Satellite Subsystems

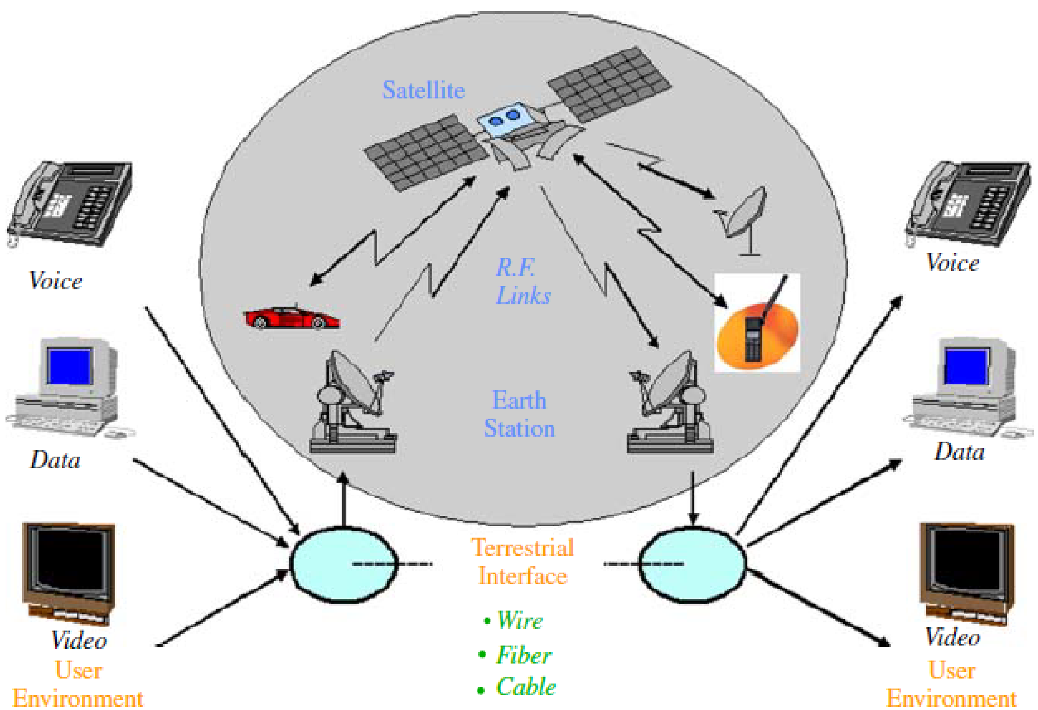
Chapter 3

Introduction

- An operating communications satellite system consists of several elements or segments, ranging from an orbital configuration of space components to ground based components and network elements.
- The particular application of the satellite system, for example, fixed satellite service, mobile service, or broadcast service, will determine the specific elements of the system.
- The basic system consists of a satellite (or satellites) in space, relaying information between two or more users through ground terminals and the satellite.
- The information relayed may be voice, data, video, or a combination of the three.
- The user information may require transmission via terrestrial means to connect with the ground terminal.
- The satellite is controlled from the ground through a satellite control facility, often called the master control center, MCC, which provides tracking, telemetry, command, and monitoring functions for the system.

Satellite system

- 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.



Space segment equipment

- The space segment equipment carried aboard the satellite can be classified under two functional areas, the **bus and the payload.**
- **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 down-links from the ground.
  - The communications payload can be further divided into the transponder and the antenna subsystems.
  - A satellite may have more than one payload. The early Tracking and Data Relay Satellites, TDRS, for example, had an "Advanced Westar" communications payload in addition to the tracking and data payload, which was the major mission of the satellite.

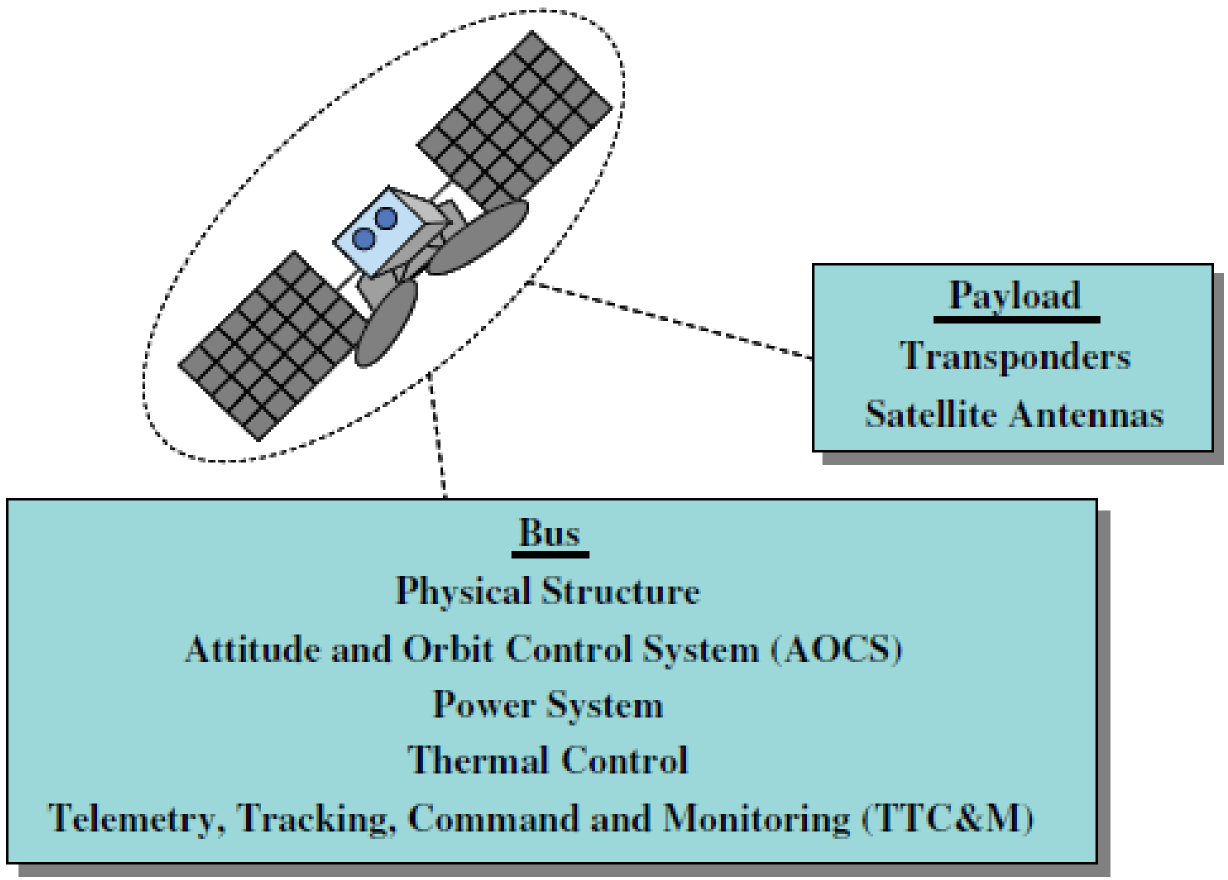


Figure 3.2 Communications satellite subsystems.

Satellite Bus subsystems

1. Physical Structure
    1. Spin Stabilization
    2. *2.* Three-Axis Stabilization
2. Power Subsystem
3. Attitude Control
4. Orbital Control
5. Thermal Control
6. Electronic Propulsion Satellites
7. Tracking, Telemetry, Command, and Monitoring

1- Physical Structure

- The physical structure of the satellite provides a "home" for all of the components of the satellite.
- The basic shape of the structure depends on the method of stabilization employed to keep the satellite stable and pointing in the desired direction, usually to keep the antennas properly oriented toward earth.
- Two methods are commonly employed:
  - ***spin stabilization, and three-axis or body stabilization.***
  - Both methods are used for GSO and for NGSO satellites.

1.1- Spin Stabilization

- A spin stabilized satellite is usually cylindrical in shape, since the satellite is required to be mechanically balanced about an axis, so that it can be maintained in orbit by spinning on its axis.
- For GSO satellites, the spin axis is maintained parallel to the spin axis of the earth, with spin rates in the range of 50 to 100 revolutions per minute.
- The spinning satellite will maintain its correct attitude without additional effort, unless disturbance torques are introduced.
- Undesired torques can be generated by external forces such as solar radiation, gravitational gradients, and meteorite impacts.
- Internal effects such as motor bearing friction and antenna subsystem movement can also produce unwanted torque in the system. Impulse type thrusters, or jets, are used to maintain spin rate and correct any wobbling or nutation to the satellite spin axis.

Spin Stabilized Satellite
(Cylindrical Structure)

Figure 3.3 Physical structure.

- The entire spacecraft rotates for spin stabilized satellites, which employ omnidirectional antennas.
- When directional antennas are used, which is the prevalent case, the antenna subsystem must be despun, so that the antenna is kept properly pointed toward earth.
- The antenna subsystem is mounted on a platform or shelf, which may also contain some of the transponder equipment.
- The satellite is spun up by small radial gas jets on the surface of the drum.
- The rotation, ranging from 30 to 100 rpm, provides gyroscopic force stability for the satellite.
- The propellants used include heated hydrazine or a bipropellant mix of hydrazine and nitrogen tetroxide.
- The despun platform is driven by an electric motor in the opposite direction of the satellite spin, on the same spin axis and at the same spin rate as the satellite body, to maintain a fixed orientation for the antennas, relative to earth.

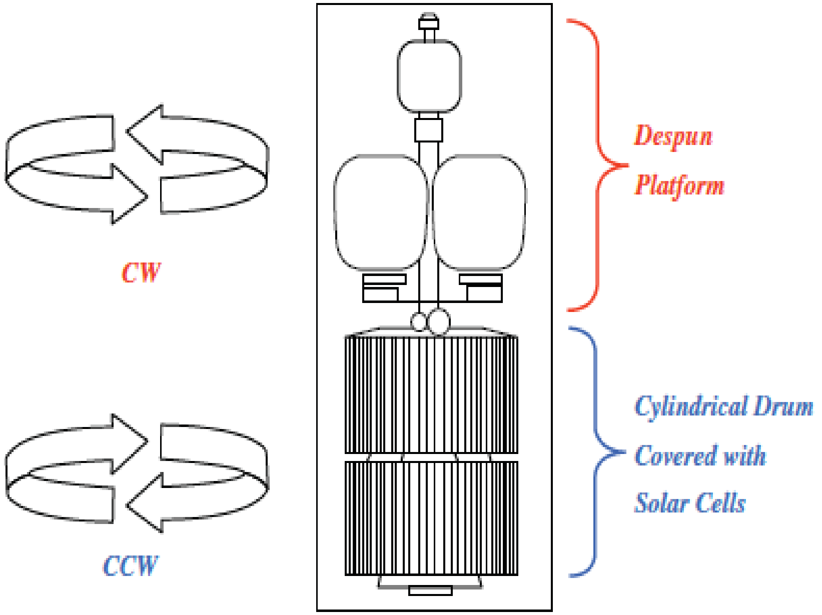


Figure 3.4 Despun platform on spin stabilized satellite.

1.2- Three-Axis Stabilization

- A three-axis stabilized satellite is maintained in space with stabilizing elements for each of the three axes, referred to as roll, pitch, and yaw.
- The entire body of the spacecraft remains fixed in space, relative to the earth, which is why the three-axis stabilized satellite is also referred to as a body stabilized satellite.
- Active attitude control is required with three-axis stabilization.
- Control jets or reaction wheels are used, either separately or in combination, to provide correction and control for each of the three axes.
- A reaction wheel is basically a flywheel that absorbs the undesired torques that would shift spacecraft orientation.
- Fuel is expended for both the control jets and for the reaction wheels, which must periodically be “unloaded” of momentum energy that builds up in the wheel.
- The three-axis stabilized satellite does not need to be symmetric or cylindrical, and most tend be box-like, with numerous appendages attached.
- Typical appendages include antenna systems and solar cell panels, which are often unfurled after placement at the on-orbit location.

Body Stabilized

or

Three-Axis Stabilized Satellite

(*Box Structure*)

2- Power Subsystem

- The electrical power for operating equipment on a communications satellite is obtained primarily from solar cells, which convert incident sunlight into electrical energy.
- The radiation on a satellite from the sun has an intensity averaging about 1.4 kW/m^2.
- Solar cells operate at an efficiency of 20–25% at *beginning of life (BOL), and can degrade to* 5–10% at *end of life (EOL), usually considered as 15 years.*
  - Because of this, large numbers of cells, connected in serial-parallel arrays, are required to support the communications satellite electronic systems, which often require more than one to two kilowatts of prime power to function.

2- Power Subsystem (continued)

- The spin-stabilized satellite usually has cylindrical panels, which may be extended after deployment to provide additional exposure area.
  - A cylindrical spin-stabilized satellite must carry a larger number of solar cells than an equivalent three-axis stabilized satellite, since only about one-third of the cells are exposed to the sun at any one time.
- The three-axis stabilized satellite configuration allows for better utilization of solar cell area, since the cells can be arranged in flat panels, or sails, which can be rotated to maintain normal exposure to the sun – levels up to 10 kW are attainable with rotating panels.
- All spacecraft must also carry storage batteries to provide power during launch and during eclipse periods when sun blockage occurs.
- The power generating and control systems on a communications satellite account for a large part of its weight, often 10 to 20% of total dry weight.

3- Attitude Control

- The attitude of a satellite refers to its orientation in space with respect to earth.
- Attitude control is necessary so that the antennas, which usually have narrow directional beams, are pointed correctly towards earth.
- Several forces can interact to affect the attitude of the spacecraft.
  - These include gravitational forces from the sun, moon, and planets; solar pressures acting on the spacecraft body, antennas, or solar panels; and earth's magnetic field.
- Orientation is monitored on the spacecraft by infrared **horizon detectors,** which detect the rim of earth against the background of space.
- Four detectors are used to establish a reference point, usually the center of the earth, and any shift in orientation is detected by one or more of the sensors.
- A control signal is generated, which activates attitude control devices to restore proper orientation.
- Gas jets, ion thrusters, or momentum wheels are used to provide active attitude control on communications satellites.

4- Orbital Control

- Often called station keeping, is the process required to maintain a satellite in its proper orbit location.
- It is similar to, although not functionally the same, as attitude control.
- GSO satellites will undergo forces that would cause the satellite to drift in the east-west (longitude) and north-south (latitude) directions, as well as in altitude, if not compensated for with active orbital control jets.
- Orbital control is usually maintained with the same thruster system as is attitude control.

4- Orbital Control (Continued)

- The expendable fuel that must be carried on-board the satellite to provide orbital and attitude control is usually the determining factor in the on-orbit lifetime of a communications satellite.
  - As much as one-half of the satellite launch weight is station-keeping fuel.
  - The lifetimes of most of the critical electronic and mechanical components usually exceed the allowable time for active orbit control, which is limited by the weight of fuel that can be carried to orbit with current conventional launch vehicles.
  - It is not unusual for a communications satellite to “run out of fuel” with most of its electronic communications subsystems still functioning.

5- Thermal Control

- Orbiting satellites will experience large temperature variations, which must be controlled in the harsh environment of outer space.
- Thermal radiation from the sun will heat one side of the spacecraft, whereas the side facing outer space is exposed to the extremely low temperatures of space.
- Much of the equipment in the satellite itself will generate heat, which must be controlled.
- Low orbiting satellites can also be affected by thermal radiation reflected from the earth itself.

5- Thermal Control (continued)

- Several techniques are employed to provide thermal control in a satellite.
  - **Thermal blankets and thermal shields are** placed at critical locations to provide insulation.
  - **Radiation mirrors** are placed around electronic subsystems, particularly for spin stabilized satellites, to protect critical equipment.
  - **Heat pumps** are used to relocate heat from power devices such as traveling wave power amplifiers to outer walls or heat sinks to provide a more effective thermal path for heat to escape.
  - **Thermal heaters** may also be used to maintain adequate temperature conditions for some components, such as propulsion lines or thrusters, where low temperatures would cause severe problems.

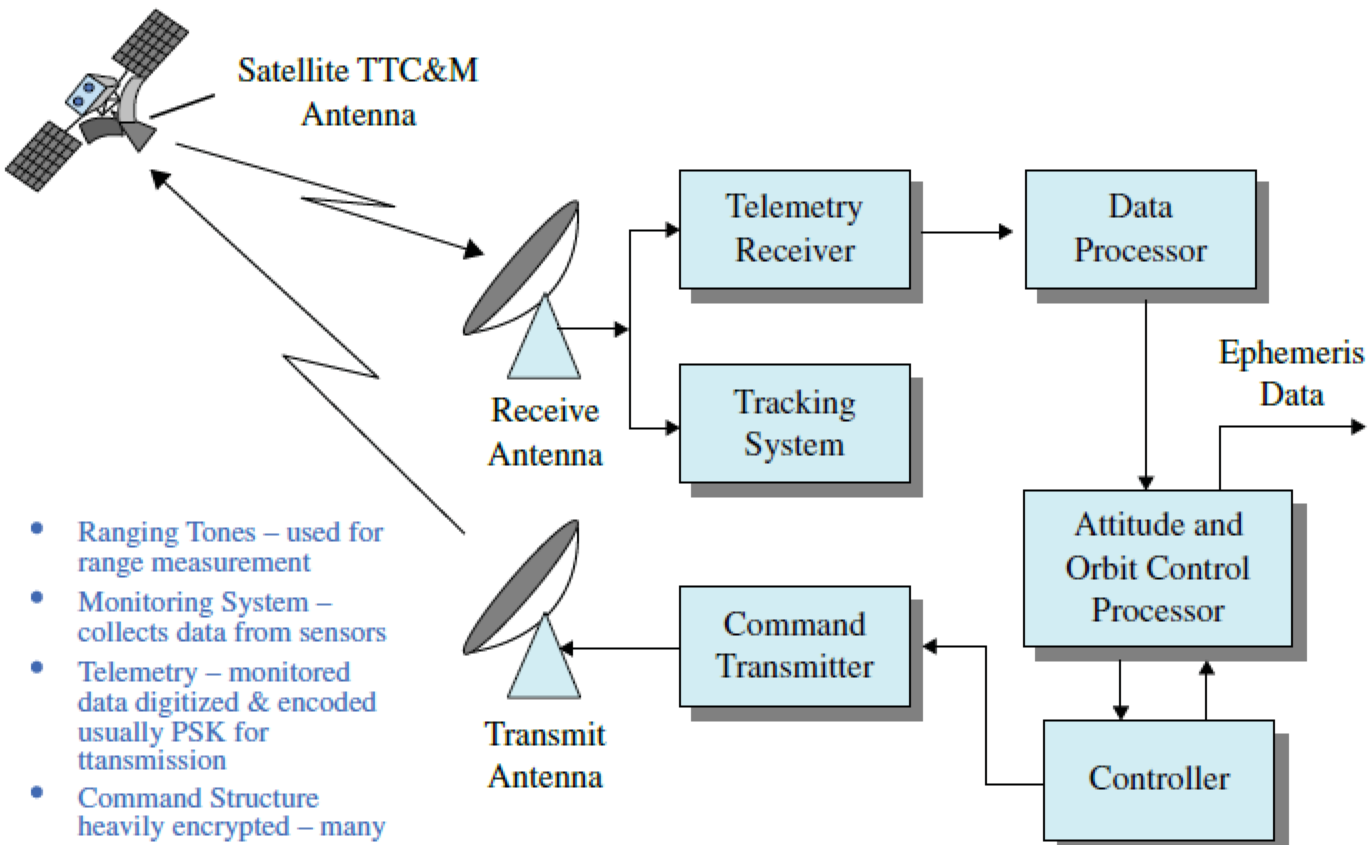
6- Electronic Propulsion Satellites

- The term **all electric satellite** is often used to describe recent technology developments focusing on the use of electric powered spacecraft propulsion instead of chemical propulsion for satellite attitude and orbit control.
- Electric propulsion thrust is much weaker than chemical propulsion, so orbital maneuvers can take significantly longer (up to six months longer) to achieve final orbit.
- Electric thrusters use less propellant than chemical rockets but can provide a small thrust for extended periods of time.
- High speeds can be achieved over the extended periods, which make electric propulsion a popular option for deep space missions.

6- Electronic Propulsion Satellites (continued)

- Two direct benefits derived from electric propulsion are:
  - Spacecraft **payload can be increased because of weight savings from removal of** chemical propellant storage on-board the spacecraft.
  - Reduced spacecraft weight can lower **launch costs – a smaller launch vehicle can be** used, or multiple satellites can be launched from the single launch vehicle.
- The first U.S. spacecraft bus to employ all electric propulsion was the Boeing 702SP, introduced in 2012.

7- Tracking, Telemetry, Command, and Monitoring



- Ranging Tones – used for range measurement
- Monitoring System – collects data from sensors
- Telemetry – monitored data digitized & encoded usually PSK for ttansmission
- Command Structure heavily encrypted – many built in checks

Figure 3.7 Tracking, telemetry, command, and monitoring (TTC&M).

Main functions of TTC&M

- One TTC&M facility may maintain several spacecraft simultaneously in orbit through TTC&M links to each vehicle.
- The satellite TTC&M subsystems consist of the antenna, command receiver, tracking and telemetry transmitter, and possibly tracking sensors.
- Telemetry data is received from the other subsystems of the spacecraft, such as the payload, power, attitude control, and thermal control.
- Command data is relayed from the command receiver to other subsystems to control such parameters as antenna pointing, transponder modes of operation, battery, and solar cell changes, and so on.
- The elements on the ground include the TTC&M antenna, telemetry receiver, command transmitter, tracking subsystem, and associated processing and analysis functions.
- Satellite control and monitor is accomplished through monitors and keyboard interface.
- Major operations of TTC&M may be automated, with minimal human interface required.

7.1- Tracking

- Refers to the determination of the current orbit, position and movement of the spacecraft.
- The tracking function is accomplished by a number of techniques, usually involving satellite beacon signals that are received at the satellite TTC&M earth station.
- The Doppler shift of the beacon (or the telemetry carrier) is monitored to determine the rate at which the range is changing (the range rate).
- Angular measurements from one or more earth terminals can be used to determine spacecraft location.
- The range can be determined by observing the time delay of a pulse or sequence of pulses transmitted from the satellite.
- Acceleration and velocity sensors on the satellite can be used to monitor orbital location and changes in orbital location.

7.2- Telemetry

- It involves the collection of data from sensors on-board the spacecraft and the relay of this information to the ground.
- The telemetered data includes such parameters as: voltage and current conditions in the power subsystem, temperature of critical subsystems, status of switches and relays in the communications and antenna subsystems, fuel tank pressures, and attitude control sensor status.
- A typical communications satellite telemetry link could involve over 100 channels of sensor information, usually in digital form, but occasionally in analog form for diagnostic evaluations.
- The telemetry carrier modulation is typically frequency or phase shift keying, FSK or PSK, with the telemetry channels transmitted in a time division multiplex, TDM, format.
- Telemetry channel data rates are low, usually only a few Kbps.

7.3- Command

- It is the complimentary function to telemetry. The command system relays specific control and operations information from the ground to the spacecraft, often in response to telemetry information received from the spacecraft.
- Parameters involved in typical command links include:
  - changes and corrections in attitude control and orbital control
  - antenna pointing and control
  - transponder mode of operation
  - battery voltage control.
- The command system is utilized during launch to control the firing of the boost motor, deploy appendages such as solar panels and antenna reflectors, and to “spin up” a spin stabilized spacecraft body.

7.3- Command (continued)

- Security is an important factor in the command system for a communications satellite.
  - The structure of the command system must contain safeguards against intentional or unintentional signals corrupting the command link, or unauthorized commands from being transmitted and accepted by the spacecraft.
  - Command links are nearly always encrypted with a secure code format to maintain the health and safety of the satellite.
  - The command procedure also involves multiple transmissions to the spacecraft, to assure the validity and correct reception of the command, before the execute instruction is transmitted.

Satellite Payload

1. Transponder
    1. Frequency Translation Transponder
    2. On-Board Processing Transponder
2. Antennas
    1. Antenna Parameters
    2. Common types of antennas

1- The transponder

- The transponder in a communications satellite is the series of components that provides the communications channel, or link, between the uplink signal received at the uplink antenna, and the downlink signal transmitted by the downlink antenna.
- A typical communications satellite will contain several channels or transponders, and some of the equipment may be common to more than one channel.

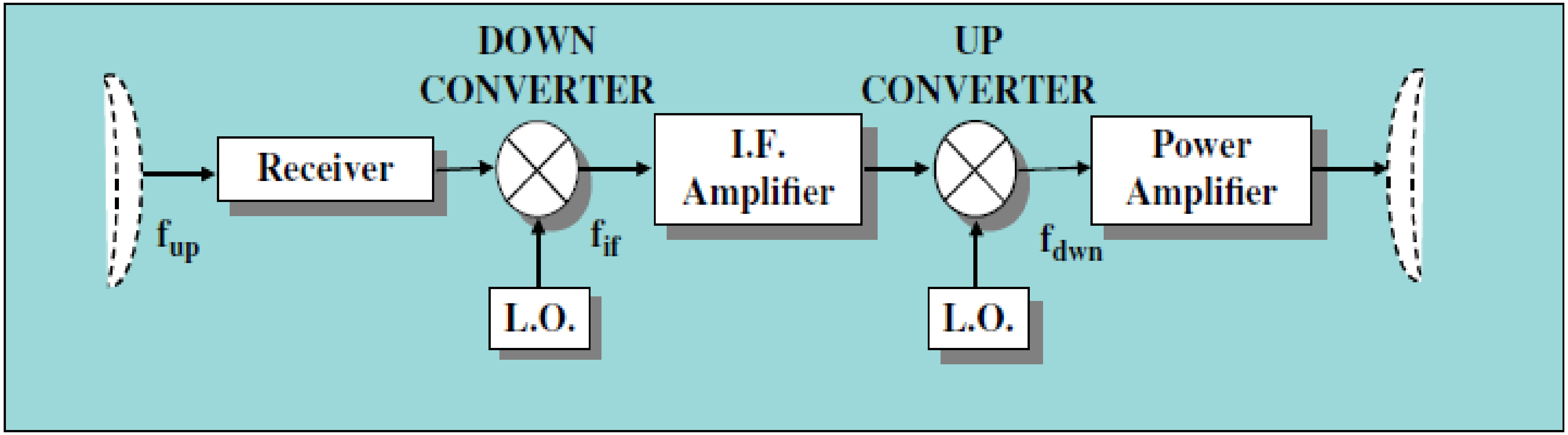
1- The transponder (continued)

- Each transponder generally operates in a different frequency band, with the allocated frequency spectrum band divided into slots, with a specified center frequency and operating bandwidth.
  - The C-band FSS service allocation, for example, is 500 MHz wide. A typical design would accommodate 12 transponders, each with a bandwidth of 36 MHz, with guard bands of 4MHz between each.
  - A typical commercial communications satellite today can have 24 to 48 transponders, operating in the C-band, Ku-band, or Ka-bands.

- The communications satellite transponder is implemented in one of two general types of configurations:
  - the frequency translation transponder, and the on-board processing transponder

1.1- Frequency Translation Transponder

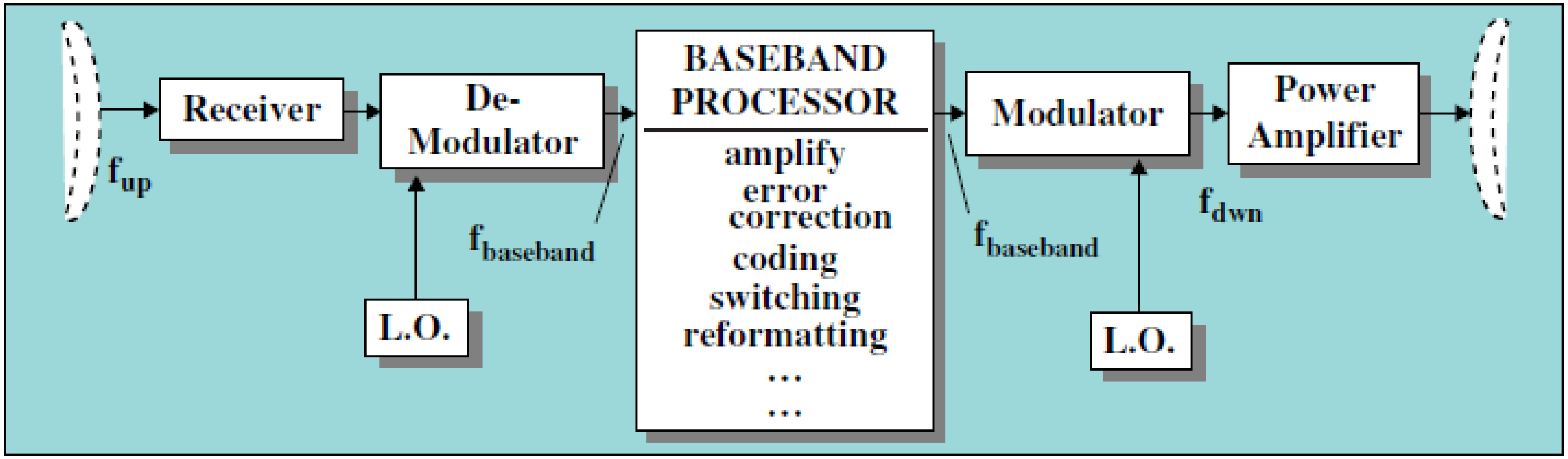
- Receives the uplink signal, and, after amplification, retransmits it with only a translation in carrier frequency.



- Frequency Translation Transponder, also called
  - Repeater
  - Non-Regenerative Satellite
  - 'Bent Pipe'
- The dominant type of transponder currently in use
  - FSS, BSS, MSS
- Uplinks and downlinks are codependent

1.2- On-Board Processing Transponder

- The uplink signal at f_{up} is demodulated to baseband, $f_{baseband}$.
- The baseband signal is available for processing on-board, including reformatting and error-correction.
- The baseband information is then re-modulated to the downlink carrier at f_{dwn}, possibly in a different modulation format than the uplink, and, after final amplification, transmitted to the ground.
- The demodulation/remodulation process removes uplink noise and interference from the downlink, while allowing additional on-board processing to be accomplished.
- Thus the uplinks and downlinks are independent with respect to evaluation of overall link performance.



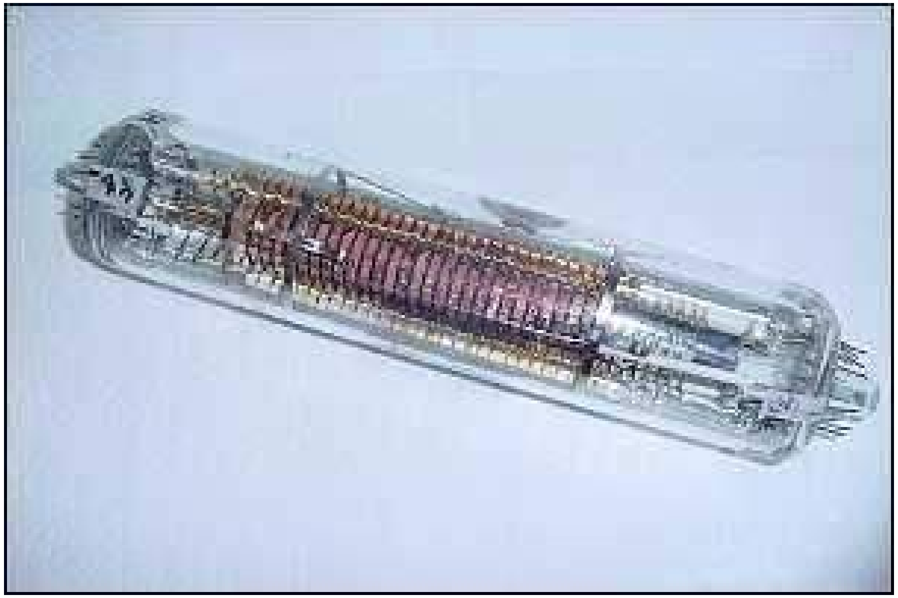
- On-Board Processing Transponder, also called
  - Regenerative Repeater
  - Demod/Remod Transponder
  - 'Smart Satellite'
- First generation systems:
  - ACTS, MILSTAR, IRIDIUM, …
- Uplinks and downlinks are independent

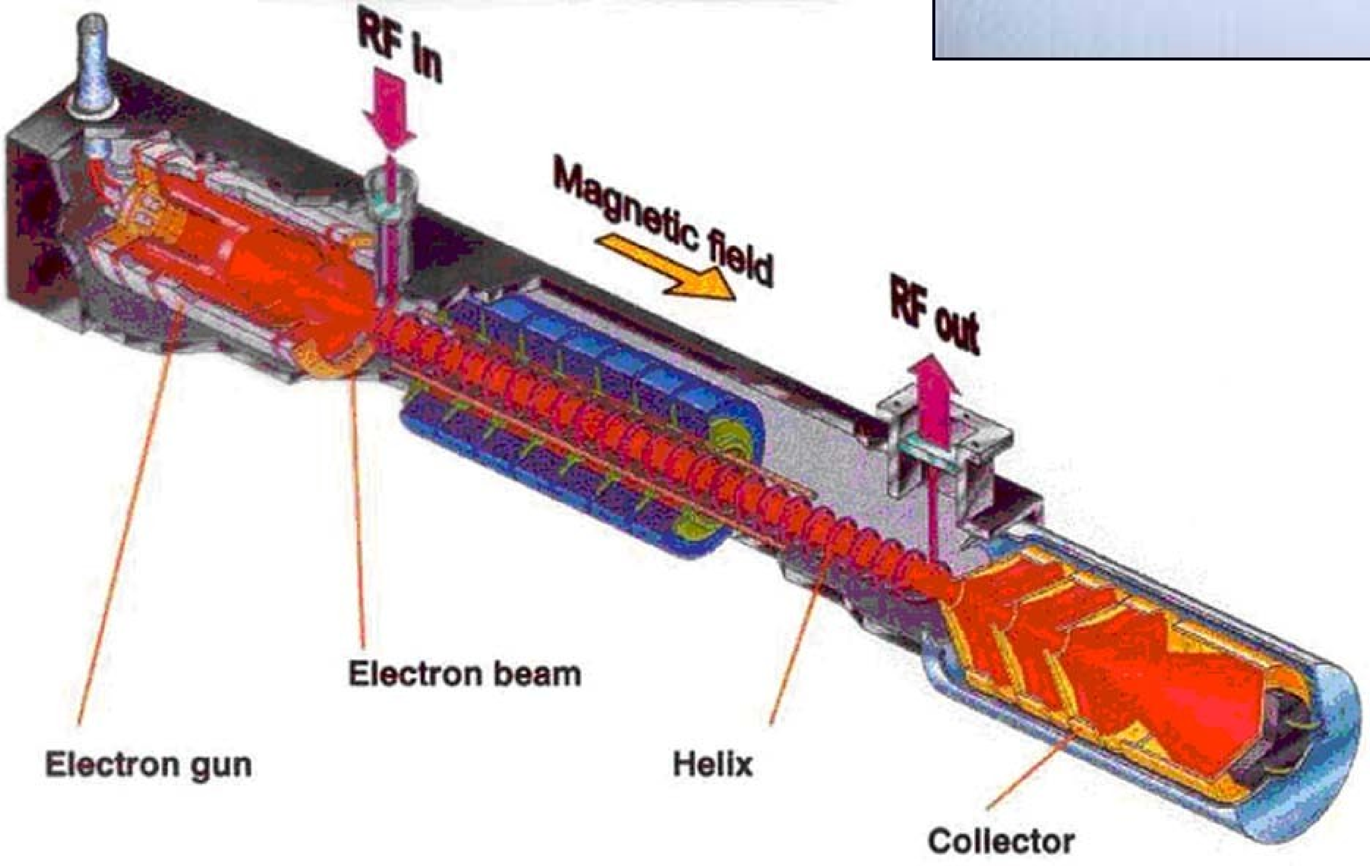
Figure 3.9 On-board processing transponder.

- On-board processing satellites tend to be more complex and expensive than frequency translation satellites; however they offer significant performance advantages, particularly for small terminal users or for large diverse networks

Traveling wave tube amplifiers

- TWTAs, or solid state power amplifiers, SSPAs are used to provide the final output power required for each transponder channel.
- The TWT is a slow wave structure device, which operates in a vacuum envelope, and requires permanent magnet focusing and high voltage DC power supply support systems.
- The major advantage of the TWT is its wide bandwidth capability at microwave frequencies.




RF in
Magnetic field
RF out
Electron beam
Electron gun
Helix
Collector

2- Antennas

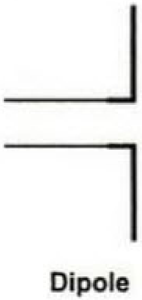
- Used for transmitting and receiving the RF signals which comprise the space links of the communications channels.
- The antenna system is the essential element in increasing the strength of the transmitted or received signal to allow amplification, processing, and eventual retransmission.
- The most important parameters that define the performance of an antenna are:
  - antenna gain, antenna beamwidth, and antenna sidelobes

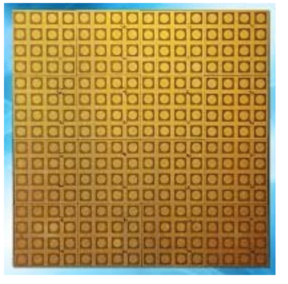
2.1- Antenna Parameters

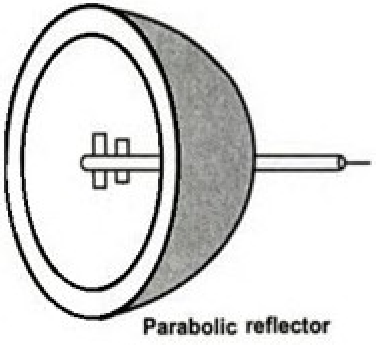
- The **gain** defines the increase in strength achieved in concentrating the radiowave energy, either in transmission or reception, by the antenna system.
  - The antenna gain is usually expressed in dBi, decibels above an isotropic antenna, which is an antenna that radiates uniformly in all directions.
- The **beamwidth** is usually expressed as the half-power beamwidth or the 3-dB beamwidth, which is a measure of the angle over which maximum gain occurs.
- The **sidelobes** define the amount of gain in the off-axis directions.
- Most satellite communications applications require an antenna to be highly directional (high gain, narrow beamwidth) with negligibly small sidelobes.

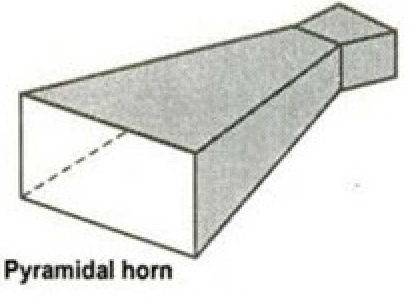
2.2- Common types of antennas

1. Linear dipole
2. Horn antenna
3. Parabolic reflector
4. Array antenna









2.2.1- Linear dipole antenna

- It is an isotropic radiator which radiates uniformly in all directions.
- Four or more dipole antennas are placed on the spacecraft to obtain a nearly omni-directional pattern.
- Dipole antennas are used primarily at VHF and UHF for tracking, telemetry and command links.
- Dipole antennas are also important during launch operations, where the spacecraft attitude has not yet been established, and for satellites that operate without attitude control or body stabilization (particularly for LEO systems).

2.2.2- Horn antennas

- Used at frequencies from about 4 GHz and up, when relatively wide beams are required, such as global coverage from a GSO satellite.
- A horn is a flared section of waveguide, which provides gains of up to about 20 dBi, with beamwidths of 10^{o} or higher.
- If higher gains or narrower bandwidths are required, then a reflector or array antenna must be used.

2.2.3- Parabolic reflector antenna

- The most often used antenna for satellite systems, particularly for those operating above 10 GHz.
- Parabolic reflector antennas are usually illuminated by one or more horn antenna feeds at the focus of the paroboloid.
- Parabolic reflectors offer a much higher gain than that achievable by the horn antenna alone.
- Gains of 25 dB and higher, with beamwidths of 1^o or less, are achievable with parabolic reflector antennas operating in the C, Ku, or Ka bands.
- Narrow beam antennas usually require physical pointing mechanisms (gimbals) on the spacecraft to point the beam in the desired direction.

2.2.4- Array antennas

- There is an increasing interest in the use of array antennas for satellite communications applications.
- A steerable, focused beam can be formed by combining the radiation from several small elements made up of dipoles, helices, or horns.
- Beam forming can be achieved by electronically phase shifting the signal at each element.
- Proper selection of the phase characteristics between the elements allows the direction and beamwidth to be controlled, without physical movement of the antenna system.
- The array antenna gain increases with the square of the number of elements.
- Gains and beamwidths comparable to those available from parabolic reflector antennas can be achieved with array antennas.