Spacecraft Thermal Control Handbook

Volume I: Fundamental Technologies

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Editor

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1 Spacecraft Systems Overview

D. G. Gilmore*

Introduction

During the past 40 years, hundreds of spacecraft have been built in support of scientific, military, and commercial missions. Most can be broadly categorized as either three-axis-stabilized spacecraft, spin-stabilized spacecraft, or pallets; these types are distinguished by their configurations, internal equipment, and thermal-control designs. This chapter is a brief overview of the characteristics of each of these different types of spacecraft and the missions they support. Representative thermal designs for each type are discussed in more detail in Chapter 3.

Spacecraft Configurations

The most common spacecraft configuration today is three-axis-stabilized. This type of spacecraft is characterized by a body that is roughly box-shaped and by deployable solar-array panels. Examples are the Defense Meteorological Satellite Program (DMSP), the Japanese Earth Resources Satellite (JERS), and the Russian communications satellite Gorizont, shown in Fig. 1.1. The bodies of these spacecraft are usually kept inertially stable except for a slow rotation induced about one axis to keep the payload antennas or sensors continuously pointed toward Earth as the satellite orbits. The solar-array panels are then counterrotated relative to the spacecraft body to keep them inertially fixed on the sun. Some three-axis spacecraft, such as the European Infrared Space Observatory (ISO, Fig. 1.1), have restrictions on attitude (the vehicle's orientation relative to an inertial coordinate system) or low power requirements that allow them to use fixed solar arrays that do not rotate to track the sun.

A typical internal equipment complement for a three-axis-stabilized spacecraft is shown in the exploded view of a Fleet Satellite Communications (FLTSATCOM) satellite in Fig. 1.2. The spacecraft is commonly referred to in terms of a "payload" and a "bus," or "platform." The payload is the equipment that services the primary mission—for example, a cloud-cover camera for a weather satellite or an infrared (IR) sensor for a missile early-warning system. Since FLTSATCOM is a communication satellite, the payload is the communications subsystem, which consists of the antennas on the Earth-facing side of the vehicle and the communications electronics boxes mounted in the upper hexagonal compartment, as shown in Fig. 1.2. The bus consists of all other spacecraft subsystems that support the payload. These subsystems typically include

- Structures subsystem: the physical structure of the spacecraft, to which all electronics boxes, thrusters, sensors, propellant tanks, and other components are mounted

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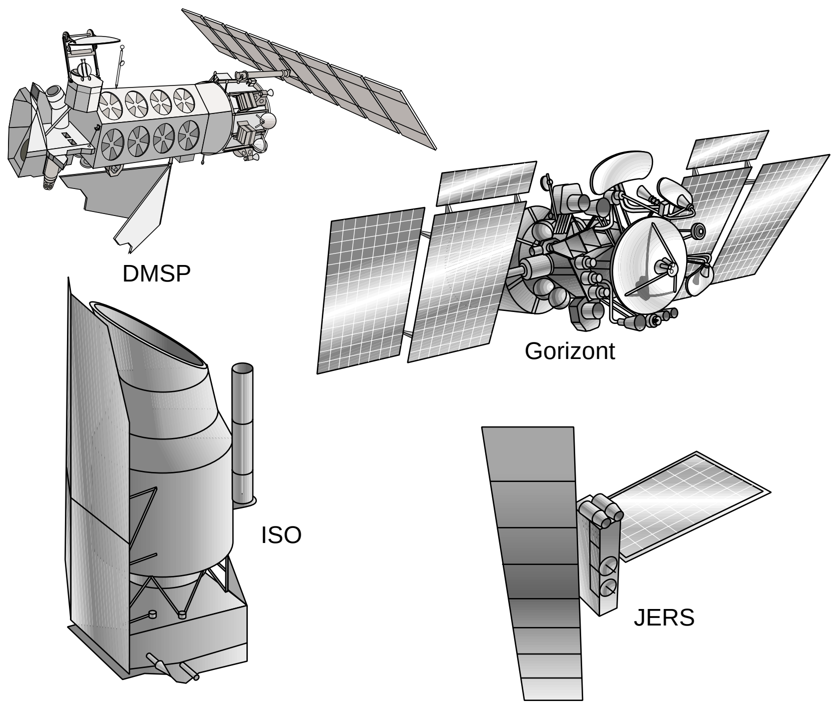

Fig. 1.1. Three-axis-stabilized satellites.

- Electrical power/distribution subsystem (EPS or EPDS): the equipment used to generate and distribute electrical power to the spacecraft, including solar arrays, batteries, solar-array controllers, power converters, electrical harnesses, battery-charge-control electronics, and other components
- Telemetry, tracking, and command subsystem (TT&C): The electronics used to track, monitor, and communicate with the spacecraft from the ground. TT&C equipment generally includes receivers, transmitters, antennas, tape recorders, and state-of-health sensors for parameters such as temperature, electrical current, voltage, propellant tank pressure, enable/disable status for various components, etc.
- Attitude/velocity control subsystem (ACS or AVCS): The devices used to sense and control the vehicle attitude and velocity. Typical components of the ACS system include sun and Earth sensors, star sensors (if high-precision pointing is required), reaction or momentum wheels, Inertial Measurement Units (IMUs), Inertial Reference Units (IRUs), and the electronics required to process signals from the above devices and control satellite attitude.

- Propulsion subsystem: Liquid and solid rockets or compressed-gas jets and associated hardware used for changing satellite attitude, velocity, or spin rate. Solid rockets are usually used for placing a satellite in its final orbit after separation from the launch vehicle. The liquid engines (along with associated plumbing lines, valves, and tanks) may be used for attitude control and orbit adjustments as well as final orbit insertion after launch.
- Thermal-control subsystem (TCS): The hardware used to control temperatures of all vehicle components. Typical TCS elements include surface finishes, insulation blankets, heaters, and refrigerators.

Many of these subsystem components are shown in the drawing of FLTSATCOM in Fig. 1.2.

The second category of spacecraft is spin-stabilized. These are less common than the three-axis-stabilized type and have been used mostly for relatively high-altitude missions in geosynchronous or Molniya orbits (p. 9). Some spinning satellites, however, are used in low-altitude orbits. A typical "spinner," Intelsat VI, is shown in Fig. 1.3. As the category name implies, these satellites achieve attitude stability by spinning like a top. Each spins at approximately 15 rpm about the axis of a cylindrical solar array. In the case of Intelsat VI, the communications payload is mounted on a large shelf, which is despun relative to the rest of the spacecraft so that it points continuously at Earth.

A spinner has the same basic subsystems as a three-axis-stabilized spacecraft: structures, EPS, TT&C, ACS, propulsion, and TCS. Usually, the payload is contained entirely on the despun section, while most of the other subsystems are on the spinning side. Some types of spinners, however, such as the Defense Support Program satellites (DSP; Fig. 1.4), do not have a despun shelf. In the case of DSP, the payload, an IR telescope/sensor, spins with the rest of the satellite; the rotation of the vehicle provides a scanning motion for the sensor.

A pallet is technically a collection of one or more payloads plus some limited support services, such as power distribution, data recording, or telemetry sensors. Pallets may be anything from a small experiment mounted to the side of a host spacecraft to a large structure containing many instruments and mounted in the payload bay of the space shuttle. The principal difference between the pallet and other spacecraft is that the pallet is not able to function autonomously, but instead relies on the host vehicle for ACS, EPS, and TT&C support.

The Experiment Support System (Fig. 1.5) is a typical pallet system. It consists of a rather large structure that supports a half-dozen experiments and an equipment compartment containing power distribution, command processing, and data recording equipment. The pallet is mounted in the space-shuttle payload bay, and the shuttle provides ACS, EPS, and TT&C functions. In addition to the pallet itself, there is a command monitor panel mounted in the crew compartment to allow the astronauts to control the operation of the experiments on the pallet. Because of the support provided by the shuttle, the pallet does not have propulsion, ACS, EPS, or TT&C subsystems, and it is incapable of operating on its own in space.

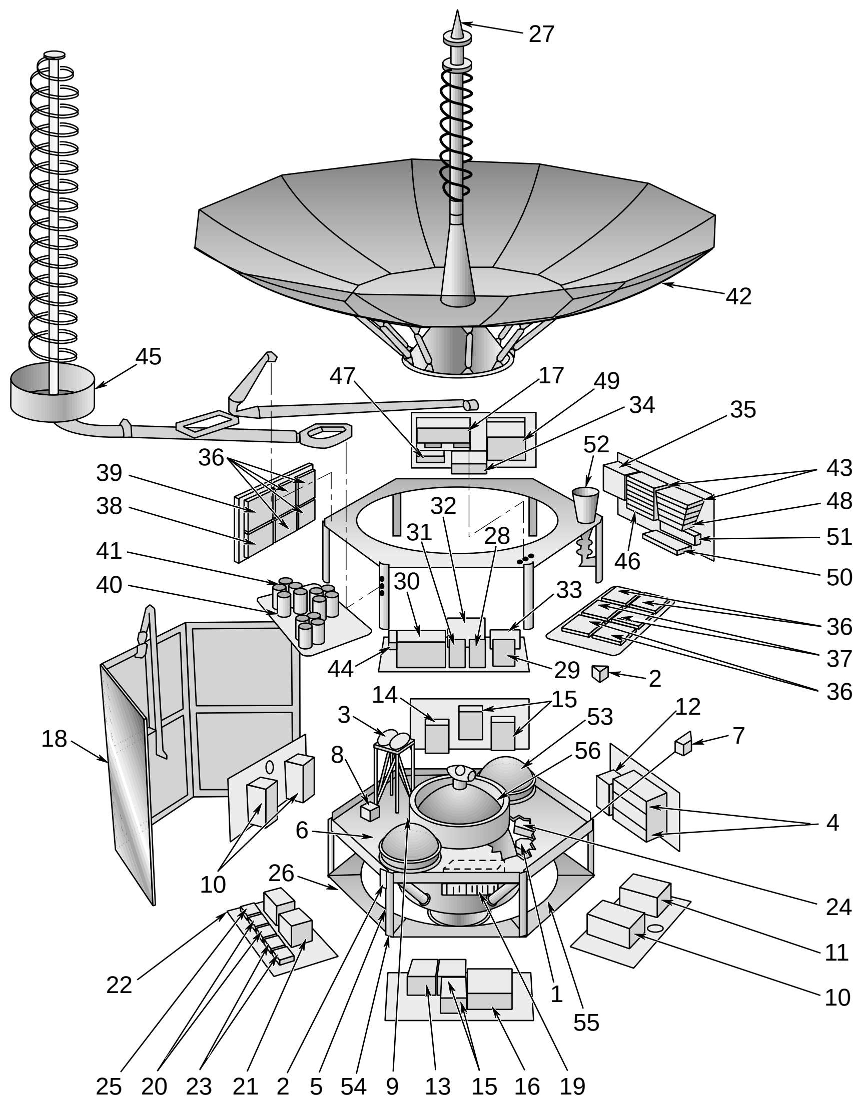

Fig. 1.2. Exploded view of FLTSATCOM. (Legend on facing page.)

Legend for Fig. 1.2.

Attitude and Velocity Control

1. Solar array drive assembly
2. Sun sensor assembly
3. Earth sensor assembly
4. Control and auxiliary electronics
5. Spinning Earth sensor assembly
6. Reaction wheel assembly
7. Coarse sun sensor assembly
8. Earth sensor electronics
9. Nutation damper assembly

Electrical Power/ Distribution System

10. Battery assembly
11. Power control unit
12. Converter, spacecraft equipment
13. Converter, communications no. 1
14. Converter, communications no. 2
15. Converter, transmitter
16. Payload switching unit no. 1
17. Payload switching unit no. 2
18. Solar panel assembly
19. Electrical integration assembly

Telemetry, Tracking, and Command System

S-Band Command Group

20. S-band receiver
21. Decrypter KIR23 (2 required)
22. Command unit

S-Band Telemetry Group

23. S-band telemetry transmitter
24. PCM encoder

S-Band Antenna Group

25. S-band diplexer
26. RF coaxial switch
27. S-band antenna

Communication System UHF Transponder

28. Preamp/downconverter/IF limiter no.1
29. IF filter limiter no. 2
30. Processor receiver/synthesizer
31. Repeater receiver
32. Command receiver/synthesizer
33. Oven-controlled crystal oscillator (2)
34. AF processor
35. UHF command decoder
36. UHF transmitter Navy low power
37. UHF transmitter Navy high power
38. UHF transmitter (DODWB)
39. UHF transmitter (AFNB)
40. UHF transmitter filter
41. UHF multicoupler filter assembly
42. Transmit antenna assembly
43. Frequency generator
44. Receiver filter
45. UHF receive antenna assembly
46. Signal distribution unit no. 1
47. Signal distribution unit no. 2
48. Passive hybrid

SHF Transponder

49. FB processor
50. SHF receiver
51. SHF transmitter
52. SHF antenna

Propulsion System

53. Propellant tank
54. Fill and drain valve
55. Thruster assembly
56. Apogee kick motor

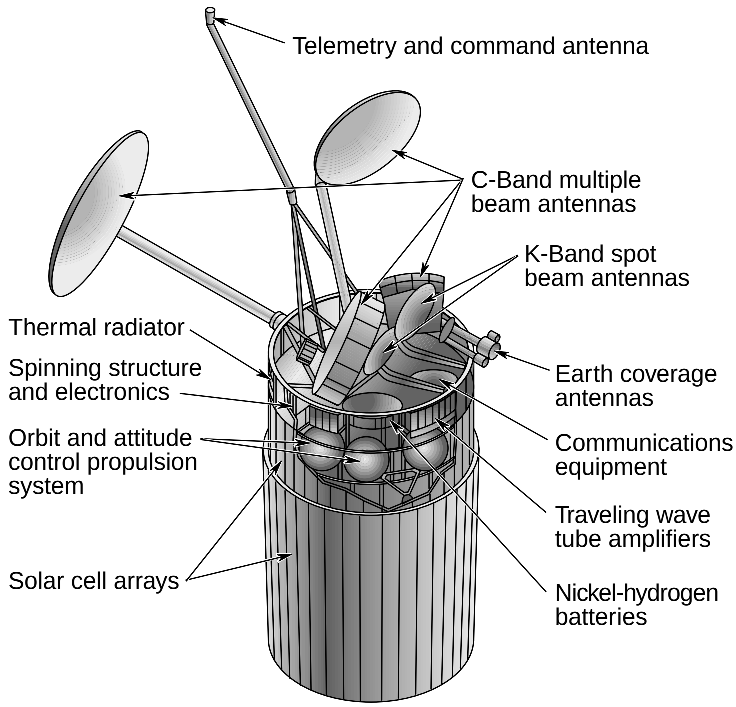

Fig. 1.3. Intelsat VI satellite.

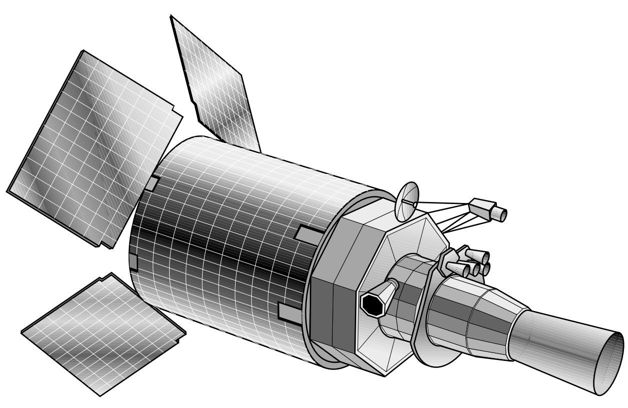

Fig. 1.4. DSP satellite.

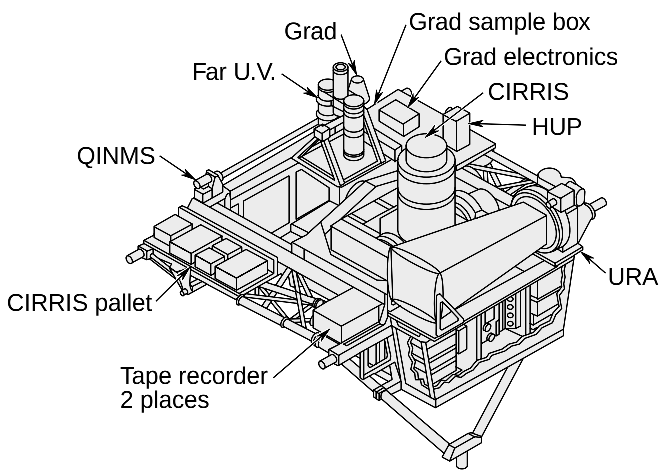

Fig. 1.5. Experiment Support System.

Another spacecraft configuration worth noting here is that of upper stages. Although they are not spacecraft per se, upper stages may be of a similar level of complexity, and they may contain some of the same subsystems. They are included in this handbook because upper-stage thermal control after separation from the booster is quite similar to the thermal control of spacecraft.

Upper stages are generally used to raise a spacecraft to a higher operational orbit from the relatively low orbit to which the booster delivers it. The duration of their missions varies from a few hours to several days. Upper stages can use solid, liquid, or cryogenic propellants. The Inertial Upper Stage (IUS, Fig. 1.6) is an example of a solid-propellant upper stage that can be used in conjunction with either the space shuttle or expendable boosters. The IUS itself has two stages; the first is generally used to put the spacecraft into a highly elliptical transfer orbit, and the second is fired at transfer-orbit apogee (the point in the orbit with the greatest altitude above the planet surface) to make the orbit circular at the higher altitudes. Like a satellite, the IUS has structures, EPS, TT&C, ACS, propulsion, and thermal-control subsystems.

Earth Orbits

A variety of orbits are used for different types of Earth-oriented missions. The most common orbits, in order of increasing altitude, are low Earth (LEO), Molniya, and geosynchronous (GEO). These are drawn to scale in Fig. 1.7. The following section briefly describes these orbits, and a more detailed discussion of orbit parameters can be found in Chapter 2.

Orbits whose maximum altitudes are less than approximately 2000 km are generally considered low Earth orbits. They have the shortest periods, on the order of an hour and a half. Some of these orbits are circular, while others may be somewhat elliptical. The degree of eccentricity is limited by the fact that the orbit is not much larger than Earth, whose diameter is approximately 12,760 km (Fig. 1.7). The inclination of these orbits, which is the angle between the plane of the equator

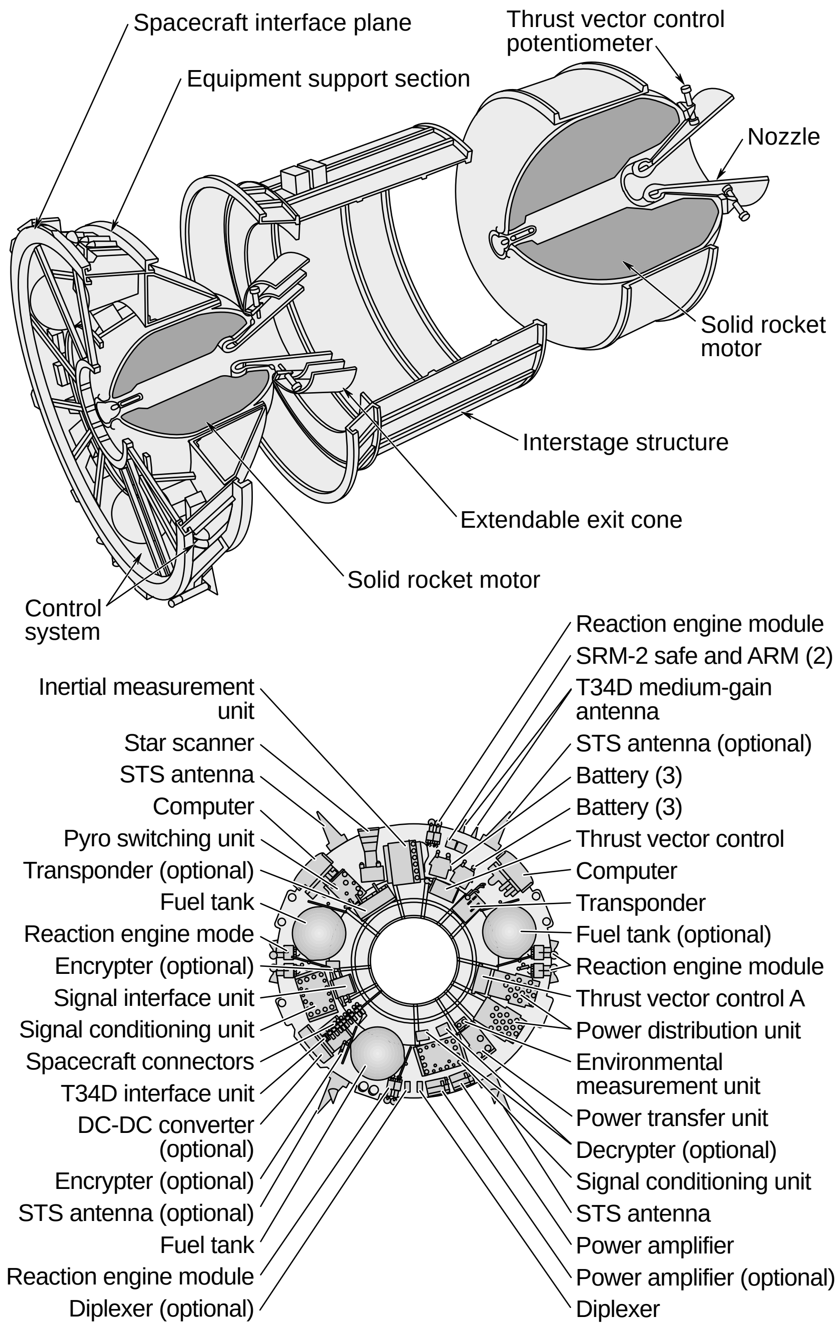

Fig. 1.6. Inertial upper stage.

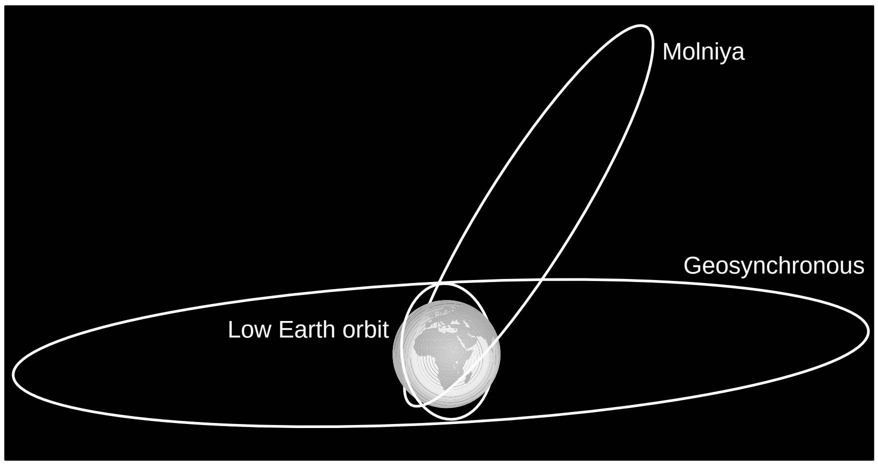

Fig. 1.7. Orbit types.

and the plane of the orbit, can vary from 0 deg to greater than 90 deg. Inclinations greater than 90 deg cause a satellite in LEO to orbit in a direction opposite to Earth's rotation. Low Earth orbits are very often given high inclinations so that the satellite can pass over the entire surface of Earth from pole to pole as it orbits. This coverage is important for weather and surveillance missions.

One particular type of low Earth orbit maintains the orbit plane at a nearly fixed angle relative to the sun (Fig. 1.8). The result of this is that, on every orbit, the satellite passes over points on Earth that have the same local time, that is, the same local sun-elevation angle. Because Earth rotates beneath the orbit, the satellite sees a different swatch of Earth's surface on each revolution and can cover the

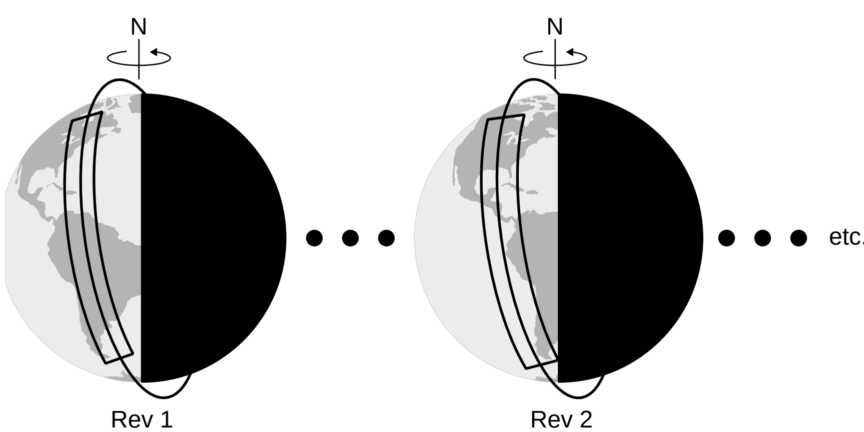

Fig. 1.8. Sun-synchronous orbit.

entire globe over the course of a day. The ability to see the entire surface of Earth at the same local sun angle is important for weather observation and for visual-surveillance missions. This type of orbit is known as sun-synchronous and is discussed in more detail in Chapter 2. Sun-synchronous orbits may be positioned so that satellites always see points on Earth at a specific time, anywhere from local sunrise/sunset to local noon. They are often known as “noon” or “morning” orbits.

The next higher type of common orbit is known as Molniya. These orbits are highly elliptical (apogee 38,900 km, perigee [the point in the orbit with the lowest altitude above the planet surface] 550 km) and highly inclined (62 deg). They provide good views of the north polar region for a large portion of the orbit (Fig.1.9). Because the satellite travels very slowly near apogee, it has a good view of the polar region for up to eight hours out of its 12-hour period. A constellation of three satellites in Molniya orbits can provide continuous coverage of the northern hemisphere for missions such as communication with aircraft flying over the polar region.

The highest common orbit type is geosynchronous. These orbits are circular and have very low inclinations (< 10 deg). They have an altitude of 35,786 km. Their distinguishing characteristic is a period matching Earth’s rotation, which allows a satellite to remain over the same spot on Earth at all times. This characteristic is valuable for a wide variety of missions, including weather observation, communication, and surveillance.

One final useful observation is that most Earth-orbiting satellites travel through their orbits in a counterclockwise motion as seen from above the north pole. They move in this direction to take advantage of the initial eastward velocity given to the the satellite as a result of Earth’s rotation (approximately 1500 km/h at the Kennedy

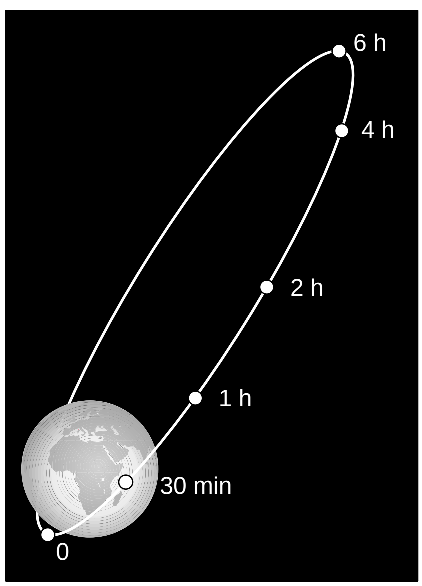

Fig. 1.9. Molniya orbit.

Space Center). To travel the orbit in the opposite direction would require the booster to overcome the initial 1500 km/h eastward velocity before starting to build up speed in a westerly direction. This requirement would significantly affect booster size and allowable payload weight.

Interplanetary Orbits

Orbits used in interplanetary missions range from simple, direct planet-to-planet transfer orbits to complicated trajectories involving close flybys past multiple planets on the way to a final destination. Lunar transfer orbits, such as those used on the Apollo program (Fig. 1.10), offer direct, minimum-energy transfer to the moon. Similar direct transfers are usually used for missions to Mars or Venus, as shown in Fig. 1.11. Spacecraft going to the outer planets often take advantage of gravity assists from flybys past other planets along the way. In a flyby, the spacecraft enters the gravitational field of a planet it is passing, and it achieves a net acceleration as a result of the planet's own velocity. This gravitational "slingshot" effect allows for either a smaller, lower-cost launch vehicle or the accommodation of more payload equipment mass. The Venus-Venus-Earth-Jupiter Gravity Assist trajectory (VVEJGA) of the Cassini mission to Saturn is shown in Fig. 1.12, and Table 1.1 summarizes the key orbital parameters for the planets of our solar system. The wide range of environments encountered in a Cassini-type trajectory can complicate the spacecraft thermal design process; this idea is discussed in subsequent chapters.

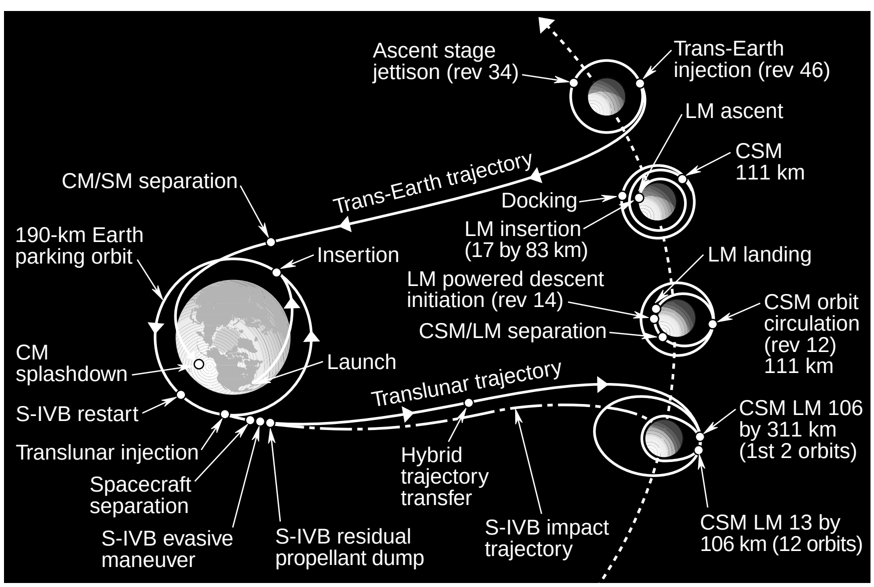

Fig. 1.10. Lunar transfer orbits (NASA). Spacecraft modules: CM, command module; CSM, command-service module; LM, lunar module; SM, service module; S-IVB, Saturn IVB.

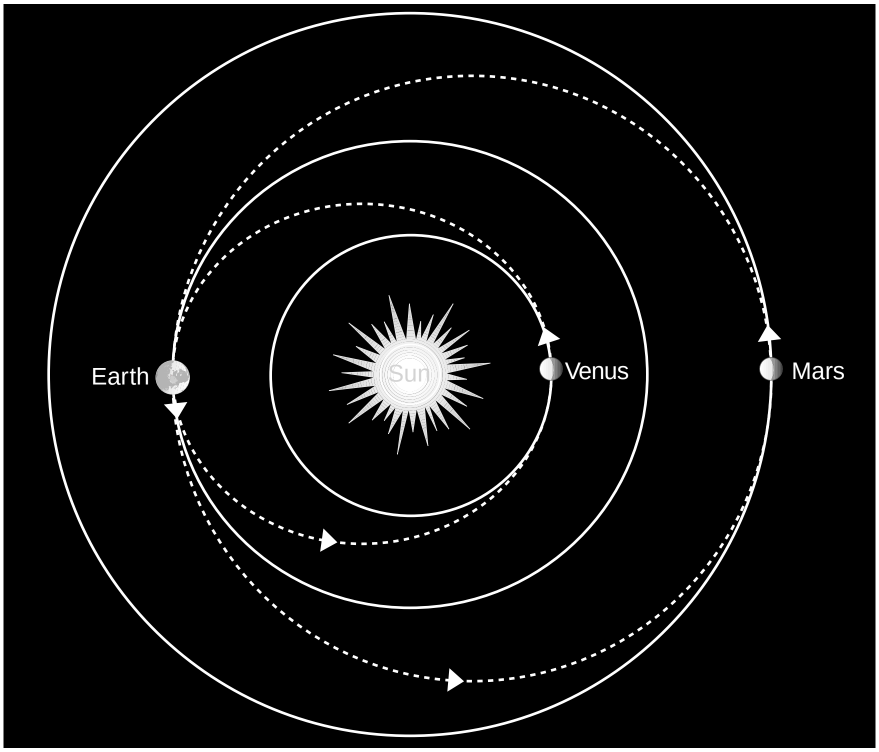

Fig. 1.11. Minimum-energy direct transfers used for missions to Mars or Venus.

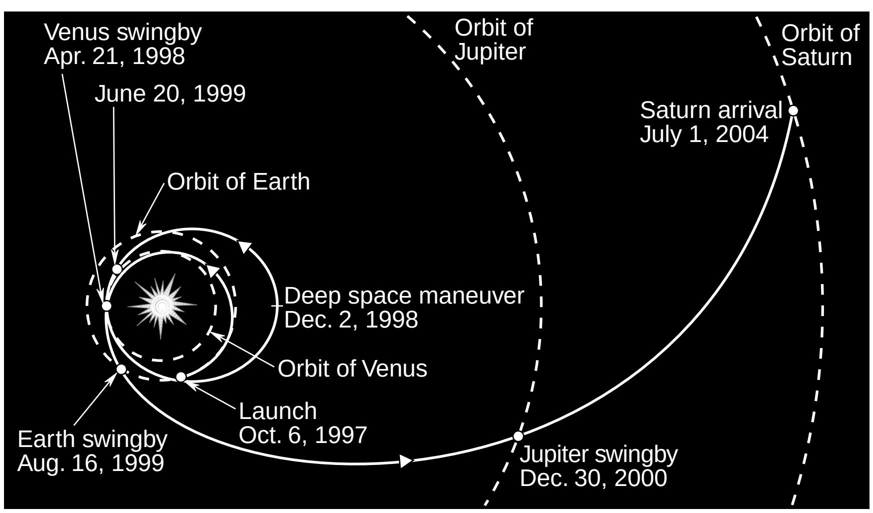

Fig. 1.12. VVEJGA trajectory. (Courtesy of NASA)

In some interplanetary missions, aerocapture maneuvers (Fig. 1.13) are used to slow the spacecraft and place it in orbit around a planet. This process involves sending the spacecraft close enough to the planet so that it actually passes through the upper reaches of the planet's atmosphere. Friction in the atmosphere slows the vehicle to a velocity that is below the planet's escape velocity. Injecting the spacecraft into orbit around the planet at just the right altitude and direction is critical to avoid its being either excessively heated or deflected back into interplanetary space. Several orbits around the planet may be required to gradually lower the orbit altitude.

Table 1.1. Planetary Orbit Parameters

	Orbit Semimajor Axis (AU)	Min. Distance from Sun (AU)	Max. Distance from Sun (AU)	Equatorial Radius (km)
Mercury	0.3871	0.3075	0.4667	2425
Venus	0.7233	0.7184	0.7282	6070
Earth	1.000	0.9833	1.0167	6378
Moon	1.000	0.9833	1.0167	1738
Mars	1.524	1.381	1.666	3397
Jupiter	5.20	4.95	5.45	71,300
Saturn	9.54	9.01	10.07	60,100
Uranus	19.18	18.28	20.09	24,500
Neptune	30.06	29.80	30.32	25,100
Pluto/Charon	39.44	29.58	49.30	3200 (Pluto)

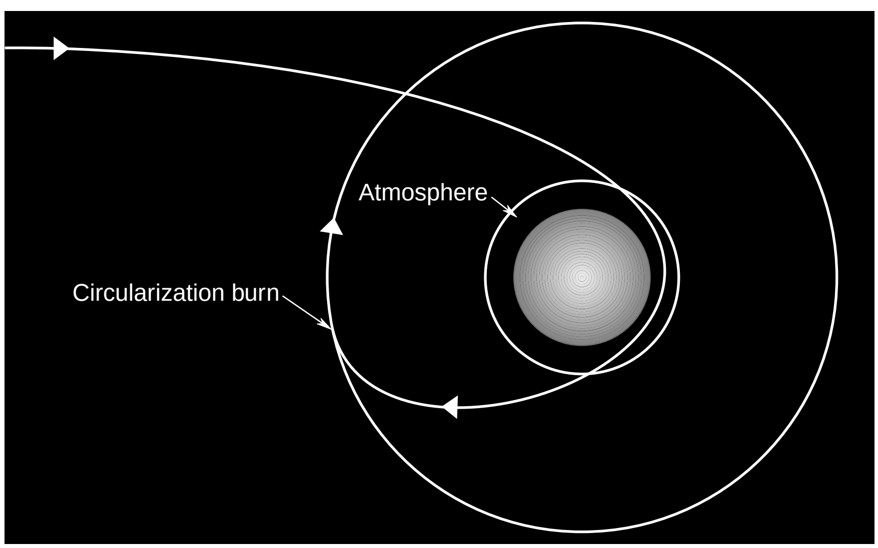

Fig. 1.13. Aerocapture maneuvers.

In some cases, a similar process helps minimize the use of propellant when certain kinds of orbit changes are required during a spacecraft's orbital mission. Aerocapture maneuvers create significant heat loads that must be addressed in the thermal design process.

Some rather unique orbits rely on balances between centrifugal and gravitational forces among multiple bodies. The Italian-French mathematician Josef Lagrange discovered that in cases where one body orbits around a much larger one, such as the moon around Earth or Earth around the sun, the centrifugal force and the two gravitational forces balance each other at five points. A body located precisely at any of these points will therefore remain there unless perturbed. These points, known as the Lagrange points, are designated L1 through L5, as shown in Fig. 1.14. L1, L2, and L3 are so unstable that, for a body positioned at any of them, a slight perturbation can knock the body out of equilibrium and send it on its way. The other two points, L4 and L5, are stable enough for a body positioned at either one to return to equilibrium if perturbed. For the unstable Lagrange points, a spacecraft can be placed in a small, fairly stable orbit around the point that requires little in the way of corrective maintenance maneuvers. The Solar and Heliospheric Observatory (SOHO) is placed at the Earth-sun L1 point; the Microwave Anisotropy Probe (MAP) satellite and the Next Generation Space Telescope are considering the Earth-sun L2 point as a possible home.

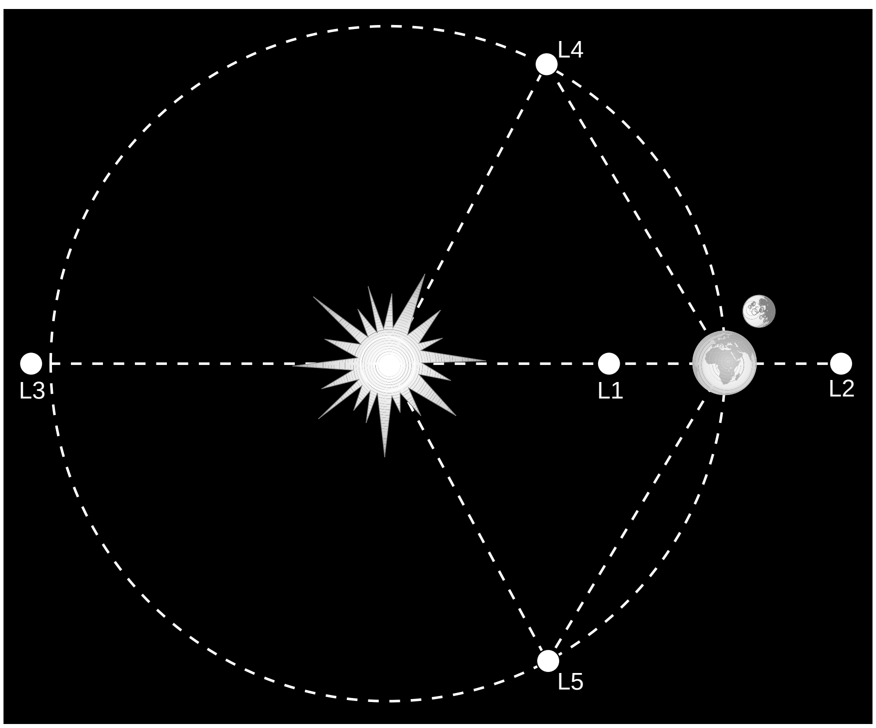

Fig. 1.14. Lagrange points.

Missions

A wide variety of missions are supported by the three general types of spacecraft platforms discussed earlier. The type of mission will dictate the orbit, the payload, and, in some cases, the platform. Typical missions include communication, scientific observation, weather monitoring, navigation, remote sensing, surveillance, and data relay. This section briefly describes each of these missions.

The most common mission for both commercial and military satellites is communication; there are currently 294 operating communication satellites in orbit. Thuraya and Singapore Telecom-1 (ST-1, Fig. 1.15) are commercial communication satellites. “Comsats” relay radio, telephone, television, or data signals from one point on Earth to another. These satellites are usually, but not always, in high-altitude geosynchronous orbits, where they remain over the same point on Earth at all times. Communication can be provided between any two points on the side of Earth to which the satellite has a direct view. Communication between two points

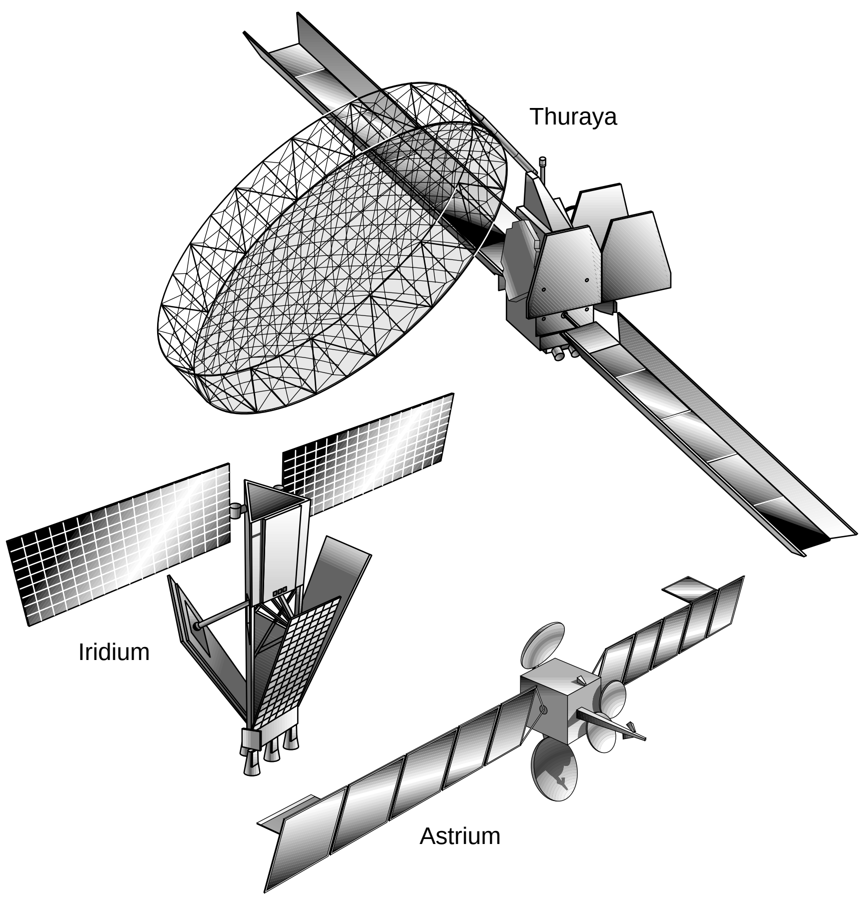

Fig. 1.15. Comsats.

on opposite sides of Earth, however, requires the use of multiple satellites with crosslinks between them. Both Thuraya and ST-1 are typical communication satellites that do not have crosslink capability. Iridium (Fig. 1.15) is a satellite constellation that has crosslinks and is able to provide communication between any two points on Earth.

Weather monitoring is another mission common to civilian and military space programs. The DMSP spacecraft (Fig. 1.16) is a typical low-altitude weather satellite. It carries visual and IR cameras that continuously photograph cloud patterns, as well as secondary sensors, such as Special Sensor Microwave Imager/Sounder (SSMIS), that can monitor phenomena such as surface wind speeds, soil moisture content, and precipitation rates. Low-altitude weather satellites are usually in sun-synchronous orbits. This allows them to scan the entire surface of Earth at the same local sun angle over the course of a day. High-altitude weather satellites, such as NASA's GOES (Geostationary Operational Environmental Satellite, Fig. 1.16), are usually in geosynchronous orbits that allow them to continuously photograph one entire hemisphere of Earth.

Navigation constitutes a third type of spacecraft mission. For the United States, this mission is currently fulfilled by one satellite program, NAVSTAR-GPS (Global Positioning System). The GPS system includes a constellation of 24 satellites in 12-hour circular orbits. Each GPS satellite (Fig. 1.17) continuously broadcasts a signal that can be picked up by small receivers on the ground, in aircraft, or even

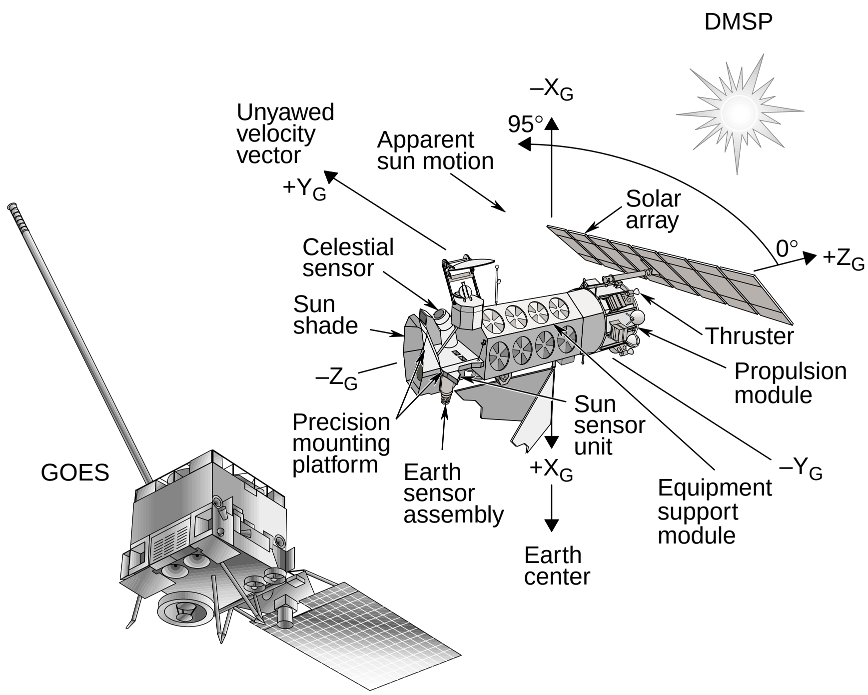

Fig. 1.16. Weather satellites.

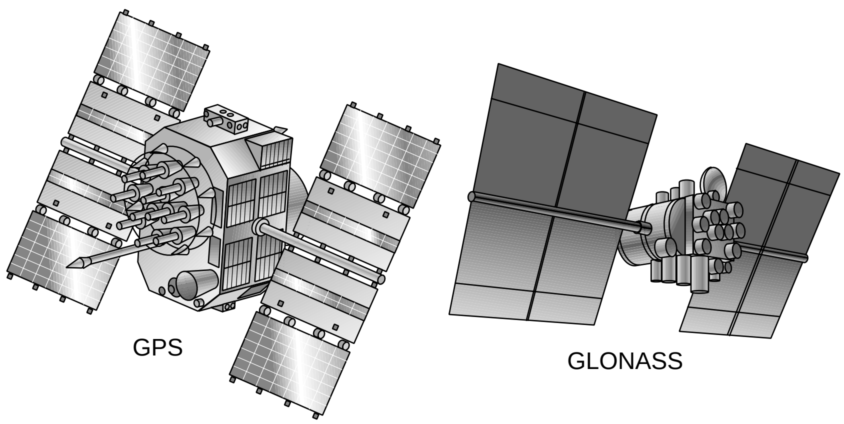

Fig. 1.17. Positioning satellites.

in another satellite. If three or more GPS satellites are visible at any one time, the receiver can determine its own position and velocity to within 1 m and 0.1 m/sec. Russia also operates a system of positioning satellites, known as GLONASS (Global Navigation Satellite System, Fig. 1.17), that are located in similar orbits. A next-generation navigation satellite program, aptly named Galileo, is also currently planned by the European Space Agency.

Surveillance is a general category for satellites whose mission is to monitor various activities on Earth. This surveillance can be in the form of IR sensors to detect missile launches, radar to track aircraft or ships, visual observation of ground activities, or intercept of radio transmissions. Satellites designed to support each of these different missions have markedly different configurations.

Space Imaging's Ikonos (Fig. 1.18) is a commercial optical-surveillance satellite. It provides 1-m panchromatic and 4-m color resolution digital imagery of Earth's

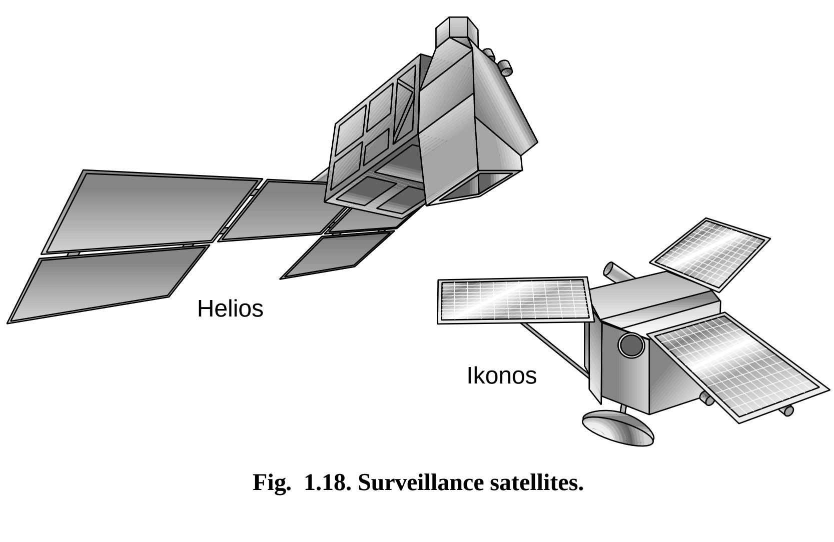

Fig. 1.18. Surveillance satellites.

surface. Its photos are used for mapping, urban planning, and environmental assessment. Helios (Fig. 1.18) is a national optical-surveillance satellite operated by France.

The DSP spacecraft shown in Fig. 1.4 is an example of an IR surveillance satellite. The payload is an IR telescope that detects and tracks missiles by the heat emitted from their rocket plumes. The detectors in the telescope are cooled to approximately 150 K by a cryogenic radiator with a helium-coolant loop. The entire satellite rotates at 6 rpm to provide a scanning motion that sweeps the linear detector array across Earth's surface. Ground software reconstructs the sweep into an Earth image with all heat sources displayed. DSP provides the United States with its first warning of missile launches.

Space Based Radar (SBR, Fig. 1.19) is an example of a radar-surveillance satellite. Spacecraft proposed for this program are quite large, with antenna dimensions on the order of 30 m. They would be developed to track aircraft and ships, with some designs being proposed to track missiles and individual warheads for defense applications. Radarsat, a remote-sensing satellite program led by the Canadian Space Agency, is also shown in Fig. 1.19.

Relay satellites support another type of mission similar to that of communication satellites except that the communication link is between the ground and a second satellite (Fig. 1.20). Such links eliminate the need for ground stations spaced throughout the world, and they provide continuous contact with satellites in any orbit. An example of a relay satellite is NASA's Tracking and Data Relay Satellite System (TDRSS), shown in Fig. 1.20. TDRSS is used to provide ground-to-ground and ground-to-satellite links and to communicate with shuttle astronauts.

Most Earth-orbiting scientific satellites need go no higher than low Earth orbit to accomplish their missions. Astronomical satellites, such as the Earth Observing

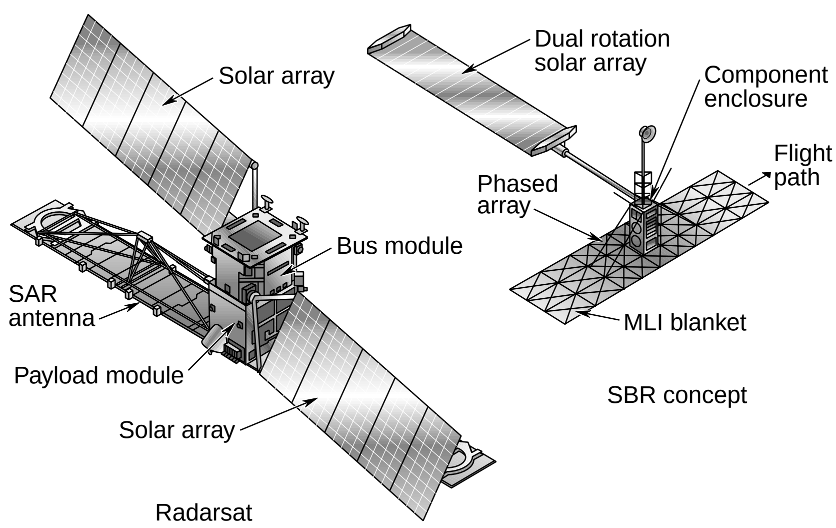

Fig. 1.19. Radar satellites.

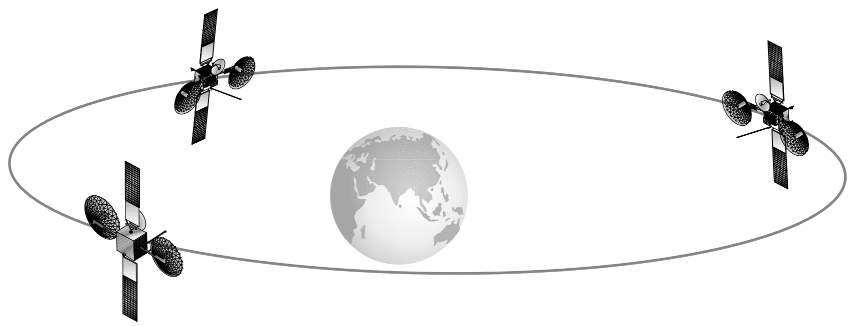

Fig. 1.20. TDRSS relay.

System (EOS) and the Hubble Space Telescope (Fig. 1.21), need only get above Earth's atmosphere to conduct their observations. A low-altitude orbit is an advantage for programs like EOS, whose mission is to study Earth. Some missions, like the Russian Granat X-ray and gamma-ray observatory (Fig. 1.21), do require high-altitude Earth orbits. There are also, of course, missions that require interplanetary scientific spacecraft to leave Earth's orbit entirely. These programs, such as Cassini (Fig. 1.21), sometimes must follow complicated trajectories through the solar system to get to their final destination.

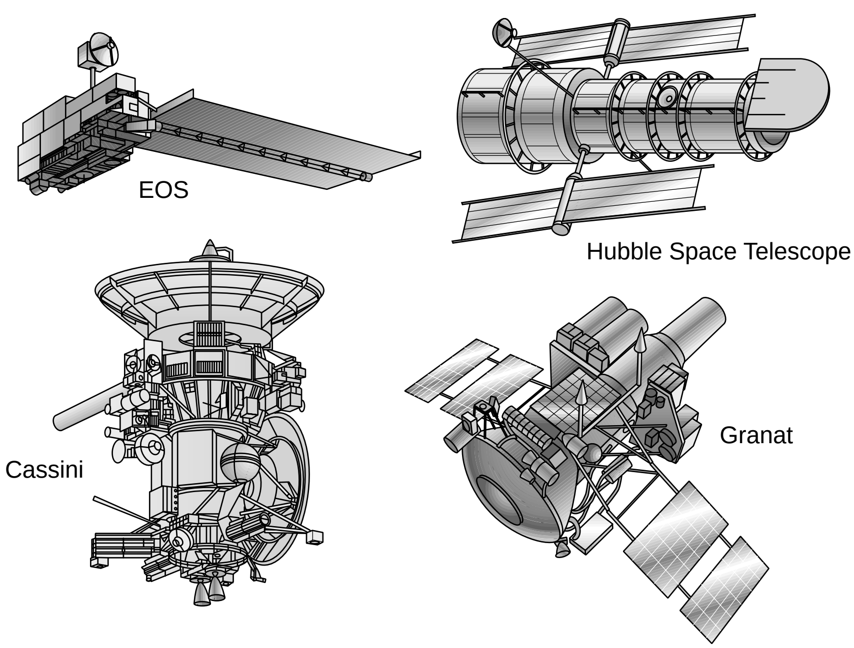

Fig. 1.21. Scientific satellites.

Remote-sensing missions are accomplished by satellites such as the U.S. Landsat, the French SPOT (*Systeme Pour l'Observation de la Terre*), and the European ERS (Earth Resources Satellite) (Fig. 1.22). These vehicles gather images in a variety of wavelengths. This information is used to manage crops and other Earth resources and to support environmental and global change research. For this kind of mission, the satellites are usually placed in sun-synchronous polar orbits at an altitude of approximately 830 km.

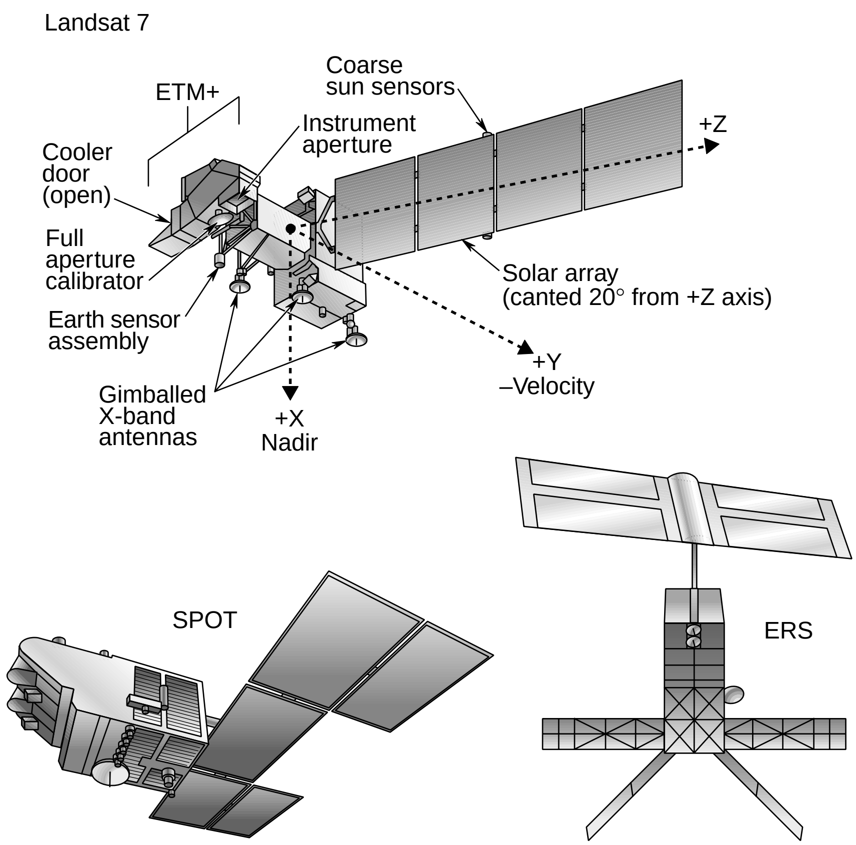

Fig. 1.22. Remote-sensing satellites.