1 Introduction

1.1 Subject of Satellite Geodesy

Following the classical definition of Helmert (1880/1884), geodesy is the *science of the measurement and mapping of the Earth's surface.* This definition includes the determination of the terrestrial external gravity field, as well as the surface of the ocean floor, cf. (Torge, 2001). *Satellite Geodesy* comprises the observational and computational techniques which allow the solution of geodetic problems by the use of precise measurements to, from, or between artificial, mostly near-Earth, satellites. Further to *Helmert*'s definition, which is basically still valid, the objectives of satellite geodesy are today mainly considered in a functional way. They also include, because of the increasing observational accuracy, time-dependent variations.

The basic problems are

1. determination of precise global, regional and local three-dimensional positions (e.g. the establishment of geodetic control)
2. determination of Earth's gravity field and linear functions of this field (e.g. a precise geoid)
3. measurement and modeling of geodynamical phenomena (e.g. polar motion, Earth rotation, crustal deformation).

The use of artificial satellites in geodesy has some prerequisites; these are basically a comprehensive knowledge of the satellite motion under the influence of all acting forces as well as the description of the positions of satellites and ground stations in suitable reference frames. Consequently satellite geodesy belongs to the domain of *basic sciences*. On the other hand, when satellite observations are used for solving various problems satellite geodesy can be assigned to the field of *applied sciences*. Considering the nature of the problems, satellite geodesy belongs equally to *geosciences* and to *engineering sciences*.

By virtue of their increasing accuracy and speed, the methods and results of satellite geodesy are used more and more in other disciplines like e.g. *geophysics*, *oceanography* and *navigation*, and they form an integral part of *geoinformatics*.

Since the launch of the first artificial satellite, SPUTNIK-1, on October 4, 1957, satellite geodesy has developed into a self-contained field in geodetic teaching and research, with close relations and interactions with adjacent fields (Fig. 1.1). The assignments and contents are due to historical development.

In *Geodetic Astronomy*, based on the rules of Spherical Astronomy, the orientation of the local gravity vector (geographical longitude Λ, geographical latitude Φ), and the astronomical azimuth A of a terrestrial mark are determined from the observation of natural celestial bodies, particularly fixed stars. By *Gravimetry* we mean the measurement of gravity (gravity intensity g) which is the magnitude of the gravity acceleration vector $\boldsymbol{g}$ (Torge, 1989). With *Terrestrial Geodetic Measurements* horizontal angles,

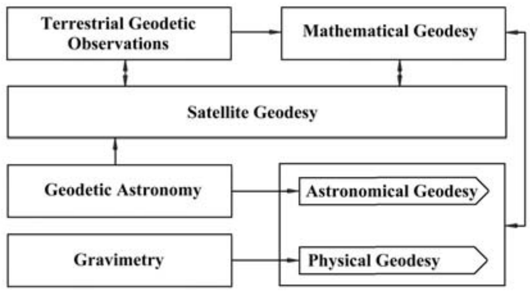

Figure 1.1. Main relations between geodetic fields of teaching and research

distances, zenith angles, and levelled height differences are provided, and serve for the determination of surface point locations. *Satellite Geodesy*, finally, is based on the observation of artificial celestial bodies. Directions, ranges, and range-rates are determined between Earth surface locations and satellites or between satellites. Some measurements, for instance accelerations, are taken within the satellites themselves.

The results of geodetic-astronomic or gravimetric observations are used within the field of *Astronomical and Physical Geodesy* for the determination of the figure and gravity field of Earth (Torge, 2001). In German, this classical domain is called *Erdmessung* (Torge, 2003) and corresponds to the concept of *Global Geodesy* in the English language. The main problems are the determination of a mean Earth ellipsoid and a precise geoid (cf. [2.1.5]).

The determination of coordinates in ellipsoidal or three-dimensional coordinate systems, mainly based on terrestrial geodetic measurements, is treated within the field of *Mathematical Geodesy*. Alternate expressions for this domain are *Geometrical Geodesy* or, in German, *Landesvermessung*, e.g. Großmann (1976). The separate classification of observation- and computation techniques, as developed within the classical fields of geodetic teaching and practice, has not occured to the same extent in satellite geodesy. Here, observation, computation, and analysis are usually treated together. As far as global problems are concerned, satellite geodesy contributes to global geodesy, for example to the establishment of a global reference frame. In regional and local problems, satellite geodesy forms part of surveying and geoinformatics.

Conversely, the fields of mathematical geodesy and geodetic astronomy provide important foundations in satellite geodesy with respect to reference systems. The same is true for the field of astronomical and physical geodesy, which provides information on Earth's gravity field. Due to these close interactions, a sharp separation of the different fields in geodesy becomes more and more difficult, and it is no longer significant.

A combined consideration of all geodetic observables in a unified concept was developed rather early within the field of *Integrated Geodesy*, e.g. Hein (1983). It finds a modern realization in the establishment of integrated geodetic-geodynamic observatories (see [12.5], Rummel et al. (2000))

The term *Satellite Geodesy* is more restrictive than the French denomination *Géodésie Spatiale* or the more general expression *Geodetic Space Techniques*. The latter term includes the geodetic observation of the Moon, as well as the use of planets and objects outside the solar system, for instance in radio interferometry. Occasionally the term *Global Geodesy* is used, where global stands for both global measurement techniques and for global applications.

In this book the term *Satellite Geodesy* is employed, because it is in common usage, and because artificial near-Earth satellites are almost exclusively utilized for the observations which are of interest in applied geodesy. Where necessary, other space techniques are dealt with.

1.2 Classification and Basic Concepts of Satellite Geodesy

The importance of artificial satellites in geodesy becomes evident from the following basic considerations.

(1) Satellites can be used as high orbiting *targets*, which are visible over large distances. Following the classical concepts of Earth-bound trigonometric networks, the satellites may be regarded as “fixed” control points within large-scale or global three-dimensional networks. If the satellites are observed simultaneously from different ground stations, it is of no importance that the orbits of artificial satellites are governed by gravitational forces. Only the property that they are targets at high altitudes is used. This purely geometric consideration leads to the *geometrical method* of satellite geodesy. The concept is illustrated in Fig. 1.2. It has been realized in its purest form through the BC4 World Network (see [5.1.5]).

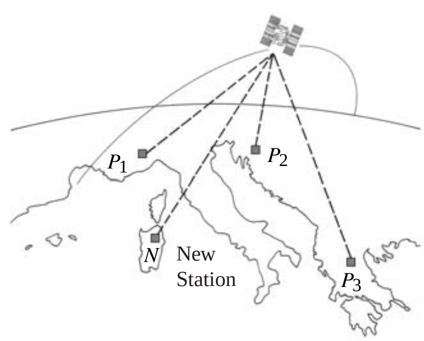

Figure 1.2. Geometrical method; the satellite is a high target

Compared with classical techniques, the main advantage of the satellite methods is that they can bridge large distances, and thus establish geodetic ties between continents and islands. All ground stations belonging to the network can be determined within a uniform, three-dimensional, global coordinate reference frame. They form a polyhedron which goes around Earth.

As early as 1878 H. Bruns proposed such a concept, later known as the *Cage of Bruns*. Bruns regarded this objective to be one of the basic problems of scientific geodesy. The idea, however, could not be realized with classical methods, and was forgotten. The geometrical method of satellite geodesy is also called the *direct method*, because the particular position of the satellite enters directly into the solution.

(2) Satellites can be considered to be a *probe* or a *sensor* in the gravity field of Earth. The orbital motion, and the variation of the parameters describing the orbit, are observed in order to draw conclusions about the forces acting. Of particular interest is the relation between the features of the terrestrial gravity field and the resulting deviations of the true satellite orbit from an undisturbed Keplerian motion [3.1.1]. The essential value of the satellite is that it is a moving body within Earth's gravity field. This view leads to the *dynamical method* of satellite geodesy.

The main advantage of satellite observations, when compared with classical techniques, is that the results refer to the planet Earth as a whole, and that they have a global character by nature. Data gaps play a minor role. Among the first spectacular results were a reasonably accurate value of Earth's flattening, and the proof that the figure of Earth is non-symmetrical with respect to the equatorial plane (i.e. the *pear-shape* of Earth, cf. [12.2], Fig. 12.5, p. 517).

In dynamical satellite geodesy orbital arcs of different lengths are considered. When arc lengths between a few minutes and up to several revolutions around Earth are used, we speak of *short arc techniques*; the term for the use of longer arcs, up to around 30 days and more, is *long arc techniques*. The orbits are described in suitable geocentric reference frames. The satellite can thus be considered to be the "bearer of its own coordinates". The geocentric coordinates of the observing ground stations can be derived from the known satellite orbits. This so-called *orbital method* of coordinate determination is illustrated in Fig. 1.3.

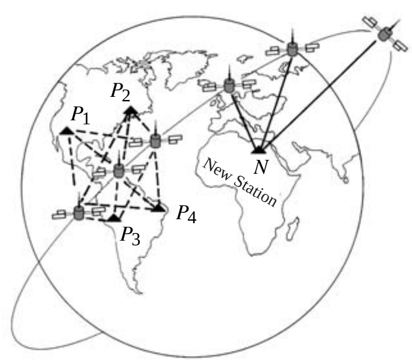

Figure 1.3. Orbital method; the satellite is a sensor in Earth's gravity field

The combined determination of gravity field parameters and geocentric coordinates within the domain of dynamical satellite geodesy leads to the general problem of *parameter determination* or *parameter estimation*. This may include the determination of the rotational parameters of Earth (Earth rotation, polar motion) as well as other geodynamical phenomena (cf. [4.1]). The dynamical method of satellite geodesy is also characterized as the *indirect method*, because the required parameters are determined implicitly from the orbital behavior of the satellites.

The distinction *geometric–dynamic* has, for many years, characterized the development of satellite geodesy. Today, most of the current techniques have to be considered as combinations of both viewpoints.

A further classification of the observation techniques refers to the relation between the observation platform and the target platform. We distinguish the following groups:

(1) *Earth to Space* methods
- directions from camera observations,
- satellite laser ranging (SLR),
- Doppler positioning (TRANSIT, DORIS), and
- geodetic use of the Global Positioning System (GPS, GLONASS, future GNSS).

(2) *Space to Earth* methods
- radar altimetry,
- spaceborne laser, and
- satellite gradiometry.

(3) *Space to Space* methods
- satellite-to-satellite tracking (SST).

Earth-bound methods are the most advanced, because the observation process is better under control. With the exception of radar altimetry, the methods mentioned in (2) and (3) are still under development or in their initial operational phase.

1.3 Historical Development of Satellite Geodesy

The proper development of satellite geodesy started with the launch of the first artificial satellite, SPUTNIK-1, on October 4, 1957. The roots of this development can, however, be identified much earlier. If we include the use of the natural Earth satellite, the Moon, then dynamical satellite geodesy has existed since the early 19th century. In 1802, *Laplace* used lunar nodal motion to determine the flattening of Earth to be $f = 1/303$. Other solutions came, for example, from *Hansen* (1864) with $f = 1/296$, *Helmert* (1884) with $f = 1/297.8$, and *Hill* (1884) with $f = 1/297.2$ (see Wolf (1985), Torge (2001)).

The geometrical approach in satellite geodesy also has some forerunners in the *lunar methods*. These methods have undergone comprehensive developments since the beginning of the last century. In this context, the Moon is regarded as a geometric target, where the geocentric coordinates are known from orbital theory. The directions between the observer and the Moon are determined from relative measurements of nearby stars, or from occultation of stars by the Moon. Geocentric coordinates are thereby received. Within the framework of the *International Geophysical Year* 1957/58 a first outcome from a global program was obtained with the *Dual Rate Moon Camera*, developed by Markovitz (1954). The methods of this so-called *Cosmic Geodesy* were treated comprehensively in 1960 by Berroth, Hofmann. They also form a considerable part of the classical book of Mueller (1964) “Introduction to Satellite Geodesy”.

Further foundations to satellite geodesy before the year 1957 were given by the work of Väisälä (1946), Brouwer (1959), King-Hele (1958) and O’Keefe (1958). Therefore, it was possible to obtain important geodetic results very soon after the launch of the first rockets and satellites. One of the first outstanding results was the determination of Earth’s flattening as $f = 1/298.3$ from observations of EXPLORER-1 and SPUTNIK-2 by O’Keefe (1958), King-Hele, Merson (1958). Some significant events during the years following 1957 are

1957	Launch of SPUTNIK-1,
1958	Earth's Flattening from Satellite Data ($f = 1/298.3$),
1958	Launch of EXPLORER-1,
1959	Third Zonal Harmonic (*Pear Shape* of Earth),
1959	Theory of the Motion of Artificial Satellites (*Brouwer*),
1960	Launch of TRANSIT-1B,
1960	Launch of ECHO-1,
1960	Theory of Satellite Orbits (*Kaula*),
1962	Launch of ANNA-1B, and
1962	Geodetic Connection between France and Algeria (*IGN*).

By the year 1964, many basic geodetic problems had been successfully tackled, namely the

- determination of a precise numerical value of Earth's flattening
- determination of the general shape of the global geoid
- determination of connections between the most important geodetic datums (to ± 50 m).

With hindsight, the development of satellite geodesy can be divided into several phases of about one decade each.

1. 1958 to around 1970. Development of basic methods for satellite observations, and for the computation and analysis of satellite orbits. This phase is characterized by the optical-photographic determination of directions with cameras. The main results were the determination of the leading harmonic coefficients of the geopotential, and the publication of the first Earth models, for instance the Standard Earth models of the Smithsonian Astrophysical Observatory (SAO SE I to SAO SE III), and the Goddard Earth Models (GEM) of the NASA Goddard Space Flight Center. The only purely geometrical and worldwide satellite network was established by observations with BC4 cameras of the satellite PAGEOS.

2. 1970 to around 1980. Phase of the scientific projects. New observation techniques were developed and refined, in particular laser ranging to satellites and to the Moon, as well as satellite altimetry. The TRANSIT system was used for geodetic Doppler positioning. Refined global geoid and coordinate determinations were carried out, and led to improved Earth models (e.g. GEM 10, GRIM). The increased accuracy of the observations made possible the measurement of geodynamical phenomena (Earth rotation, polar motion, crustal deformation). Doppler surveying was used worldwide for the installation and maintenance of geodetic control networks (e.g. EDOC, DÖDOC, ADOS).

3. 1980 to around 1990. Phase of the operational use of satellite techniques in geodesy, geodynamics, and surveying. Two aspects in particular are remarkable. Satellite methods were increasingly used by the surveying community, replacing conventional methods. This process started with the first results obtained with the NAVSTAR Global Positioning System (GPS) and resulted in completely new perspectives in surveying and mapping. The second aspect concerned the increased observation accuracy. One outcome was the nearly complete replacement of the classical astrometric techniques for monitoring polar motion and Earth rotation by satellite methods. Projects for the measurement of crustal deformation gave remarkable results worldwide.

4. 1990 to around 2000. Phase of the international and national permanent services. In particular two large international services have evolved. The International Earth Rotation Service IERS, initiated in 1987 and exclusively based on space techniques, provides highly accurate Earth orientation parameters with high temporal resolution, and maintains and constantly refines two basic reference frames. These are the International Celestial Reference Frame ICRF, based on interferometric radio observations, and the International Terrestrial Reference Frame ITRF, based on different space techniques. The International GPS Service IGS, started in 1994 and evolved to be the main source for precise GPS orbits as well as for coordinates and observations from a global set of more than 300 permanently observing reference stations. At the national level permanent services for GPS reference data have been established and are still growing, e.g. CORS in the USA, CACS in Canada and SAPOS in Germany.

5. 2000 onwards. After more than 40 years of satellite geodesy the development of geodetic space techniques is continuing. We have significant improvements in accuracy as well as in temporal and spatial resolution. New fields of application evolve in science and practice. For the first decade of the new millennium development will focus on several aspects:

- launch of dedicated gravity field probes like CHAMP, GRACE, and GOCE for the determination of a high resolution terrestrial gravity field,
- establishment of a next generation Global Navigation Satellite System GNSS with GPS Block IIR and Block IIF satellites and new components like the European Galileo,
- refinement in Earth observation, e.g. with high resolution radar sensors like interferometric SAR on various platforms,
- further establishment of permanent arrays for disaster prevention and environmental monitoring, and
- unification of different geodetic space techniques in mobile integrated geodetic-geodynamic monitoring systems.

1.4 Applications of Satellite Geodesy

The applications of geodetic satellite methods are determined by the achievable accuracy, the necessary effort and expense of equipment and computation, and finally by the observation time and the ease of equipment handling. A very extensive catalogue of applications can be compiled given the current developments in precise methods with real-time or near real-time capabilities.

Starting with the three basic tasks in satellite geodesy introduced in [1.1], we can give a short summary of possible applications:

Global Geodesy
- general shape of Earth's figure and gravity field,
- dimensions of a mean Earth ellipsoid,
- establishment of a global terrestrial reference frame,
- detailed geoid as a reference surface on land and at sea,
- connection between different existing geodetic datums, and
- connection of national datums with a global geodetic datum.

Geodetic Control
- establishment of geodetic control for national networks,
- installation of three-dimensional homogeneous networks,
- analysis and improvement of existing terrestrial networks,
- establishment of geodetic connections between islands or with the mainland,
- densification of existing networks up to short interstation distances.

Geodynamics
- control points for crustal motion,
- permanent arrays for 3D-control in active areas,
- polar motion, Earth rotation, and
- solid Earth tides.

Applied and Plane Geodesy
- detailed plane surveying (land register, urban and rural surveying, geographic information systems (GIS), town planning, boundary demarcation etc.),
- installation of special networks and control for engineering tasks,
- terrestrial control points in photogrammetry and remote sensing,
- position and orientation of airborne sensors like photogrammetric cameras,
- control and position information at different accuracy levels in forestry, agriculture, archaeology, expedition cartography etc.

Navigation and Marine Geodesy
- precise navigation of land-, sea-, and air-vehicles,
- precise positioning for marine mapping, exploration, hydrography, oceanography, marine geology, and geophysics,
- connection and control of tide gauges (unification of height systems).

Related Fields
- position and velocity determination for geophysical observations (gravimetric, magnetic, seismic surveys), also at sea and in the air,
- determination of ice motion in glaciology, Antarctic research, oceanography,
- determination of satellite orbits, and
- tomography of the atmosphere (ionosphere, troposphere).

With more satellite systems becoming operational, there is almost no limit to the possible applications. This aspect will be discussed together with the respective techniques. A summarizing discussion of possible applications is given in chapter [12].

1.5 Structure and Objective of the Book

Satellite geodesy belongs equally to fundamental and applied sciences. Both aspects are dealt with; however, the main emphasis of this book is on the observation methods and on the applications.

Geodetic fundamentals are addressed in chapter [2], in order to help readers from neighboring disciplines. In addition, some useful information is provided concerning fundamental astronomy and signal propagation. The motion of near-Earth satellites, including the main perturbations and the basic methods of orbit determination, are discussed in chapter [3], as far as they are required for an understanding of modern observation techniques and applications.

The increasing observational accuracy requires a corresponding higher accuracy in the determination of orbits. In practice, particularly for today's applications, the user must be capable to assess in each case the required orbital accuracy, and the influence of disturbing effects. This is only possible with a sufficient knowledge of the basic relations in celestial mechanics and perturbation theory. For further studies, fundamental textbooks e.g. Schneider (1981), Taff (1985), or Montenbruck, Gill (2000) are recommended. Special references are given in the relevant sections.

The different observation methods of satellite geodesy are discussed in chapters [4]–[11]. The grouping into currently important observation methods is not without problems, because common aspects have to be taken up in different sections, and because the topical methods develop very quickly. This classification is nevertheless preferred because the user is, in general, working with a particular observation technique, and is looking for all related information. Also a student prefers this type of grouping, because strategies for solving problems can be best studied together with the individual technique. Cross-references are given to avoid unnecessary repetitions.

The possible applications are presented together with the particular observation technique, and illustrated with examples. In chapter [12], a problem-orientated summary of applications is given.

The implications of satellite geodesy affect nearly all parts of geodesy and surveying. Considering the immense amount of related information, it is often only possible to explain the basic principle, and to give the main guidelines. Recommendations for further reading are given where relevant. For example, an exhaustive treatment of satellite motion (chapter [3]), or of the Global Positioning System GPS (chapter [7]) could fill several volumes of textbooks on their own. As far as possible, references are selected from easily accessible literature in the English language. In addition, some basic references are taken from German and French literature.