocentric coordinates; absolute heights; contribution to ITRF, crustal deformations;
- Earth Orientation Parameters (EOP) [8.5.5]: polar motion, variation of Earth rotation, LOD; and
- Particular applications [8.5.6]: tides, precise time transfer, relativity.

8.5.1 Realization of Observation Programs, International Laser Ranging Service (ILRS)

Progress in the different tasks listed above is only possible through international cooperation and by the use of data from globally distributed stations. This is why, from the beginning of SLR activities, a close cooperation developed between the agencies and
groups responsible for SLR stations. About 20 fixed stations, and several mobile systems, contributed permanently to the NASA Crustal Dynamics Project [12.4.1]. About 30 stations participated with SLR equipment within the framework of the MERIT campaign (Monitor Earth Rotation and Intercompare the Techniques) (Moritz, Mueller, 1987). The International Earth Rotation Service (IERS), during the first years after its establishment in 1988, was primarily based on continuous input from about 25 laser-sites and still uses SLR data [8.5.5], [12.4.2]. Several regional groups have worked together with dedicated objectives, for example the MEDLAS (Mediterranean Laser ranging project) group within the WEGENER (Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research) framework.

The meaningful use of the observation results is only possible if international standards are agreed upon for data production, data reduction, and data analysis. Such standards were formulated in 1983 with the MERIT Standards (Melbourne et al., 1983), and they are maintained and updated as necessary with the IERS Standards and now the IERS Conventions (McCarthy, 2000).

Today, the role of laser ranging for some products and applications has decreased due to the strength of other technologies. This holds in particular for the determination of recent crustal motion in regional projects, where GPS is much more efficient, or for the analysis of high resolution Earth orientation parameters, where VLBI and GPS are of increasing importance. On the other hand, SLR data are mandatory for the determination of absolute coordinates; they still form an essential part in gravity field models; they are a backup system and sometimes the only means for precise orbit determination; and they play an increasing role in various scientific space experiments.

With the objective to concentrate international efforts in the field of satellite and lunar laser ranging, the International Laser Ranging Service (ILRS) was established in 1998 as a service of the IAG. The objectives and organization of the ILRS are similar to the IGS [7.8.1]. Following the Terms of Reference (ILRS, 2000), the “ILRS provides global satellite and lunar laser ranging data and their related products to support geodetic and geophysical research activities as well as IERS products important to the maintenance of an accurate ITRF”.

The ILRS collects, archives and distributes SLR and LLR observation data sets of sufficient accuracy and uses the data to generate data products, including

- Earth orientation parameters,
- station coordinates and velocities,
- time-varying geocenter coordinates,
- static and time-varying coefficients of Earth’s gravity field,
- centimeter accuracy satellite ephemerides,
- fundamental physical constants,
- lunar orientation parameters, and
- lunar ephemerides and librations.

The organizational components of the ILRS are, besides the Governing Board and the Central Bureau:

- Tracking Stations and Subnetworks,
− Operations Centers,
− Global and Regional Data Centers,
− Analysis and Associate Analysis Centers, and
− Permanent and Temporary Working Groups.

Detailed information on the ILRS can be found in the annual reports and the ILRS website. The global SLR network (about 40 stations in 2002) is reflected in Fig. 8.13. At the moment, we can distinguish three regional subnetworks:
− the European Laser Network (EUROLAS) incorporating the European stations,
− the NASA network in North America, with some stations in South America, South Africa and the Pacific,
− the Western Pacific Laser Tracking Network (WPLTN) encompassing Japan, China, Eastern Russia and Australia.

According to the “System Performance Standards” [8.3.4], the ILRS tracking stations are divided into three categories:
− Core Stations, meeting the highest standards of performance,
− Contributing Stations, contributing significantly to ILRS goals, and
− Associate Stations, presently providing intermittent, variable quality data.

By the end of 2002 about two thirds of the total number of ILRS stations belong to the first two categories.

An essential prerequisite for sufficient data points and high quality data are good predictions of satellite passes. Some of the Associate Analysis Centers serve as Prediction Centers and provide so-called Inter-Range Vectors (IRV) or Tuned Inter-Range Vectors (TIV) to the stations. Prediction centers compute precise orbits and extrapolate them forward. An IRV file is derived from the predicted orbit and contains position and velocity of the satellite for a given epoch, say 00:00 UT each day. The IRV are tuned such that a simple orbit integrator is capable to generate a prediction file at the particular tracking station. The prediction file contains altitudes, azimuths, ranges, and velocities at close intervals (e.g. every minute) and serves to control the observation process (telescope motion and detector gating). Along-track errors can be easily detected and modeled on-site as a time bias. For low orbiting satellites, like CHAMP or GRACE, more sophisticated force models and shorter tuning intervals (e.g. 6 hours) may be necessary (Wood, 1999).

Satellites are tracked following an ILRS Tracking Priority List. The general rules are that priorities decrease with
− increasing orbital altitude, and
− increasing orbital inclination (at a given altitude).

Particular satellites can be supported by higher priority, namely
− active missions (such as altimetry),
− special campaigns (such as the tandem mission ERS-2–ENVISAT), and
− post-launch intensive tracking phases.

Current lists are available from the ILRS website. As of January 2003, a total of 22 satellites were included in the tracking priority list.
8.5.2 Parameter Estimation

In principle, two different concepts can be used, namely geometrical and dynamical methods [1.2]. The geometrical method can only be applied for the determination of positions and baselines. Basically, simultaneous range measurements from at least four ground stations to a target satellite have to be carried out at identical epochs. The distance between the participating ground stations can be derived in the concept of spatial trilateration (cf. Fig. 1.2, p. 3), or new stations can be related to a network of existing control points.

The method corresponds to the classical SECOR technique [4.4.1]. It has conceptual advantages, because no assumptions are needed, for example in orbit modeling. However, from the practical point of view it cannot be applied, because weather conditions do not allow rigorous simultaneous observations at four or more stations. The larger the station separation, the smaller the probability of meeting favorable weather conditions at the same time. Experiences from the geometrical BC4-network [5.1.5] demonstrate that common observations are very rare at three stations, and nearly impossible at four. Consequently, the pure geometric method of laser ranging is more of theoretical interest, and has never been applied in practice. For model calculations see Campbell et al. (1973).

In the dynamical method all observed ranges can be used. The motion of the satellite is described with an adequate orbital model and relates all observations to each other. To exploit the high accuracy level of the observations, all forces acting on the satellite have to be carefully modeled, and the rotational behavior of Earth, with respect to the orbital plane, has to be known. The satellite motion refers to Earth’s center of mass, hence geocentric coordinates are determined.

It is clear, for the dynamical method, that the determination of station coordinates is not an isolated problem. Station coordinates have to be estimated together with other quantities in the course of a general parameter estimation process [4.1]. Possible parameters are:

- geocentric station coordinates,
- gravity field coefficients,
- pole components,
- Earth rotation and universal time (UT1),
- model parameters of Earth and ocean tides, and
- additional parameters for the description of the satellite orbit.

It is not generally possible to derive all parameters of interest from the same set of observations, because the solution system may become unstable (cf. [4.1]). Usually, the coefficients of Earth’s gravity field will be held fixed in the estimation of station coordinates, or the station coordinates will be treated as known quantities in the determination of Earth rotation parameters. Hence we have two groups of parameters in dynamic modeling:

(a) parameters contained in the solution, and
(b) adopted parameters, not contained in the solution.
Today the dynamic approach is almost exclusively used, based on all available tracking data from the global SLR network.

In all parameter estimation processes the necessity arises to fit a precise trajectory to the observed data. Usually, the SLR analysis is performed in several steps, (e.g. Devoti et al., 2001). In the first step, satellite orbits are reduced piecemeal, solving for arc dependent parameters like the state vector, non-gravitational forces and measurement biases. The arc length is shorter for low orbiting satellites (e.g. five days for STARLETTE, STELLA, ERS-2) and longer for high orbiting satellites (e.g. between 1 week and 1 month for LAGEOS). In a second step, the arc solutions are combined in a multi-arc solution, and global parameters are estimated, such as coordinates, Earth orientation parameters and coefficients of the gravity field. In a final step, very long arcs, over many years, are analyzed to verify fundamental physical models or to solve for the secular drift of certain parameters like low order zonals.

Two particular effects were derived rather early from analysis of LAGEOS orbits over many years. These are a secular nodal acceleration and an unexpected decrease in the semi-major axis at the submillimeter/day level. The nodal acceleration is related to a secular change of $J_2$ and reflects a decrease of Earth’s flattening. This effect can be explained by relaxation of the Earth since the last glaciation. The decrease of the semi-major axis is mostly explained by thermal effects on the corner-cube reflectors caused by Earth’s infrared radiation (Rubicam, 1986).

The possibilities and techniques for orbit modeling have been continuously improved since the launch of the first laser satellites. A 1 month arc of the LAGEOS orbit can be modeled with about ±1 to 2 cm accuracy. For lower, and hence more disturbed satellites, like STARLETTE or ERS-1/2, the accuracy in orbit modeling is about ±5 cm or slightly better. Fig. 8.12 demonstrates the improvement over about 15 years in the modeling of 1 month LAGEOS arcs (Pavlis et al., 1991).

![Figure 8.12. Accuracy improvement in the modeling of 1-month LAGEOS arcs](image)

### 8.5.3 Earth Gravity Field, Precise Orbit Determination (POD)

Because of their high accuracy, laser distance measurements to satellites have been included in the computation of Earth models since the launch of the first satellites
equipped with retro-reflectors (cf. [12.2]). The last gravity field model in the pre-LAGEOS era, computed by the NASA Goddard Space Flight Center, was named GEM-9 and contained about 200 000 laser ranges to 9 satellites. The model was developed up to degree and order 20 (Lerch et al., 1979). Because of the decreasing sensitivity of satellite orbits to smaller gravity anomalies it is necessary to incorporate results from the direct mapping of the gravity field (satellite altimetry [9], satellite-to-satellite tracking, gradiometry [10], or surface gravity data) into the solutions with higher order coefficients. It can be stated, as a general rule, that the limit of resolution of gravity field structures by orbit analysis is within a wavelength of about 1000 km. The influence of high-frequency terms in the gravity field on the satellite orbits decreases with increasing height.

Because of this relationship between gravity field development and satellite orbital height, it is very important to know precisely the low frequency components of the gravity field for the exact orbit modeling of dedicated satellites like STARLETTE, STELLA, LAGEOS, or ETALON, in order to meet the requirements of geodynamical research and reference frame stability. Vice versa, LAGEOS orbit analysis permits the isolation of long wavelength geopotential signals within gravity field solutions, because LAGEOS is rather insensitive to the gravity field above degree 10, and is unaffected by terms above degree 20 (Klosko, 1999).

Dedicated gravity fields of this type are called tailored gravity fields. The GEM-L2 solution (Lerch et al., 1983) is an early such tailored field for LAGEOS orbits; the related long-wave geoid can be modeled to degree and order (4,4), with an accuracy level of 8 cm. An equivalent tailored gravity field has been designed for STARLETTE with the PGS-1331 model up to degree and order 36 (Marsh, Lerch, 1985). This model is also of value for other missions at a similar orbital height, such as STELLA, ERS-1 and ERS-2.

With the availability of new precise laser ranging data to LAGEOS and other satellites, and with the requirements for a precise modeling of the TOPEX/POSEIDON altimeter mission, a new GEM-series of satellite based long wavelength gravity field models was started in 1987. The model GEM-T1, was exclusively based upon direct satellite tracking observations. It is complete to degree and order 36 (Marsh et al., 1987), and contains about 440 000 laser observations. The follow-up model GEM-T2 (Marsh et al. 1990) was improved by additional laser observations to LAGEOS, STARLETTE, and AJISAI, as well as by older arcs of GEOS-1 and GEOS-2. GEM-T3 (Lerch, 1992) was complete to degree 50, using tracking data from 31 satellites, and in addition altimeter data from GEOS-3, SEASAT and GEOSAT.

The availability of laser targets in low altitudes, like GFZ-1, gave rise to the development of higher order satellite-only gravity models. About 74 000 laser data to GFZ-1 together with 2.8 million older tracking observations were used to estimate the gravity field model GRIM4-S4G complete to degree and order 60 with higher degree terms (up to 100) in zonal and resonant bands (König et al., 1999).

Many more gravity field models have been developed where the SLR data form a substantial part of the data base, in particular for the long-wavelength part. Frequently
used models are the Joint Gravity Model 3, JGM-3 (Tapley et al., 1996), a tailored model for TOPEX/POSEIDON and complete to degree 70, and the NASA and NIMA Joint Geopotential Model EGM96 (Lemoine et al., 1998), complete to degree 360. An excellent overview of historical and current models is given by Rapp (1998); see also [12.2]. The realization of the importance of SLR as a long-lived “passive” tracking technique for the estimation and continuous improvement of gravity models is enlightened by the fact that several old, long abandoned satellites like BE-C, D1-C, D1-D or GEOS-3 have been included in new international tracking programs (Klosko, 1999; ILRS, 2000).

Laser ranging to geodetic satellites with stable orbits (in particular LAGEOS-1 and LAGEOS-2) is useful to measure the evolution over time of the long wavelength part of the gravity field. Several authors have reported time derivatives of the zonal coefficients $J_2$ to $J_6$ (Devoti et al., 2001). So far, only the term $J_2$ could be determined significantly:

$$J_2 = -2.6 \ldots 3.0 \pm 0.2 \ldots \pm 0.5 \cdot 10^{-11} \text{ / yr.}$$

The effect can be related to post-glacial rebound, the ongoing mass redistribution following Pleistocene deglaciation in the northern hemisphere.

LAGEOS is particularly suitable for the determination of the geocentric gravitational constant $GM$ (cf. [12.2.2]), because of its fairly undisturbed orbit and the high ranging accuracy. The value of $GM$ is estimated each time as part of a global solution. The precision of the estimate has improved by an order of magnitude in each of the last two decades (Smith et al., 2000). The current value from recent LAGEOS estimations is

$$GM = 398 600.44187 \pm 0.00020 \text{ [km}^3/\text{sec}^2\text{].}$$

The results are confirmed by estimates from SLR data from STELLA, STARLETTE, AJISAI and ETALON, however with a much higher scatter. The value of $GM$ defines the scale in satellite orbit determination. The value from recent LAGEOS observations is about 1ppb higher than the previously adopted value from SLR observations (Ries et al., 1992). This difference corresponds to a difference in orbital height of about 3 mm (Smith et al., 2000).

For further discussion on gravity field determination from satellite data see [12.2], or Torge (2001).

**Precision Orbit Determination (POD)** is one of the most important applications of today’s SLR technology. Based on a tailored gravity field for a particular satellite, and an appropriate dynamical model, all available SLR data from the ILRS tracking network are used to estimate a precise orbit. The unique feature of SLR data is that the orbits are absolute in the sense that they refer to Earth’s center of mass. In many cases the orbit determination is based on SLR and additional tracking systems such as GPS, DORIS or PRARE. In some cases, SLR is the only tracking device because of a failure of the primary tracking system, such as PRARE for ERS-1, or GPS for GFO (GEOSAT Follow On). SLR is hence an excellent backup system with an extremely long lifetime that survives all other tracking systems.
In combined orbit determination, for example DORIS and SLR for TOPEX/POSEIDON, the DORIS data provide the main contribution to the overall orbit accuracy, and SLR contributes in the crucial centering of the orbit. Centering errors in the absolute height of altimeter satellites would introduce asymmetry in the estimated sea surface variations and hence corrupt the oceanographic interpretation. Recent studies indicate a POD accuracy for TOPEX/POSEIDON of 2 to 3 cm in the radial direction (ILRS, 2000).

The high accuracy of SLR determined orbits is of eminent importance for the absolute calibration of sensor errors in new missions. This is in particular true for the radial altimeter errors, such as in the JASON-1 or ENVISAT-1 mission [9.2]. SLR also contributes, in combination with GPS, to the precise orbit determination of gravity field missions like CHAMP and GRACE [10.2]. The high value of the SLR tracking data for orbit determination is illuminated in the long list of tracking priorities and SLR missions set up by the ILRS [8.5.1]. For the technique of precise orbit determination including SLR data see [3.3] and e.g. Rim, Schutz (1999); Montenbruck, Gill (2000).

8.5.4 Positions and Position Changes

The dynamical modeling of satellite laser range data offers the possibility of estimating geocentric three-dimensional positions. If gravity field parameters form part of the solution, the coordinates refer conceptually to the Earth’s center of gravity. Today, in most cases, a tailored gravity field model is used, such as JGM-3. The scale is introduced through the velocity of light and the adopted $GM$ value.

During the early years of satellite laser ranging the technique was mainly used for the determination of crustal motion along selected baselines or in regional networks. One example is the continuous monitoring of crustal deformation along the San Andreas Fault. For a 400 km baseline between Quincy and Monument Peak a significant deformation of about 6 cm $\pm 3$ mm/year could be detected (Watkins et al., 1990). Another example is the WEGENER/MEDLAS project in the Mediterranean. Three transportable laser systems have provided accurate epoch positions for sites in Italy, Greece, and Turkey since 1985. The apparent motions, with respect to a coordinate system that is rigidly attached to the Eurasian tectonic plate, reach 20 to 40 mm/year (Ambrosius et al., 1991).

Today, particular SLR campaigns are no longer arranged; instead the continuously available tracking data from the global ILRS network are used to estimate coordinates and coordinate changes. Some of the ILRS analysis or associate analysis centers do this on a regular basis (ILRS, 2000). The usual procedure is firstly to compute weekly solutions (or from similar short intervals up to one month) for the total time span of analysis. These solutions are used to clean the data and they offer a valuable insight into the quality of the station data. The variations of the weekly coordinates are in the order of 2 cm for high performance laser stations. In a second step, improved weekly or monthly solutions for coordinates and velocities are generated which are combined in a final adjustment over the total time span of, say, several years. Fig. 8.13 shows as an example the results of a 10 years global solution for 40 global SLR stations based
on tracking data to LAGEOS-1/2. The estimated accuracy is 6 mm for the coordinates and 2 mm/a for the velocities (Angermann et al., 2001).

Figure 8.13. Station velocities of a combined LAGEOS-1/2 solution from 10 years of LAGEOS data, cf. Angermann et al. (2001)

One disadvantage of SLR solutions is the rather inhomogeneous distribution of data quantity and data quality. For a given orbital arc, some stations only contribute 10% of the data of other stations. This is why, in most cases, SLR solutions are combined with solutions from other space techniques [12.1]. This holds in particular for the various realizations of the ITRS [2.1.2.2]. Five different SLR solutions were included in the ITRF97 alongside four VLBI, six GPS, and three DORIS solutions (Boucher et al., 1999). In total, 10 different SLR solutions were included in the ITRF2000 solution. The main contribution of SLR to ITRF2000 is seen as follows (IERS, 2001):

- the origin and its rate are defined by a weighted average of the most consistent SLR solutions, and
- the scale and its rate are defined by a weighted average of VLBI and the most consistent SLR solutions.

Absolute coordinates refer to Earth’s center of mass, including the oceans and atmosphere. Analyses of SLR data have shown that the ensemble of tracking stations on Earth’s crust is always moving with respect to the center of mass. This motion, regarded from the crust-fixed stations, is called motion of the geocenter (Rothacher, 2000b). The detected variation is below 1 cm and shows annual and semiannual periods. It is mainly caused by mass movements in the atmosphere and the oceans.

8.5.5 Earth Rotation, Polar Motion

The stability of the LAGEOS orbits provides an excellent external reference frame for Earth-based observations of Earth’s orientation. Earth Orientation Parameters (EOP) or Earth Rotation Parameters (ERP) are the pole coordinates \( (x_p, y_p) \), Greenwich Apparent Sidereal Time \( \text{GAST} = \Theta \).
The pole coordinates (cf. Fig. 2.6, p. 20) are defined as the difference between the actual orientation of Earth’s rotational axis (instantaneous pole) and an agreed mean orientation (Conventional Terrestrial Pole CTP) [2.1.2.3]. The Greenwich sidereal time, GAST, is equivalent to the universal time UT1 [2.2.2]. Variations in the rate of Earth rotation can be described by the difference UT1 – UTC. They are also expressed by the period of one complete Earth revolution about its axis (length of day, LOD).

Due to polar motion and daily fluctuations in the rotational velocity, any coordinate system fixed to the Earth (Earth-fixed system) experiences variations with respect to a space-fixed (inertial) reference frame. These variations can be described, cf. (2.24), as

\[ X_{\text{CIS}} = R_3(-\Theta)R_1(y_p)R_2(x_p)X_{\text{CTS}}, \]

in which \( X_{\text{CIS}} \) and \( X_{\text{CTS}} \) are the position vectors of arbitrary points in the instantaneous space-fixed or conventional Earth-fixed reference frame, respectively. The well described orbits of laser satellites can be regarded as a realization of the inertial reference system.

Fig. 8.14 explains how the instantaneous pole coordinates can be derived from distance measurements to satellites. The instantaneous pole position is identified from a several days long satellite arc as the point around which the observation stations rotate beneath the “stable” satellite orbit. The fluctuations of Earth rotation are accordingly analyzed from the range residuals. For the individual distance measurement we find the observation equation, e.g. (Montag, 1984):

\[
ds = \frac{rR}{s} \left( \sin \Phi (\cos (\Theta - \lambda - \Omega) \cos u + \sin (\Theta + \lambda - \Omega) \sin u \cos i) \right.
- \cos \Phi \sin u \sin i d\Phi + \frac{rR}{s} \cos \Phi (\sin (\Theta + \lambda - \Omega) \cos u
- \cos (\Theta + \lambda - \Omega) \sin u \cos i) (d\Theta + d\lambda - d\Omega),
\]

with
\[ d\Phi = \cos \lambda \, dx_p - \sin \lambda \, dy_p, \text{ variation in the geographic latitude,} \]
\[ d\lambda = (\sin \lambda \, dx_p + \cos \lambda \, dy_p) \tan \Phi, \text{ variation in the geographic longitude,} \]
\[ s \text{ topocentric satellite range,} \]
\[ r, R \text{ geocentric ranges to satellite and ground station,} \]
\[ \Theta \text{ sidereal time, and} \]
\[ \Omega, i, u \text{ orbital elements, } u = \omega + \nu. \]

Equation (8.10) describes the relationship between the variations of Earth orientation parameters, \( dx_p, dy_p, d\Phi, \) and the resulting range variations to the satellites.

Earth orientation parameters derived from satellite laser ranging have played an important role since about 1980 because they were at least one order of magnitude more precise than the classical astrometric and Doppler techniques. As a result of the MERIT campaign (Mueller, Wei, 1985), cf. [12.4.2], SLR data were routinely introduced into the EOP products of the BIH and, since 1988, of the IERS. Fig. 8.15 gives an impression on the data quality around 1980.

Under the framework of the ILRS, EOP parameters are estimated on a routine basis as one of the operational data products. The accuracy is of the order

- 0.1 mas [milliarcseconds] for the pole coordinates \( x_p, y_p, \) and
- 0.05 ms [milliseconds] for Earth rotation (UT1-UTC).

The contribution of SLR to the generation of Earth orientation parameters within the IERS has been substituted more and more by VLBI and GPS because of their weather independence and higher temporal resolution. As of 2000, the percentage of SLR contribution to the polar motion components was only 10, compared with 20 for VLBI and 70 for GPS. UT1-UTC is exclusively based on VLBI (IERS, 2001).

The unique advantage of SLR data, when compared with other space techniques, is the steadily increasing length of homogeneous data series since the launch of LAGEOS-1 in 1976. The long-term analysis of Earth’s rotation and orientation reveals changes in the distribution of mass and exchange of angular momentum in the Earth system.

![Figure 8.15](image.png)

Figure 8.15. Earth rotation parameters from LAGEOS observations (1976–1982), (Smith, et al., 1985)
8.5.6 Other applications

Some additional uses of satellite laser range observations are summarized here.

**Solid Earth and Ocean Tides**
In precise satellite tracking and data analysis three tidal effects caused by lunar and solar gravitation have to be considered. These are the

(1) direct perturbation of the satellite orbit relative to the adopted terrestrial reference frame,

(2) tidal deformation of the oceans and of the solid Earth, and

(3) gravitational effects of these deformations on the satellite orbit.

The direct orbital perturbation (1) is by far the largest effect, but it can be modeled very accurately [3.2.3.2].

Modeling of Earth’s tidal response to lunar and solar forces is rather difficult because of the lack of detailed knowledge of Earth’s internal structure. It is usually described by elasticity parameters (Love’s numbers, $k$). The periodic deformation of the Earth (2) causes a purely geometrical periodic change of range between the observation station and a given satellite. The radial component (tidal uplift) reaches 30 to 40 cm, and has to be modeled in the parameter estimation process. The effect is similar for adjacent stations. For larger station separations the differential effect has to be considered.

The gravitational effect of Earth’s tidal response on satellite orbits (3) can be modeled for near-Earth satellites along with the orbit analysis from precise laser ranging. STARLETTE and STELLA are particularly well suited for this purpose (Williamson, Marsh, 1985). The effect of the tidal induced gravitational potential on satellite orbits can reach several meters. The analysis supplies a better knowledge of the elasticity parameters and hence leads to a better model of Earth’s tidal response. From STARLETTE (and STELLA) orbital data the Love’s number, $k_2$, can be derived with an accuracy of 1% for the leading tidal terms, and the amplitude and phases of the main ocean tidal parameters can be determined (Williamson, Marsh, 1985).

Tidal parameters, derived from satellite orbits, are global in character. Terrestrial methods have a higher resolution, but they may be influenced by local effects.

**Precise Time Transfer**

Laser ranging from two or more stations to a properly equipped satellite can be used for time comparisons of remote atomic station clocks. The satellite carries an active on-board package, capable of detecting and dating a laser pulse. For time comparison, two laser stations fire to the satellite so that the two beams arrive very close in time. The on-board oscillator measures the interval between the arrival times of each laser pulse. Together with the ground measured round-trip times from the stations to the satellite, it is possible to compare the station time scales. The simple equation is

$$\Delta T = t_A - t_B + \tau_A - \tau_B + R,$$

with
$t_A$ epoch of range measurement at station A,
$t_B$ epoch of range measurement at station B,
$\tau_A$ pulse travel time from station A to the satellite,
$\tau_B$ pulse travel time from station B to the satellite,
$R$ interval between pulse arrival times at the satellite, and
$\Delta T$ epoch difference between time scales at both stations.

A dedicated experiment LASSO (LAser Synchronization from a Stationary Orbit) was proposed already in 1980 and tested by the end of 1992. The accuracy expectation was 100 ps, but could not be verified because of bad weather conditions (Lewandowski et al., 1999). A future generation of LASSO, designated T2L2 (Time Transfer by Laser Link), is expected to provide an uncertainty of 50 ps or better (Samain, Fridelance, 1998). Because of their sensitivity to weather conditions, LASSO and T2L2 are not suited for operational use; but are excellent tools for assessing the accuracy of GPS or GLONASS time transfers (cf. [7.6.2.9]).

**Fundamental physics**

SLR will support research in fundamental physics. As stated in [8.5.3] SLR measurements of LAGEOS have provided the most accurate values of $GM$, and have confirmed that $GM$ does not change with time. SLR also contributes to tests of theories of gravitation. As soon as a third LAGEOS satellite is launched into an orbit with a supplementary inclination to that of either LAGEOS-1 or LAGEOS-2, a pair of satellites would be sensitive to the Lense-Thirring Precession or frame-dragging effect on a satellite orbit, that is the orbit plane is “dragged” in the direction of Earth’s rotation. This important test of general relativity, as well as other tests of relativistic formulations, could be made with such a satellite pair to the 3 to 4 percent level (Beutler et al., 1997).

**Precision tracking application**

Satellites equipped with retro-reflectors benefit from SLR when active tracking systems fail (e.g. ERS-1). In addition, SLR provides an excellent opportunity to calibrate active tracking systems and to estimate biases like center-of-mass corrections or antenna offsets. This is possible for all GLONASS spacecraft, but for the time being only for two GPS satellites. The forthcoming GALILEO spacecraft will also carry retro-reflectors for independent orbit determination.

For scientific satellites without an active tracking system, like the Tether Physics and Survivability Experiment (TIPS), SLR forms an essential part of the experiment.

### 8.6 Lunar Laser Ranging

Since 1969 it has been possible to determine precise distances between Earth and the Moon by laser ranging techniques. In the course of the manned American space missions three reflector assemblies were installed on the lunar surface and pointed toward Earth (Fig. 8.16):
The three reflector assemblies form a triangle with side lengths of 950, 1100, and 1250 km, and are well distributed in latitude and longitude. They are hence well suited for the separation of the lunar libration components. The assembly is completed by two French reflectors L17 (Sea of Rains) and L21 (Sea of Serenity) which were deployed by two Soviet automatic lunar missions in November 1970 and January 1973. The reflector L21 is regularly included in Lunar Laser Ranging (LLR) programs. The reflector L17 gives no return signals because it may have been covered with dust from the departing spacecraft. The reflector with highest priority is A15.

The Moon can be regarded as a highly stable satellite with a precisely modeled orbit and a long data series of more than 30 years. Valuable insights into the dynamics of Earth as well as the dynamics of the Earth-lunar-system can be derived from the analysis of continuous LLR observations.

Laser ranging to the Moon is technically much more challenging than satellite laser ranging. The energy balance is very weak. Even with a laser firing rate of 10 Hz less than a few tens of photoelectrons per minute out of the $10^{19}$ per second transmitted are routinely received. This corresponds to an overall signal loss of approximately $10^{-21}$ (Dickey et al., 1994; Shelus et al., 1996). To aim at the reflector on the Moon the required pointing accuracy is about $2''$. A very short time interval of $\Delta t = 200$ ns is necessary to filter the return signal from the disturbance background. The time interval of 200 ns corresponds to a necessary prediction accuracy of $\pm 15$ m for the lunar distance.

Because of these extremely demanding requirements only very few observatories can successfully measure to the Moon. The only observatory with continuous ranging since 1970 is the McDonald Observatory in Western Texas. During the first 15 years after the deployment of the Apollo 11 reflector array, it was also the only facility worldwide that routinely ranged to the Moon. The 2.7 m reflector telescope, however,
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was mainly used for other astronomical purposes. In the mid-1980s a transition was made to the dedicated 0.76 m *McDonald Laser Ranging System* (MLRS), capable of ranging to artificial satellites as well as to the Moon.

Since 1984, another dedicated LLR station is continuously ranging to the Moon, namely a French station near Grasse: *Observatoire de la Côte d’Azur - Centre d’Études et de Recherche en Géodynamique et Astronomie* (OCA/CERGA). Since about 1985 other observatories have also been successfully contributing to Lunar Laser Ranging for limited time periods. These are *Haleakala* on the Island of Maui (Hawaii), the station *Orroral* in Australia and the German fundamental station *Wettzell*. Another joint SLR/LLR station is being built up in *Matera*, Italy (Matera Laser Ranging Observatory, MLRO). The operational *Lunar Laser Ranging Network* (LLRN) of the ILRS hence, for the time being, only consists of two stations.

The earliest LLR ranges had accuracies of several meters and were improved to 20 cm during the 1980s. Current measurement accuracies at the two LLRN observatories are about ±1 to 3 cm. This corresponds to a relative accuracy of better than one part in ten billion (1:10¹⁰). Sub-centimeter normal point accuracy is aimed for. Because of the high measurement accuracy, it is necessary to formulate the analysis models in post-Newtonian approximation.

The geometric relationship in the lunar laser ranging technique is explained in Fig. 8.17. The basic observable is the range, $\rho$, between the Earth-based observatory, $O$, and the reflector, $R$, on the lunar surface. $E$ is the terrestrial center of mass and $M$ the lunar center of mass. $B$ is the barycenter of the solar system. The ephemerides of the Earth and lunar orbits refer to $B$.

![Geometrical relationship in lunar laser ranging](image.png)

The equation linking the coordinates of the telescope and of the reflector is written in the mean heliocentric (barycentric) coordinate system as

$$r_O - m_R = \rho.$$  \hspace{1cm} (8.12)
Equation (8.12) is only fulfilled if several corrections are applied. The coordinates, $r_E$, of the telescope, written in the Earth-fixed reference system, differ from the coordinates in the barycentric system because of

- Earth rotation,
- pole coordinates,
- precession, and
- nutation.

The reflector coordinates, $m_R$, expressed in the barycentric system, have to be corrected for lunar motions, for example libration. The measured ranges, finally, are influenced by tides, aberration and other relativistic effects, as well as by variations of the station coordinates due to crustal motion. The modeling of the whole process hence constitutes a rather complicated problem of parameter estimation. Dickey et al. (1983) report on more than 80 Earth-Moon parameters to be introduced into the model. Basic models are given in the early literature, for example Stolz (1979); Ballani (1982). For an analysis of LLR observations in the concept of a post-Newtonian theory see e.g. Müller (1991); Nordtvedt (2001).

The long series of what is now more than 30 years of continuous data provides an excellent opportunity for long-term, as well as short-term, studies of the behavior of the Earth-Moon system. The LLR technique contributes and/or is expected to contribute to, among others, the following problems (Dickey et al., 1994; Soffel, Müller, 1997):

**Global parameters of the Earth-Moon system**

- geocentric coordinates of the tracking stations, including drift rates,
- selenocentric reflector coordinates,
- lunar orbit,
- lunar rotation (libration),
- low harmonic coefficients of the lunar gravity field,
- combined mass of Earth and Moon,
- tidal friction (momentum exchange between Earth and Moon),
- Love number of the Moon, and
- control of precession and nutation theories for a deformable Earth.

**Earth rotation**

- universal time (UT0), length of the day (LOD),
- polar motion, and
- long-term variation of the Earth rotation.

**Gravitational physics and relativity**

- test of Newton’s law of gravitation (possible $G/\ddot{G}$),
- test of the equivalence principle (general relativity),
- principles of special relativity (e.g. Lorentz contraction), and
- verification of the geodesic precession.
Within an iterative process, some of the parameters are held fixed in the solution or taken from other sources. For example, Earth orientation parameters may be held fixed while parameters of the Earth-Moon system are solved for. Based on the long-term series of precise ranges to the Moon it is now possible to compute a very precise ephemeris of the lunar orbit; it is precise enough to permit accurate analysis of solar eclipses as far back as 1400 B.C. From the current evolution of the orbit, it is possible to derive interesting conclusions. For instance, due to the tidal interaction, the Moon is receding from the Earth at about 3.8 cm/year.

The geocentric gravitational constant was determined from more than 20 years of lunar laser ranging as (Dickey et al., 1994)

\[
GM = 398,600.443 \pm 0.004 \text{ [km}^3/\text{s}^2].
\] (8.13)

The strong influence of the Sun on the lunar orbit also permits a precise determination of the relation of masses of the Sun, Moon, and Earth (Soffel, Müller, 1997):

\[
mS/(mE + mM) = 328,900.560 \pm 0.002.
\] (8.14)

The over thirty years of data (the longest time series available from any of the modern space techniques) are especially valuable in solving for corrections to the 18.6-year nutation terms and the precession constant (Dickey et al., 1994).

Earth rotation (UT0 and LOD) can be derived with high accuracy from LLR observations in particular. Fig. 8.18 depicts the geometrical situation. Let \( s \) be the distance of the tracking station from Earth’s rotation axis. Then the range observation, \( \rho \), must follow a cosine-function where the amplitude is a measure of \( s \). The phase of the cosine-function is given by the moment of shortest lunar distance and hence is equivalent to the geographic longitude of the tracking station. Variations in longitude are related to variations in Earth’s rotation velocity. With good modeling of the observations UT0 can be determined with a resolution of 0.05 ms.

In order to determine both pole coordinates, it is necessary to use data from at least two laser stations, sufficiently separated in geographic location. This is also true...
for the determination of UT1, because Earth rotation variations cannot be separated
from the pole components with only one input station (Stolz, 1979). Because of strong
correlations between pole coordinates and errors in the lunar ephemerides as well as
variations of UT1, lunar laser range observations are less suited for the determination
of polar motion than are range measurements to artificial satellites. Within the IERS,
therefore, LLR does not contribute to the determination of pole coordinates.

For results and new insights from lunar laser ranging in gravitational physics and
relativity see, for example, Dickey et al. (1994); Soffel, Müller (1997). Two notable
findings are that the relativistic geodesic precession of 19 mas/year is confirmed within
0.35%, and that the gravitational constant G has no detectable rate for dG/dt/G within
1.1 \cdot 10^{-12}/year (ILRS, 2000).

8.7 Spaceborne Laser

The use of SLR equipment at a large number of terrestrial observation stations for the
determination of precise coordinates is very expensive and time consuming. This is
why several proposals were made early on for reversing the principle, that is to deploy
the laser ranging system in an orbiting platform and to install reflectors on the ground,
e.g. Mueller (1975); Kahn et al. (1980); Drewes, Reigber (1982); Cohen et al. (1990).
The concept has many attractions because a dense network of ground reflector points
can be installed in active tectonic areas, and be controlled on a regular basis. With the
use of additional beacons in areas of tectonic stability (fiducial stations), the orbit of
the spaceborne laser system can be precisely modeled.

Feasibility studies have demonstrated that spaceborne laser systems can be realized,
and would provide baseline accuracies on the order of a few cm over distances from a
few km to 1000 km. The concept, however, was never realized because GPS developed
to be an extremely accurate and efficient tool to provide geodetic control for monitoring
crustal deformation.

Instead, a spaceborne laser altimeter mission was planned and has been realized
with the Geoscience Laser Altimeter System (GLAS) as an integral part of the NASA
Earth Observing System (EOS) program. GLAS is the primary instrument on the
Ice, Cloud and Land Elevation Satellite ICESAT, launched on January 12, 2003. The
main scientific objective of ICESAT is to better understand the mass balance of the
polar ice sheets and their contribution to sea level change. Furthermore cloud heights,
topography of land surfaces, vegetation heights, and sea-ice surface characteristics
will be measured (Schutz, 1998).

ICESAT flies in a near polar low Earth orbit (LEO) at an altitude of 600 km with an
inclination of 94 degrees. The mission orbit sets a 183 day repeat pattern which yields
15 km track spacing at the equator and 2.5 km at 80 degrees latitude. The on-board
dual-frequency GPS receiver is designed to provide 5 cm radial orbit position; SLR
reflectors serve as a back-up system. On-board star cameras and gyros control the
spacecraft orientation and laser pointing direction.
The GLAS instrument uses three Q-switched Nd:YAG lasers, but only one will operate at a time. The pulse length is 5 ns, the shot repetition rate 40 Hz. The laser beam, nominally in nadir direction, has a 0.110 mrad divergence and illuminates a spot on Earth’s surface with a diameter of about 66 m (footprint). The surface reflected part of the signal is collected in a 1 m on-board telescope.

The laser pulse travel time provides the scalar altitude. Together with the pointing information from the orientation system and the GPS position of the spacecraft, an altitude vector can be determined which provides the ITRF location of the illuminated spot on the surface. The error budget is estimated as follows (Schutz, 1998):

- Instrument precision: 10 cm,
- Radial orbit determination: 5 cm,
- Pointing determination: 7.5 cm,
- Tropospheric delay: 2 cm,
- Atmospheric scattering: 2 cm,
- Other: 1 cm,
- Total: 13.8 cm

The single shot error of about 14 cm enters an adjustment process as in satellite altimetry [9.4] using the crossover technique. Considering the high number of possible crossovers in high latitudes, error estimates indicate that the required accuracy of 1.5 cm/year can be met, and the surface variability of large ice sheets in Antarctica and Greenland can be determined (Schutz, 1998).