2 Basic Orbits

How Spacecraft Move in Orbit

BEFORE getting to the business of discussing the orbital aspects of modern spacecraft missions later in this chapter, there are a few fundamentals about the orbital motion of a spacecraft that we need to discuss, and a few popular misconceptions about it that need to be put to rest.

The first of these fundamentals is how a spacecraft remains in orbit around Earth, effectively forever, without having to fire rockets to sustain the motion. The answer lies in understanding that the spacecraft, like a stone falling down a deep well, is in a state of continual free-fall. Clearly, we do not expect the stone's motion to be assisted by rockets; it just falls unaided in the gravity field until it impacts the water at the bottom of the well. Free-fall in a gravity field is also the key to understanding the spacecraft's motion, although in this case it is perhaps not so apparent. And, of course, the spacecraft operator hopes that, in the process, it does not impact the ground like the stone!

To help with this discussion, we turn to a device that has become known as *Newton's cannon,* after its originator Isaac Newton. He first introduced the idea around 1680 in *A Treatise of the System of the World*, which he wrote as a popularization of his great work the *Principia* (see Chapter 1). Newton produced a diagram of his cannon in his treatise similar to that in Figure 2.1. To start with we have to imagine an impossibly high mountain, let's say 200 km (124 miles) high, for the sake of argument—a real challenge to the climbing fraternity. Not only is it a long way to the top, but when you get there you are effectively in the vacuum of space. Then you have to envisage dragging all the materials necessary to the summit to build a large cannon there that is capable of firing projectiles at a range of barrel speeds. This is also illustrated rather unimaginatively in Figure 2.1.

The cannon crew, presumably all dressed in space suits, now begins the serious business of firing cannonballs at the unsuspecting population below. You can see that if the crew fires a cannonball out of the gun with a barrel speed of, say, 2 km/sec (1.24 miles/sec), then it will do as you expect it to –

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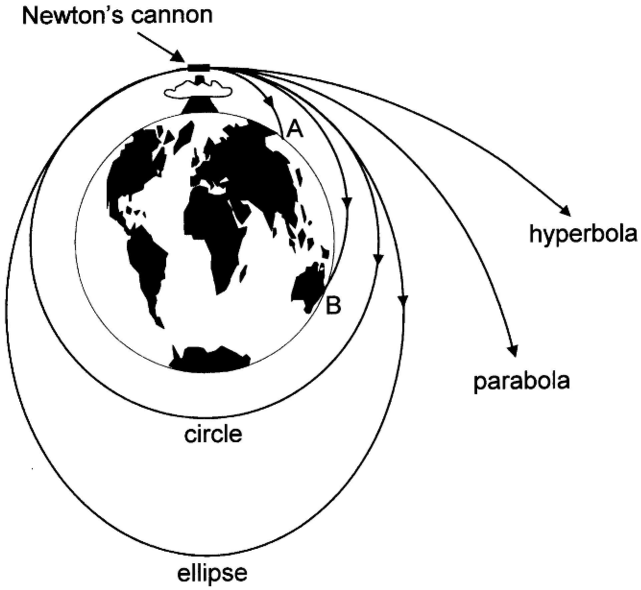

Figure 2.1: Newton's cannon—a "thought experiment" devised by Isaac Newton to explain the nature of orbital motion.

that is, take a curved path and impact the ground some distance away at point A (Figure 2.1). If the barrel speed is then ramped up to, say, 6 km/sec (3.73 miles/sec), the cannonball becomes intercontinental and travels a whole lot further to point B before impacting Earth's surface. However, something really interesting happens when the crew further increase the barrel speed to around 8 km/sec (5 miles/sec). Now the cannonball's path curves toward Earth's surface once again, but the curvature of the trajectory is matched by the curvature of Earth, and the ball continues to fall toward Earth without actually making contact! The projectile has now entered a circular orbit around Earth (Figure 2.1), and the cannon crew had better watch out as the ball will whizz past the gun about 90 minutes later, after making a complete orbit of Earth. Like the stone, the ball is now in a state of free-fall, and will continue to orbit Earth indefinitely.

To reinforce this idea, we can look at the same situation but consider Earth's curvature. At the mountain summit, the curvature is such that Earth's surface falls away below a truly flat horizontal plane by about 5 m (16 ft) in approximately every 8 km (5 miles) traveled over the ground. You may also recall that 5 m is roughly the distance fallen by Newton's apple in 1 second (Chapter 1). If you fire a cannonball from the gun at an initially horizontal speed of around 8 km/sec, it too will fall 5 m in the first second of flight, thus matching Earth's curvature. Therefore, no ground impact results, and you have orbital motion. To be more precise, for the cannonball to enter a circular orbit, it must be fired at a speed of 7.78 km/sec (4.84 miles/sec) from the summit cannon. For those of you who like more familiar units, this is about 28,000 km per hour (17,400 mph), which is a typical speed for a space shuttle in low orbit.

Newton's other orbital trajectories (Chapter 1) can also be produced using the summit cannon. For example, if we further increase the barrel speed to around, say, 9 km/sec (5.59 miles/sec), this has the effect of raising the height of the ball's trajectory on the other side of the globe, producing an elliptical trajectory (Figure 2.1). Since this is a closed trajectory, the cannonball will come back to haunt the cannon crew, about $2\frac{3}{4}$ hours after the projectile is fired, in this case. Note that the ball always returns to the low point on the orbit, the summit cannon, which is referred to as the orbit *perigee*. The high point, on the other side of Earth from the mountain, is called the orbit *apogee*. These are rather strange terms, but as the topic of orbit dynamics has been with us for so many years, a lot of wonderful terminology has come to us from history, as we will see later. Getting back to our cannon, further ramping up the barrel speed will result in higher and higher apogees, giving more and more elongated ellipses. Eventually, the apogee height will effectively reach infinity, an extremely long way away, and then the trajectory becomes an open parabola (Figure 2.1).

If you ask the cannon crew to check the barrel speed, the crew members will tell you that the parabolic trajectory occurred at around 11 km/sec (6.84 miles/sec). If you also recall the discussion about the parabola in Chapter 1, it is the trajectory that results in escape from Earth's gravity with the minimum energy given to the cannonball. The ball flashes out of the cannon at huge speed, but this energy is consumed by the gravity field as it climbs away from Earth, and when it reaches infinity it effectively has no energy left to go anywhere, that is, it has zero speed. Any further increase in the barrel speed of the cannon will result in the ball's trajectory being a hyperbola (Figure 2.1). If you recall, this gives the ball sufficient energy to escape Earth's gravity, with some left over to give it a constant speed once it has reached a great distance from Earth.

While Newton's cannon is helpful in revealing the nature of orbital motion, as you have probably guessed it does not have much to do with the realities of launching current spacecraft into orbit. This is done using launch vehicles, and we shall discuss in Chapter 5 how these are related to Newton's cannon.

Weightlessness

Now that we have a good feel for the nature of orbital motion—essentially a spacecraft is in a state of free-fall under gravity—we can also achieve a similarly good understanding of the phenomenon of weightlessness.

Weightlessness is something we see routinely on news coverage of manned space missions. (In this book I use the phrase *manned space missions* to mean flights involving people—both men and women. I know that the phrase may not be quite politically correct, but I dislike the other possibilities, such as "crewed" missions or "peopled" missions.) We have become familiar with crew members floating about their space ships, performing tricks such as swallowing floating globules of water, which would of course be impossible back on Earth. Despite this familiarity, however, there are again misconceptions about the nature of weightlessness, but it can be easily understood in terms of objects—spaceships, astronauts, and globules of water—free-falling together in a gravity field.

The key to understanding is an appreciation that all objects, independent of size and mass, fall with the same acceleration in a gravity field. The first statement of this principle is attributed to Galileo Galilei, who was born near the city of Pisa in 1564. To prove it, he is said to have dropped a cannonball and a wooden ball of the same size from the top of the famous leaning tower to demonstrate that the two balls would impact the ground at the same time, despite their different weights. Unfortunately, it is agreed by historians that this rather splendid story is of doubtful authenticity.

A much better demonstration was performed on the moon's surface in July 1971, by Apollo 15 astronaut Dave Scott, who dropped a feather and a hammer together to see which of them would reach the lunar dust first. Since all three astronauts on this mission were serving members of the United States Air Force, the landing module was named Falcon, after the mascot of the U.S. Air Force Academy. The feather had to be that of a falcon, a detail that is of course entirely immaterial! You can perform this experiment now—if you happen to have a feather in one pocket and hammer in the other—but I think you can guess the outcome. Clearly the feather, being much lighter than the hammer, will hit the ground some time after the hammer in apparent contradiction of Galileo's assertion that all things fall with the same acceleration. However, the experimental method in this case is flawed; there is the unfortunate presence of air in the room—fortunate for you, but not for the experiment! In the lunar surface experiment there is no air to influence the motion of the feather, and the feather and the hammer hit the dust at the same moment, giving a convincing demonstration that objects do fall at the same rate in a gravity field.

We can gain an understanding of weightlessness in orbit in terms of the spacecraft, the astronaut, and all other free objects inside the vehicle all falling together with the same acceleration in Earth's gravity field.

To consolidate this idea, we can attempt to do an experiment on the ground to reproduce the effects of weightlessness by replacing our spaceship with an elevator in a very tall building. Strangely, the elevator is equipped with a weighing machine, as shown in Figure 2.2a. When we enter the elevator, while it is stationary, we can climb on the weighing machine, and we know that it will register our normal weight. We also have sufficient experience of riding elevators to know that, if we were to press a button to go up, we will feel heavier while the lift cable is accelerating the elevator upward—the weighing machine will register this increase in weight (Fig. 2.2b). However, the part of the experiment to simulate weightlessness (Fig. 2.2c) is not to be recommended, as it involves cutting the elevator cable while disabling the elevator breaking system! In this case, the elevator and all objects within it will free-fall under gravity with the same acceleration, giving the same effects of weightlessness as seen on a spacecraft but for a rather shorter period of time!

Interestingly, a number of research laboratories around the world offer such a facility commercially (called a drop tower), in which hardware experiments—but not people!—are dropped to produce brief periods of weightlessness. Note that, in this discussion, it is important to make a clear

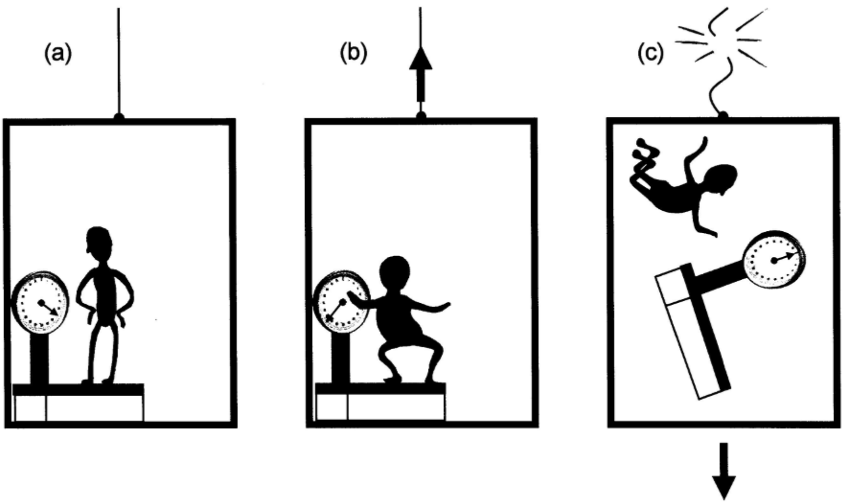

Figure 2.2: (a) Elevator stationary. (b) Acceleration of elevator upward causes increase in weight. (c) Elevator in free-fall produces weightlessness.

distinction between weight and mass. Our unfortunate elevator rider in Figure 2.2 may have a mass of, say, 80 kg (175 lb), which remains constant throughout his scary adventure, but as we have noted his weight varies considerably depending on the state of motion of the elevator. Mass, according to Isaac Newton, is a fixed attribute of an object that characterizes its inertia; massive objects like pianos require a significant push to get them moving, whereas smaller objects require much less effort.

This difference between mass and weight also had a surprising consequence for the Apollo moon-walking astronauts, who found they fell over rather more often than they were anticipating. A typical astronaut's mass, including space suit and backpack, was on the order of 130 kg (285 lb), but of course their weight in the lunar surface gravity was around one sixth of their Earth weight. This difference meant that the friction between their boots and the moon's surface was similarly reduced to one sixth of that on Earth. As they moved around on the moon's surface, sometimes quite rapidly, they had less contact friction with which to manage their significant mass—with some interesting results!

Spacecraft Mission Analysis

After the historical perspective of Chapter 1, and the earlier sections of this chapter, we now move on to begin to tell the story of modern spacecraft design. In the remainder of this chapter and the subsequent two chapters, we continue the theme of orbits, but in the context of spacecraft in orbit around Earth, or around another planet, or indeed around the Sun. *Spacecraft mission analysis* is a rather fancy term that spacecraft engineers use to describe the design of the orbital aspects of a spacecraft mission. On any spacecraft project there will be a team of people tasked with this job, which involves things like selecting the rocket that will launch the spacecraft, selecting the best orbit for the spacecraft to achieve the objectives of its mission, and determining how the spacecraft will be transferred from launch pad to final orbital destination.

Orbit Classification

To discuss the types of closed Earth orbits that are commonly used by spacecraft operators, we need to consider the characteristics of typical orbits that uniquely distinguish one orbit from another. Principally, these distinguishing features are shape, size, and inclination.

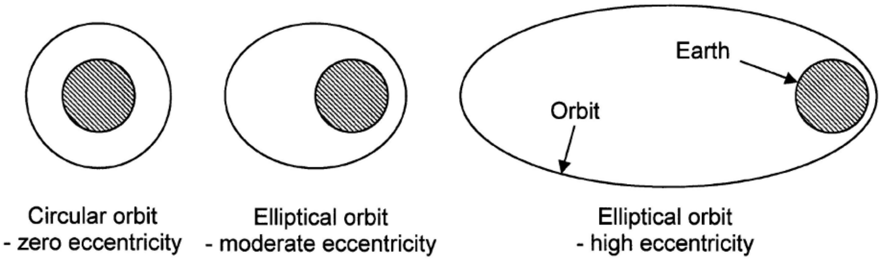

Figure 2.3: Shape is a principal distinguishing characteristic of orbits. The degree of elongation of an orbit is defined by its eccentricity.

For closed orbits, the relevant *shapes* are circles and ellipses. Of course, some ellipses are more elongated than others, as shown in Figure 2.3, and this degree of elongation is referred to as *eccentricity*, with high eccentricity orbits being more elongated.

Similarly, *size* is an easy idea, being defined by the orbit height. More precisely, a circular orbit will be defined by its radius, measured from Earth's center, or by its altitude above Earth's surface, as shown in Figure 2.4a. For elliptical orbits, the overall size of the orbit can be defined in terms of the distance between perigee and apogee (Fig. 2.4b). The perigee and apogee points may also be pinned down by their respective distances from Earth's center or surface.

The third principal characteristic, *orbital inclination*, essentially defines the orientation of the orbit plane with respect to Earth's equator, as illustrated in Figure 2.5. The orbital inclination is defined as the angle between the orbit plane and the equatorial plane, measured at the ascending node of the orbit. Again in terms of the jargon, a *node* is simply a

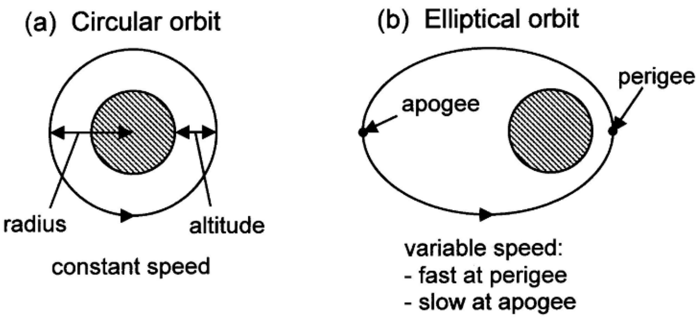

Figure 2.4: The size of an orbit is a principal characteristic, and this is defined by the orbit's altitude above Earth's surface, or its distance from Earth's center.

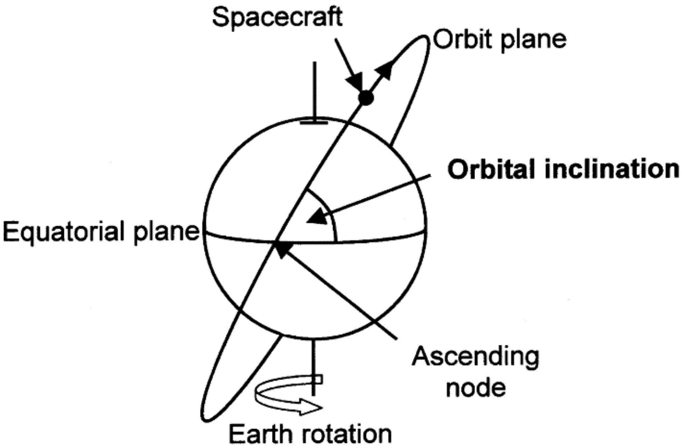

Figure 2.5: The angle between the orbit plane and the equatorial plane is called the orbital inclination. This is the third principal distinguishing characteristic of an orbit.

point on the orbit where the spacecraft crosses the equator, and an *ascending node* is one where the spacecraft is traveling from south to north. Looking at Figure 2.6a, we can see that an orbital inclination of 0 degrees gives an equatorial orbit, that is, one that overflies the equatorial region only. Conversely, an orbital inclination of 90 degrees gives an orbit plane perpendicular to the equatorial plane, as shown in Figure 2.6b. This type of orbit is referred to as a polar orbit. Of course, the orbital inclination may take any value between 0 and 180 degrees; a value of about 45 degrees is illustrated in Figure 2.6c.

Another property of the orbit that is of interest, implied in Figure 2.4, is the *orbital speed* with which spacecraft move along their orbital path. This is not a principal characteristic, but an attribute that arises as a result of the

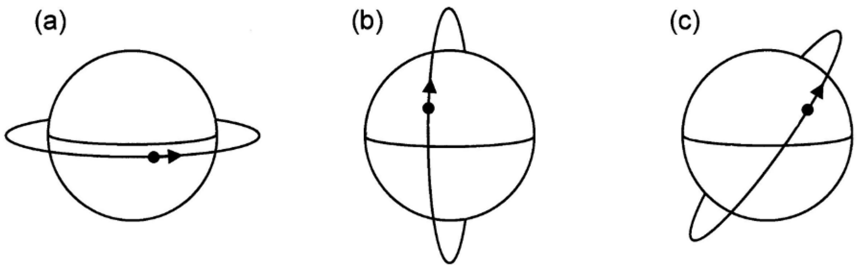

Figure 2.6: Orbits of differing orbital inclinations. (a) An equatorial orbit. (b) A polar orbit. (c) An orbit with an inclination of about 45 degrees.

orbit shape and size. The mathematics tells us that in a circular orbit, the spacecraft's speed is dependent on the mass of the central body and the orbit height. Given that we are considering Earth orbits, the mass of the central body, Earth, is of course constant, so the spacecraft's speed then becomes dependent only on the orbit height. A spacecraft in a circular orbit at particular altitude will move at a precisely defined speed. For example, in a 200-km (124-mile) altitude circular orbit, the spacecraft moves at 7.78 km/sec (4.84 miles/sec), as we have already seen in our discussion earlier of Newton's cannon. This is a low Earth orbit (LEO). The rule is that as the circular orbit height increases, the orbit speed decreases; for example, a spacecraft in a 10,000-km (6200-mile) altitude circular orbit will travel at around 5 km/sec (3 miles/sec).

In an elliptical orbit, the spacecraft speed along its trajectory is slightly more difficult to quantify, as the mathematics are a little more involved. But it can be understood easily in terms of the sharing of the spacecraft's energy between height and speed. As the spacecraft's altitude increases, its energy is sapped by its climb out of the gravity field and it slows down. At the apogee point of an elliptic orbit, the spacecraft speed will be lower than its speed at perigee. We have seen this already, expressed in a rather geometrical (17th century) way by Kepler's second law of planetary motion (see Chapter 1). A good parallel to help remember the variation in speed in elliptical orbits is bike riding on hilly terrain; your speed in the valleys is much higher than when climbing to the high points, for the same reasons of converting height into speed, and vice versa, as you ride.

Popular Operational Orbits

Now that we have a grasp of the three principal distinguishing characteristics of orbits—shape, size and orbital inclination—we can begin to look at the Earth orbit types that are most commonly used by spacecraft operators. Obviously, if we allow all possible variations in these three characteristics, then there is an infinite number of resulting Earth orbits to choose from! The popular orbits that we are about to introduce, therefore, are a small subset of this vast number of possibilities, and these are widely used simply because they have useful properties that enhance the performance of scientific and applications spacecraft. In writing this chapter, I found it difficult to decide what to include and what to leave out. No doubt other experts would say, "Well, what about such and such an orbit, which is often used for this or that?" I guess the reader has to accept that sometimes things are simplified and generalized a little to aid clarity.

Bearing in mind these comments, five types of popular operational orbit are identified, and these are summarized in the following box for quick reference.

Some popular operational Earth orbits

1. **Low inclination LEO**
   A circular Low Earth Orbit with an orbit plane varying from equatorial up to about 50° inclination.
2. **Near-polar LEO**
   A circular Low Earth Orbit with an orbit plane inclined near 90°.
3. **HEO**
   A Highly Eccentric Orbit.
4. **GEO**
   A circular, equatorial orbit at a height where the orbit period is 1 Earth day. This is referred to as a Geostationary Earth Orbit.
5. **Satellite constellation orbits.**
   A network of usually identical circular, inclined orbits, often accommodating a large number of satellites.

Low-Inclination LEO

This is a circular low Earth orbit, with an orbit plane that is near-equatorial (Fig. 2.7). However, the simplicity of this statement is deceptive, and what we mean by "low" and "near-equatorial" requires qualification.

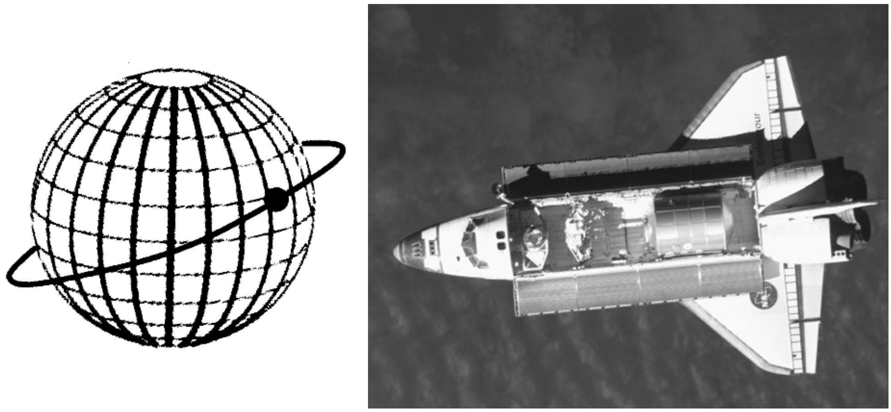

Figure 2.7: Low-inclination low Earth orbit (LEO). Large vehicles, such as space shuttles and space stations, are often accommodated in this type of orbit. (Image courtesy of the National Aeronautics and Space Administration [NASA].)

Surprisingly there is much debate among experts about the meaning of the word *low*, but my working definition is altitudes below about 2000 km (1240 miles). The phrase *near-equatorial* similarly gets a wide interpretation, meaning orbit planes ranging up to around 50 degrees in orbital inclination. The kinds of spacecraft found in this type of orbit are often large, that is, massive, manned vehicles such as shuttles and space stations, or large unmanned spacecraft. An example of this class of unmanned vehicle is the well known Hubble Space Telescope, which is about the same size and mass as a double-decker bus—around 11,000 kg (24,000 lb). The mass of space vehicles and the type of orbit in which they are accommodated are related. As we will explain in more detail in Chapter 5, it is much easier to launch large spacecraft into low, near-equatorial orbits.

Also, given that the plane in which the planets orbit the Sun is close to Earth's equatorial plane, spacecraft destined to probe distant planets are often launched into a near-equatorial LEO. This is then used as a kind of *parking orbit*, to check out the spacecraft's onboard systems, before a rocket is fired to take the probe to its ultimate destination.

Near-Polar LEO

This orbit is used mostly by operators of Earth observation and surveillance spacecraft (Fig. 2.8). It is a popular operational orbit, particularly at altitudes in the region of 700 to 1000 km (435 to 620 miles), and this is mainly driven by a need to get a global perspective on environmental issues such as climate change. Consequently, many national and international space agencies have launched (and are planning to launch) an armada of spacecraft equipped with powerful instrumentation directed downward to the Earth's surface. Earth observation also has a military dimension, and many military agencies are launching surveillance satellites to gain the new military "high ground." It is perhaps not well known that the biggest spender on space in the world is the U.S. Air Force, and details of most of their spacecraft and activities are classified. However, to get a feel for the capabilities of their optical surveillance satellites, you have to imagine a spacecraft with similar imaging power to the Hubble Space Telescope, but directed down instead of up!

It is easy to see why near-polar LEOs are good for Earth observation. Figure 2.8 demonstrates that there is potential for our spacecraft to see most of the planet's surface if we wait long enough; this is called *global coverage*. As our spacecraft orbits once every 100 minutes (typically), and Earth rotates once every 24 hours beneath the orbit plane, the spacecraft operators can image most targets of interest worldwide within a day or two. The targets of interest can vary substantially in character, from the health of a crop of maize to tank movements on a battlefield.

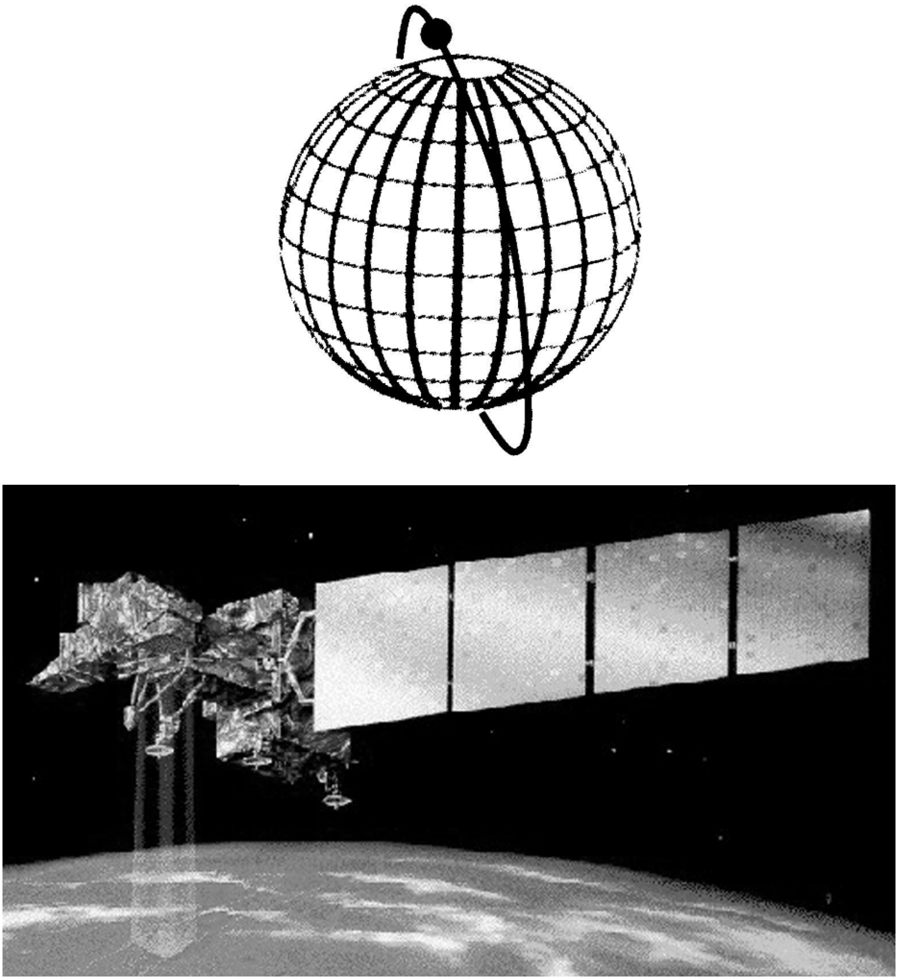

Figure 2.8: Near-polar LEO. This is commonly used by Earth-observation satellites, like the Landsat spacecraft shown. (Image courtesy of NASA.)

If we compare the near-polar LEO with the low inclination LEO, we can get a good idea of why the near-polar orbit is so well suited to Earth observation missions. It is obvious from Figure 2.7 that if we launched an Earth observation satellite into a low-inclination orbit, we would get a good look at the near-equatorial regions of Earth, but not much else.

HEO

The geometry of a typical highly eccentric orbit is shown in Figure 2.9, which is inherently useful for a variety of missions.

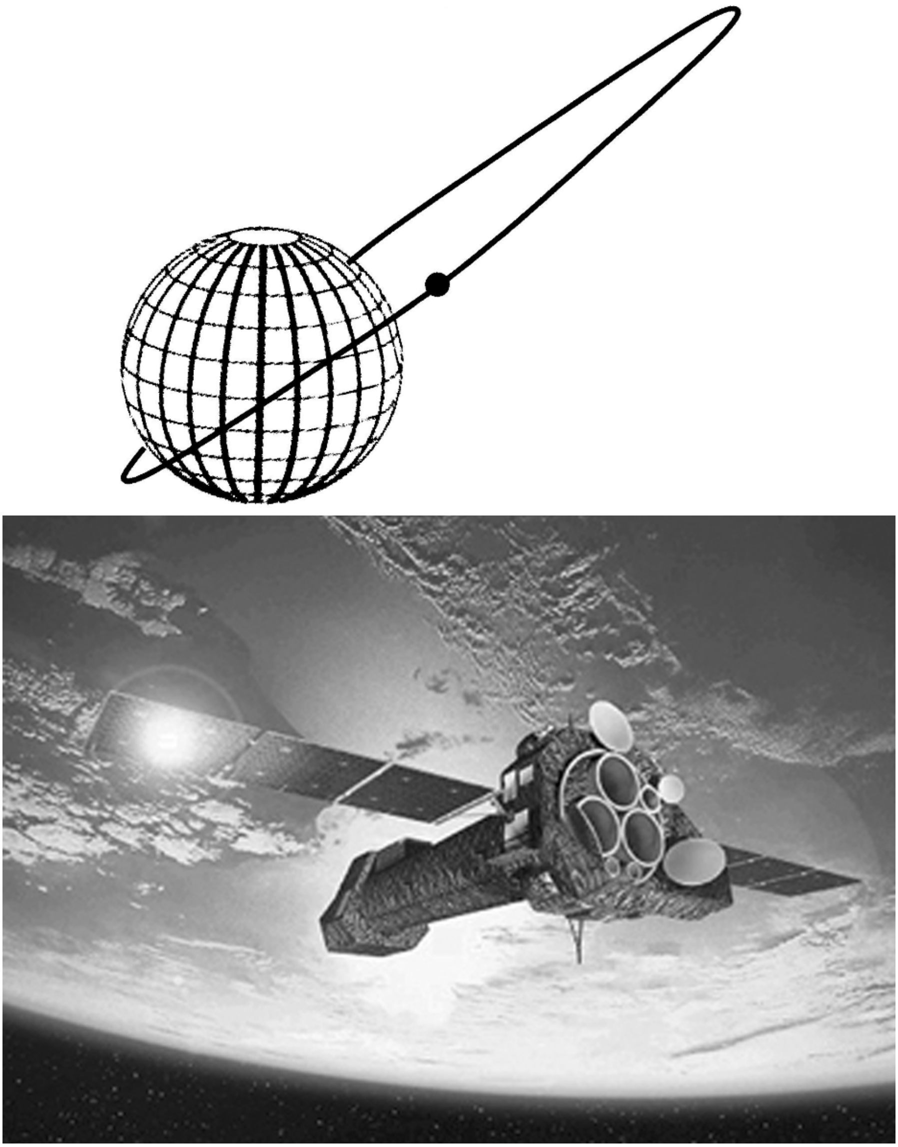

Figure 2.9: The highly eccentric orbit (HEO). One type of mission that it accommodates is astronomical observatories, such as the XMM Newton X-Ray Telescope. (Image courtesy of the European Space Agency [ESA].)

The HEO has accommodated many scientific spacecraft, for example, the European Space Agency Cluster mission, dedicated to exploring Earth's magnetic field, and the energetic atomic particles that are trapped within it.

The source of these particles is the solar wind, a stream of high-speed ions—atoms stripped of their electrons—emanating from the Sun. When these encounter the magnetic field of Earth, some of them are trapped in near-Earth space to form doughnut-shaped regions filled with energetic particles (see Chapter 6). These regions were named the Van Allen radiation belts in 1958 after their discoverer, and the particle radiation they contain is hazardous to both man and spacecraft systems. Understanding this hazard has been an important endeavor, and the HEO provides the best means of doing this, as a spacecraft in this orbit is able to sample the magnetic field and particles over a wide range of altitudes on each orbit.

The HEO is also a popular orbit for space observatories. An observatory at the apogee of a HEO has good *sky viewing efficiency*, as the distant Earth obscures only a small part of the sky. Also the relatively slow speed at apogee means the spacecraft spends most of its time there, providing good opportunities for extended periods of communication with the ground. This allows ground operators to command the telescope and receive its data as if it were effectively on the ground in a dome next to the control room. This way of operating is referred to as *observatory mode operation* and is an important attribute for space telescopes. Also the high apogee of the HEO means that the observatory spends most of its time above the Van Allen radiation belts, which is beneficial for some instruments that cannot operate in a high radiation environment.

The HEO has also been used extensively as a communications orbit, mainly by the former Soviet Union and by Russia today. A HEO inclined at 63 degrees to the equator, with an orbit period of 12 hours, is called a *Molniya* (Russian for "lightning") orbit after a series of communications satellites accommodated in this orbit. The Soviet Union began to use this orbit in the 1960s for communications between ground sites at high northern latitudes, by positioning the apogee of the orbit above the Northern Hemisphere. The low speed of the spacecraft in the apogee region means that it spends the majority of its orbit period high in the sky above these northern regions, giving an opportunity for extended, uninterrupted periods of communication with terrestrial users. Between 1964 and 1998, around 170 spacecraft were launched into *Molniya* orbits to provide telephone communication and satellite TV to high-latitude regions bordering the Arctic Ocean.

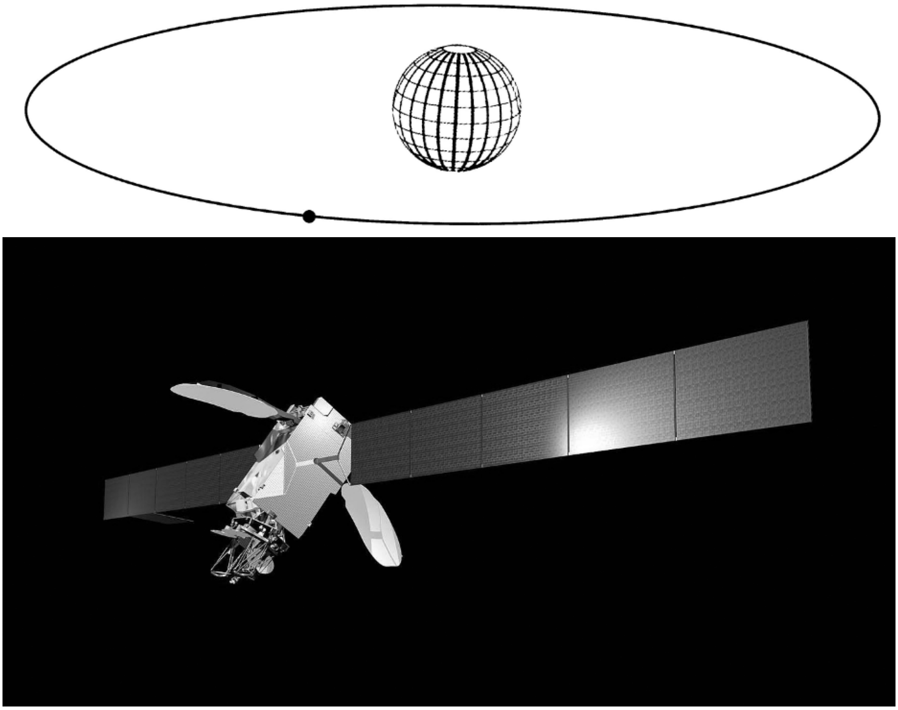

Figure 2.10: The geostationary Earth orbit, shown to scale. There are many communication satellites in this orbit, such as the Intelsat spacecraft illustrated. (Image courtesy of EADS Astrium.)

GEO

The geostationary Earth orbit is a widely used operational orbit, mostly for communications, but also for scientific and Earth observation satellites (Fig. 2.10). An example of a GEO orbit Earth observation satellite is Meteosat, which provides those impressive weather pictures we see each evening on the television weather forecast. The invention, if such it can be called, of the GEO is attributed to the science-fiction author Arthur C. Clarke in 1945. Unfortunately, he failed to patent the idea; if he had done so, he would probably be very rich today! The reason for the popularity of the GEO as an operational orbit is its unique characteristic that satellites in this orbit appear to be stationary when seen from Earth's surface—hence the name. To achieve this, the orbit needs to be circular and equatorial, but in addition the orbit height has to be such that the spacecraft orbits Earth in the same time as it takes for Earth to rotate once on its axis.

There is often confusion about the meaning of the term *geosynchronous orbit* (GSO) and how it relates to the GEO. GSO is the name used for any orbit that has an orbital period equal to one Earth rotation, so the GEO is a special case of the GSO. There are obviously a whole bunch of GSOs with a 1-day period, but having an elliptical shape, or a plane inclined to the equator, or both. The important distinction is that a spacecraft in one of these GSOs does not appear stationary relative to a ground-based observer.

Usually the orbit period of a GEO is said to be 24 hours, but it is actually a little shorter than that—23 hours and 56 minutes. The day on which we base our calendar is the familiar 24 hours, which is called the *solar day,* and this is the time it takes for Earth to rotate once with respect to the Sun. If the Sun is precisely due south (or due north if we live in the Southern Hemisphere) and we measure the time it takes for it to return to the same position in the sky the next day, we will find it to be the familiar 24 hours. The period of the GEO satellite, 23 hours 56 minutes, is called the *sidereal day,* which is the time it takes for Earth to rotate once with respect to the distant stars. The reason for the difference is Earth's orbital motion around the Sun; because of this, the Sun appears to move relative to the stars. As Earth rotates, it takes 23 hours and 56 minutes to do one revolution with respect to the stars, and then it has to rotate for an extra 4 minutes to catch up with the Sun, as the Sun's position has changed from the day before.

Getting back to our GEO spacecraft, we can calculate the orbit height corresponding to this orbit period using Kepler's third law of planetary motion (see Chapter 1). If we do this, we get a precise altitude for our GEO of 35,786 km (22,237 miles). If we have a circular, equatorial orbit at this height, a satellite initially positioned above a particular geographical feature on the equator will remain above that feature as it orbits; it appears to stand still in the sky from the point of view of someone on the ground.

This property is the key to its popularity. It makes communication with the spacecraft easier, as you don't need to track the satellite with your dish antenna—you just point it in a fixed direction. And of course it also means that the communications link with the spacecraft is uninterrupted. This is a familiar idea, as evidenced by the large number of small satellite TV receiving dishes we see bolted to the exterior walls of houses, staring fixedly at a particular point in the sky where the service provider's invisible GEO satellite resides.

The GEO orbit is most commonly used by communication spacecraft, and there are literally hundreds of active communication satellites (comsats) on the GEO arc. People routinely use this technology day to day, without really noticing, which is of course the way it should be. If I pick up the phone to say, "Hi, this is Graham" to a friend on another continent, then my electronic voice will transit over land lines or microwave links to the nearest satellite ground station, where it will be transmitted into the sky to a GEO comsat by a large fixed dish antenna. This signal will be received and amplified by the spacecraft, and then transmitted down to another ground station in the region of my friend's home, ultimately arriving at his telephone handset. When he responds by saying, "Oh hello! How are you?," the whole process begins again in the reverse direction—amazing technology that is transparent to the user!

The nature of the GEO arc is that it is literally a one-dimensional line in space, and as such it is a limited natural resource that needs to be protected and managed for the future, like any other. Unfortunately, as well as all the active comsats on GEO, there are many defunct spacecraft that are essentially debris polluting the orbit. Because of the pressure of use on the GEO arc, spacecraft operators are now expected to boost their comsats to a higher graveyard orbit—200 or 300 km above GEO—when they reach the end of their operational life.

Satellite Constellation Orbits

The orbits associated with a satellite constellation are usually a network of identical inclined circular orbits, often accommodating a large number of satellites. A typical constellation geometry is illustrated in Figure 2.11, where the black dots represent the orbiting satellites comprising the constellation. Constellations have been most commonly used over several decades for satellite navigation (satnav), which uses satellites to determine your position on the ground (or on the ocean, in the air, or wherever you happen to be). More recently, constellations have been used for satellite communications, and there is currently an interest in using them for Earth observation as well.

Perhaps the best known example of a constellation is the global positioning system (GPS) navigation system. Navstar GPS satellites (see Chapter 1) are operated by the U.S. Department of Defense, mainly for use by the U.S. military. However, satnav in automobiles is becoming commonplace, as well as in leisure activities such as hiking and sailing, giving the user's position with an accuracy on the order of 10 m (32 feet). To triangulate a user's position on the ground, the receiver needs to access signals from at least four GPS satellites simultaneously. To make this work, the constellation must be designed so that the user can see at least four GPS satellites from any location on Earth's surface at any time. This ground coverage requirement leads to the design of the geometry of the satellite constellation. In this case, the required ground coverage is achieved by the operation of 24 satellites in the constellation. The resulting geometry of the constellation consists of six circular orbit planes at 20,200 km (12,500 miles) altitude, spread out around the equator. Each orbit plane is inclined at 55 degrees to the equator and accommodates four satellites. Figure 2.12a shows

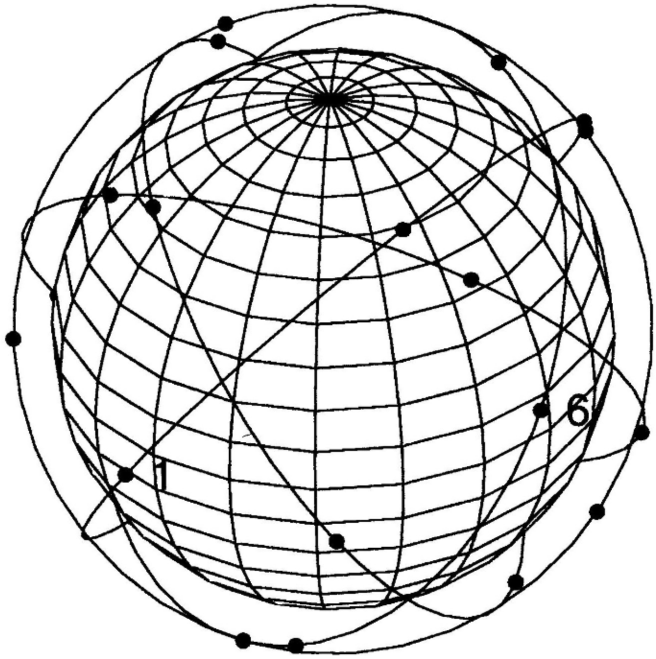

Figure 2.11: An illustration of a typical LEO constellation geometry for a communications system. The black circles represent the orbiting satellites that comprise the system.

the GPS constellation geometry, illustrating well the old saying that a picture is worth a thousand words! A typical GPS satellite configuration is shown in Figure 2.12b.

However, the Navstar GPS system is unlikely to be the future of space-based navigation systems because of its military ownership. Quite reasonably, the Department of Defense reserves the right to limit the signal strength, to erode the positional accuracy of the GPS system, and to shut down public access to GPS completely in times of military conflict. This political aspect of the GPS system has overridden the amazing technological benefits, and means that civilian agencies have been reluctant to embrace space-based navigation systems wholeheartedly. Just think how useful satnav would be if fully utilized for things like air traffic control, particularly now when the density of air traffic is growing at such a phenomenal rate. To overcome these political difficulties, the European Union has proposed launching a new satellite navigation constellation called Galileo, which will have civilian ownership. This system, comprising 30 satellites, is due to be operational in around 2012, and should allow space-

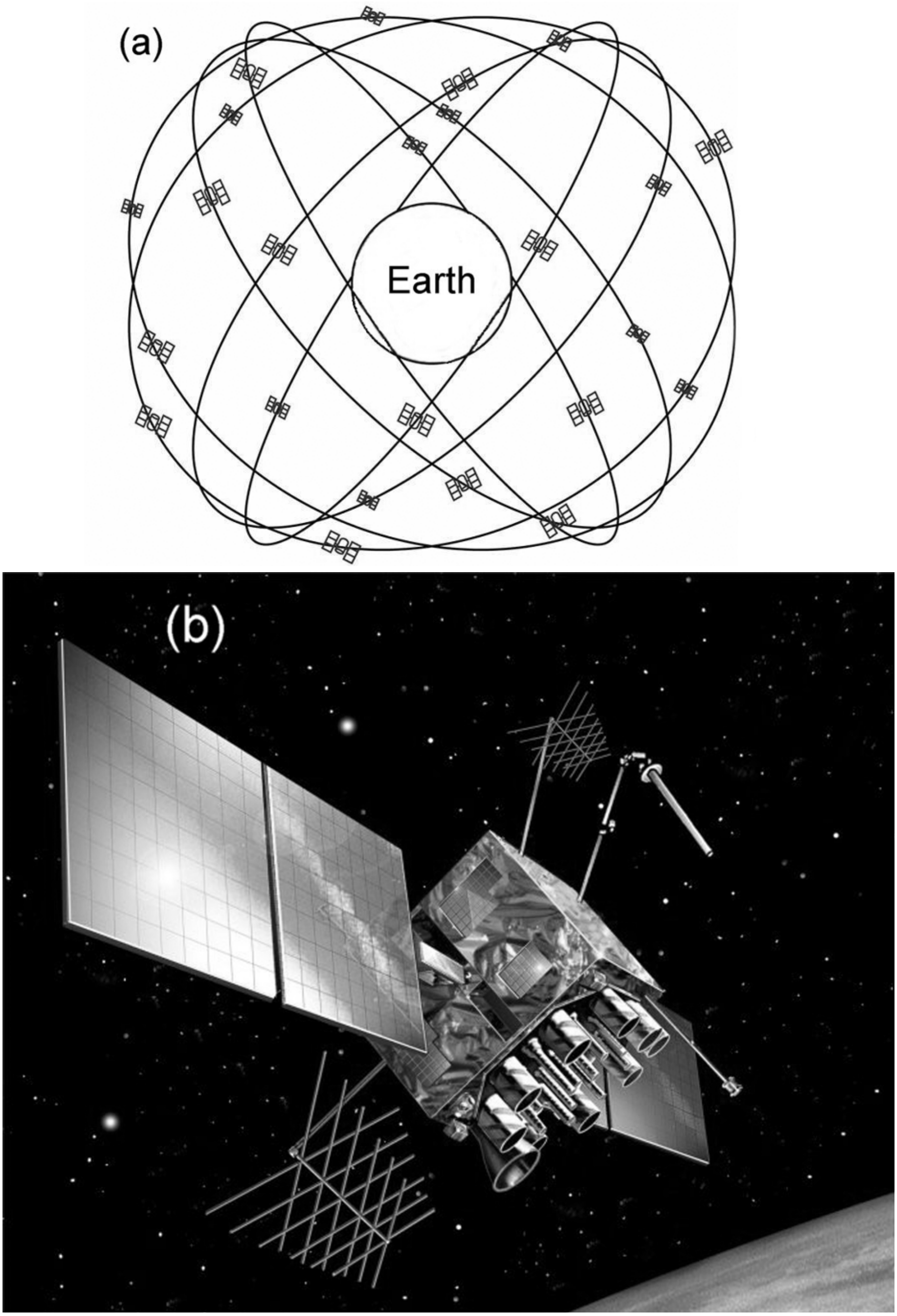

Figure 2.12: (a) Schematic of the global positioning system (GPS) Navstar constellation geometry. (b) A typical GPS satellite configuration. (Image courtesy of Lockheed Martin.)

based navigation techniques to become more fully integrated into all aspects of human activity where high precision positioning is required.

Satellite constellations have also been proposed for communications, and in this application low-altitude orbits are required. An example of this type of LEO constellation is shown in Figure 2.11. We have already discussed the usefulness of the GEO orbit for global communications, so why is there a need to propose a whole new way of doing the same thing? Well, the spur for this development is the craving we have for communications using small hand-held terminals, or, put another way, mobile phones. This love affair with mobile phone technology has created a huge expansion in terrestrial cell phone networks. As we roam around the planet, the communications with our friends or business associates is achieved by the links between our phones and a network of fixed, ground-based, mobile phone antenna masts. This works well most of the time, as the cell phone network operators have located the fixed phone masts in places where population is concentrated. This is, of course, driven by market forces. However, we all know that if we go for a hike in a remote mountain region and we wish to contact someone, the mobile phone will probably not work as we are out of range of the terrestrial network of mobile phone masts. What do we do if we find ourselves on top of Mount Everest and wish to contact a friend who is traversing the Gobi Desert? Yes, I know—a rather unlikely scenario—but it makes the point. In this situation we can adopt a satellite solution to the problem of mobile communications. Instead of having a network of fixed masts on the ground, we can establish a network of satellites in the sky that perform the same function. If we design the orbital geometry of the sky network or satellite constellation appropriately so that we always have line of sight to at least one satellite member of the constellation, then truly global mobile phone communications become possible. The sort of constellation geometry we see in Figure 2.11 is again driven by the coverage requirement that we need to see at least one satellite from all terrestrial locations, and at all times.

Why do we need a LEO constellation of satellites for mobile phone communications? Why can't we just talk through the existing network of GEO satellites? The simple answer is that the GEO satellites are just too far away. If our mobile phones had enough microwave transmission power to reach the 36,000 km (22,400 miles) or so to GEO, then they would literally fry our brains in the process—quite a major physiological constraint on the technology!

If we take account of all these various considerations, then mobile phone constellations usually end up comprising a network of near-polar LEOs. Perhaps the best-known example of this type of communications constellation is the Iridium system. The original proposal for this constellation was to have 77 active satellite members, equal to the number of electrons of an iridium atom, thus giving rise to its name. Subsequently this was reduced to 66 active satellites in a network of near-polar, circular LEOs at a height of approximately 780 km (485 miles). Because of competition from terrestrial mobile phone networks, Iridium has had a checkered commercial history, which has inhibited the growth of space-based mobile communications. However, if the economics can be gotten right, then, in the words of the ad, the future's bright for this type of space application!

The third main application of constellations is Earth observation, which is currently the least well-developed, although there may be military developments of which I am ignorant! When we briefly discussed Earth-observation satellites in the near-polar LEO section, we commented that the spatial resolution of current imaging payloads were amazing. Objects the size of a fraction of a meter can be easily seen from orbit with the right payload equipment, provided that the ground is not obscured by cloud. However, one problem with conventional Earth-observation spacecraft is their temporal coverage. As the satellite orbits every 100 minutes or so, and Earth rotates once every 24 hours beneath the orbit plane, it may take a while for the spacecraft to have an opportunity to over-fly and image a particular ground target of interest. The temporal coverage is not good using a single satellite. Overcoming this limitation is particularly important in military operations, where uninterrupted strategic battlefield information may be a requirement. Various civilian applications, such as disaster monitoring, would also benefit from improved temporal coverage, and using constellations of Earth-observation satellites is a way of achieving this. In principle, a continuous line of sight to a ground target of interest is achievable using a constellation provided that sufficient imaging satellites are launched.

From the above discussion, it is obvious that there a lot of advantages to using satellite constellations. Another one that we have not mentioned is *graceful degradation.* If you launch one satellite to provide a service, such as communications or Earth-observation, and it suffers a serious system or payload failure, then the service it provides is abruptly interrupted. However, if the function of providing the service is distributed among a large number of constellation satellites, then clearly the failure of one satellite means that the service may be compromised a little, but nevertheless it can be maintained. This characteristic of a more robust operation, associated with constellations, is particularly important in military space activities, where an adversary may be actively seeking to interrupt normal service!

Finally, constellations have the disadvantage of the cost of manufacturing, launching, and operating the many satellites in a constellation system, which is much higher than the cost of a single satellite system. However, as we have seen with navigation and mobile communications services, this burden of the cost has been taken on by the operators, as the many-satellite attribute of a constellation is essential in achieving the objective.

Choosing the Best Orbit

The five types of orbit we have discussed are popular with spacecraft operators, but how do we select the best of the huge number of possible orbits to choose from for a particular spacecraft mission? This question is central to the activities of the team of project engineers tasked with the job of the spacecraft mission analysis.

The quick answer is that the spacecraft needs to be in the right place, that is, the right orbit, so that the spacecraft payload can most effectively achieve its mission objectives. We need to pause a moment to reflect on this concise but not so simple statement. First, what is the *spacecraft payload*? Essentially it is the part of the spacecraft that fulfills the mission objectives—the business end of the spacecraft. For example, the payload of an Earth-observation satellite will be the camera instruments used to acquire the image data, or the payload of a communications satellite will be all the telecommunications equipment and antennas needed to maintain the desired communications service. Second, what is a *mission objective?* This is the purpose behind the whole project, its *raison d'être*. Some typical spacecraft mission objectives are the following:

1. The provision of high-resolution imagery of Earth with global coverage
2. The provision of a telecommunications service for the Australasian region using large, fixed ground antennas
3. The acquisition of high-resolution astronomical imagery

The process of linking the mission orbit selection with the mission objective usually involves the following steps:

- Definition of the spacecraft mission objective: the formulation of a precise statement defining the prime purpose of the spacecraft.
- Choice of payload instruments or equipment, usually done by a group of experts who can produce a detailed specification of the payload hardware required to achieve the objective.
- Development of payload operational requirements: How does the payload hardware need to operate to best achieve the objective? This

includes where the payload needs to be physically located to maximize its effectiveness.
- Finally, the consideration of the payload's location leads naturally to the selection of an appropriate, or even optimal mission orbit.

All this may sound rather formal and complicated, but we can return to our example mission objectives above to show that sometimes the process can be rather straightforward.

If we look again at mission objective 1, above, related to Earth observation, the requirement for *high-resolution* imagery of Earth means that the imaging payload instruments need to be close to their terrestrial *targets of interest*, which in terms of an orbit translates to a LEO. The need for *global coverage* means that our LEO must be near-polar in inclination to provide the instruments the opportunity to "see," after some period of time, the Earth's entire surface. Without too much difficulty, the use of a near-polar LEO (see Fig. 2.8) seems the obvious choice in this case. Similarly, it is easy to see that the choice of "best" mission orbit for mission objective 2, above, is a GEO.

These two examples illustrate well the process of how the mission objective drives the choice of mission orbit for a particular spacecraft project. However, just to muddy the waters a little, we can look at an example that shows that sometimes the choice of the mission orbit is not quite so obvious. The third example, mission objective 3, above, relates to the operation of an orbiting astronomical observatory, and if we look at the orbits of such spacecraft in current operation we find them in a variety of orbits. For example, the Hubble Space Telescope can be found in a LEO, the XMM Newton X-Ray telescope orbits in a HEO, and the Hipparcos observatory was designed to fly in GEO (although, due to a rocket engine failure, it did not make GEO and went into a HEO instead!). This variety suggests that the choice in this case is perhaps not quite so simple.

In cases such as this, a more detailed analysis is required to select the orbit, involving consideration of both spacecraft payload and system requirements which influence the decision. This kind of process is illustrated in Table 2.1, which is a simplified version of a trade-off table that engineers might use to help make an orbit selection for a space observatory. In a typical trade-off process, the objective is to make a choice among a number of different options; in this case the orbit options are LEO, HEO, and GEO (the right-hand columns of the table). To make this choice, a number of criteria or trade-off parameters, are specified (in the left-hand column of the table) against which the options are judged.

In our choice of parameters, three are related to the payload (telescope) operation, and three are related to spacecraft system operation. You may

Table 2.1: A simple orbit trade-off table for an orbiting astronomical observatory

Parameter	Type of parameter		Favoured orbit		
	Payload	System	LEO	HEO	GEO
Observatory mode operation (duration of ground communications link)	✓			✓	✓
Uninterrupted source observation	✓			✓	✓
Sky viewing efficiency	✓			✓	✓
Radiation exposure		✓	✓		
Ease of orbit acquisition		✓	✓		
In-orbit repair and maintenance		✓	✓		

recall, from the discussion about observatories in HEOs earlier, the explanation of *observatory mode operation* and *sky viewing efficiency*. A third payload parameter, *uninterrupted source observation*, is introduced, which relates to how long the telescope can point at a particular nebula or galaxy without interruption. To maximize sensitivity, telescopes often operate in a kind of time-exposure mode, where they point at the object of interest for long periods of time to collect as much light as possible. When you are looking at extremely distant objects at the edge of the universe, collecting every photon of light counts. If you think about an observatory in a LEO with a period of around 100 minutes, this kind of operation is difficult to achieve because Earth can get in the way of the telescope for about 30 minutes on each orbit revolution. Table 2.1 shows that high orbits—HEO apogee and GEO—are favored when we consider the payload parameters.

On the other hand, when we look at our system-related parameters, the LEO is the preferred option. The *radiation exposure* in LEO is less severe than in the higher orbits, so the reduced degradation of the spacecraft systems caused by particle radiation favors the LEO. The *ease of orbit acquisition* parameter relates to the amount of propulsive effort required to reach the mission orbit. Again the LEO orbit is favored as it requires the least amount of rocket fuel to get there, compared to the higher orbits. And savings in fuel mass in getting to your mission orbit can be usefully invested in increasing the payload mass, resulting in an improvement in the overall effectiveness of the spacecraft in achieving its objective. The third parameter, *in-orbit repair and maintenance*, is a means of effectively increasing the mission lifetime of the observatory. This maintenance is usually done by space-walking astronauts, and since manned vehicles can only visit LEOs routinely, this form of maintenance can only be performed on LEO spacecraft.

After all that, when we look at the checked boxes on the right-hand side of Table 2.1 we may be disappointed to find that the choice of mission orbit for our observatory is still unresolved! In truth, the process illustrated above is too simple to make any real progress, but it is useful in illustrating the trade-off process. In a real project situation, the trade-off exercise would be much more finely tuned to the specific spacecraft characteristics. Also, some of the parameters that are considered to be particularly important would be weighted in the trade-off process. For example, in choosing the best orbit for the Hubble Space Telescope, the issues of ease of orbit acquisition and in-orbit maintenance were paramount. The sheer size and mass of the telescope meant that LEO was the only real option for the orbit. Also, the desire to extend its useful lifetime by the process of in-orbit maintenance requires the use of astronaut repairmen taken aloft by the U.S. Space Shuttle, so the telescope's orbit is again constrained as the shuttle is unable to operate above LEO. As a consequence, the Hubble Space Telescope ended up in a LEO, even though we can see from Table 2.1 that it is not the best orbit for a space observatory!

In this chapter we have come a long way from Newton's cannon to popular operational orbits for modern scientific and applications spacecraft, and in the process have acquired an understanding of the nature of orbital motion. In Chapter 3, which discusses real orbits, we delve into this topic a little more deeply, to discuss the mysteries of orbital perturbations and how they influence the process of mission analysis. Give it a try, but if you find it hard going, skip it and move on. The rest of the book is not crucially dependent on the content of Chapter 3.