1. Around the World in a Hundred Minutes

Even though the first man-made spacecraft was only launched in 1957, satellite orbits had already been already studied two centuries before this. Starting from Newton's formulation of the law of gravity, scientists sought continuously to develop and refine analytical theories describing the motion of the Earth's only natural satellite, the Moon. Today, several thousand man-made satellites orbit the Earth, together with countless pieces of space debris (Fig. 1.1). Much as celestial mechanics studied the laws of motion of solar system bodies, the branch of astrodynamics is concerned with the mathematical and physical description of artificial satellite orbits, as well as their control. Here, the term orbit refers to a trajectory that is essentially periodic in nature, and does not consider the special case of objects leaving the realm of the Earth towards interplanetary space.

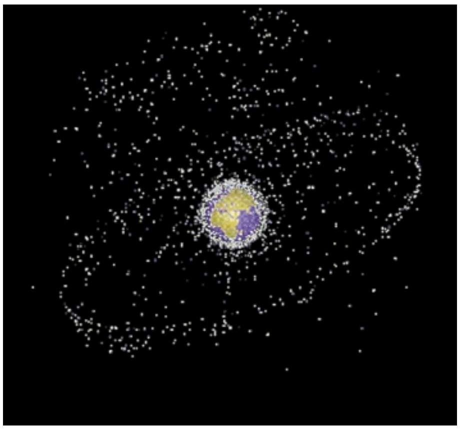

Fig. 1.1. A snapshot of orbiting satellites and known pieces of space debris resembles a swarm of mosquitoes dancing around a bulb. Most objects stay in low-Earth orbits with altitudes typically less than 1500 km. Aside from that, many satellites populate the geostationary ring at a height of 36 000 km. The cloud of satellites in the northern hemisphere mainly comprises navigation and science satellites (photo courtesy ESA/ESOC)

1.1 A Portfolio of Satellite Orbits

Aside from the eternal dream of mankind to overcome the two-dimensional surface of the Earth, there are a number of other compelling reasons to launch a satellite into orbit (Fig. 1.2). Satellites are the only means of obtaining in-situ measurements of the upper atmosphere or the Earth's magnetosphere. Astronomical telescopes in orbit provide an uncorrupted, diffraction-limited view of the sky at all regions of the electromagnetic spectrum. By the very nature of things, one has to leave the

Earth to collect large-scale images of its continents, oceans, and atmosphere. Likewise, satellites are able to communicate with a large number of places on Earth simultaneously, thus forming the basis for worldwide telephone and data networks as well as TV transmissions. Finally, constellations of navigation satellites nowadays provide the means for precision localization and aircraft navigation around the world.

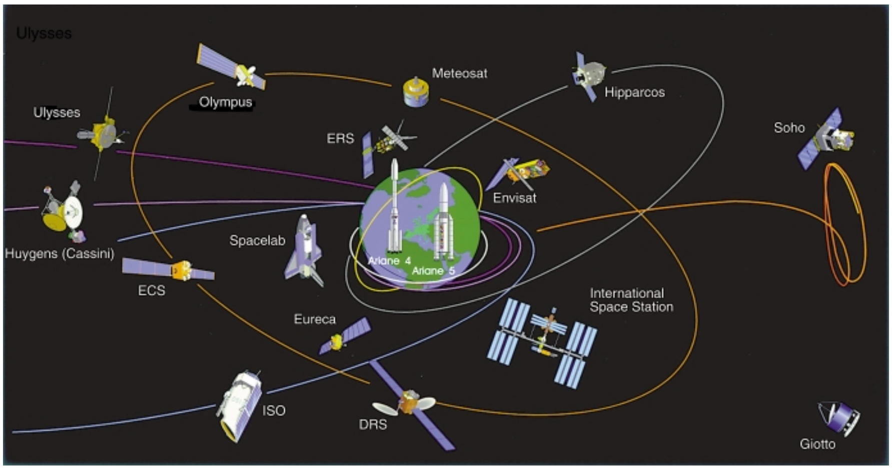

Fig. 1.2. An album of ESA's space missions: manned and microgravity (Space station, Spacelab, Eureca), Earth observation (ERS, Meteosat, Envisat), telecommunications (Olympus, ECS, DRS) and science (Hipparcos, ISO). Photo credit ESA

1.1.1 Low-Earth Orbits

The applications just mentioned and the technical (and commercial) constraints of existing launch vehicles have led to certain commonalities among the orbits of present satellites. The great majority of satellites are launched into near-circular orbits with altitudes of 300–1500 km. Below that level, a satellite's orbit would rapidly decay due to the resistance of the Earth's atmosphere, thus restricting extremely low-altitude orbits to short-term ballistic missions or powered trajectories. Higher altitudes, on the other hand, are neither required nor desirable for many missions. A space observatory (like the Hubble Space Telescope or the XMM X-ray satellite) already has an unobstructed view at 600 km altitude, where the atmospheric distortion and absorption is wholly negligible. Remote sensing satellites benefit from a higher spatial resolution at lower altitudes and, last but not least, a higher altitude requires more powerful launchers.

Among the low-Earth satellites there is a wide range of orbital inclinations. The inclination describes the angle between the orbital plane and the equator, which is often determined by the geographical latitude of the launch site. Making use of the

Earth's rotation, one achieves the highest orbital velocity by launching a satellite in an easterly direction. The orbital plane, which is spanned by the instantaneous inertial position and velocity vector, thus exhibits an inclination that is equal to the geographical latitude at separation of the spacecraft from the launcher. Any change in inclination – to either higher or lower values – requires a different launch direction, with an associated loss in performance.

1.1.2 Orbits of Remote Sensing Satellites

Irrespective of the launch site restrictions, however, there is a pronounced interest in injecting spacecraft into highly inclined polar orbits, to obtain a maximum coverage of the Earth's surface. Remote sensing satellites are designed to collect high-resolution images of the Earth in a variety of spectral bands (Kramer 1996). These comprise both optical frequencies (visible and infrared) as well as radio frequencies (radar) that provide an unobstructed view independent of clouds and weather phenomena. Resolutions presently provided by civil satellites and sensors (SPOT, Landsat, MOMS-2P) are in the order of 5–10 m for panchromatic images and 10–30 m for multispectral sensors. Synthetic aperture radar (SAR) images, obtained by e.g. the European ERS satellite from an altitude of 750 km, achieve a resolution of roughly 20 m.

Fig. 1.3. The ERS-1 remote sensing satellite as seen by an artist (*left*; courtesy ESA) and imaged in orbit by the French Spot-4 satellite on May 6, 1998 over the Tenere Desert of Niger from 41 km altitude (*right*; photo credit CNES)

Besides the global or near-global coverage, there are other requirements that affect the selection of remote sensing orbits. The ground track should be repetitive but free from gaps, to ensure that each point on Earth can be imaged again and again. Clearly the orbits should be circular, to achieve a constant spacecraft altitude when taking repeated images of the same area. Furthermore, identical illumination conditions are a prerequisite for comparative studies and analysis of images from different areas. Fortunately these requirements may simultaneously be met by a specific set of orbits, known as sun-synchronous repeat orbits.

Here use is made of the fact that the Earth's oblateness causes a secular precession of the orbital plane. For orbital inclinations of 97°–102° and associated altitudes of 500–1500 km, the nodal line of the orbital plane on the equator is shifted by almost 1° per day in a clockwise direction. This value matches the apparent mean motion of the Sun along the equator, and results in a (near-)constant alignment of the orbital plane and the projected direction of the Sun. Accordingly, the mean local time when the satellite crosses the equator is the same for each orbit (typically 10:00 a.m. at the ascending node), giving optimum and reproducible illumination conditions for image data takes.

By making a proper choice of the orbital altitude, one may further achieve an orbital period in resonance with the Earth's rotation. At 900 km, for example, the satellite performs exactly 14 orbits per day, after which period the ground track is repeated again and again. To avoid inherent gaps in the ground coverage, a rational ratio is preferable, however, as is e.g. the case for the orbit of the ERS satellites. They performs a total of 43 orbits in a period of 3 days, which results in a ground track separation of about 1000 km at the equator. In order to maintain the orbital characteristics of a remote sensing satellite, regular adjustments of its semi-major axis are required, which compensate the perturbations due to atmospheric drag.

1.1.3 Geostationary Orbits

The idea of geosynchronous satellites was addressed by Arthur C. Clarke in his 1945 article on *Extra-Terrestrial Relays* (Clarke 1945), i.e. more than a decade before the first satellite, Sputnik 1, was launched. Even earlier, H. Noordung (1929) had pointed out that a satellite placed at an altitude of 35 800 km above the equator would have an orbital period matching the period of the Earth's rotation. The two writers may not have anticipated the future significance of their ideas.

Starting with the first geostationary satellite Syncom 2, launched in 1963, and the transmission of the 1964 Olympic games in Tokyo via Syncom 3, geostationary satellites quickly formed the basis for a commercial utilization of space. Today some 300 active satellites are flying in a geosynchronous orbit, serving as a platform for all kinds of telecommunications activities. The exceptional characteristics of the geostationary belt and the associated space limitations have resulted in international regulations governing the assignment of individual longitude slots to interested countries and agencies. The assigned windows usually cover a range of $\pm 0.1°$ in longitude, which the satellite should not violate, to avoid signal interference (or even physical contact) with neighboring spacecraft. To do so, regular station keeping maneuvers are required, typically once a week, to counteract the perturbations of the Sun, Earth, and Moon, which would otherwise drive the satellite out of its assigned slot (Soop 1983, 1994).

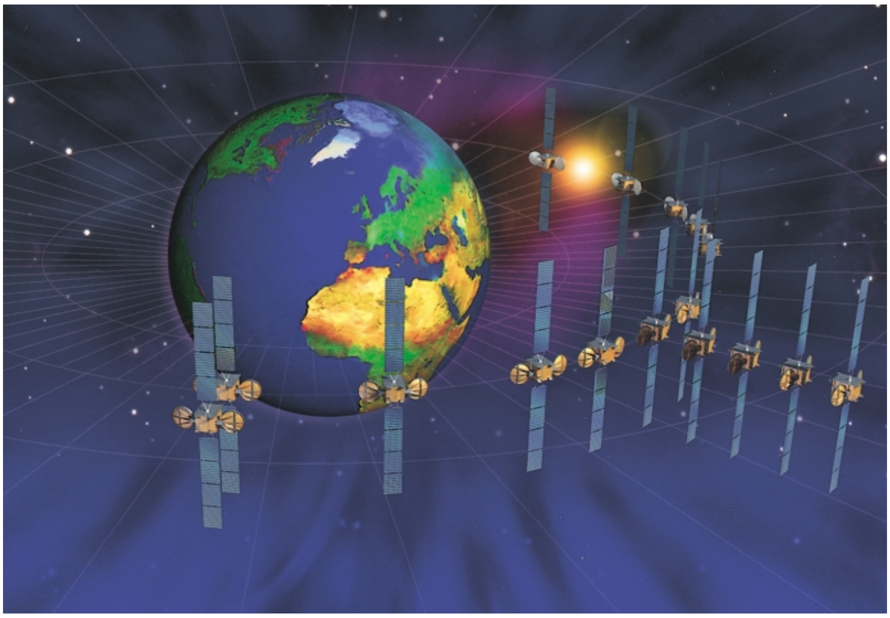

Fig. 1.4. Orbital positions of geostationary satellites controlled by the European telecommunications organization Eutelsat (photo courtesy Eutelsat)

Increasing communication needs could only partly be fulfilled by more and more powerful satellites, which has resulted in a need to co-position (or colocate) multiple satellites in a single control window. At present, a total of 7 ASTRA satellites are actively controlled in a box of $\pm 0.1^\circ \times \pm 0.1^\circ$ size in longitude and latitude at 19.2° East, giving the owners of a single antenna the opportunity to receive an ever-increasing number of TV and radio programs.

Aside from telecommunications, the geostationary orbit is also of interest for weather satellites like Goes and Meteosat. A single satellite can provide an almost hemispherical coverage of the Earth at low resolution, thus making it particularly useful for the study of global weather phenomena. Finally, geostationary satellites are of growing importance as a complement to traditional satellite navigation systems. The European EGNOS system, for example, makes use of an auxiliary navigation payload onboard the Inmarsat III satellites to provide users with real-time corrections to the existing GPS system, which increase the available navigation accuracy and reliability to the level required for precision aircraft landing.

A more specialized application of geostationary satellites is given by the United States' Tracking and Data Relay Satellite System (TDRSS). It offers the possibility of continuous communication with the Space Shuttle and satellites in low-Earth orbit. Furthermore, it can provide tracking data with full orbital coverage, which would not be possible with conventional ground stations, due to their limited visibility.

1.1.4 Highly Elliptical Orbits

When a satellite is brought into geostationary orbit, it is first injected into an eccentric transfer orbit, which is later circularized by a suitable apogee boost maneuver. Here, the highly elliptic trajectory mainly serves as an intermediate orbit. There are a couple of other applications, however, that intentionally select an eccentric orbit for a spacecraft.

Fig. 1.5. Since 1965 Molniya satellites have provided telephone communications and television within the USSR as well as to western states. Photo by Karl D. Dodenhoff, USAF Museum

Among these, the Russian Molniya and Tundra satellites (Fig. 1.5) are most common. Considering the fact that geostationary satellites provide unfavorable visibility for users in polar regions (e.g. Siberia), an alternative concept of telecommunications satellites was devised in the former Soviet Union. It is based on synchronous 12-hour orbits of 1000×40000 km altitude that are inclined at an angle of 63.4° to the equator. The apocenter, i.e. the point farthest away from the Earth, is located above the northern hemisphere, thus providing visibility of the satellite from high latitudes for most of its orbit. Contact is lost for only a few hours, while the satellite passes rapidly through its pericenter, before it becomes visible again to the user. This gap is overcome by additional satellites in a similar, but rotated orbit. Despite the larger number of satellites required, the concept provides a well-suited and cost-effective solution for the communication needs of polar countries.

The second application of elliptic orbits is primarily of scientific interest. In order to explore the magnetosphere of the Earth and the solar-terrestrial interaction, spacecraft orbits that cover a large range of geocentric distances up to 15 or 20

Earth radii are useful. Examples of related missions are the joint US/European ISEE-1 satellite, with an apocenter height of 140 000 km, or ESA's Cluster mission with four satellites flying in highly eccentric orbits in a tetrahedron formation (Schoenmaekers 1991).

1.1.5 Constellations

Constellations consist of multiple satellites that orbit the Earth in similar, but suitably shifted or rotated trajectories. A famous example is the Global Positioning System (GPS), which allows users to accurately determine their location based on measuring the delays of ranging signals received from at least four GPS satellites. The fully operational GPS system comprises a total of 24 satellites in six orbital planes at 55° inclination. Four satellites each share the same orbit of 20 200 km altitude, but are offset from their neighbors by a 90° longitudinal phase shift. Likewise the nodal lines of the three orbital planes are separated by 120° in right ascension. This configuration ensures that a minimum of six satellites are continuously visible from any point except the polar regions. Due to the orbital period of 12 hours, the configuration of all satellites relative to the Earth is exactly repeated twice every (sidereal) day. GLONASS, the Russian counterpart of the United States' Global Positioning System, utilizes a similar constellation of 24 satellites evenly distributed in three planes, with an orbital inclination of 64.8° (Ivanov & Salischev 1992). At an altitude of 19 100 km, the orbital period of 11.25 hours is somewhat less than that of the GPS satellites.

Within the past decade, the high potential of low-Earth satellite constellations for global mobile communication has been realized. In contrast to geostationary

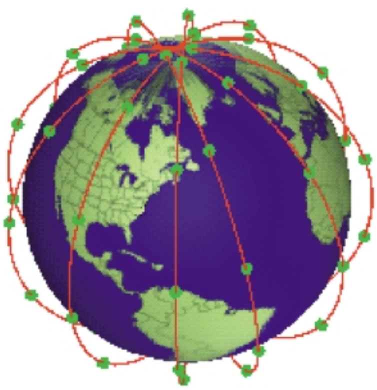

Fig. 1.6. The IRIDIUM constellation (Graphics by SaVi, The Geometry Center, Univ. of Minnesota)

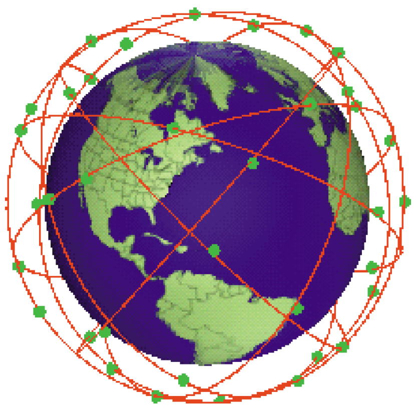

Fig. 1.7. The Globalstar constellation (Graphics by SaVi, The Geometry Center, Univ. of Minnesota)

satellites, which require bulky user antennas, communication with low-Earth satellites can be established from a hand-held phone, due to the much shorter signal paths. At least one satellite is always visible from any location. Making use of intersatellite links, telephone calls can then be routed around the world to other mobile-phone users or to a suitable ground network terminal. Following IRIDIUM, a 66 satellite constellation at an altitude of 700 km, which was put into operation in 1999 (Fig. 1.6, Pizzicaroli 1998), a couple of other constellations have been designed and partly implemented. These include Globalstar with 48 satellites at 1 414 km altitude (Fig. 1.7), ICO with 10 satellites at 10 400 km, ORBCOMM (Evans & Maclay 1998) and Teledesic with 288 satellites at 1 350 km (Matossian 1998). Constellations require regular orbital control maneuvers to avoid a change in the relative configuration and alignment of satellites.

1.2 Navigating in Space

Irrespective of the level of autonomy that may be achieved with present-day satellites, any spacecraft would rapidly become useless if one were unable to locate it and communicate with it. Furthermore, many of the spacecraft described earlier necessitate an active control of their orbit in accordance with specific mission requirements. Navigation is therefore an essential part of spacecraft operations. It comprises the planning, determination, prediction, and correction of a satellite's trajectory in line with the established mission goals.

1.2.1 Tracking Systems

A variety of tracking systems may be used to obtain measurements related to the instantaneous position of a satellite or its rate of change. Most of these systems are based on radio signals transmitted to or from a ground antenna (Fig. 1.8). Common radio tracking systems are able to perform angle measurements by locating the direction of a radio signal transmitted by a satellite. The resolution of these measurements depends on the angular diameter of the antenna cone, which is determined by the ratio of the carrier wavelength to the antenna diameter. Given a frequency of 2 GHz as applied in common antenna systems, a diameter of 15 m is required to achieve a beam width of 0.5°. Distance and velocity information can be obtained by measuring the turn-around delay or Doppler-shift of a radio signal sent to the spacecraft and returned via a transponder. Representative ranging systems achieve an accuracy between 2 m and 20 m, depending on the frequency band used and the type of ranging signal applied. Doppler measurements can provide the range rate of an Earth-orbiting satellite with an accuracy of typically 1 mm/s. In the absence of an active transmitter or transponder onboard the spacecraft, sufficiently powerful radar may also be applied for spacecraft tracking. Its use, however, is mainly restricted to emergency cases or space surveillance tasks (Pensa & Sridharan 1997).

For low-Earth satellites, a purely ground-based tracking suffers from the limited station contacts that constrain the available tracking measurements to a small

Fig. 1.8. The ground station complex at Redu, Belgium, provides telemetry, tracking, and telecommand operations for low-Earth and geostationary satellites (courtesy ESA)

fraction of the orbit. To overcome this restriction, geostationary satellites like the United Sates' Tracking and Data Relay Satellite (TDRS) can be used to track a user satellite via a relay transponder. Going even further, GPS ranging signals offer the opportunity to obtain position measurements onboard a satellite completely independently of a ground station.

Aside from radiometric tracking, optical sensors may likewise be used to locate a satellite, as illustrated both by the early days' Baker–Nunn cameras (Henize 1957) and today's high-precision satellite laser ranging systems (Fig. 1.9). Imaging telescopes are well suited for detecting unknown spacecraft and space debris up to geostationary distances, which makes them a vital part of the United States' space surveillance network. Instead of photographic films employed in former Baker–Nunn cameras, the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) telescopes are equipped with electronic sensors that allow online image processing and removal of background stars. Other applications of optical telescopes include the monitoring of colocated geostationary satellites, which are not controlled in a coordinated way by a single control center. Besides being completely passive, telescopic images can provide the plane-of-sky position of geostationary satellites to much better accuracies (typically $1'' \approx 200\,\mathrm{m}$) than angle measurements of common tracking antennas.

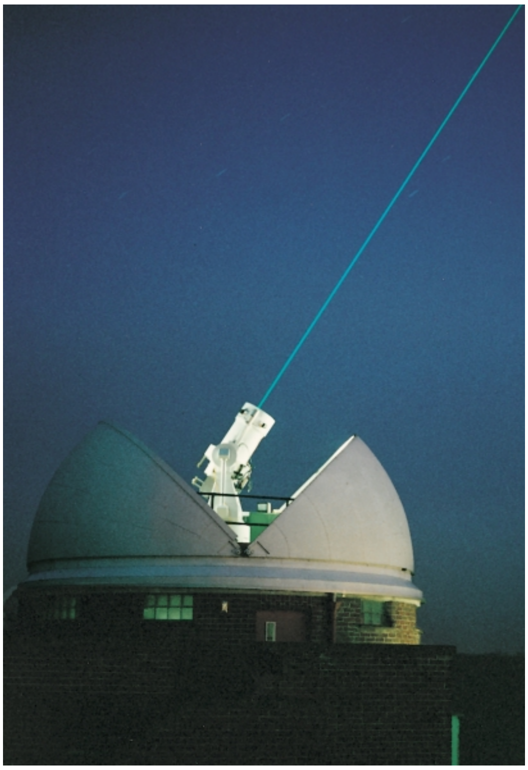

Fig. 1.9. Satellite laser ranging facility of the Natural Environment Research Council (photo: D. Calvert)

Satellite laser ranging (SLR) systems provide highly accurate distance measurements by determining the turn-around light time of laser pulses transmitted to a satellite and returned by a retro-reflector. Depending on the distance and the resulting strength of the returned signal, accuracies of several centimeters may be achieved. Satellite laser ranging is mainly used for scientific and geodetic missions that require an ultimate precision. In combination with dedicated satellites like Starlet and Lageos (Rubincam 1981, Smith & Dunn 1980), satellite laser ranging has contributed significantly to the study of the Earth's gravitational field. Other applications of SLR include independent calibrations of radar tracking systems like GPS or PRARE (Zhu et al. 1997).

1.2.2 A Matter of Effort

A discussion on spacecraft navigation sooner or later ends up with a question on the achieved accuracy. As illustrated in Fig. 1.10, widely varying levels of accuracy apply for the knowledge of a satellite's orbit, depending on the particular goals of a space project. In accord with these requirements, widely varying tracking systems are employed in present space projects.

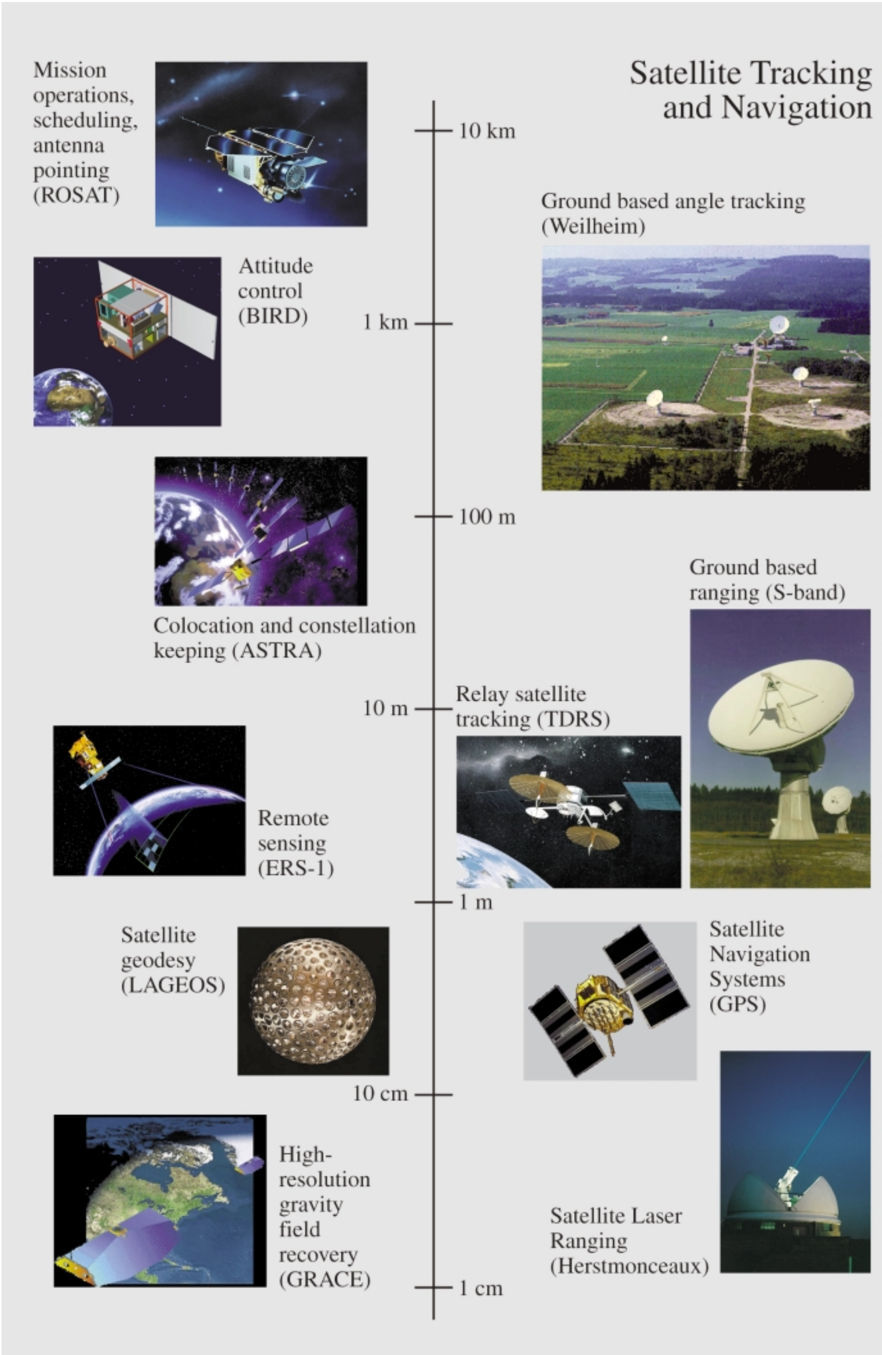

Fig. 1.10. Representative tracking and orbit determination accuracies employed in current space missions (pictures courtesy DLR, DSS, NASA, SES)

An upper threshold to the permissible position uncertainty is generally given by the need for safe communication with the spacecraft from the ground. Considering, for example, an orbital altitude of 800 km and the 0.3° (0.005 rad) half-beam width of a 15 m S-band antenna, the spacecraft trajectory must be predicted to within an accuracy of 4 km to permit accurate antenna pointing throughout an entire station pass. A similar level of accuracy is required for many scheduling functions. Spacecraft-specific events like shadows, station contacts, or payload activation are commonly considered in the operations timeline with a one-second resolution. Considering an orbital velocity of 3–7 km/s, the spacecraft position must be known to within several kilometers in order to predict an orbit-related event with the desired accuracy. An angle tracking system locating the direction of the downlink signal is generally sufficient to meet these types of basic operational requirements. Aside from a transmitter, which is employed anyway for ground communication, no specific onboard equipment is required for this type of tracking.

Quite a different accuracy can be achieved by ground-based or space-based range and Doppler measurements. Their use is typically considered for missions requiring active orbital control. Colocated geostationary satellites, for example, may experience intentional proximities down to the level of several kilometers. Accordingly, the position knowledge and the associated tracking accuracy must at least be one order of magnitude better. Similar considerations hold for remote sensing satellites. In order to enable a reliable geocoding of images with a resolution of up to 10 m, a consistent orbit determination accuracy is mandatory. Considering the visibility restrictions of common ground stations for low-Earth orbits, space-based tracking systems like TDRSS, GPS, or DORIS are often preferred to achieve the specific mission requirements. While ground-based tracking requires a conventional transponder, the use of the other systems necessitates specialized onboard equipment like steerable antennas (TDRSS) or a Doppler measurement unit (DORIS). Utilization of GPS, in contrast, offers position accuracies of 100 m (navigation solution) to 25 m (with dynamical filtering) even for simple C/A code receivers. GPS tracking is therefore considered to be the sole source of orbit information for more and more spacecraft.

Leaving the field of traditional spacecraft operations, one enters the domain of scientific satellite missions with even more stringent accuracy requirements. Among these, geodetic satellite missions like Starlet and Lageos have long been the most challenging. Using satellite laser ranging systems, their orbits have been tracked with an accuracy in the centimeter to decimeter region, thus allowing a consistent improvement in trajectory models and Earth orientation parameters. For other Earth exploration missions like TOPEX (Bath et al. 1989, 1998), ERS, or JERS, the use of satellite altimeters has been a driving factor for the refinement of orbital models and tracking techniques. Besides selected laser ranging campaigns, these missions are mainly supported by space-based radio tracking systems like TDRSS, GPS, DORIS, and PRARE. Their use has enabled the achievement of orbital accuracies in the decimeter region, with focus on the exact restitution of the radial component. In the case of GPS usage, the differential processing of space-based and concurrent ground-based pseudorange and carrier phase measurements provides for the required increase in precision over the Standard Positioning Service. The GPS satellite orbits themselves are determined with position accuracies of several centimeters, using GPS measurements collected by a global network of geodetic reference stations (Springer et al. 1999).

Looking at the future, a new era will be opened by the upcoming GRACE mission (Davis et al. 1999). Making use of a K/K_a-band intersatellite link that provides dual one-way range measurements, changes in the distance of the two spacecraft can be established with an accuracy of about 0.01 mm. In combination with supplementary onboard accelerometers, this will for the first time allow the detection of short-term variations in the cumulative gravity field of the solid Earth, the oceans and the atmosphere.