Section 10: Elements of a Satellite System

Some of the intrinsic attributes of satellites make them vulnerable in ways that ground-based systems are not. Satellites in orbit move at high speeds (see Section 4), rendering collisions with even small objects disastrous. Satellites are nearly impossible to hide: just as satellites can view large swaths of the Earth, they are also visible to observers over large swaths of the Earth (see Figure 5.4). Moreover, once in orbit, a satellite's motion is predictable and it takes significant effort to appreciably change the orbit (see Section 6). Even small evasive maneuvers to escape an anti-satellite attack could add up to a prohibitively large effort, since an adversary can take multiple shots at the satellite. Satellites are also difficult to protect: Launch mass is at a premium, so armor and defensive measures come at some price. Some satellites, such as communications satellites, are designed to be easily accessed by users across the globe, a sensitivity that can be exploited to harm them or interfere with their operation. And essentially no satellite can now be repaired once damaged.

Satellite systems have a number of components, some of which make better targets than others. A satellite system comprises the satellite itself, the ground stations used to operate and control them, and the links between them. This section describes the components and their functions and how vulnerable and critical they are. We place particular emphasis on those elements that might be targeted and note that successful interference with a satellite system may not involve an attack on the satellite itself.

Satellites vary greatly in size. For example, commercial communications satellites can be large. The body of a Boeing 702 communications satellite, which was first launched in 1999, is seven meters long, and its solar panels extend to a length of 48 meters. The average Boeing 702 weighs nearly 3 tons when launched (this mass includes its stationkeeping propellant).[1]

Satellites can be small, as well. The SNAP "nano" satellite, constructed by Surrey Satellite Technology Ltd., is only 0.33 meters long, with a total mass of 6 to 12 kg, which includes a payload of up to 4 kg. This small satellite was placed in orbit in June 2000 and was able to maneuver, image, correctly keep attitude, and communicate with the ground.[2]

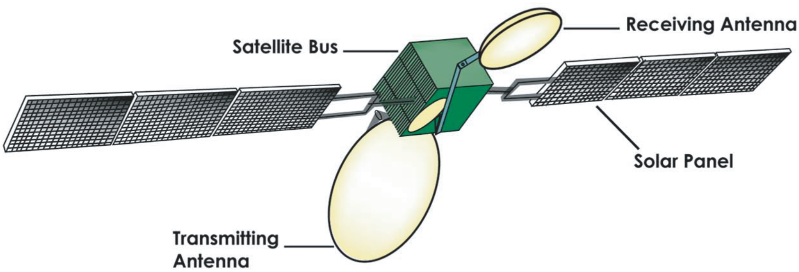
SATELLITE COMPONENTS

All satellites have some basic elements, as outlined below and shown schematically in Figure 10.1.

1. Boeing, "What Is a Satellite?" factsheet, http://www.boeing.com/defense-space/space/bss/what_is_a_satellite.pdf, accessed December 15, 2004.

2. For information on SNAP, see http://zenit.sstl.co.uk/index.php?loc=47, accessed February 3, 2005.

Figure 10.1. A schematic illustration of a satellite, including the satellite bus, the receiving and transmitting antennae, and the solar panels.



A structural subsystem, or bus. The bus is a metal or composite frame on which the other elements are mounted. Because it bears the stresses of launch, the bus is generally resilient. It may be painted with reflective paint to limit the solar heat it absorbs, which could also provide some protection from laser attacks.

A thermal regulation subsystem. This system keeps the active parts of the satellite cool enough to work properly. Active satellite components such as the computer and receiver can generate a large amount of heat. Sunlight incident on the satellite's surface also generates heat, although the satellite's surface can be made highly reflective to minimize heat absorption.[3] Without an atmosphere, conduction and convection cannot remove heat from an object as they do on Earth, so the satellite must radiate the heat to eliminate it. In most cases, the thermal regulation system is passive: just a set of well-designed thermally conducting pathways (*heat pipes*) and radiators to radiate the heat away. However, some components, such as some infrared sensors, may need cryogenic cooling; in this case, loss of the coolant would dramatically degrade the system's performance.

A large amount of heat introduced by an incident laser beam may be unmanageable: the internal electronics may fail if the bus conducts too much heat to them, or the structural integrity of the bus itself may be compromised.

A power source. Power is often supplied by arrays of solar cells ("solar panels") that generate electricity, which is stored in rechargeable batteries to ensure a power supply while the satellite is in shadow.[4] Technological improvements in battery technology have led to new battery types with high specific energy (energy stored per unit mass) and high reliability.

Solar cells are mounted on the body of a satellite or on flat panels. Mounting the solar cells on the satellite's body results in a more compact configuration (which may be desirable if space and mass are limited, or the satellite is meant to be covert), but since not all cells will be illuminated by the

3. The incident sunlight that is not reflected is absorbed. If the satellite is disguised by limiting its reflectivity (i.e., painting it black), then it has a higher heat load.

4. For geostationary satellites, eclipses occur on 90 days a year, and last as long as 70 minutes (Bruno Pattan, *Satellite Systems: Principles and Technologies* [New York: Van Nostrand Reinhold, 1993], 26-29).

Sun at any one time, the power generated is less than it would be from large panels made of solar cells that are continually positioned to face the Sun.[5]

The solar panels often have a large surface area compared with the rest of the satellite, so they sustain a relatively large number of collisions with debris particles. Solar panels are fragile and can be damaged easily, but partial damage to a solar panel may not disable the satellite:[6] satellites often can continue to function with partially working solar panels, albeit with diminished capacity. However, if the solar panels fail to deploy or are torn off, a satellite without another power source would cease functioning fairly quickly. A malfunction of the power distribution system could also totally impair the satellite.[7]

Other sources of power are available. The Soviet Union reportedly used nuclear reactors to power energy-intensive missions such as orbiting radar systems, and the United States launched one reactor-powered satellite.[8] Currently, the United States is considering a project to develop a uranium-fueled nuclear reactor to produce much higher levels of electric power in space.[9] On-board chemical sources of power are currently not used for satellites, although newer satellite designs may use fuel cells, which produce electricity by combining chemicals such as hydrogen and oxygen. Generators that produce electricity from the heat released by radioactive materials (RTGs[10]) are currently used on deep space probes that move too far from the Sun to rely on solar panels. RTGs have been used on earth-orbiting satellites in the past but are not normally used on these orbits.

5. Solar panels that are properly oriented toward the Sun can provide about 130 W/m^2 and 50 W/kg of power. Because solar cells mounted on the satellite's body will not, in general, be optimally oriented, they can typically provide 30 to 35 W/m^2 and 8 to 12 W/kg of power (Gérard Maral and Michel Bousquet, *Satellite Communications Systems*, Fourth Edition [West Sussex, England: Wiley, 2002], 598).

6. The Telstar 14/Estrela do Sul communications satellite failed to fully deploy one of its solar panels. Loral Space & Communications reports that the satellite generates enough power to maintain satellite health and to operate 17 of its 41 Ku-band transponders ("Loral To Initiate Limited Service On Telstar 14/Estrela Do Sul In March," Loral press release, January 21, 2004, http://www.loralskynet.com/news_012104.asp, accessed December 15, 2004). On March 26, 1996, a solar panel on Canada's Anik-E1 satellite was disconnected, causing a power shortage and safety shutdown of the satellite. The satellite was restarted and was able to transmit a reduced number of television programs (Martyn Williams, "Galaxy IV Failure Highlights Reliance on Satellites," *Government Computer News*, May 20, 1998).

7. In September 2003, Loral Space & Communications declared the Telstar 4 satellite a total loss after it experienced a short circuit on the primary power bus ("Loral Skynet Declares Telstar 4 A Total Loss," Loral press release, September 22, 2003, http://www.loral.com/inthe news/030922.html, December 17, 2004).

8. Regina Hagen, "Nuclear Powered Space Missions—Past and Future," taken from Martin B. Kalinowski, ed., "Energy Supply for Deep Space Mission," IANUS 5/1998 Working Paper, http://www.globenet.free-online.co.uk/ianus/npsmfp.htm, December 15, 2004.

9. Current discussions call for a reactor capable of producing 100 kW of electricity (Ben Iannotta, "Jupiter Moon Probe Goes Nuclear," *Aerospace America*, March 2004, http://www.aiaa.org/aerospace/Article.cfm?issuetocid=474&ArchiveIssueID=50, December 15, 2004.

10. Radioisotope Thermoelectric Generators (RTGs), which use the heat of radioactive decay of plutonium-238 to produce electricity, can produce up to hundreds of watts (Department of Energy Office of Space and Defense Power Systems, "Radioisotope Power Systems," http://www.ne.doe.gov/space/space-desc.html, accessed December 15, 2004.

A computer control system. The on-board computer monitors the state of the satellite subsystems, controls its actions, and processes data. High-value satellites may incorporate sophisticated anti-jamming hardware that is operated by the computer. If someone gained control of the satellite's computer, the satellite could be made useless to its owners. Computer systems are also sensitive to their electromagnetic environment and may shut down or reboot during solar storms or if barraged by high levels of electromagnetic radiation.

A communications system. Communications form the link between the satellite and its ground stations or other satellites. This system generally consists of a receiver, transmitter, and one or more radio antennae.

The radio links between a satellite and the ground are one of the most critical and most vulnerable parts of a satellite system. All satellites require a link to and from the ground to perform "telemetry, tracking, and command" (TT&C) functions.[11] The TT&C system operates the satellite and evaluates the health of the satellite's other systems; it is therefore essential. The receivers on the satellite and on the ground can be overwhelmed by an intruding signal—called *jamming*—or confused by false signals—called *spoofing*. Although interfering with the TT&C channel could cause a great deal of damage, these channels are usually well protected with encryption and encoding. Generally, the more vulnerable piece of the communications system is that used for mission-specific communications, as discussed below.

The TT&C system occupies only a small part of the satellite's total assigned bandwidth.[12] A jamming attack would need to be mounted from the broadcast and reception area of the TT&C communications channel, i.e., the region from which a user can communicate with the satellite. Restricting the size of this area by increasing the antenna's *directionality* can help protect these channels from attack by reducing the region from which a jamming attack could take place. However, this may not be a viable solution for satellites that need to support users from a broad geographic area. Moreover, at a given frequency, improved directionality requires a bigger antenna.

An attitude control system. This system, which keeps the satellite pointed in the correct direction, may include gyroscopes, accelerometers, and visual guidance systems. Precise control is required to keep antennas pointed in the right direction for communication, and sensors pointed in the right direction for collecting data. If the attitude control system were not functioning, the satellite is unlikely to be usable.[13]

11. *Telemetry* refers to the information the satellite sends the control station about the status of its various components and how they are operating. *Tracking* refers to knowing where the satellite is; for example, the time for a signal to travel between the satellite and ground can be used to accurately determine the distance to the satellite. *Command* refers to the signals that are used to tell the satellite what to do.

12. *Bandwidth* is the width of the band of frequencies that the satellite is assigned to use—the difference between the highest and the lowest frequency. The amount of data that can be sent through a band is proportional to the bandwidth.

13. In October 1997, trading on Bombay's National Stock Exchange in India was halted for four days after the Insat-2D satellite lost attitude control and began spinning in space. The problem was blamed on a power failure and cost the exchange around US$2 billion in losses

A propulsion subsystem. The satellite's propulsion system may include the engine that guides the spacecraft to its proper place in orbit once it has been launched, small thrusters used for stationkeeping and attitude control, and possibly larger thrusters for other types of maneuvering.

If the propulsion system does not function, because of damage or lack of propellant, the satellite may still be functional. However, in orbits dense with other satellites, such as geostationary orbit, satellites must be able to maintain their position very accurately or they will be a danger to their neighbors and to themselves. Satellites in low-altitude orbits need to make regular station-keeping adjustments, without which their orbits will decay.

Mission-specific equipment. In addition to the basic elements required for a satellite to operate, satellites also carry mission-specific equipment to carry out specific tasks. These may include

- Radio receivers, transmitters, and transponders: In addition to the communication equipment needed to operate the satellite, a satellite may carry similar equipment for other tasks. It may carry a radio antenna to collect radio signals, such as telephone or television signals, and to relay or rebroadcast them. The antenna serves to receive and transmit signals. It may be a parabolic dish (similar to satellite TV dishes), a feedhorn (a conical or cowbell-shaped structure), or a minimal metal construction (similar to a rooftop TV antennae). When a system is designed to automatically receive a transmission, amplify it, and send it back to Earth, possibly at a different frequency, it is called a *transponder*.

  A satellite-based radar system is also composed in part of transmitters and receivers used to send and then receive the radio waves. Receivers are also used by the military for *signals intelligence*, i.e., eavesdropping on military communications, detecting the operating frequencies of enemy radar, or collecting telemetry from ballistic missile tests. Similarly, a satellite may carry transmitters to send out radio signals, such as the navigation signals from the Global Positioning System. A satellite may be designed to transmit a signal to a specific receiver on the Earth, or to broadcast it over a large area.

- Remote-sensing systems: The satellite's mission may be to take detailed images of the Earth's surface or atmosphere or objects in space, or to collect other types of data about the Earth and the atmosphere. A satellite may therefore carry such devices as optical cameras, infrared sensors, spectrographs, and charge-coupled devices (CCDs). For civilian scientific missions, these payloads are often complex, unique, and the result of many years of development.

(Martyn Williams, "Galaxy IV Failure Highlights Reliance on Satellites," *Government Computer News*, May 20, 1998).

- Weapons systems: A satellite may carry equipment to be used for attacking other satellites or targets on the ground or in the atmosphere. For example, it could carry a laser system and the fuel and mirrors needed to use it, or an explosive charge intended to destroy another satellite.

GROUND STATIONS

Satellites are monitored and controlled from their *ground stations*. One type of ground station is the *control station,* which monitors the health and status of the satellite, sends it commands of various kinds, and receives data sent by the satellite. The antenna that the control station uses to communicate with the satellite may be located with the station, but it need not be: to maintain constant contact with a satellite not in geostationary orbit, and which therefore moves relative to the Earth, the station needs to have antennae or autonomous stations in more than one location.

Satellites may also have other types of ground stations. For example, a communication satellite's mission is to send data (voice communication, credit card authorization, video broadcast, etc.) from one user to another, and each user needs an antenna and is in effect a ground station. A satellite may therefore be communicating with many ground stations at the same time. For example, a Boeing 702 communication satellite can carry over 100 transponders.[14] Military communications satellites have ground stations that range from large, permanent command headquarters to small, mobile field terminals.

Ground stations are generally not highly protected from physical attack. Disabling a control station may have an immediate disruptive effect, but the disruption can be reduced by having redundant capabilities, such as alternate control centers. Computers at control centers may be vulnerable to attack and interference, especially if they are connected to the Internet. However, high-value command computers will have high security, and many of the military command center computers are isolated from the Internet.

LINKS

The term *link* refers to a path used to communicate with the satellite (and is sometimes used to refer to the communication itself):

- *Uplinks* transmit signals from a ground station to the satellite.
- *Downlinks* transmit signals from the satellite to a ground station.
- *Crosslinks* transmit signals from satellite to satellite.

14. "Boeing 702 Fleet," http://www.boeing.com/defense-space/space/bss/factsheets/702/702fleet.html, December 15, 2004.

- *Telemetry, tracking, and command (TT&C) link* is the part of the uplink and downlink used to control a satellite's function and monitor its health.

The uplinks and downlinks are vulnerable to interference since the strength of the radio signals when they reach the receiving antenna is often low, so that an interfering signal need not be strong. Links can also be interfered with by placing something impermeable to radio waves, such as a sheet of conducting material, in the path between the satellite and ground station. This would likely be done close to the receiver or transmitter, where it could achieve the greatest effect.