EENG 470
Satellite Communications

Lecture # 6
Chapter 3 : Satellite {Space Segment}

Prof. Mohab A. Mangoud

Professor of Wireless Communications (Networks, IoT and AI)
University of Bahrain, College of Engineering
Department of Electrical and Electronics Engineering
P. O. Box 32038- Kingdom of Bahrain

mmangoud@uob.edu.bh
http://mangoud.com

The Space Segment

Figure 7.1 The HS 376 satellite. (*Courtesy of Hughes Aircraft Company Space and Communications Group.*)

Figure 7.2 Aussat B1 (renamed Optus B), Hughes first HS 601 communications satellite is prepared for environmental testing. (*Courtesy of Hughes Aircraft Company Space and Communications Group.*)

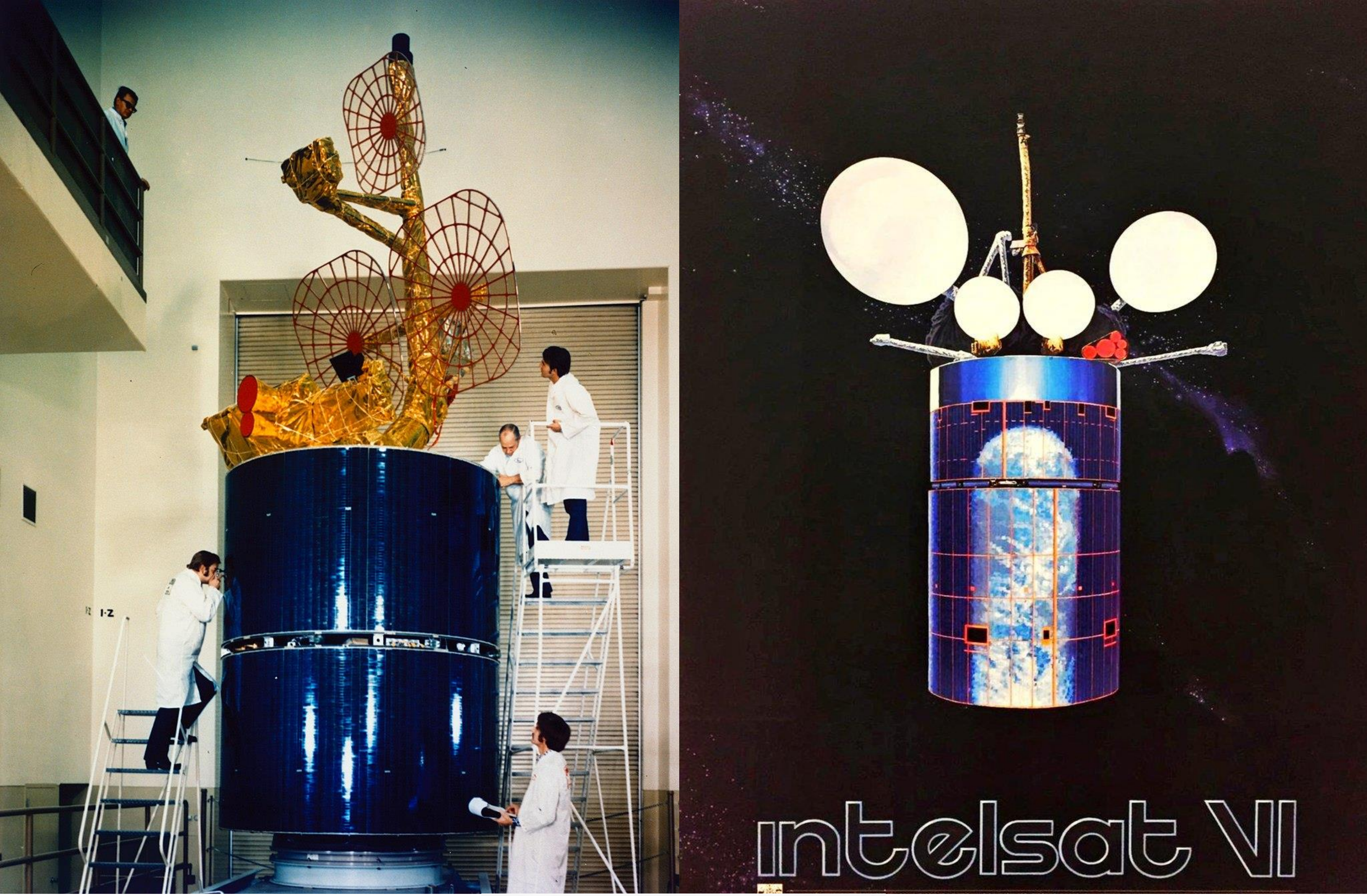


FIGURE 3.3 (*a*) A spinner satellite, INTELSAT IV A (*b*) A three-axis stabilized satellite, INTELSAT V (courtesy of Intelsat).

FIGURE 3.3 (*a*) A spinner satellite, INTELSAT IV A (*b*) A three-axis stabilized satellite, INTELSAT V (courtesy of Intelsat).

Introduction

A satellite communications system can be broadly divided into two segments,

(1) Ground segment

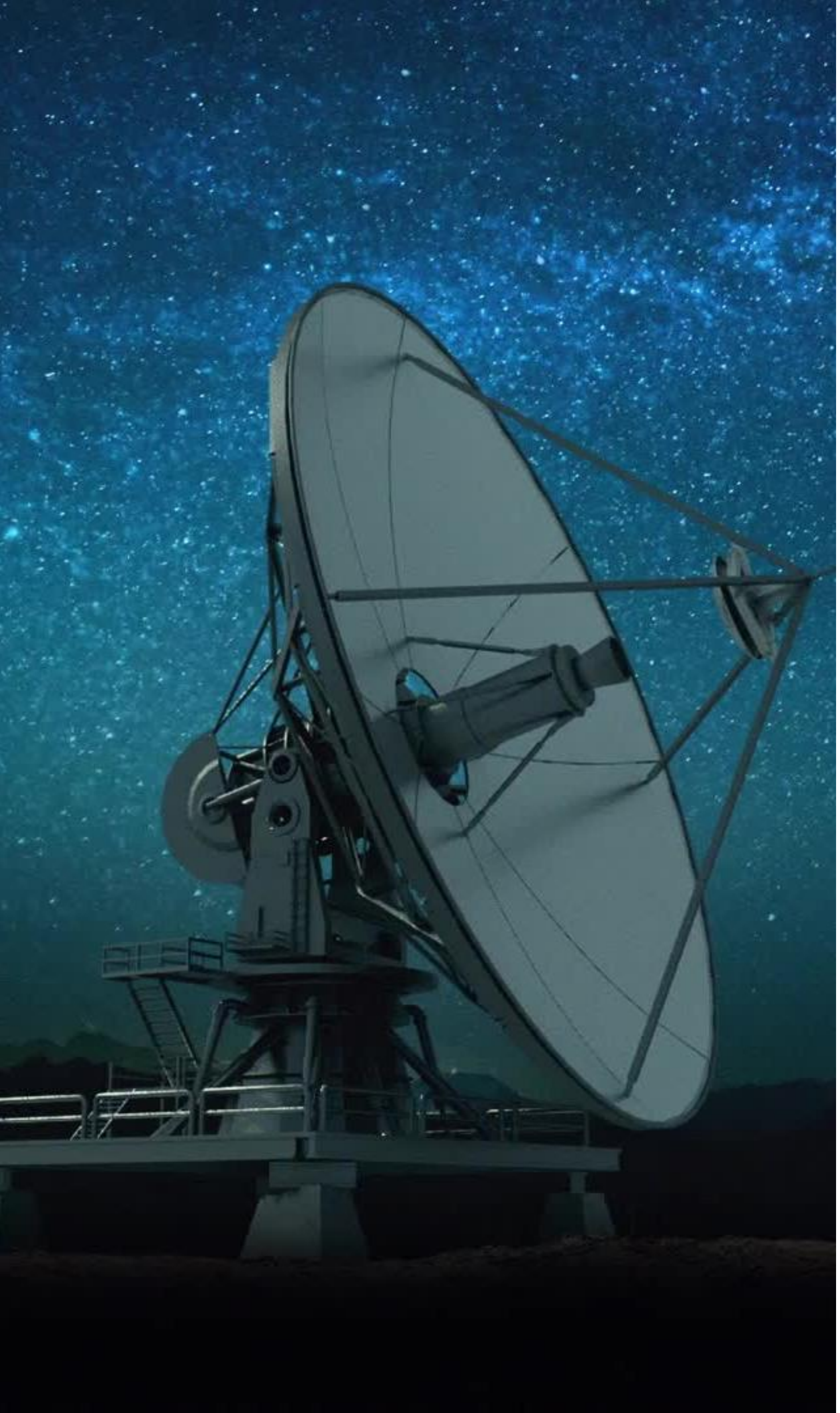
(2) Space segment.

The equipment carried aboard the satellite also can be classified according to function.

- The ***payload*** *refers to the equipment used to provide* the service for which the satellite has been launched. (In a communications satellite, the equipment which provides the connecting link between the satellite's transmit and receive antennas is referred to as the *transponder. The transponder forms one of the* main sections of the payload, the other being the antenna subsystems).

- The ***bus*** refers not only to the vehicle which carries the payload but also to the various subsystems which provide the power, attitude control, orbital control, thermal control, and command and telemetry functions required to service the payload.

In chapter 3, main characteristics of certain bus systems and payloads are described.



- The ***space segment*** of the satellite system consists of the orbiting satellite (or satellites) and the ground satellite control facilities necessary to keep the satellites operational.

- The ***ground segment***, or earth segment, of the satellite system consists of the transmit and receive earth stations and the associated equipment to interface with the user network.

- The space segment equipment carried aboard the satellite can be classified under two functional areas: the ***bus*** and the ***payload***, as shown in Figure 3.2.

- • ***Bus*** The bus refers to the basic satellite structure itself and the subsystems that support the satellite. The bus subsystems are: the physical structure, power subsystem, attitude and orbital control subsystem, thermal control subsystem, and command and telemetry subsystem.

- ***Payload*** The payload on a satellite is the equipment that provides the service or services intended for the satellite. A communications satellite payload consists of the communications equipment that provides the relay link between the up- and downlinks from the ground. The communications payload can be further divided into the transponder and the antenna subsystems.

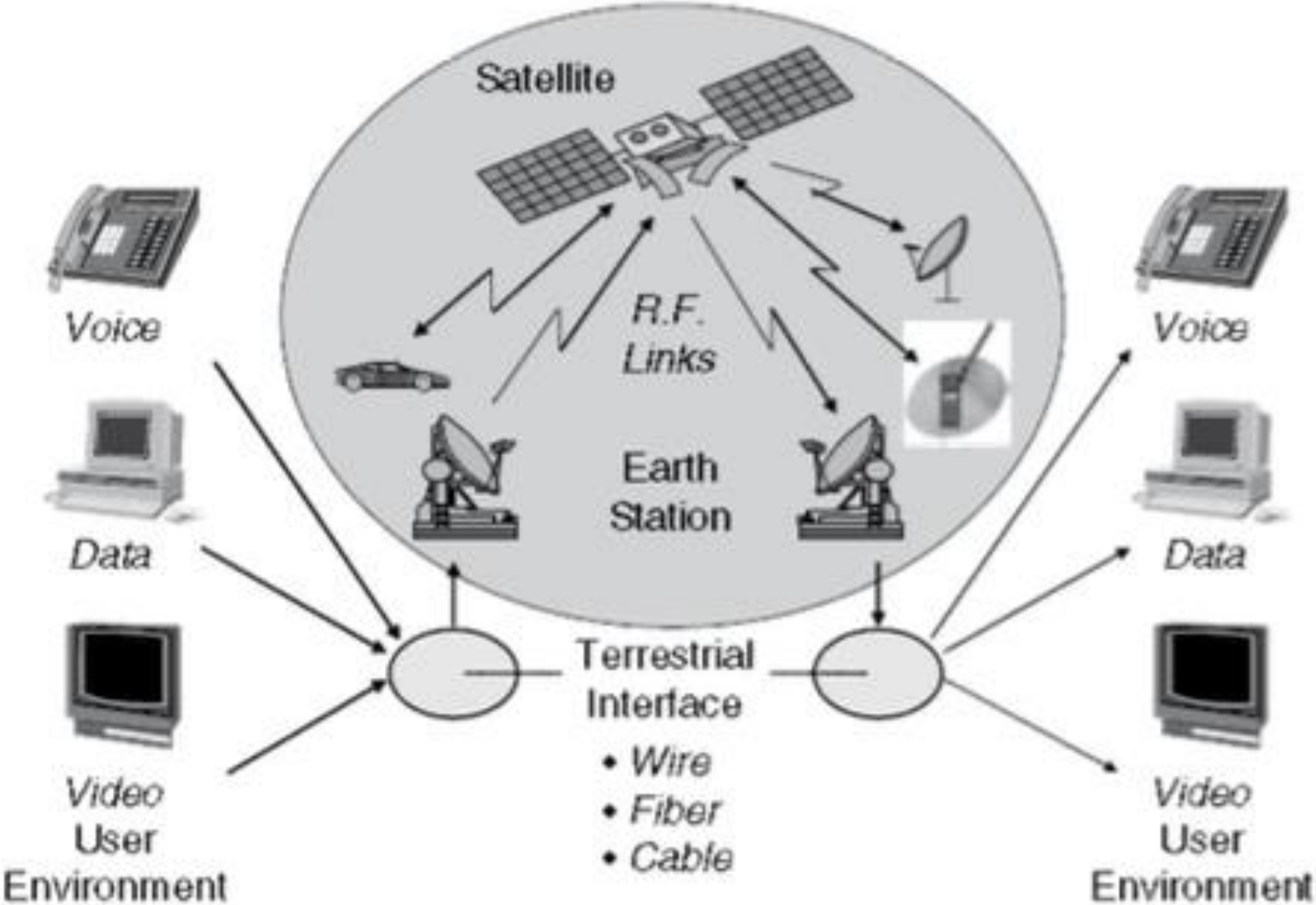


Figure 3.1 Communications via satellite

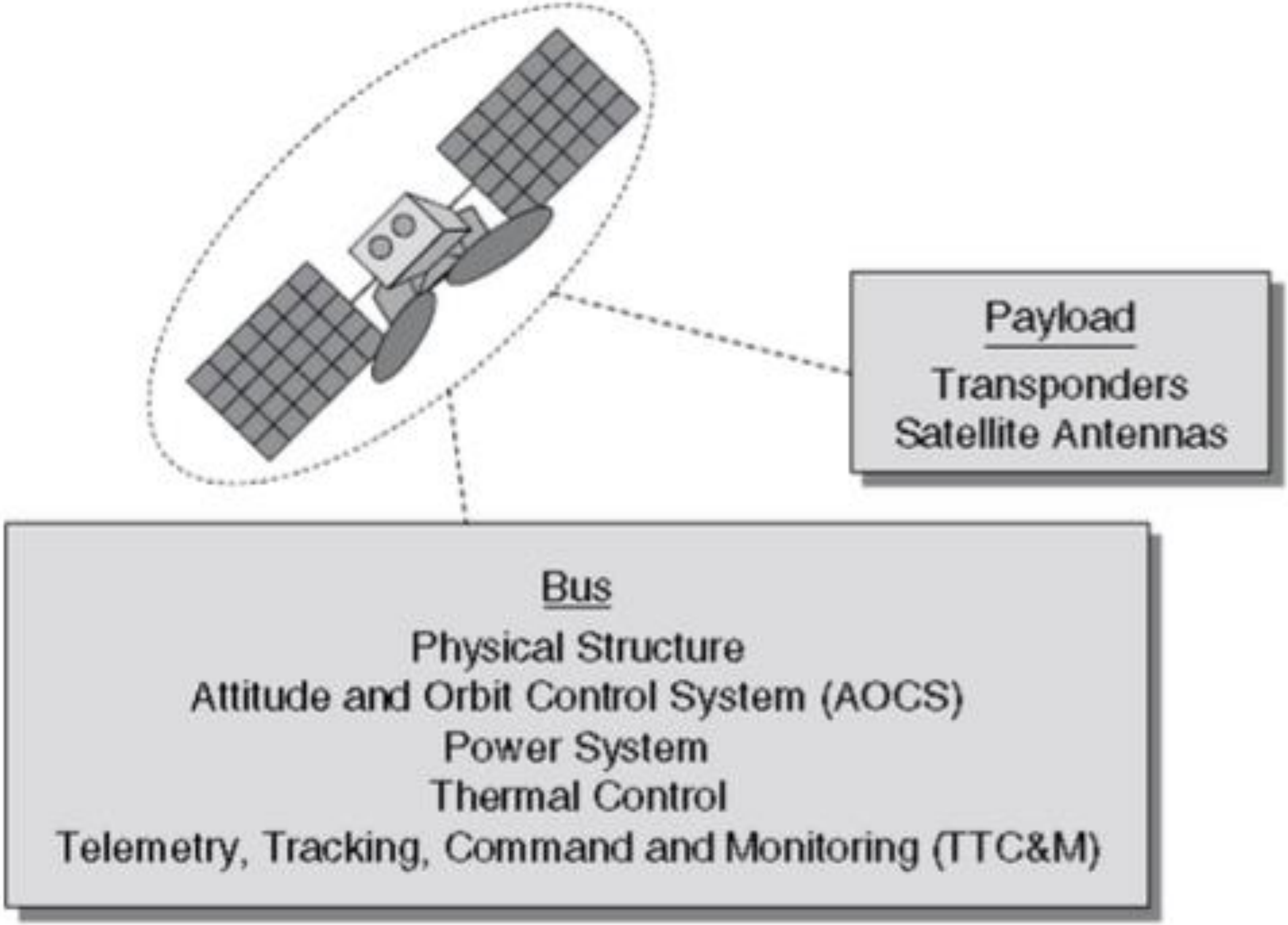


Figure 3.2 Communications satellite subsystems

Complexity and Cost: Maintaining microwave communication systems in space is complex and expensive due to the need for sophisticated satellites and earth stations.

Satellite Costs: Geostationary satellites can range from US$100M to US$500M, while a constellation of low earth orbit (LEO) satellites can exceed US$2B.

Operating Costs: Monitoring and controlling satellites from earth stations can cost several million dollars per year.

Revenue Generation: Revenue to cover costs is generated through leasing circuits, transponders, or charging for circuit use.

Satellite Lifetimes: Satellites are designed to have a lifespan of 10-15 years, during which costs need to be recouped.

Design Challenges: Designers must ensure satellites can withstand the harsh space environment, support stable communications, and provide essential functions like power and temperature control.

Historical Perspective: Geostationary satellites have historically provided the majority of communication capacity.

New Developments: Non-geostationary satellite constellations are being developed, such as those for internet access. Economies of Scale: Large-scale production of LEO satellites can reduce unit costs due to economies of scale.

3.1 Satellite subsystems

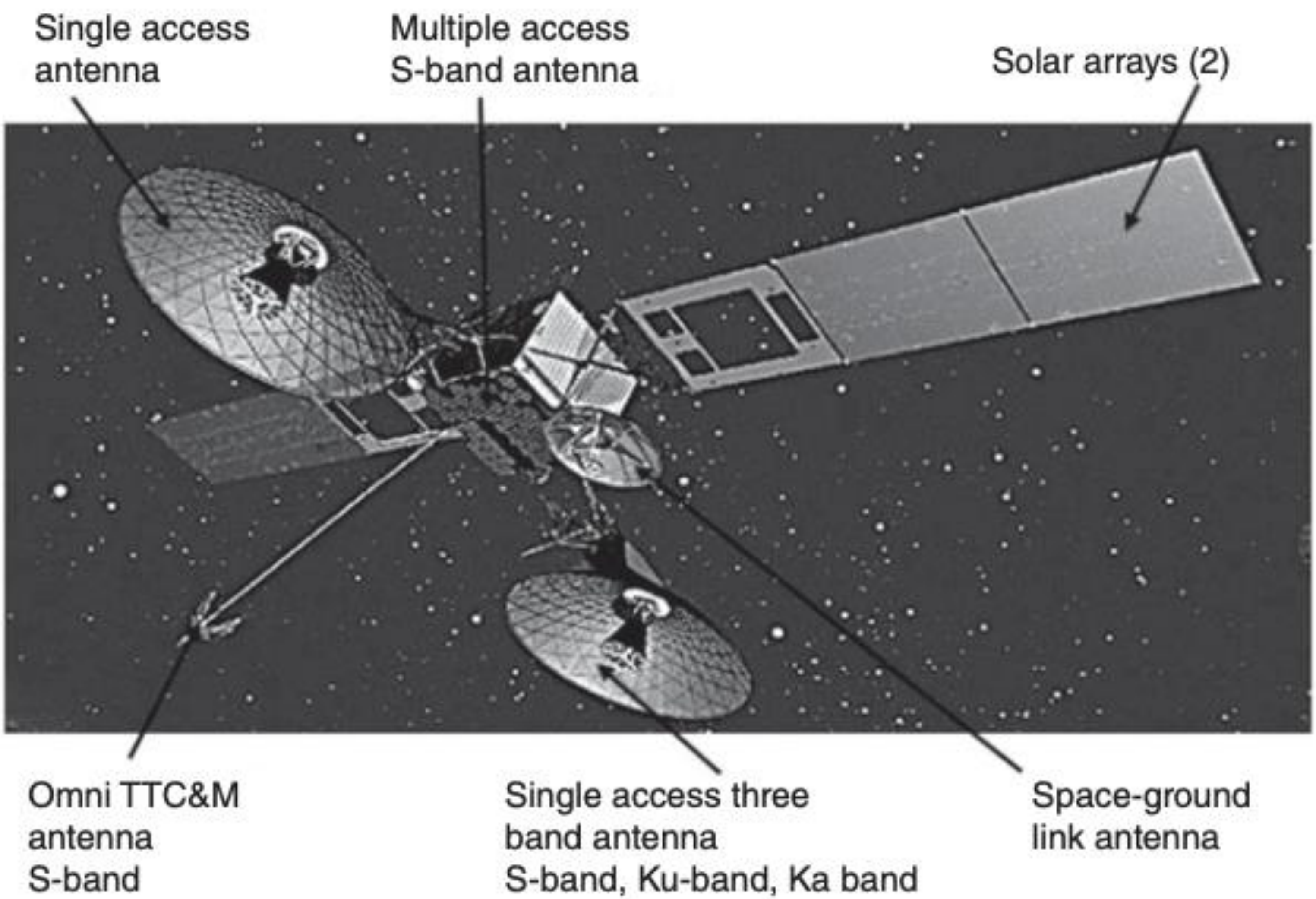
Subsystems on the Satellite: Illustrated in Figures 3.1a and 3.1b.

Example: NASA's Tracking and Data Relay Satellite (TDRS).

- Nine satellites in geostationary orbit (as of 2018).
- Provide continuous links between NASA and low Earth orbit spacecraft like the ISS and Hubble telescope.
- Track low Earth orbit spacecraft.
- Relay signals to Earth stations globally.
- 4.5 m diameter steerable antennas.
- Track LEO spacecraft; foldable for launch.
- Operate at S-band, Ku-band, and Ka-band.
- Capable of handling bit rates up to 300 Mbps at Ku-band.
- The omni antenna is part of the S-band telemetry and command system.

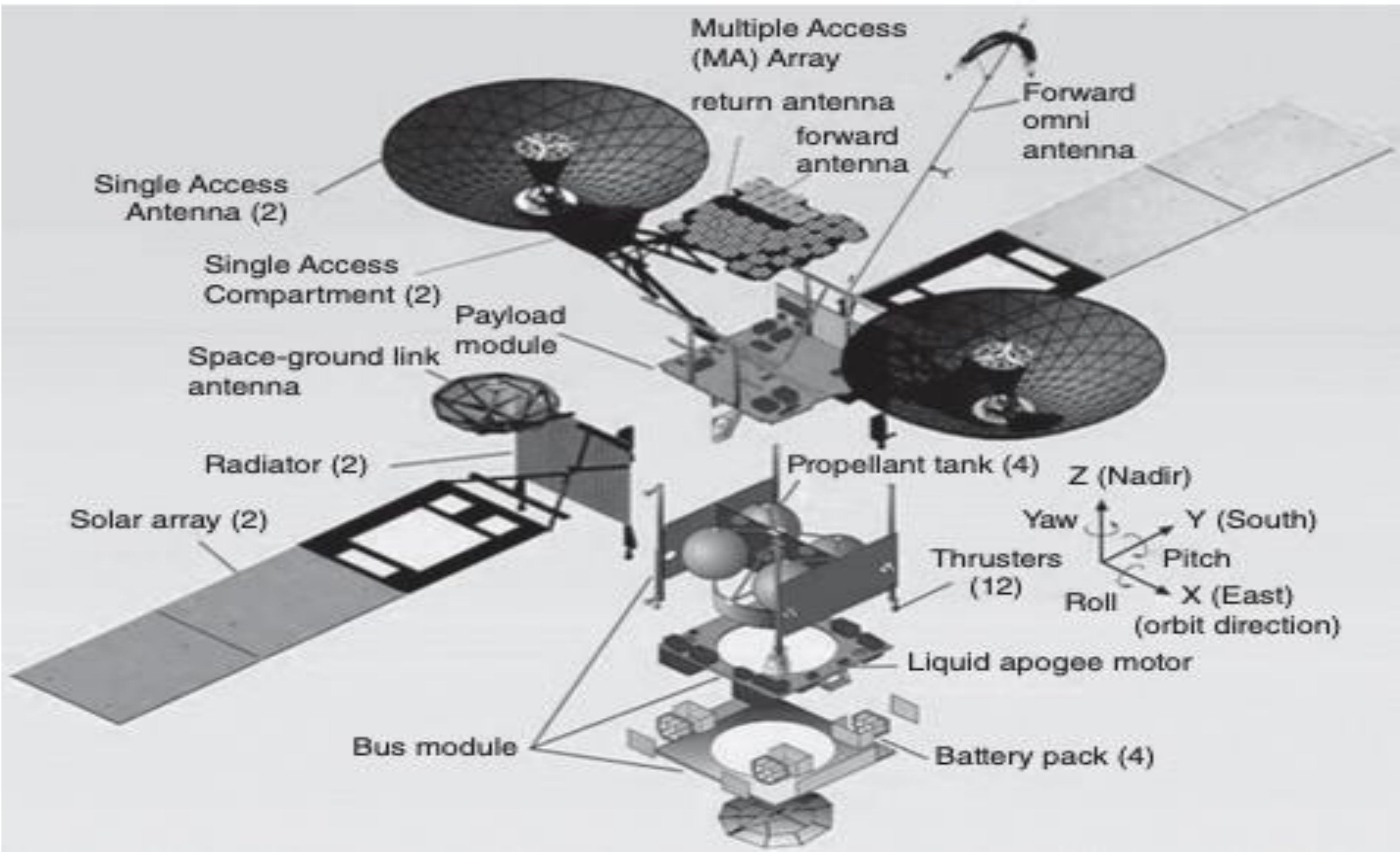
- **Redundancy**:
  - All critical components duplicated.
  - Example: If one battery pack fails, there are three backups to run the satellite.

Figure 3.1 NASA third generation TDRS satellite. (a) TDRS satellite in orbit.



(a)

Tracking and Data Relay Satellite (TDRS): The TDRS is utilized by NASA to maintain continuous links with spacecraft in low earth orbit. There are nine TDRS satellites in geostationary orbit, facilitating communication with spacecraft like the International Space Station (ISS) and the Hubble telescope. Two retired TDRS satellites have been moved to a graveyard orbit and decommissioned.



1.Subsystem Components:

1. **Steerable Antennas:** Large 4.5-meter diameter antennas capable of tracking low earth orbit spacecraft. These antennas operate at S-band, Ku-band, and Ka-band frequencies and can handle bit rates of up to 300 Mbps at Ku-band.
2. **Omni Antenna:** Part of the S-band telemetry and command system.
3. **Redundancy:** All critical components of the satellite are duplicated for redundancy purposes. For example, if one battery pack fails, there are three others available to ensure uninterrupted satellite operation.

3.1.1 Attitude and Orbit Control System (AOCS)

This subsystem consists of

- Rocket motors and Electric propulsion systems (that are used to move the satellite back to the correct orbit when external forces cause it to drift off station), and

- Gas jets or inertial devices that control the attitude of the satellite.

3.1.2 Telemetry, Tracking, Command, and Monitoring (TTC&M)

- These systems are partly on the satellite and partly at the controlling earth station
- **The telemetry system** sends data derived from many sensors on the satellite, which monitor the *satellite's health*, via a telemetry link to the controlling earth station.
- **The tracking system** is located at this earth station and provides information on the range and the elevation and azimuth angles of the satellite. Repeated measurement of these three parameters permits computation of orbital elements, from which changes in the orbit of the satellite can be detected.
- Based on telemetry data received from the satellite and orbital data obtained from the tracking system, **the control system** is used to correct the position and attitude of the satellite. It is also used to control the antenna pointing and communication system configuration to suit current traffic requirements, and to operate switches on the satellite.

3.1.3 Power System

All communications satellites derive their electrical power from ***solar cells*.**

The power is used by the communication system, mainly in its transmitters, and also by all other electrical systems on the satellite.

The latter use is termed *housekeeping*, since these subsystems serve to support the communications system.

Power systems generate as little as **1 W of DC power for a 1U cubesat and up to 20 kW for a large GEO platform.**

3.1.4 Communications Subsystems

- The communications subsystem is the major component of a communications satellite, and the remainder of the satellite is there solely to support it. Frequently, the communications equipment is only a small part of the weight and volume of the whole satellite.

- It is usually composed of two or more antennas, which receive and transmit over wide bandwidths at microwave frequencies, and a set of receivers and transmitters that amplify and retransmit the incoming signals.

- The receiver-transmitter units are known as ***transponders***. There are two types of transponder in use on satellites:

- the **linear or *bent pipe*** transponder that amplifies the received signal and retransmits it at a different frequency,

- the ***baseband processing transponder***, used only with digital signals, that converts the received signal to baseband, processes it, and then retransmits a digital signal. The latter approach is known generically as ***onboard processing* (OBP).**

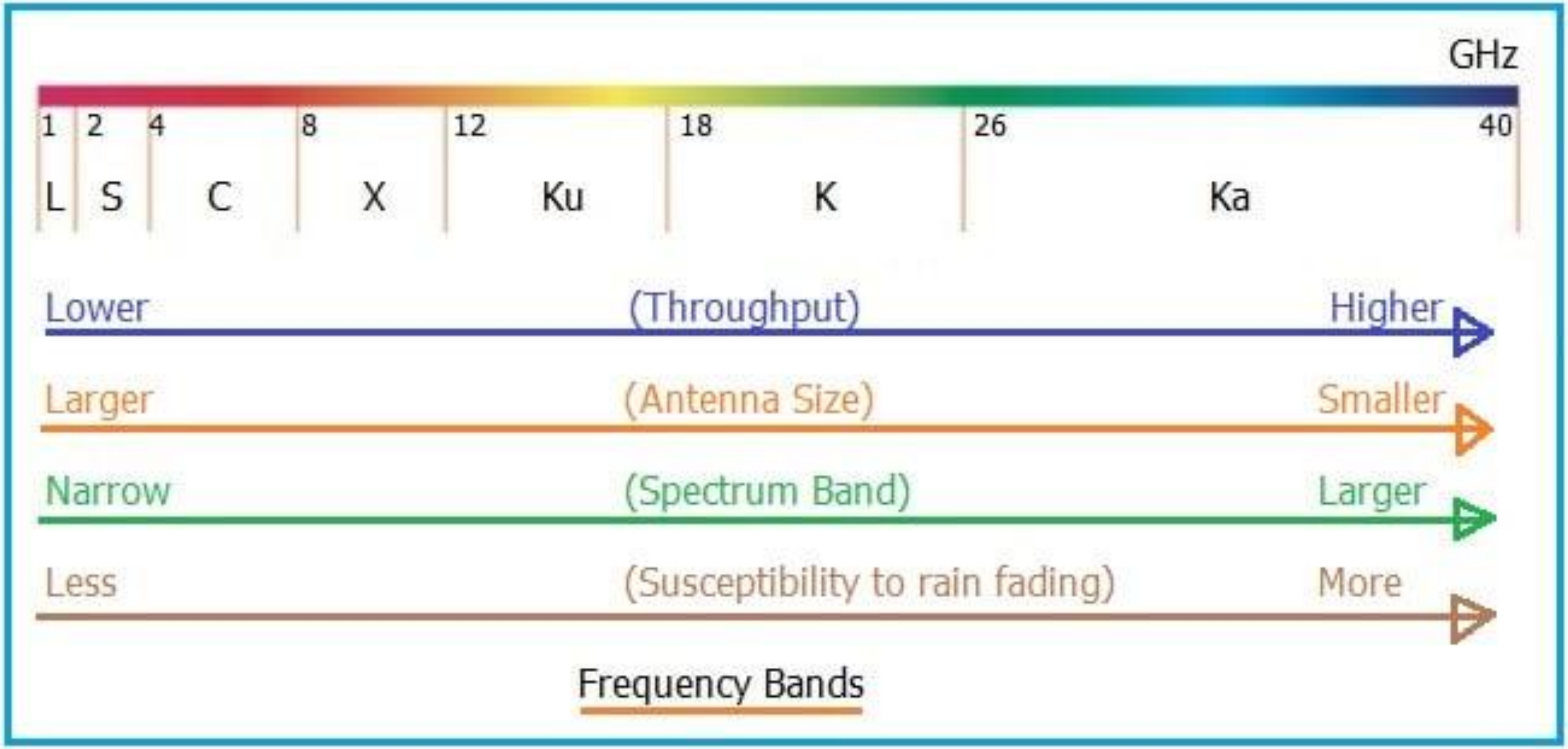
3.1.5 Satellite Antennas

- Although these form part of the communication system, they can be considered separately from the transponders.

- On large GEO satellites the antenna systems are very complex and produce beams with shapes carefully tailored to match the areas on the earth's surface served by the satellite, or multiple *spot beams* directed at specific points on earth.

- Most satellite antennas are designed to operate in a single frequency band, for example, **C-band, Ku-band, or Ka-band,** but some satellites have antennas for both C- and Ku-band, or Ku- and Ka-band, for example. A satellite that uses multiple frequency bands usually has four or more antennas.

- The communications capacity of a satellite can be increased by using spot beam antennas. The satellite can have one or more antennas creating many individual beams within the ***footprint*** of the satellite on the earth's sur- face, using two orthogonal polarizations and multiple frequency bands. LEO satellites for internet access have complex phased array antennas that can produce multiple electronically steered beams. Each beam is pointed to a *gateway* station or a user terminal and steered in angle as the satellite moves in its orbit.



C-band (4–8 GHz)

Primarily used for **satellite communications**, for full-time satellite TV networks or raw satellite feeds. **Commonly used in areas that are subject to tropical rainfall**, since it is less susceptible to rain fade than Ku band (the original Telstar satellite had a transponder operating in this band, used to relay the first live transatlantic TV signal in 1962).

Ku-band (12–18 GHz)

Used for satellite communications. In Europe, the Ku-band downlink is used from 10.7 GHz to 12.75 GHz for direct broadcast satellite services, such as Astra.

Ka-band (26–40 GHz)

Communications satellites for close up high resolutions applications, uplink in either the 27.5 GHz and 31 GHz bands, **close-range targeting radars on military aircraft**.

Part II

Altitude refers to how far the satellite is from ground level; In simple means the height at which satellite orbits.

Attitude is something different from altitude. It refers to the orientation and position of satellite. The way it's antenna are pointed on to earth , the way they spin in all the three axes.

The satellites' “attitude,” or orientation and orbit control are controlled by a system consisting of sensors, actuators and software. The Attitude and Orbit Control System provides three-axis stabilized Earth-pointing attitude control during all mission modes and measures spacecraft rates and orbital position.

3.2 Attitude and Orbit Control System (AOCS)

What is Attitute control (AC) ?

• The *attitude of a satellite refers to its orientation in space. Much of the* equipment carried aboard a satellite is for controlling its attitude.

Why we need AC ?

• Attitude control is necessary to ensure that directional antennas point in the proper directions. A number of forces, referred to as *disturbance torques,* can alter the attitude, some examples being the gravitational fields of the earth and the moon, solar radiation, and meteorite impacts.

How Attitude control is done?

AC is done by the measure of a satellite's orientation in space. In one method, infrared sensors, referred to as *horizon detectors, are used* to detect the rim of the earth against the background of space.

Where AC process takes place?

Usually, aboard the satellite, or control signals to be transmitted from earth, based on attitude data obtained from the satellite.

- **Gravitational Force Reduction:**
  - At an orbital altitude of 1000 km, the reduction in Earth's gravity is approximately **35%.**
  - At geostationary altitude of 35,786 km, the reduction is **97.7%,** or a factor of 43.7.

- **Orbital Inclination Change:**
  - Gravitational pull tends to change the inclination of a GEO satellite's orbit at an initial rate of approximately 0.86° per year.
- **Equatorial Bulges:**
  - Bulges at the equator result in accelerations towards stable points in the GEO orbit at longitudes 75°E and 252°E.
  - These bulges have a height of about 65 meters.
- **LEO Satellite Altitude:**
  - LEO satellites typically orbit at altitudes ranging from **160 km to 2,000 km** above the Earth's surface.
  - LEO satellites complete an orbit around Earth in approximately 90 minutes to 2 hours.
  - GEO satellites have an orbital period matching Earth's rotation, approximately 24 hours.
- **Solar Pressure Effects:**
  - Solar pressure can exert forces of magnitude in the micro to millinewton range on satellite surfaces, depending on their size and material properties.
- **Eccentricity Deviation:**
  - Variations in Earth's gravitational constant may cause eccentricity deviations in LEO satellite orbits of a few meters to kilometers.
- **Longitudinal Stability Maneuvers:**
  - Station-keeping maneuvers may involve thrust adjustments of a few millimeters to meters per second to maintain longitudinal stability of GEO satellites.

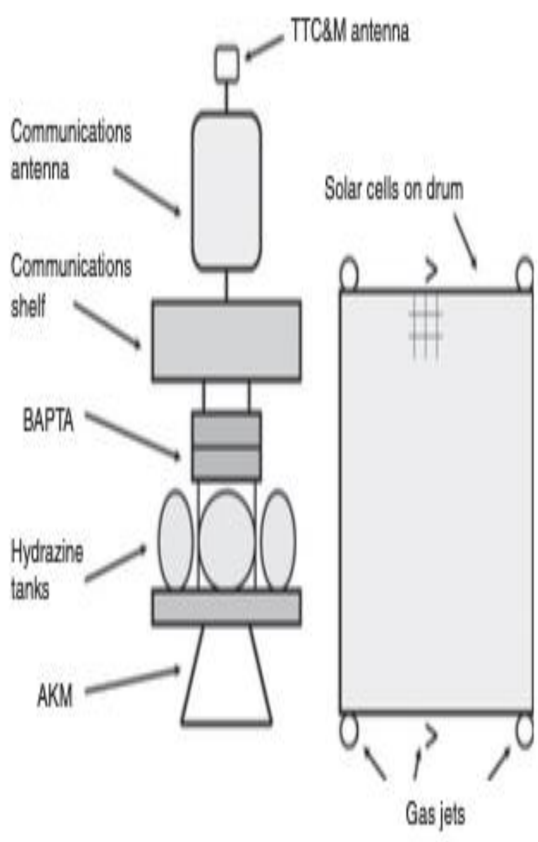


Figure 3.3b A typical spinner satellite from the 1980s. The entire satellite rotated at roughly one revolution per second. The communications equipment and antennas were driven by a motor in the opposite direction to the body of the satellite to keep the antennas pointed at earth. BAPTA, Bearing and power transfer assembly; AKM, Apogee kick motor; TTC&M, Telemetry, tracking, command, and monitoring.

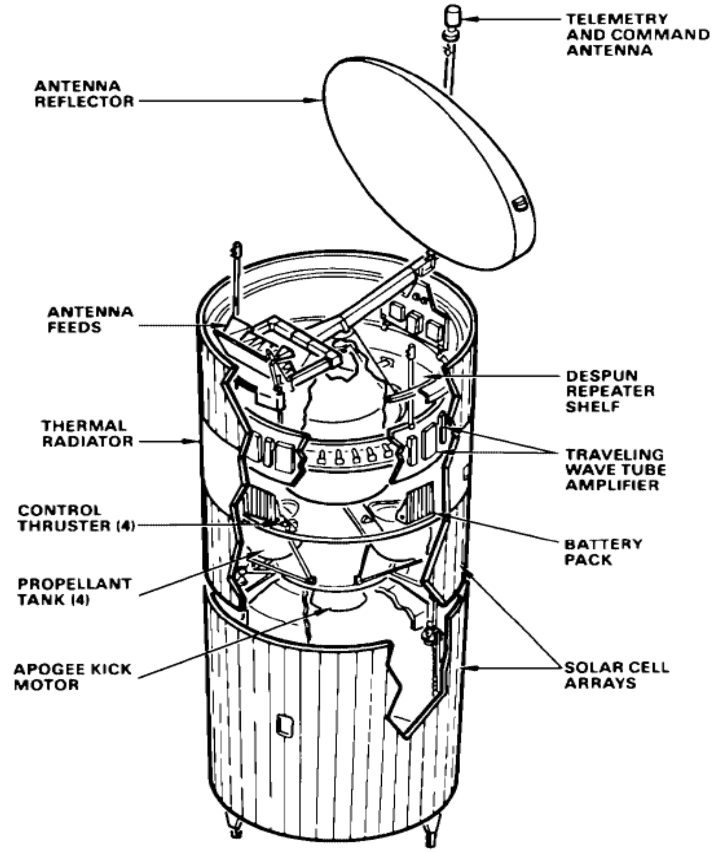
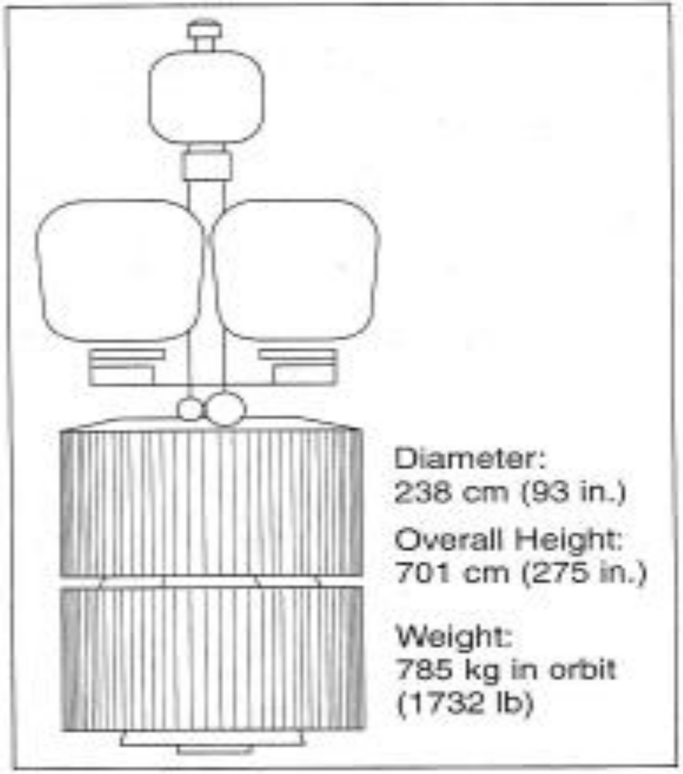
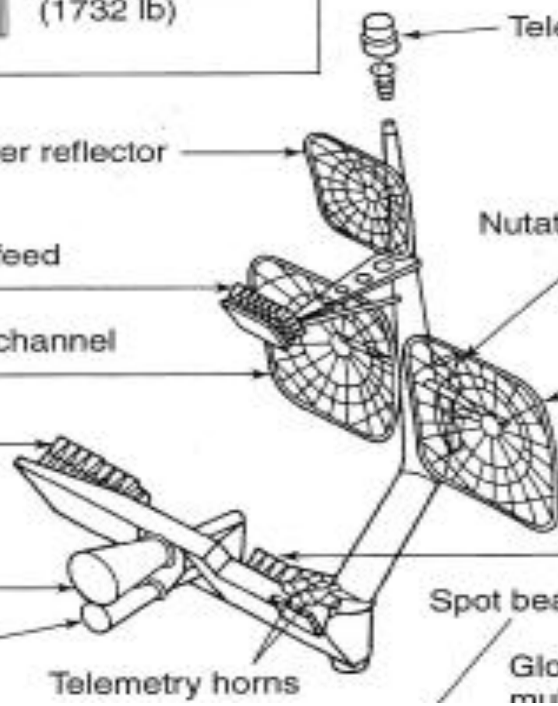


Figure 7.6 HS 376 spacecraft. (*Courtesy of Hughes Aircraft Company Space and Communications Group.*)

As shown in Figure 3.3b, the body of a spinner satellite consists of a cylindrical drum covered in solar cells with the power systems, fuel storage, and batteries inside. The communications system is mounted at the top of the drum and is driven by an electric motor in the opposite direction to the rotation of the satellite body to keep the antennas pointing toward earth. The satellite is *spun up* by operating small thrusters mounted on the periphery of the drum, at an appropriate point in the launch phase. The despin system is then brought into operation so that the main TTC&M antennas point toward earth. One advantage that spinner satellites had was simpler thermal control. One half of the satellite was in sunlight causing the solar cells to heat up, while the other half faced deep space, allowing heat to be radiated away from the solar cells.


Diameter:
238 cm (93 in.)
Overall Height:
701 cm (275 in.)
Weight:
785 kg in orbit
(1732 lb)


Telemetry & command bicones
Receiver reflector
Nutation damper
Receive feed horns
Transmit odd channel reflector
Transmit even channel reflector
Odd channel feed horns transmit
Even channel feed horns transmit
Global transmit horn
Spot beam output multiplexer
Global receive horn
Telemetry horns
Global output
Input filters
Looking

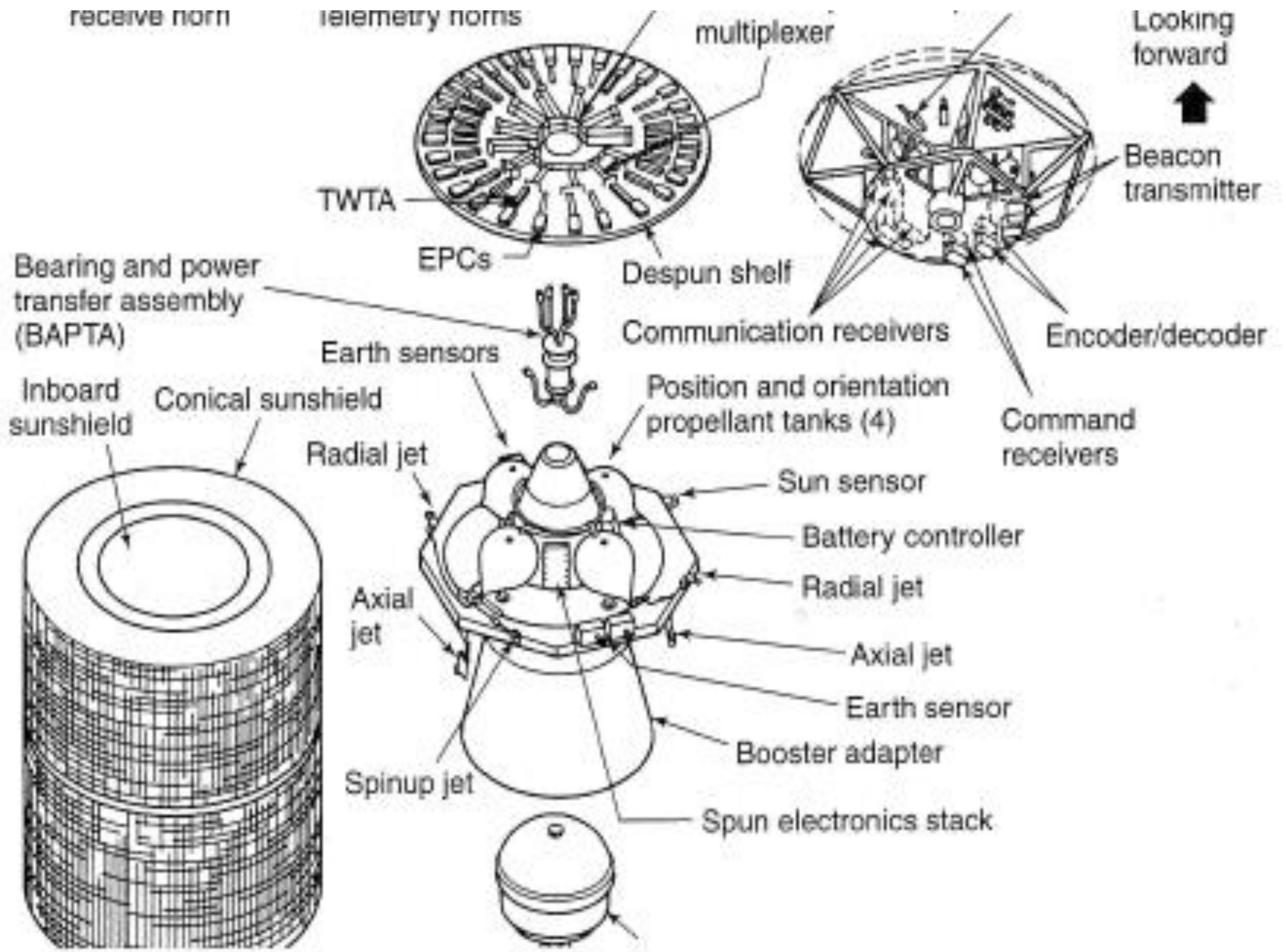


FIGURE 3.1 Exploded view of a spinner satellite based on the Boeing (Hughes) HS 376 design. INTELSAT IVA (courtesy of Intelsat)

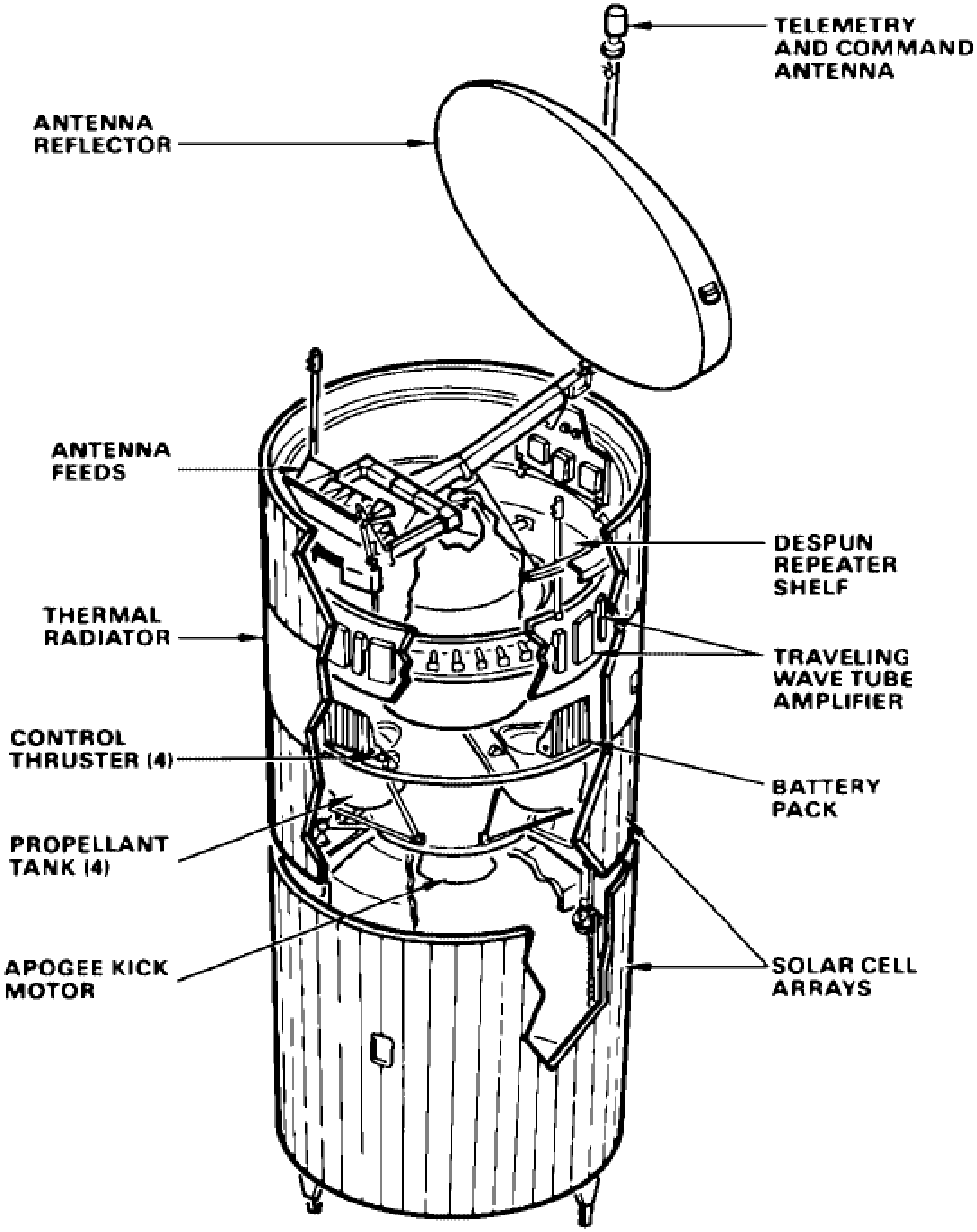


Figure 7.6 HS 376 spacecraft. (*Courtesy of Hughes Aircraft Company Space and Communications Group.*)

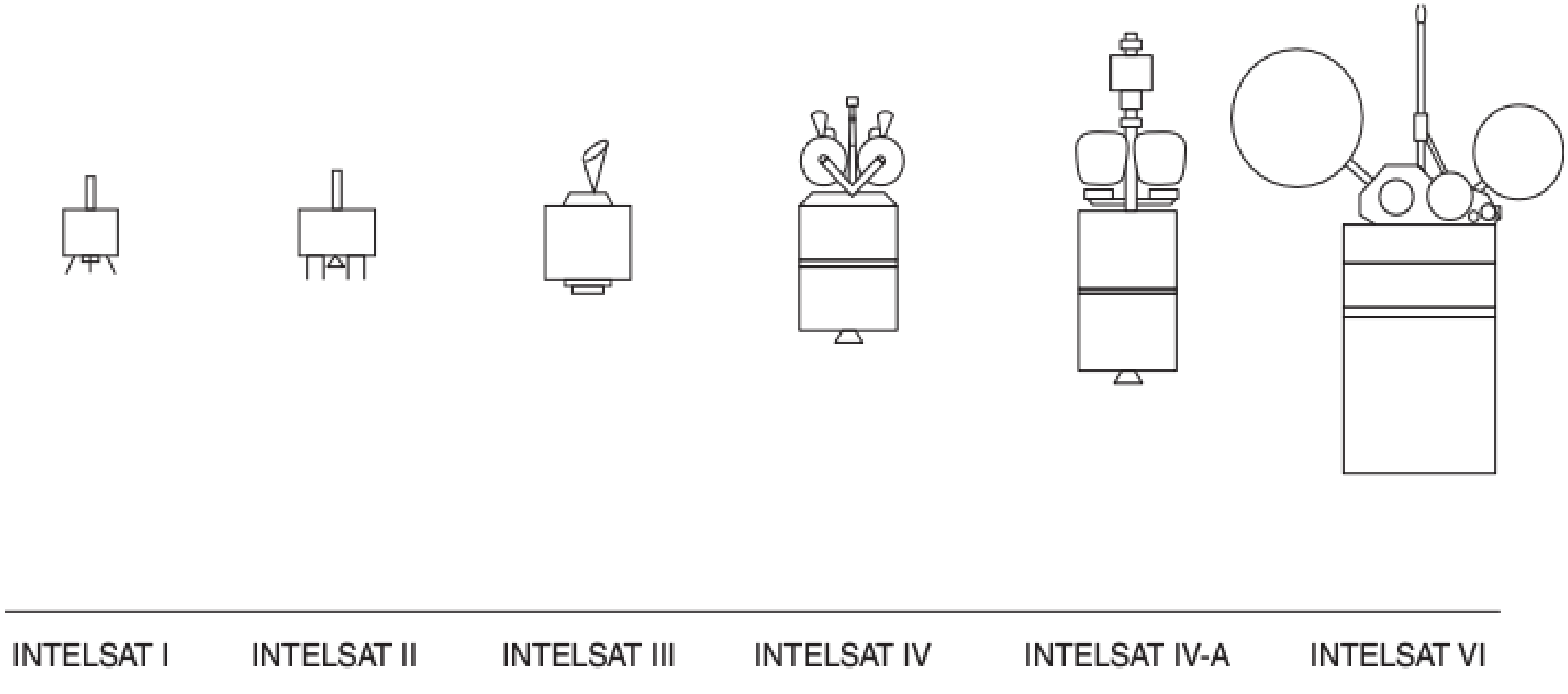


Figure 3.3a Spinner satellites launched or operated by Intelsat between 1965 and 2013. Intelsat V is missing as it was a three-axis stabilized satellite. Subsequent satellites were all three-axis stabilized. Intelsat 1 had an on-orbit mass of 34 kg and generated 46 W of power at end of life. Total effective bandwidth was 50 MHz. Intelsat 6 had an on-orbit mass of 1800 kg and generated 2100 W of power at end of life. Total effective bandwidth was 3360 MHz.

- Before 1990, GEO satellites relied on rotation (spinners) for stability.
- Spinners, like the Boeing 376 GEO satellite, rotated at speeds of 30 to 100 rpm.
- Spinners had limited power generation due to uneven sunlight exposure.
- Most large GEO communication satellites now use three-axis stabilization.
- Three-axis stabilization employs momentum wheels driven by electric motors.
- Momentum wheels counteract changes in orientation to ensure stability.
- Cubesats commonly use three-axis stabilization as well.
- Increasing momentum wheel speed induces precession, following the principle of conservation of angular momentum.
- Spinner satellites, such as those used by Intelsat for international communication, are depicted in Figure 3.3a.

- Large geostationary three-axis stabilized satellites with foldable solar arrays and reflector antennas

- Solar arrays span approximately 30 meters once in orbit, generating up to 20kW of power

- Liquid propulsion systems are commonly used, often employing hydrazine variants that decompose over a catalyst

- Bi-propellant fuels like mono-methyl hydrazine and nitrogen tetroxide are standard for thruster operations

- Fuel stored on GEO satellites is used for orbit injection and station keeping over their lifetime

- **Two types of rocket motors**: traditional bi-propellant thrusters and ion thrusters

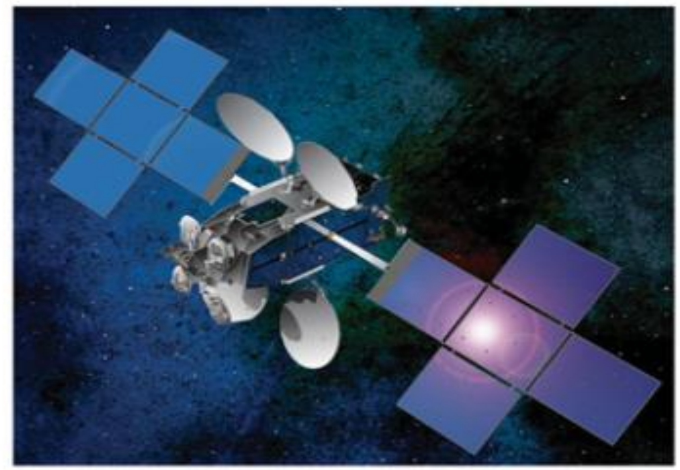
- Ion thrusters use high voltage to accelerate ions for thrust, powered by solar cells, saving expendable fuel

- Ion engines can also be used for slow orbital maneuvers, like raising a satellite from transfer orbit to GEO orbit

(a)

(b)

(c)



(d)

Figure 3.3c Examples of three-axis stabilized communication satellites. (a) A large GEO direct broadcast television satellite built by SSL, under test. (b) Same satellite as (a) folded for launch. The solar cells are folded onto the top and bottom of the body and the antennas are folded against the sides of the body, as viewed in this photograph. (c) Intelsat 35e satellite. (d) ViaSat 1 satellite. Source: For a color version of this figure please see color plate section.

• Xenon is the most common propellant used in ion propulsion due to its easy ionization, high atomic mass, inertness, and ability to be stored as a liquid under high pressure.

• Hall effect ion engines typically consist of a hollow cylindrical chamber charged to a high positive voltage, a discharge cathode, and a powerful magnetic field. Electrons are attracted towards the chamber walls but directed into a stream towards the open end, where propellant is introduced as a gas. Electrons bombard the propellant, producing positively charged ions which are then accelerated towards a negatively charged grid and emitted at high velocity.

• Ion thrusters emit a much lower volume of particles compared to chemical rocket engines but at significantly higher velocities, with typical thrust around 0.5 Newtons.

• In three-axis stabilized satellites, pairs of gas jets or ion thrusters are used for rotation in pitch, roll, and yaw directions. Additional controls allow for velocity increments in the X, Y, and Z directions, with opposing thrusters used to stop motion when the satellite reaches its new position.

• Fuel conservation is important as fuel is finite onboard a satellite, so slow movements are generally preferred despite resulting in slower progress towards the destination.

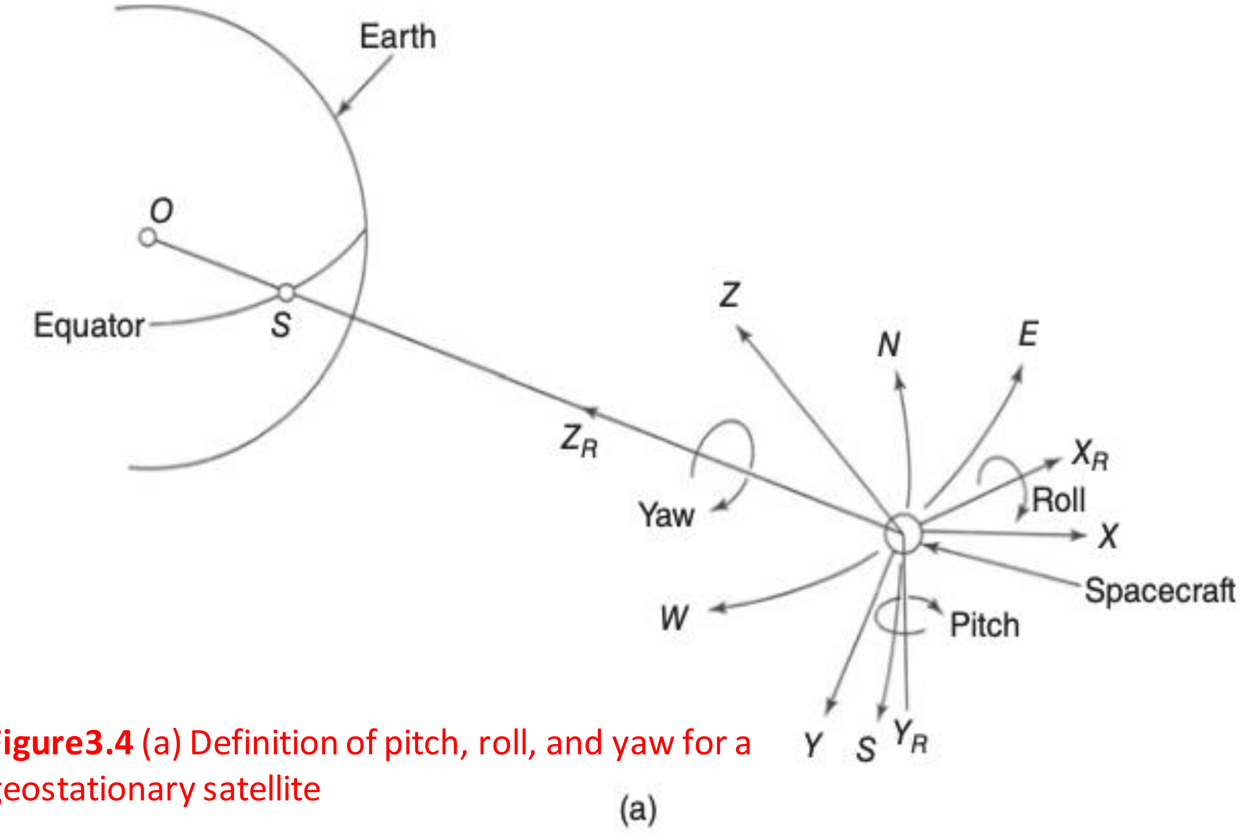


Figure3.4 (a) Definition of pitch, roll, and yaw for a geostationary satellite

•Reference Cartesian axes (XR, YR, ZR) are defined with the satellite at the origin,

• with the ZR axis directed towards the center of the Earth and aligned along the local vertical at the satellite's subsatellite point.

•The XR axis is tangent to the orbital plane and lies within it,

•while the YR axis is perpendicular to the orbital plane, typically east and south for satellites serving the Northern Hemisphere.

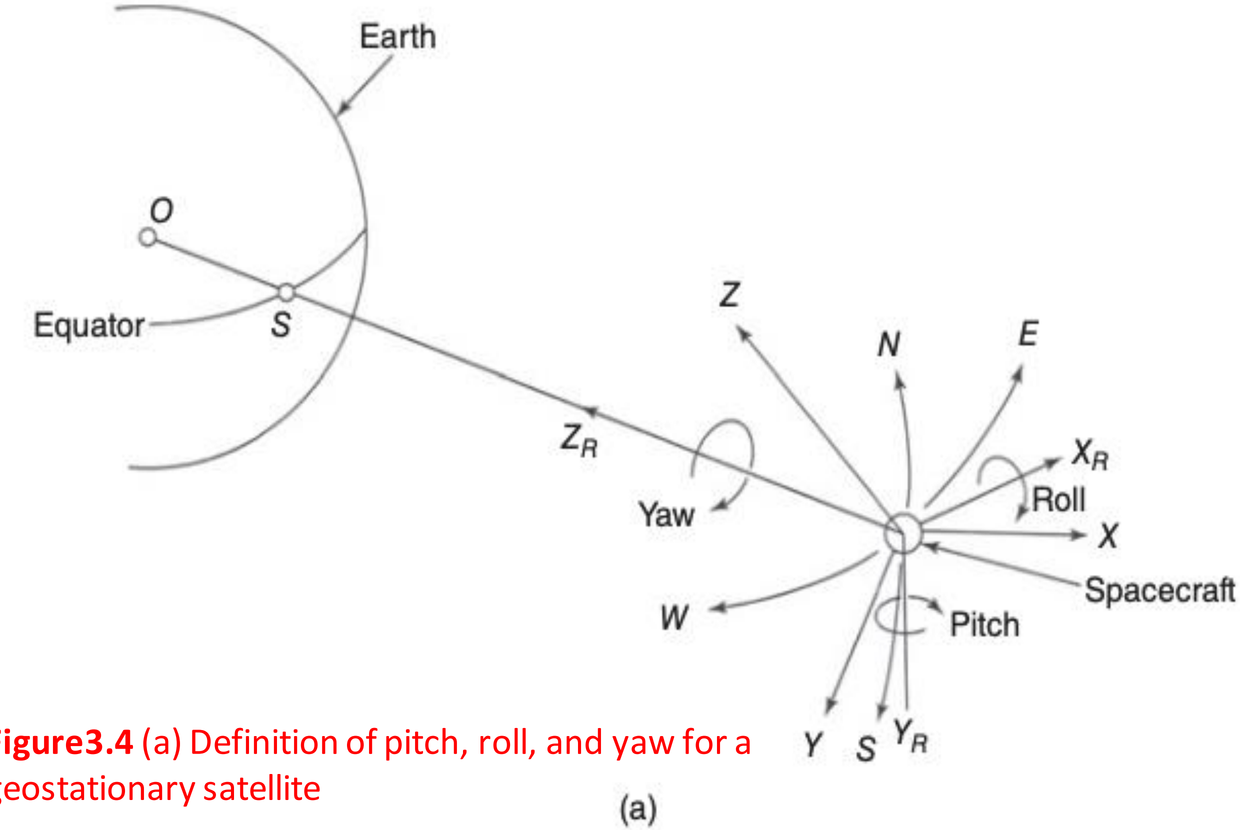
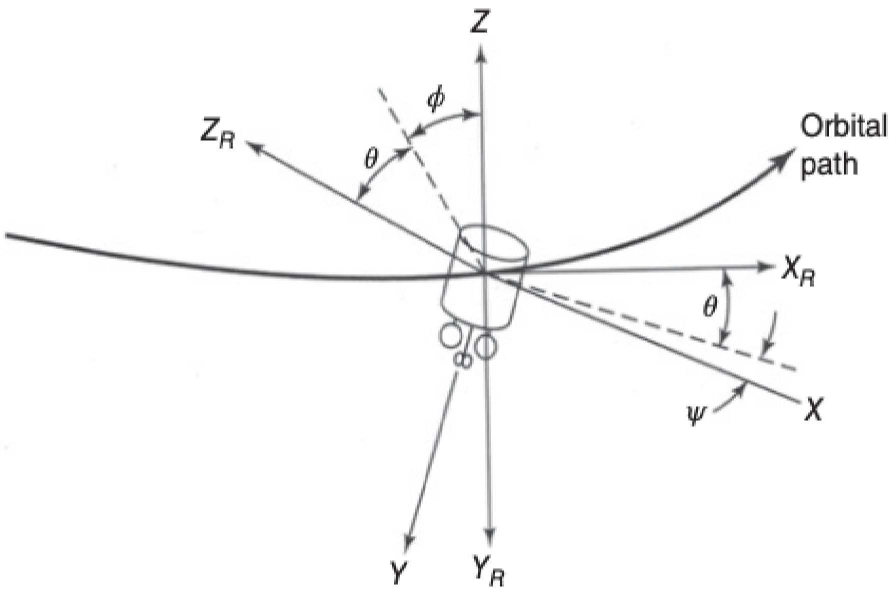


Figure3.4 (a) Definition of pitch, roll, and yaw for a geostationary satellite

Rotation about the X_R, Y_R, and Z_R axes is defined as *roll* about the X_R axis, *pitch* about the Y_R axis, and *yaw* about the Z_R axis, in exactly the same way as for an aircraft or ship traveling in the *X* direction.

The satellite must be stabilized with respect to the reference axes to maintain accurate pointing of its antenna beams.

The axes X_R, Y_R, and Z_R are defined with respect to the location of the satellite; a second set of Cartesian axes, *X, Y, Z*, as shown in Figure 3.4b, define the orientation of the satellite.



(b)

Figure 3.4 (a) Definition of pitch, roll, and yaw for a geostationary satellite. (b) Relationship between axes of a GEO satellite when in orbit. The axes X_R, Y_R, and Z_R are related to the orbit. Axes *X, Y, Z* relate to the satellite. The *Z* axis of the satellite is directed to a specific point on earth.

Changes in a satellite's attitude cause the angles ϑ, φ, and ψ in Figure 3.4b to vary as the *X, Y, Z* axes move relative to the fixed reference axes X_R, Y_R, and Z_R. The *Z* axis is usually directed toward a reference point on earth, called the *Z-axis intercept*. The location of the *Z*-axis intercept defines the pointing of the satellite antennas; the *Z*-axis intercept point may be moved to repoint all the antenna beams by changing the attitude of the satellite with the attitude control system.

Attitude control of a three-axis stabilized satellite requires an increase or a decrease in the speed of a momentum wheel.

If a constant torque exists about one axis of the satellite, a continual increase or decrease in momentum wheel speed is necessary to maintain the correct attitude.

When the upper or lower speed limit of the wheel is reached, it must be *unloaded* by operating a pair of thrusters and simultaneously reducing or increasing the wheel speed in the appropriate sense.

Closed-loop control of attitude is employed on the satellite to maintain the correct attitude. When the satellite has narrow beam antennas, the whole satellite may have to be stabilized within ±0.1° on each axis.

The references for the attitude control system may be the outer edge of the earth’s disk, as observed with infrared sensors, the sun, or one or more stars.

The control system for a three- axis stabilized satellite employs an onboard computer to process the sensor data and command the thrusters and momentum wheels (Maral and Bousquet 2002).

- Figure 3.5 is a simplified diagram of the attitude control system for a three-axis stabilized antenna.

- The earth sensor illustrated in Figure 3.5 consists of four small telescopes aimed at four points along the edge of the earth as seen from geostationary orbit. The view seen by each telescope is half of the earth and half of dark space beyond the earth.
- Sensors for 14–16 μm wavelength infrared radiation at the focus of each telescope have identical outputs when the earth is symmetrically aligned with all four sensor views.

- Long wavelength IR is used to avoid the influence of clouds. If the left hand pair of telescopes has a higher output than the right hand pair, for example, the view of the earth has moved to the left and the attitude controller will adjust the satellite pointing accordingly. The sun sensors work in the same fashion.

- Star sensors employ a telescope with an infrared detector and must track the selected star as the satellite moves in its orbit.
- Occasionally, the moon will rise above the rim of the earth and be seen by an infrared earth sensor, a condition known as a *moon hit*.

- The moon has a noise temperature of 200 K and can confuse the earth sensor system. Fortunately, the moon has a highly predictable orbit and moon hits can be accurately predicted in advance.

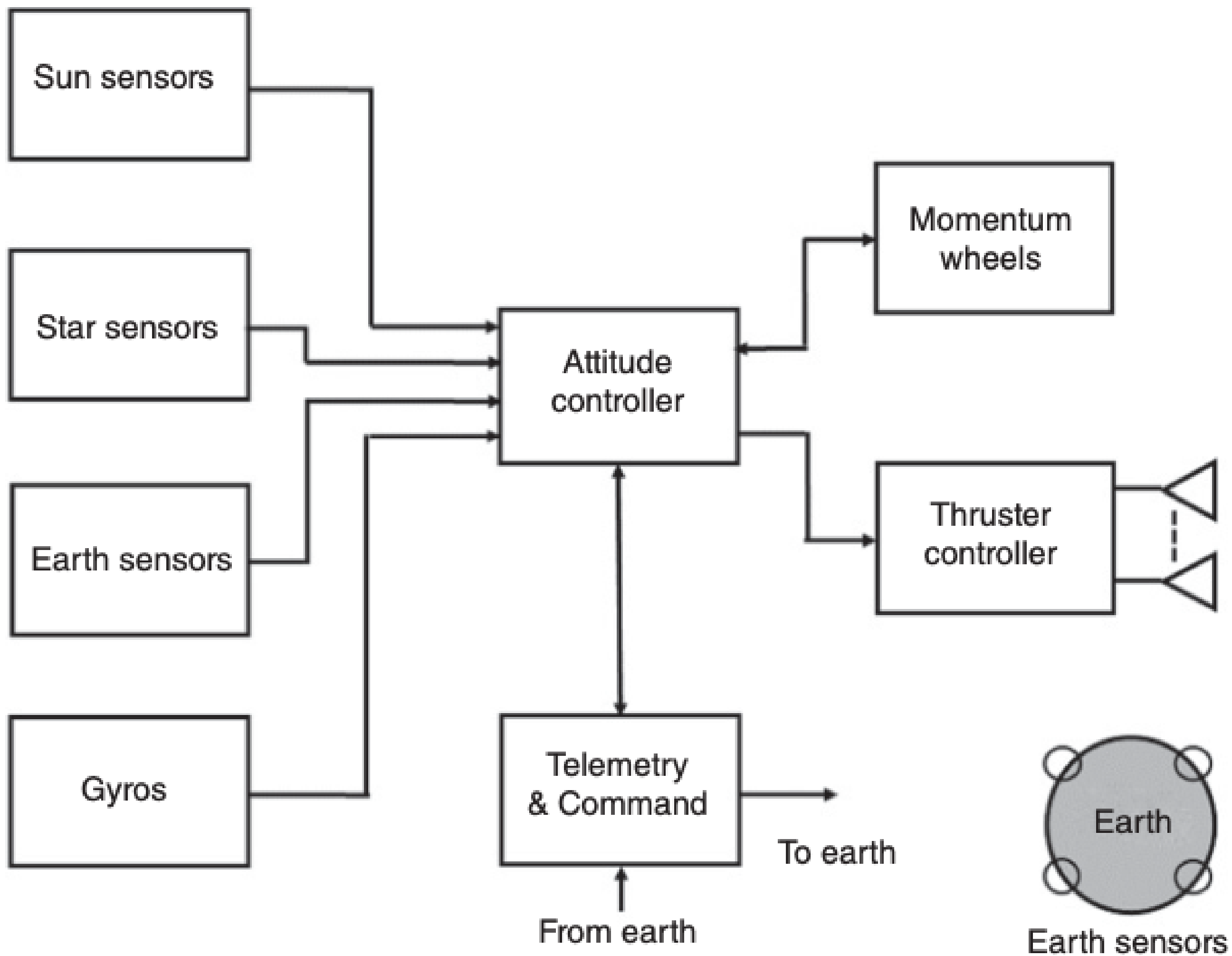


Figure 3.5 Attitude control system for a three-axis stabilized GEO satellite. The sun and star sensors are used to establish orientation with respect to space and the earth sensors are used for z-axis pointing. The gyros detect movement on the three axes of the satellite and send signals to the controller to initiate a correction with the momentum wheels. The thrusters used for attitude control are ion thrusters. The attitude controller operates autonomously and sends all sensor data and command data to the controlling earth station over the telemetry link.

2. Momentum wheel stabilization

Stability also can be achieved by utilizing the gyroscopic effect of a spinning flywheel, and this approach is used in non-cylindrical satellites such as the INTELSAT V type satellites shown in Fig and the Anik-E satellites .

The complete unit, termed a *momentum wheel, consists* of a flywheel, the bearing assembly, the casing, and an electric drive motor with associated electronic control circuitry.

The flywheel: is attached to the rotor, which consists of a permanent magnet providing the magnetic field for motor action. The stator of the motor is attached to the body of the satellite. Thus the motor provides the coupling between the flywheel and the satellite structure. Speed and torque control of the motor is exercised through the currents fed to the stator.

Momentum wheels ranging in size from 20, 26, 35, 50, to 60 cm in diameter that are used in a wide variety of satellites.

The term *momentum wheel is usually reserved for wheels that operate* at nonzero momentum. This is termed a *momentum bias*. *Such a* wheel provides passive stabilization for the yaw and roll axes when the axis of rotation of the wheel lies along the pitch axis, as shown in Fig. *Control about the pitch axis is achieved by changing the speed of* the wheel.

When a momentum wheel is operated with zero momentum bias, it is generally referred to as a ***reaction wheel***. *Reaction wheels are used* in three-axis stabilized systems. Here, as the name suggests, each axis is stabilized by a reaction wheel, as shown in Fig. 7.8*c*.

Reaction wheels also can be combined with a momentum wheel to provide the control needed .Random and cyclic disturbance torques tend to produce zero momentum on average. However, there will always be some disturbance torques which cause a cumulative increase in wheel momentum, and eventually at some point the wheel *saturates. In effect, it reaches its maximum allowable angular velocity* and can no longer take in any more momentum.

Mass expulsion devices are then used to unload the wheel, that is, remove momentum from it (in the same way a brake removes energy from a moving vehicle).
Of course, operation of the mass expulsion devices consumes part of the satellite's fuel supply.

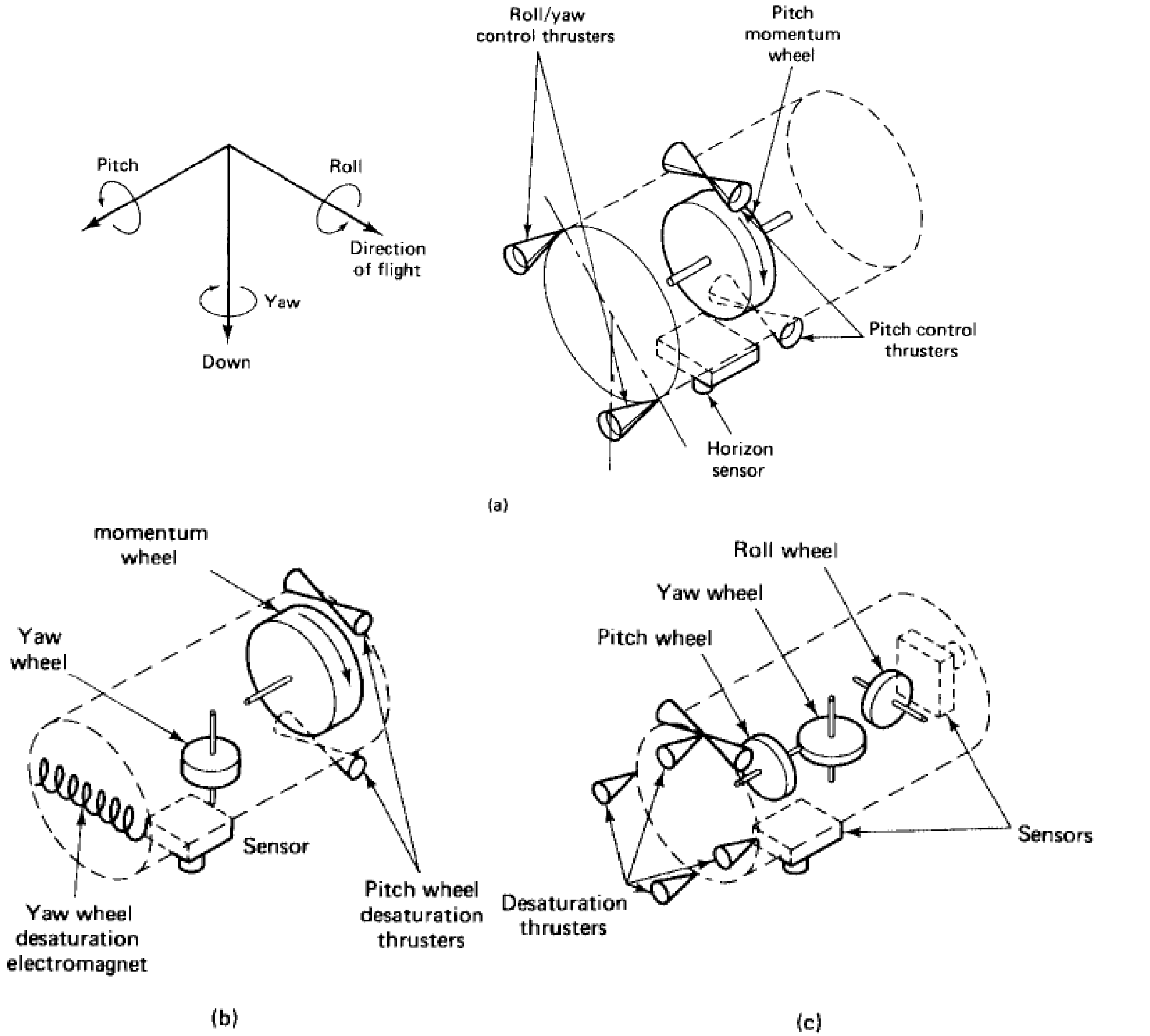


Figure 7.8 Alternative momentum wheel stabilization systems: (*a*) one-wheel; (*b*) two-wheel; (*c*) three-wheel. (*Reprinted with permission from Spacecraft Attitude Determination and Control, edited by James R. Wertz. Copyright @ 1984 by D. Reidel Publishing Company, Dordrecht, Holland.*)

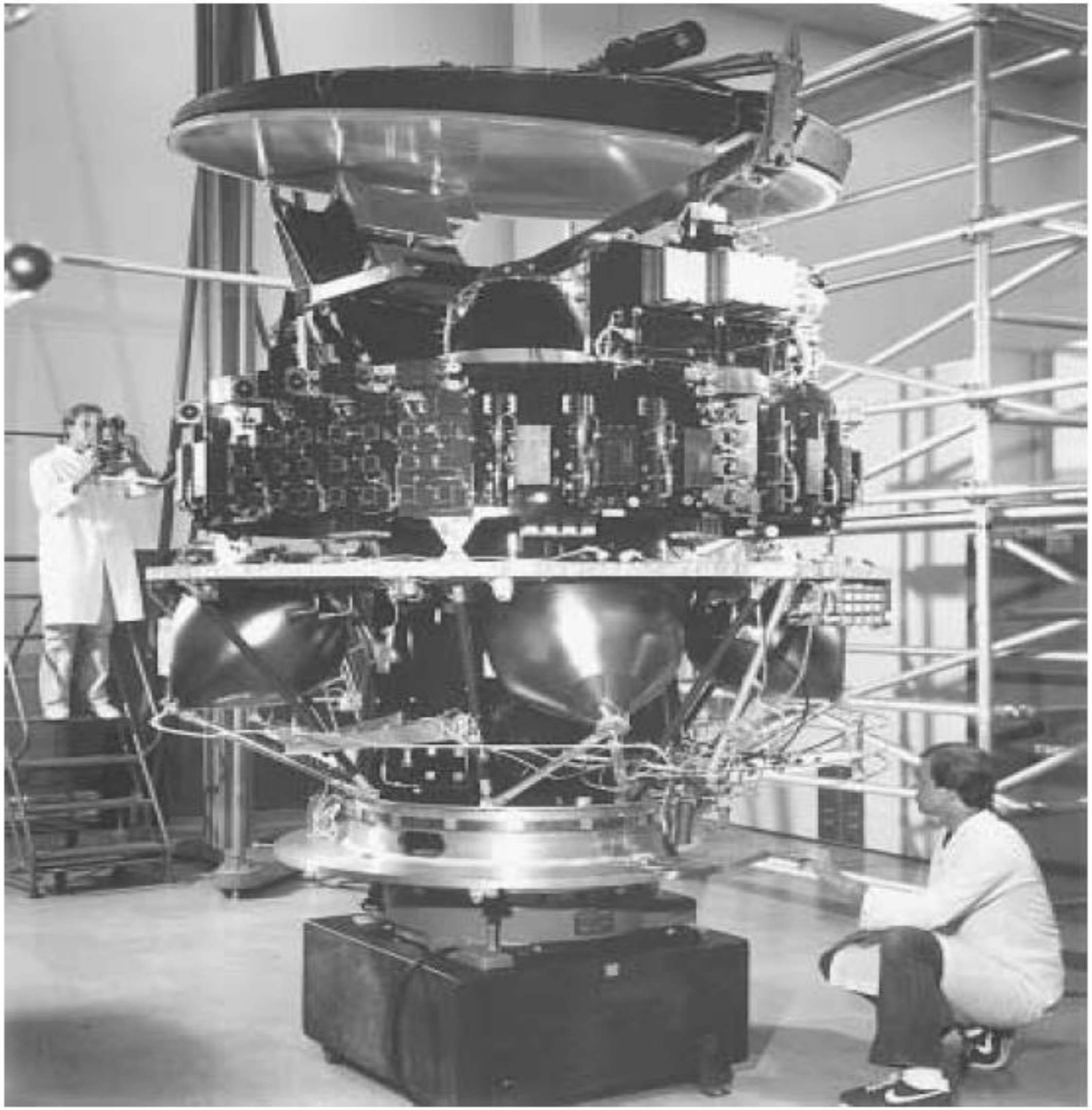


Figure 7.7 Technicians check the alignment of the Telestar 3 communications satellite, shown without its cylindrical panels. The satellite, built for the American Telephone and Telegraph Co., carries both traveling-wave tube and solid-state power amplifiers, as shown on the communications shelf surrounding the center of the spacecraft. The traveling-wave tubes are the cylindrical instruments. (*Courtesy of Hughes Aircraft Company Space and Communications Group.*)

3.3 Telemetry, Tracking, Command, and Monitoring (TTC&M)

The TTC&M system is essential to the successful operation of a communications satellite. It is part of the satellite management task, which also involves an earth station, usually dedicated to that task, and a group of personnel.

- Satellite management functions involve controlling the orbit and attitude, monitoring all sensors and subsystems, and managing communication system sections.

- The TTC&M earth station may be owned and operated by the satellite owner or by a third party providing TTC&M services under contract.

- On large geostationary satellites, some antenna repointing may be possible under the TTC&M system's command.

- Tracking primarily occurs at the earth station, which performs essential functions illustrated **in Figure 3.8.**

Telemetry, Tracking, Command, and Monitoring (TTC&M)

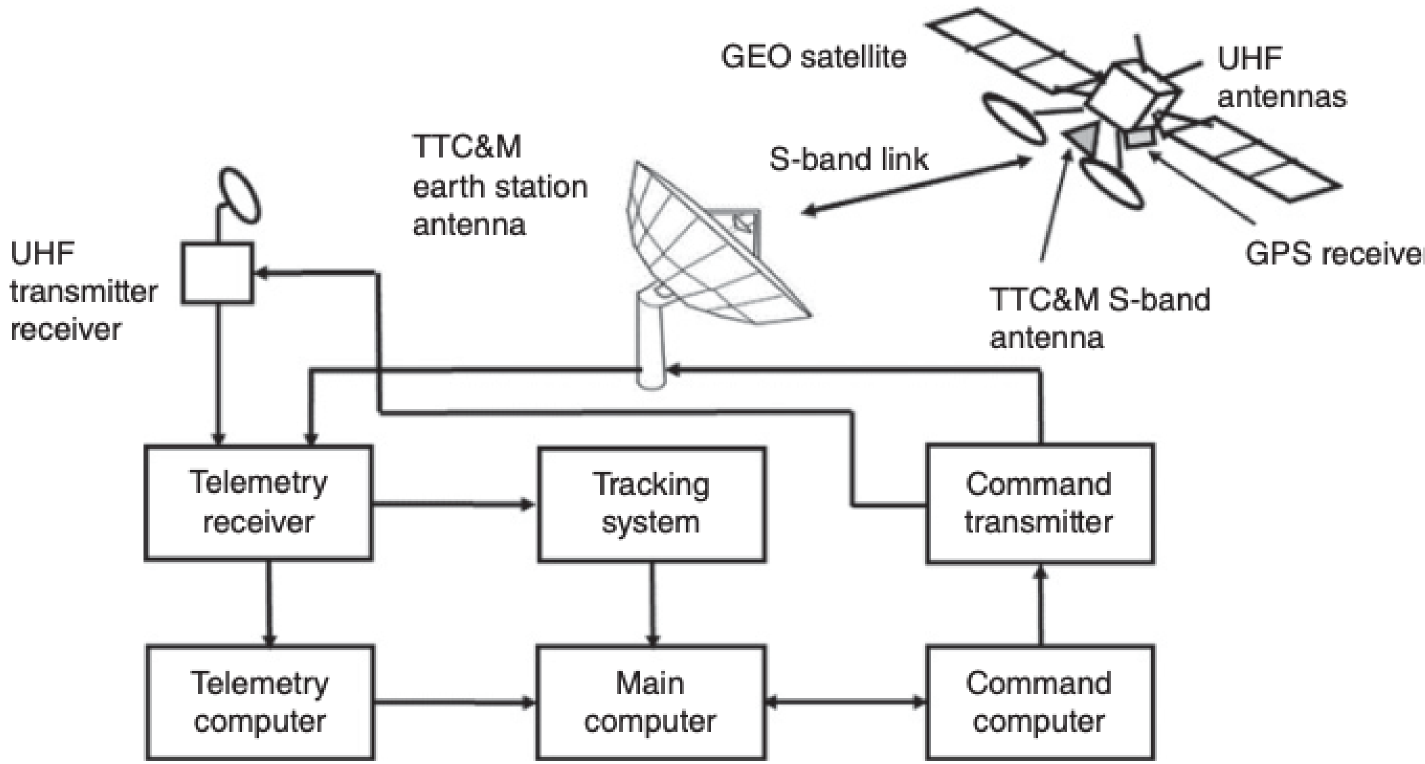


Figure 3.8 Simplified diagram of the earth based control system for a GEO satellite. The main computer receives telemetry data from the satellite's attitude and orbital control systems, as well as all the many sensors on board the satellite. Commands for station keeping maneuvers and changes to switch settings originate in the main computer and are translated to command codes by the command computer. The UHF command and telemetry system is used during the launch phase when the satellite orientation has not been stabilized. Once on station, TTC&M communications are switched to the main frequency, S-band in this example. All telemetry data is stored for later analysis to determine aging trends in critical components such as transponders.

3.3.1 Telemetry and Monitoring System

- The Telemetry and Monitoring System (TMS) collects data from numerous sensors within the satellite and transmits it to the controlling earth station.

- Hundreds of sensors on the satellite monitor various parameters such as pressure in fuel tanks, voltage, current in the power conditioning unit, subsystem currents, and critical voltages and currents in communication electronics. Temperature sensors are also installed to ensure subsystem temperatures remain within predetermined limits.

- At the controlling earth station, **a computer monitors**, stores, and decodes telemetry data in real-time, enabling immediate determination of any system or sensor status. Alarms can be triggered if any vital parameter exceeds allowable limits.

3.3.2 Tracking

- Various techniques are employed to determine the current orbit of a satellite. Velocity and acceleration sensors on the satellite can calculate the change in orbit by integrating data from the last known position.

- The controlling earth station observes the Doppler shift of the telemetry. Accurate angular measurements from the earth station antenna

- Precision equipment at earth stations enables determining the satellite's position within 10 meters. GPS receivers onboard some satellites report the satellite's position over the telemetry link.

3.3.3 Command

• A secure and effective command structure is vital to the successful launch and operation of any communications satellite.

• The command system is used to make changes in attitude and corrections to the orbit and to control the communication system. During launch, it is used to control the firing of the AKM and to extend the solar arrays and antennas of a three-axis stabilized satellite.

•Safe guard against unauthorized changes and inadvertent operations are crucial in the command structure of a satellite. Encryption of commands and responses provides security in the command system.

• Commands are converted into command words, sent in a time-division multiplexing (TDM) frame to the satellite, and checked for validity before execution.

• Command and telemetry links are usually separate from the communication system on GEO satellites, operating in the same frequency band, often C-band (6 and 4 GHz).

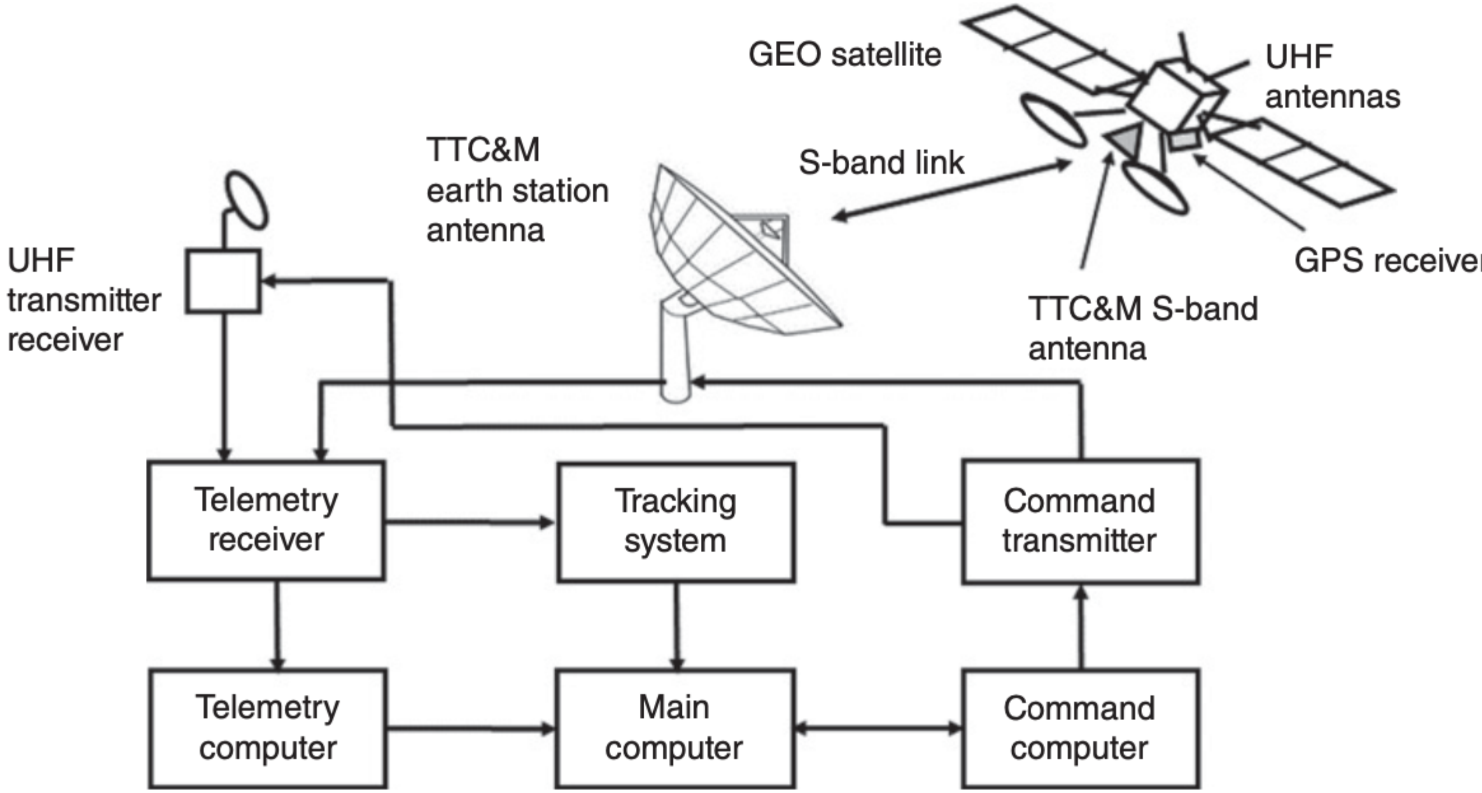


Figure 3.8 Simplified diagram of the earth based control system for a GEO satellite. The main computer receives telemetry data from the satellite's attitude and orbital control systems, as well as all the many sensors on board the satellite. Commands for station keeping maneuvers and changes to switch settings originate in the main computer and are translated to command codes by the command computer. The UHF command and telemetry system is used during the launch phase when the satellite orientation has not been stabilized. Once on station, TTC&M communications are switched to the main frequency, S-band in this example. All telemetry data is stored for later analysis to determine aging trends in critical components such as transponders.

3.4 Power Systems

- All communications satellites obtain their electrical power from solar cells, converting incident sunlight into electrical energy.

- Some deep space planetary research satellites have used thermonuclear generators to supply electrical power.

- Communications satellites have not used nuclear generators due to the danger posed to people on Earth if the launch should fail and the nuclear fuel spreads over an inhabited area.

- Thermonuclear generators are necessary on deep space probes that travel to the most distant planets because the strength of sunlight varies inversely with the square of the distance of a spacecraft from the sun.

- Solar panels are ineffective when a spacecraft is close to Jupiter, for example, at a distance of 1440 million kilometers from the sun, where the intensity of sunlight is only 1% of that in an Earth orbit.

3.4.1 Solar Power Systems

- The sun provides a powerful source of energy in outer space, with a radiation intensity of 1.36 kW/m2 at geostationary altitude.

- Solar cells, such as gallium arsenide (GaAs) cells, typically have an efficiency of 33–39% at beginning of life (BOL), but this efficiency decreases over time due to aging and micrometeor impacts.

- Silicon cells commonly used in home solar power installations have efficiencies ranging from 10% to 19%. To ensure sufficient power availability at the end of life (EOL) of a satellite, about 15% extra area of solar cells is usually provided to account for aging.

- Solar cells on three-axis stabilized satellites are arranged on flat panels along the Y-axis and are rotated by an electric motor to maintain normal incidence of sunlight, leading to heating up to 50–80° C and a subsequent drop in output voltage.

- Large geostationary Earth orbit (GEO) satellites can generate up to 20 kW of electric power, requiring each slip ring to carry a current of 200 A. However, slip ring failures have occurred, cutting available power in half on some GEO satellites.

3.4.2 Batteries

- Satellites require batteries to power subsystems during launch and eclipses, which occur twice per year around the spring and fall equinoxes.

- Eclipses, lasting up to 70 minutes, happen around March 20 and September 22 or 23, when the Earth's shadow passes over the satellite.

- To minimize impact, satellites are positioned 20°W of the service area's longitude, ensuring eclipses occur after 1 a.m. local time (when shutdown is more acceptable).

- Nickel-hydrogen batteries were commonly used due to their reliability and long life until lithium-ion batteries, with higher capacity per unit weight, became available.

- A power-conditioning unit manages charging current and redirects excess current from solar cells into heaters or load resistors on the cold side of the satellite.

- Sensors on batteries, power regulator, and solar cells monitor temperature, voltage, and current, relaying data to the onboard control system and controlling earth station via telemetry downlink.

- Typical battery voltages range from 20 to 50 V, with capacities spanning 20 to 1000 ampere hours.

Example 3.1

A large GEO satellite requires a total of 12 kW to operate its communication systems and 1.5 kW for housekeeping purposes. The solar cells on the satellite are mounted on two large sails that rotate to face the sun at all times. The efficiency of the solar cells is 36% at BOL and 33% at EOL. Using an average incident solar flux density of 1.36 kW/m^2 calculate the area of each solar sail to meet the power requirements at the end of the satellite's life.

How much power is generated at BOL?

The solar arrays are 2.0 m wide. How long are they?

Answer

The total power required by the satellite is 13.5 kW. At EOL the solar cells' efficiency is 33%. With an incident solar flux of 1.36 kW/m^2, the total area of solar sail required is

$$A = \frac{13.5}{0.33 \times 1.36} = 30.1\ m^2$$

At BOL, the 30.1 m^2 of solar cells will generate a power P kW where

$$P = 30.1 \times 0.36 \times 1.36 = 14.74\ \text{kW}$$

Each solar array must have an area of 15.05 m^2 and will have a length of 7.53 m.

Example 3.2

The large GEO satellite in Example 3.1 is subject to eclipses that last 70 minutes in spring and fall. The satellite is required to maintain full communications capacity during eclipses. Batteries on board the satellite must supply 13.5 kW for 70 minutes. The battery voltage is 50 V and the batteries must not discharge more than 50% during the eclipse.

Calculate the battery capacity required in ampere hours (AHs). A battery with a capacity of one ampere hour can supply one amp for one hour.

If lithium-ion batteries with a capacity of 200 watt hours per kilogram are used, find the weight of the battery.

Answer

First calculate the current required to supply 13.5 kW at 50 V.

$$I = \frac{P}{V} = \frac{13{,}500}{50} = 270\ A$$

The energy supplied by the battery over 70 minutes (1.167) hours is 315 ampere hours, representing 50% of the battery capacity. Hence batteries with a total capacity of 630 AH are needed.

The total battery capacity is 630 AH at 50 V, which is 31.5 kWH. Hence the battery weight is 157.5 kg. A large GEO satellite may have mass up to 6000 kg, so the battery accounts for 2.6% of the satellite's mass in this example.

Example 3.3

Calculate the total power radiated by the sun in watts and in dBW.

Hint: The sun is 93 million miles (about 150 million kilometers) from the earth. At that distance, the sun produces a flux density of 1.36 kW/m^2. This power density is present over all of a sphere with a radius of 150 million km.

Answer

The surface area A of a sphere with radius R m is given by

$$A = 4\pi R^2 \text{ m}^2$$

The sun is radiating 1.36 kW/m^2 over an area of

$$A = 4\pi R^2 = 4 \times \pi \times (150 \times 10^6)^2 = 2.83 \times 10^{17} \text{ m}^2$$

Hence the power radiated by the sun is P watts where

$$P = 2.83 \times 10^{17} \times 1.36 \times 10^3 = 3.85 \times 10^{20} \text{ W}$$

Converting to decibels

$$P = 10 \log_{10} (3.85 \times 10^{20}) = 205.9 \text{ dB W}$$

This represents a maximum value for any power system on earth.