

Satellite and Optical Communication

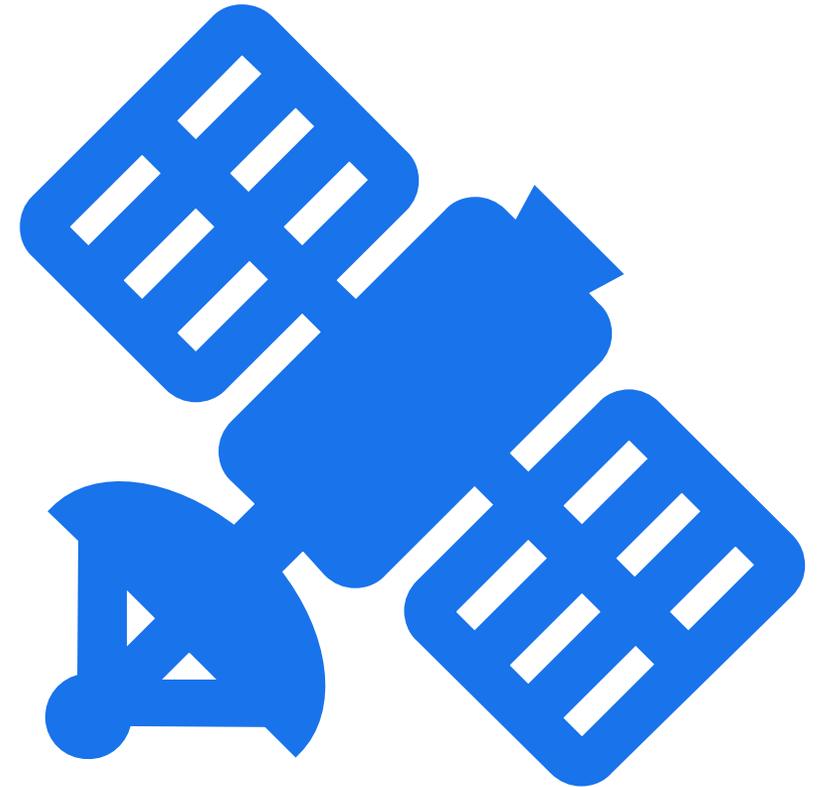
BEC515D

MODULE 2

Satellite Subsystems

Satellite Subsystems

- Different subsystems comprising a typical satellite include the following:
 1. Mechanical structure
 2. Propulsion subsystem
 3. Thermal control subsystem
 4. Power supply subsystem
 5. Telemetry, tracking and command (TT&C) subsystem
 6. Attitude and orbit control subsystem
 7. Payload subsystem
 8. Antenna subsystem



Mechanical Structure

- The *mechanical structural subsystem* provides the framework for mounting other subsystems of the satellite and also an interface between the satellite and the launch vehicle.

Propulsion Subsystem

- The *propulsion subsystem* is used to provide the thrusts required to impart the necessary velocity changes to execute all the manoeuvres during the lifetime of the satellite.
- This would include major manoeuvres required to move the satellite from its transfer orbit to the geostationary orbit in the case of geostationary satellites and also the smaller manoeuvres needed throughout the lifespan of the satellite, such as those required for station keeping.

Thermal Control Subsystem

- The *thermal control subsystem* is essential to maintain the satellite platform within its operating temperature limits for the type of equipment on board the satellite.
- It also ensures the desirable temperature distribution throughout the satellite structure, which is essential to retain dimensional stability and maintain the alignment of certain critical equipments.

Power Supply Subsystem

- The primary function of the *power supply subsystem* is to collect the solar energy, transform it to electrical power with the help of arrays of solar cells and distribute electrical power to other components and subsystems of the satellite.
- In addition, the satellite also has batteries, which provide standby electrical power during eclipse periods, during other emergency situations and also during the launch phase of the satellite when the solar arrays are not yet functional.

Telemetry, Tracking and Command (TT&C) Subsystem

- The *telemetry, tracking and command (TT&C) subsystem* monitors and controls the satellite right from the lift-off stage to the end of its operational life in space.
 - The tracking part of the subsystem determines the position of the spacecraft and follows its travel using angle, range and velocity information.
 - The telemetry part gathers information on the health of various subsystems of the satellite, encodes this information and then transmits the same.
 - The command element receives and executes remote control commands to effect changes to the platform functions, configuration, position and velocity.

Attitude and Orbit Control Subsystem

- The *attitude and orbit control subsystem* performs two primary functions.
 - It controls the orbital path, which is required to ensure that the satellite is in the correct location in space to provide the intended services.
 - It also provides attitude control, which is essential to prevent the satellite from tumbling in space and also to ensure that the antennae remain pointed at a fixed point on the Earth's surface.

Payload Subsystem

- *The **payload subsystem*** is that part of the satellite that carries the desired instrumentation required for performing its intended function and is therefore the most important subsystem of any satellite.
- The nature of the payload on any satellite depends upon its mission.
 - In communication satellites, the transponder is the basic payload, which acts as a receiver, an amplifier and a transmitter.
 - In a weather forecasting satellite, a radiometer is the most important payload.
 - In a remote sensing satellite, high resolution cameras, multispectral scanners and thematic mappers are the main payloads
 - In scientific satellites, telescopes, spectrographs, plasma detectors, magnetometers, spectrometers, etc. are the payload, depending upon the mission

Antenna Subsystem

- *Antennas* are used for both receiving signals from ground stations as well as for transmitting signals towards them.
- There are a variety of antennas available for use on board a satellite.
 - The final choice depends mainly upon the frequency of operation and required gain.
- Typical antenna types used on satellites include horn antennas, centre-fed and offset-fed parabolic reflectors and lens antennas.

Power Supply Subsystem



Power Supply Subsystem

- The power supply subsystem generates, stores, controls and distributes electrical power to other subsystems on board the satellite platform.
- The electrical power needs of a satellite depend upon the intended mission of the spacecraft and the payloads that it carries along with it in order to carry out the mission objectives.
- The power requirement can vary from a few hundreds of watts to tens of kilowatts.

Types of Power System

- Satellite power systems use:
 - Solar energy
 - Chemical energy (Batteries)
 - Nuclear energy
- Solar energy is the most widely used
 - Reason: Abundant and uninterrupted sunlight in space

Solar Power Systems

- Based on photon energy in solar radiation
- Solar constant: $\sim 1370 \text{ W/m}^2$ at Earth's orbit
- Primary method for satellite power generation

Heat Generators

- Use heat energy from solar radiation
- Parabolic mirror → Boiler → Generator → Electricity
- Advantages: Renewable, efficient under sunlight
- Disadvantages: Very large & heavy → suitable only for large satellites
- Can be combined with rechargeable batteries

Batteries

- Store power as chemical energy
- Always used with solar power generators
- Function:
 - Charged during sunlight exposure
 - Provide power during eclipse periods
- Only rechargeable batteries used

Nuclear Power Systems

- Generated via Radioisotope Thermoelectric Generators (RTGs)
- Current tech: Nuclear fission
- Future possibility: Nuclear fusion
- Advantage: Practically limitless power supply
- Limitation: Radioactive risk if launch fails
- Applications:
 - Not used for Earth-orbiting satellites
 - Orbit decay → re-entry → radioactive spread
 - Used for deep space exploration
 - Far from Sun → solar energy ineffective
 - Not economical for commercial satellites



Solar Energy Driven Power Systems

Solar Energy Driven Power Systems

- The major components of a solar power system are the
 - solar panels (of which the solar cell is the basic element)
 - rechargeable batteries
 - battery chargers with inbuilt controllers
 - regulators and inverters
- During the sunlight condition, the voltage of the solar generator and also the bus is maintained at a constant amplitude with the voltage regulator connected across the solar generator.
- The battery is decoupled from the bus during this time by means of a battery discharge regulator (BDR) and is also charged using the battery charge regulator (BCR).
- During the eclipse periods, the battery provides power to the bus and the voltage is maintained constant by means of the BDR.

Solar Energy Driven Power Systems

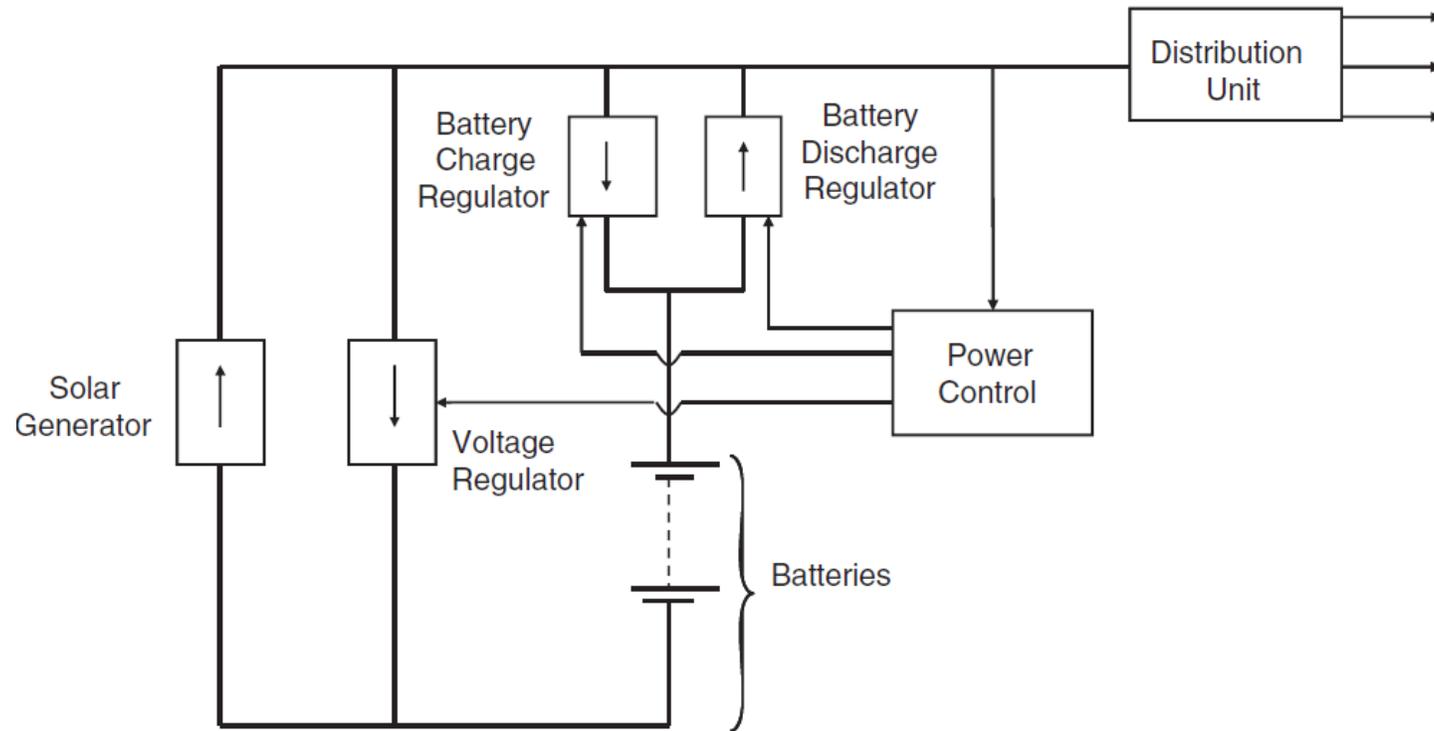
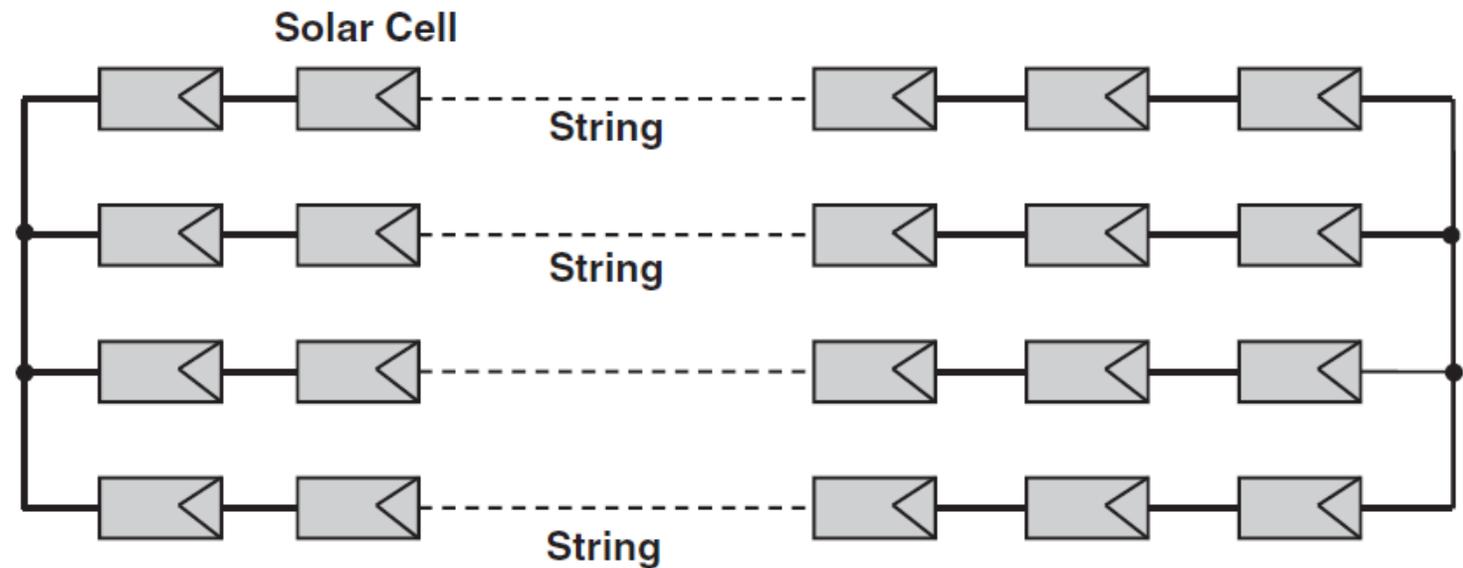


Figure 4.13 Basic block schematic arrangement of a regulated bus power supply system

Solar Panels

- The solar panel is nothing but a series and parallel connection of a large number of solar cells.



(a)

Figure 4.14 (a) Series–parallel arrangement of solar cells

Solar Panels

- Individual solar cells produce very little power.
- Solar panels use a series-parallel arrangement to achieve the required voltage and power output.
- A balance must be struck between the need for large panels to generate power and the need for a light, small satellite.

Solar Panels

Three-Axis Body Stabilized Satellites

- **Panel Type:** Use flat solar panels.
- **Advantage:** Panels can be rotated to constantly face the sun, intercepting maximum solar energy.
 - *Example: 15-foot long panels on Intelsat-V satellites produce over 1.2 kW of power.*
- **Disadvantage:** Panels operate at higher temperatures and have reduced efficiency because they are always in direct sunlight.

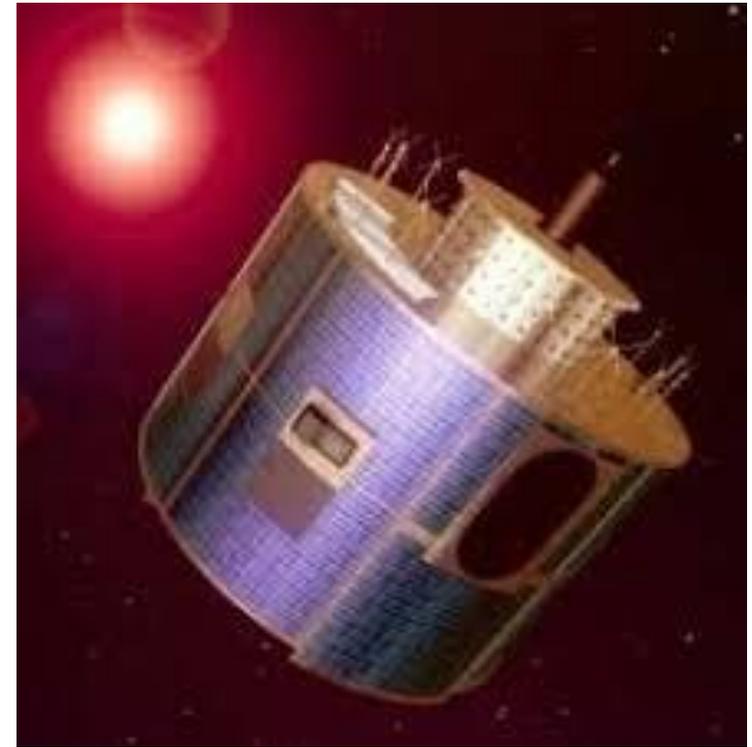


Flat solar panels used on three-axis stabilized satellites

Solar Panels

Spin-Stabilized Satellites

- **Panel Type:** Use cylindrical solar panels.
- **Advantage:** Cells cool down when in shadow, leading to higher efficiency.
- **Disadvantage:** Only about one-third of the cells face the sun at any given time, requiring a much larger number of cells to achieve the same power output.
 - This results in an increase in the satellite's mass.



Cylindrical solar panels used on spin-stabilized satellites

Solar Panels

- For newer satellites requiring higher power, the balance is shifting towards three-axis stabilized designs.
- The high power output of the three-axis stabilized design outweighs its thermal inefficiency for these modern missions.

Principle of Operation of a Solar Cell

- The operational principle of the basic solar cell is based on the *photovoltaic effect*.
- According to the photovoltaic effect, there is a generation of an open circuit voltage across a P-N junction when it is exposed to light, which is the solar radiation in the case of a solar cell.
- This open circuit voltage leads to a flow of electric current through a load resistance connected across it.

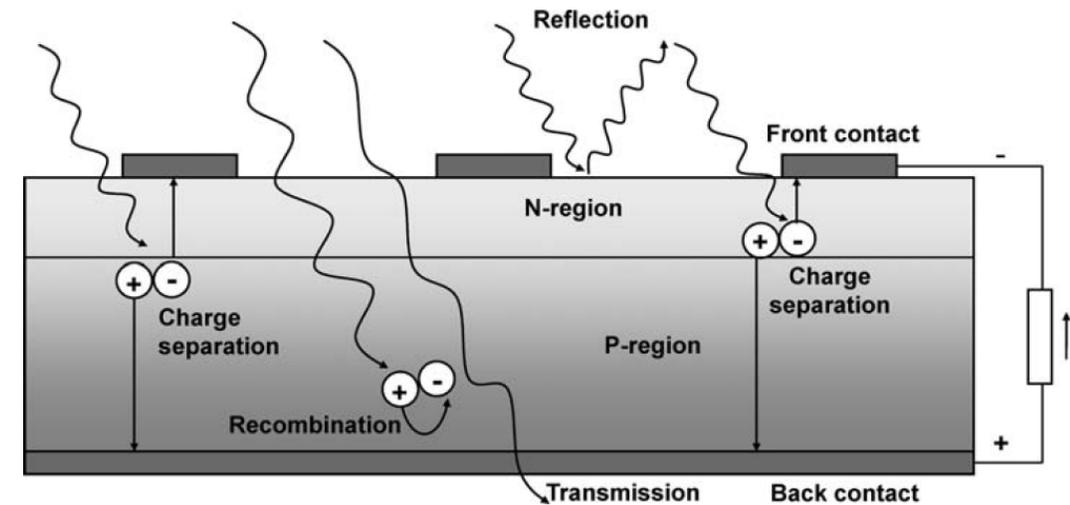


Figure 4.17 Principle of operation of a solar cell

Principle of Operation of a Solar Cell

- The impinging photon energy leads to the generation of electron–hole pairs.
- The electron–hole pairs either recombine and vanish or start to drift in the opposite directions, with electrons moving towards the N-layer and holes moving towards the P-layer.
- This accumulation of positive and negative charge carriers constitutes the open circuit voltage.
- This voltage can cause a current to flow through an external load.
- When the junction is shorted, the result is a short circuit current whose magnitude is proportional to the incident light intensity.

Principle of Operation of a Solar Cell

- The Power-Voltage (P-V) curve shows that a solar cell has a distinct operating point where it generates maximum power.
 - This optimal point is known as the *Maximum Power Point (MPP)*.
- The voltage and current at this peak (V_{MPP} and I_{MPP}) are always less than the cell's open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) respectively

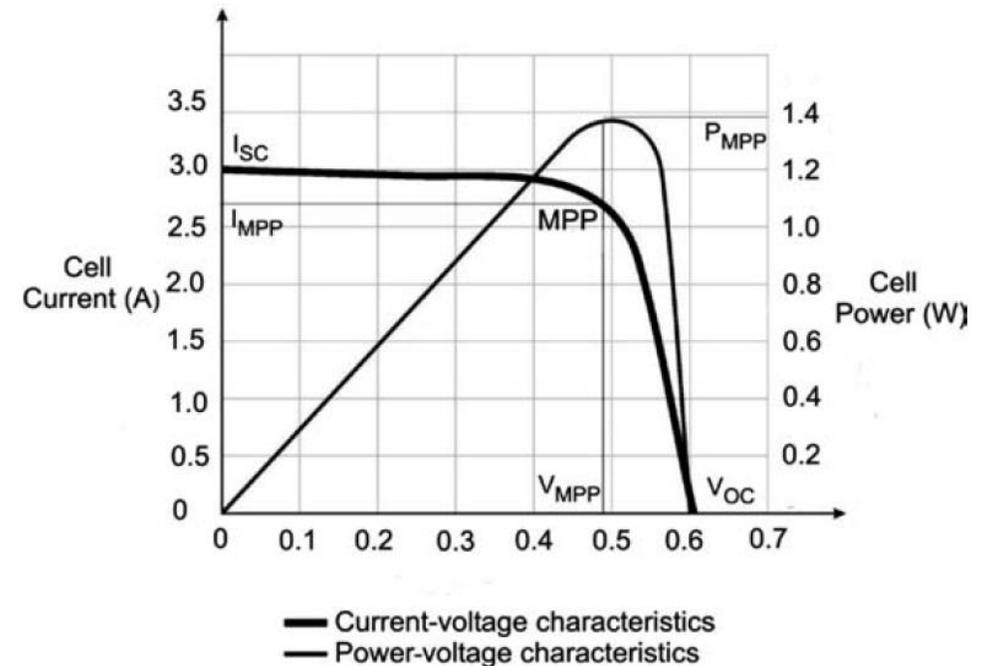


Figure 4.18 Current-voltage and power-voltage characteristics of a solar cell

Principle of Operation of a Solar Cell

- **Solar Cell Efficiency:** The ratio of electrical power output to incident light power.
 - Modern crystalline silicon cells can exceed 20%.
- **Key Materials used in Solar Cells:**
 - **Silicon (Si):** The most common material.
 - **Gallium Arsenide (GaAs):** A future material promising higher efficiency and lower weight.



Batteries

Batteries

- Essential for power during eclipse periods & launch phase
- Provide peak power backup when solar panels are insufficient
- Rechargeable batteries used almost invariably
- Charged during sunlight exposure
- Used during:
 - Eclipse (no sunlight)
 - Launch phase (before solar panel deployment)
 - Short-term peak power demands

Factors Governing Battery Choice

- Frequency of use
- Magnitude of load
- Depth of discharge (DoD)
- Relation to satellite orbit (LEO vs GEO)
- Temperature dependence of capacity

Orbital Considerations

- Low Earth Orbit (LEO):
 - Orbital period ~100 min
 - Eclipse: 30–40 min/orbit
 - Higher cycles, lower DoD (~40%)
- Geostationary Orbit (GEO):
 - Orbital period: 24 hrs
 - Eclipse: 0–72 min (equinoxes)
 - Lower cycles, higher DoD (~80%)

Temperature Effect on Batteries

- Battery capacity is strongly dependent on temperature
 - Example: NiMH battery
 - Max capacity at 10–15 °C
 - Decreases $\sim 1 \text{ Ah}/^\circ\text{C}$ outside this range

Battery Types & Specific Energy

- Nickel–Cadmium (NiCd): 20–30 Wh/kg
 - Used in small LEO satellites
- Nickel–Metal Hydride (NiMH): 35–55 Wh/kg
- Nickel–Hydrogen (NiH₂): 35–55 Wh/kg
 - Higher energy, longer life, used in GEO
- Lithium–Ion (Li-ion): 70–110 Wh/kg
 - Future technology, suitable for LEO/MEO/GEO

Nickel- Cadmium Batteries



Nickel–Cadmium Batteries

- Rechargeable batteries widely used in early space and household applications
 - Example: SPOT-4 Satellite Battery Pack
- **Anode (negative electrode):** Cadmium (oxidation)
- **Cathode (positive electrode):** Nickel hydroxide (reduction)
- **Electrolyte:** Alkaline solution
- **Cell Voltage:** ~1.2 V (constant discharge)



Nickel–Cadmium Batteries

- **Features**

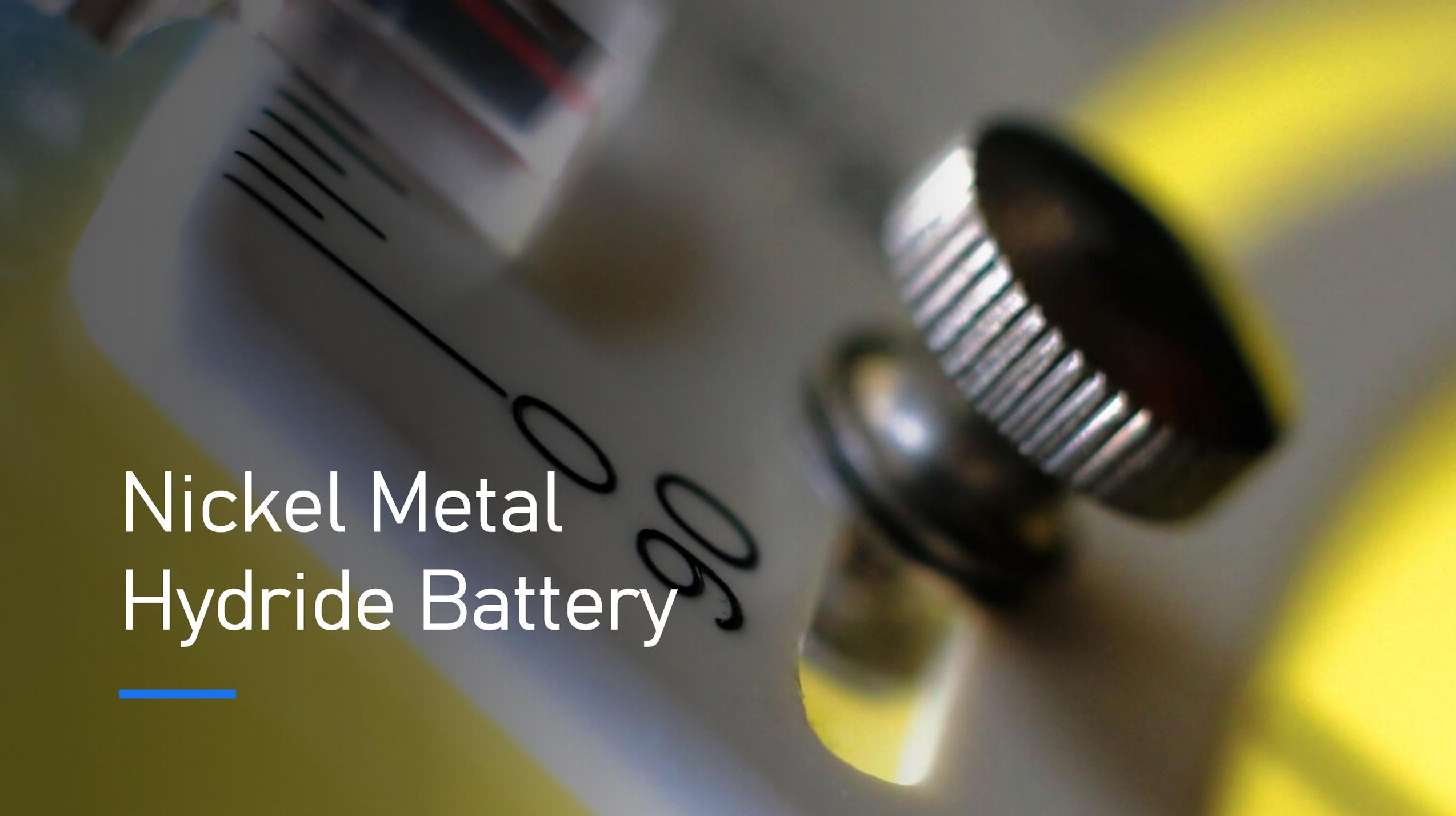
- High current capability
- Robust against cycle numbers
- Rechargeable, stable performance
- Voltage remains almost constant during discharge

- **Limitations**

- Memory Effect: Partial discharge before charging leads to reduced usable capacity
 - Prevention: Regular full charge–discharge cycles
- Cadmium Toxicity: Requires careful recycling/disposal
- Low Energy Density: Heavier than NiMH and Ni–H₂ batteries

Nickel–Cadmium Batteries

- Space Applications
 - Commonly used in LEO satellites (orbital period ~100 min; eclipse 30–40 min)
 - Example: SPOT Satellites
 - Replaced by Ni–H₂ in GEO satellites (1960s–70s)

A close-up photograph of a battery terminal. A silver screw with a ribbed head is being tightened onto a metal terminal. A white label with the handwritten number '06' is attached to the terminal. The background is a blurred yellow and grey.

Nickel Metal Hydride Battery

Nickel Metal Hydride Battery

- Cadmium-free replacement for nickel-cadmium batteries
- Higher energy density, eco-friendlier option
- **Anode:** Hydrogen storage metal alloy
- **Cathode:** Nickel oxide
- **Electrolyte:** Alkaline solution
- **Cell Voltage:** ~1.2 V

Nickel Metal Hydride Battery

- **Key Features**
 - Cadmium-free → Environmentally safer
 - Higher **energy density** → Longer run time without added weight
 - Reduced **memory effect** compared to Ni-Cd
- **Limitations**
 - Poor performance at extreme temperatures (very high or very low)
 - Not suitable for space applications
 - Shorter cycle life compared to Ni-H₂

Nickel Metal Hydride Battery

- Applications
 - Widely used in consumer electronics (cameras, toys, laptops, etc.)
 - Hybrid vehicles (e.g., early Toyota Prius)
 - Portable devices requiring rechargeable batteries



Nickel- Hydrogen Batteries

Nickel-Hydrogen Batteries

- The nickel-hydrogen battery combines the technologies of batteries and fuel cells.
- Widely used in aerospace applications
- **Anode:** Hydrogen gas (active element, like in fuel cells)
- **Cathode:** Nickel hydroxide (similar to Ni-Cd)
- **Electrolyte:** Alkaline solution
- **Design:** Pressure vessel containing hydrogen



Nickel–Hydrogen Batteries

- **Key Features**
 - High specific energy: > 50 Wh/kg
 - High power density
 - High cyclic stability: > 5000 cycles
 - Resistant to deep discharge
 - Tolerant to overcharge
- **Limitations**
 - High cost of production
 - Low volumetric energy density
 - Complex structure (requires pressure vessel)

Nickel–Hydrogen Batteries

- Space Applications
 - Ideal for LEO & GEO satellites
 - Typical Depth of Discharge (DoD):
 - LEO: ~40%
 - GEO: ~80%
 - Some satellites using Ni–H₂ batteries: Arabsat-2, Arabsat-3, Hispasat-1C, INSAT-3, Intelsat-7, Intelsat-7A, MTSat (Japan), Nstar, Superbird, Thaicom series

Lithium Ion Battery



Lithium Ion Battery

- Lightweight, high-performance satellite power source
- **Key Features**
 - Same **energy capacity** as NiMH, but **~30% lighter**
 - **No memory effect** → better recharge efficiency
 - High energy-to-weight ratio → efficient for space missions
- **Limitations**
 - Requires **special handling** → lithium is highly flammable
 - Needs advanced **safety and thermal management systems**

Lithium Ion Battery

- Space Applications
 - Suitable for LEO, MEO, and GEO satellites
 - Increasingly preferred in modern satellite missions due to weight savings

Comparison of Satellite Batteries

Feature	Ni-Cd	NiMH	Ni-H ₂	Li-Ion
Cell Voltage	~1.2 V	~1.2 V	~1.25 V	~3.6 V
Energy Density	Low	Higher than Ni-Cd	Moderate (high specific, low volumetric)	High (~30% lighter than NiMH)
Cycle Life	2000–2500	500–1000	>5000	1000–3000
Memory Effect	Severe	Mild	None	None
Toxicity / Safety	Cadmium (toxic)	Cadmium-free	Safe (high-pressure vessel)	Flammable (needs handling)
Weight	Heavy	Lighter than Ni-Cd	Heavy (pressure vessel)	Lightest
Applications	LEO satellites (SPOT)	Consumer devices, cars	LEO & GEO satellites	LEO, MEO, GEO satellites
Cost	Low	Moderate	High	High (but reducing)

Attitude and Orbit Control



Attitude and Orbit Control Subsystem

- Controls orbital path to keep satellite in correct location.
- Provides attitude control to prevent tumbling in space.
- Ensures antennae remain fixed on target point on Earth.

Attitude Control

- Attitude refers to **orientation of satellite axes (yaw, pitch, roll)** w.r.t reference plane.
- Essential during:
 - **Launch phase** – correct orientation for link & manoeuvre.
 - **In orbit** – antenna pointing & service accuracy.
- Precision depends on **antenna beam width**:
 - Spot/shaped beams → higher precision.
 - Earth/regional coverage → lower precision.

Attitude Control

- Types of Attitude Control Systems
 - Spin Stabilization
 - Pitch correction: by varying spin motor speed.
 - Yaw & Roll: by pulsing radially mounted jets.
 - Three-axis Stabilization
 - Controlled by varying speed of inertia wheel.

Attitude Control

- Gravity Gradient Boom
 - Used in LEO/MEO satellites.
 - Long pole points towards Earth's centre.
 - Exploits **difference in gravitational pull** at top & bottom.
 - Dampens oscillations → stabilizes satellite orientation.

Attitude Control

- **Passive Systems**
 - Equilibrium-based.
 - No feedback mechanism.
- **Active Systems**
 - Sense orientation → compute error → correct.
 - Components:
 - **Sensor** → detects current attitude.
 - **Computer** → calculates deviation.
 - **Control unit** → generates correction torque.

Attitude Control

- Attitude Sensors
 - Earth Sensors
 - Detect infrared emissions.
 - Control roll & pitch.
 - Sun Sensors / Star Sensors
 - Measure yaw errors.
- Error → compared with desired attitude → correction torque applied.

Orbit Control

- Orbit control corrects effects of perturbation forces
- Perturbations alter orbital parameters
- Corrections made by firing thrusters
- Used during launch and for maintaining orbit

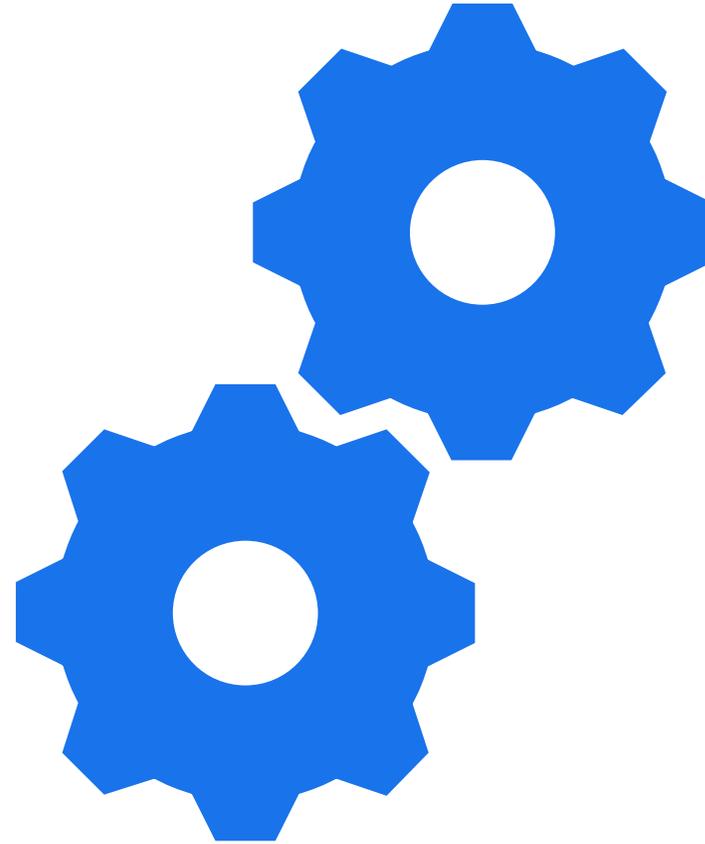
Orbit Control

- In the case of geostationary satellites, the inclination of the orbit increases at an average rate of about 0.85° per year.
- In general, the geostationary satellites have to remain within a block of $\pm 0.05^\circ$ or so.
- The east-west and north-south station keeping manoeuvres are carried out at intervals of two weeks each.
- North-south manoeuvres require more fuel to be expended than any other orbital correction.

Orbit Control

- In the case of non-circular orbits, the velocity of the satellite needs to be increased or decreased on a continuous basis.
- This is done by imparting corrections in the direction tangential to the axis lying in the orbital plane.
- In a spin stabilized satellite, radial jets are fired in this direction whereas in the case of three-axis stabilized satellites, two pairs of X-axis jets acting in opposite directions are used.

Tracking, Telemetry and Command Subsystem



Tracking, Telemetry and Command Subsystem

- The tracking, telemetry and command (TT&C) subsystem monitors and controls the satellite right from the lift-off stage to the end of its operational life in space.
- The TT&C subsystem is very important, not only during orbital injection and the positioning phase but also throughout the operational life of the satellite.
- **Tracking Function**
 - Determines the position of the spacecraft and follows its travel using angle, range and velocity information
- **Telemetry Function**
 - Gathers information on the health of various subsystems of the satellite, encodes this information and then transmits the same towards the Earth control centre.
- **Command Function**
 - Receives and executes remote control commands from the control centre on Earth to effect changes to the platform functions, configuration, position and velocity.

Tracking, Telemetry and Command Subsystem

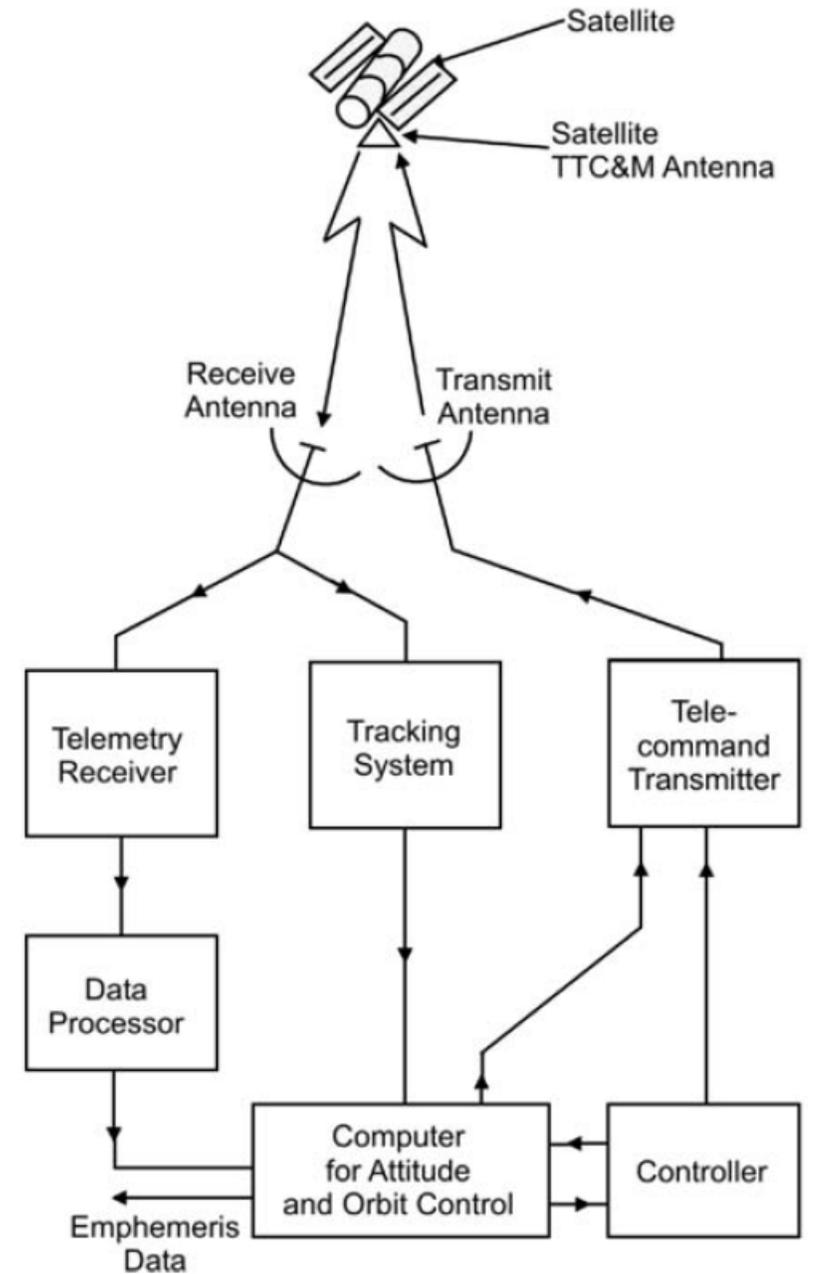


Figure 4.21 Block schematic arrangement of the basic TT&C subsystem

Tracking Function

- Determines orbital parameters regularly
- Provides look-angle info (azimuth, elevation) to Earth stations
- Techniques:
 - **Angle tracking** → azimuth & elevation
 - **Ranging** → via time interval measurement
 - The rate of change of range can be determined either by measuring the phase shift of the return signal as compared to that of the transmitted signal or by using a pseudorandom code modulation and the correlation between the transmitted and the received signals.

Telemetry Function

During Injection & Positioning

- Establishes communication with Earth control centre
- Provides data during orbital injection phase
- Enables tracking & orbit determination

Telemetry Function

In Orbit

- Monitors health of satellite subsystems
- Collects electrical & non-electrical parameters
- Digitization of analog signals when needed
- Multiplexing → **Time Division Multiplexing (TDM)**
- Low bit rate → smaller receiver bandwidth, better SNR

Command Function

- Receives, verifies & executes remote control commands
- Functions during **launch & positioning phase**:
 - Firing apogee boost motor
 - Deploying solar panels
- Functions in **orbit**:
 - Transponder switching
 - Antenna pointing control
 - Battery reconditioning

Command Function

Command Verification Process

- Commands stored on satellite
- Retransmitted via telemetry for **ground verification**
- After verification → execution signal sent from Earth
- Ensures secure and accurate satellite control

Tracking, Telemetry and Command Subsystem

- Two well-established and better-known integrated TT&C networks used worldwide
 - ESTRACK (European space tracking) network of the ESA (European Space Agency)
 - ISTRAC (ISRO telemetry, tracking and command) network of the ISRO (Indian Space Research Organization).

Case Study – ISTRAC Network – ISRO's TT&C Backbone

- **Headquarters:** Bangalore
- **Ground Stations:** Bangalore, Lucknow, Sriharikota, Port Blair, Thiruvananthapuram, Mauritius, Bearslake (Russia), Brunei, Biak (Indonesia)
- **Connectivity:** SPACENET links all ISRO centres
- **Control Centre:** Multi-mission spacecraft control centre, Bangalore
- **Major Functions:**
 - **Launch Support:** TT&C and range tracking from lift-off to satellite injection
 - **Satellite Operations:** Health monitoring, housekeeping data, and control for LEO satellites
 - **Payload Data:** Reception & processing for scientific payloads
 - **Commercial Services:** TT&C support to international space agencies via Antrix

Payload



Payload

- The *payload subsystem* is that part of the satellite that carries the desired instrumentation required for performing its intended function.
- Payload is the most important subsystem of any satellite.
- Payload can be considered as the brain of the satellite that performs its intended function.
- The payload carried by a satellite depends upon the mission requirements.

Communication Satellite Payload

- Core Payload: Transponder
 - Functions as receiver → amplifier → transmitter
 - Acts as a microwave relay channel with frequency translation (uplink → downlink)
- Key Components:
 - High-gain transmit/receive antennas
 - Repeaters, filters, frequency shifters
 - Low Noise Amplifiers (LNAs)
 - Frequency mixers
 - Power amplifiers

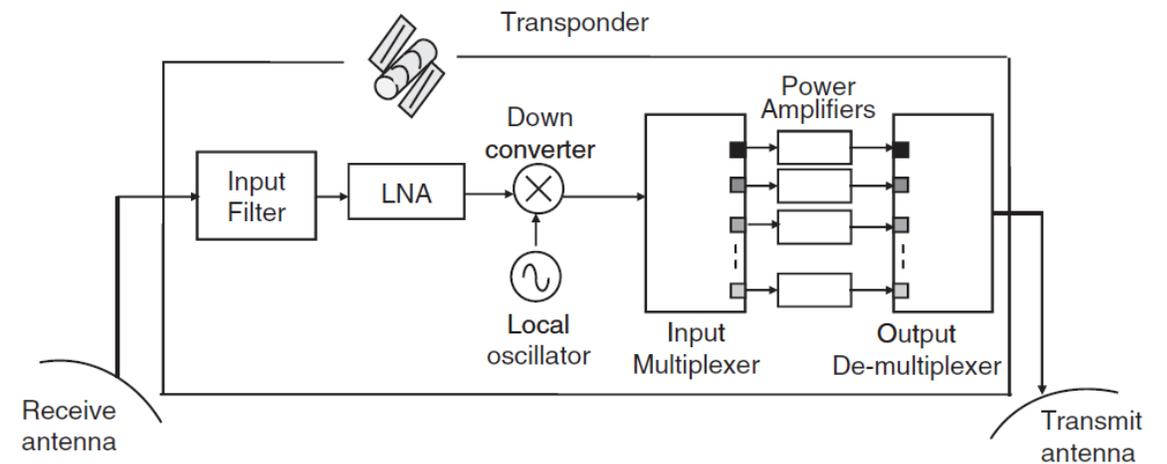


Figure 4.22 Transponder

Communication Satellite Payload

- Frequency Bands Used:
 - L (2/1 GHz), S (4/2 GHz), C (6/4 GHz) → Low atmospheric absorption, early use in broadcasting
 - C Band → Most popular; domestic & international telephony
 - Ku (12–18 GHz), Ka (27–40 GHz) → Higher bandwidth, smaller antennas
- Applications:
 - DTH (Direct-to-Home) services
 - TV & broadcast with 30–50 cm antennas

Weather Forecasting Satellite Payload

- Core Payload: Radiometer (acts like a camera)
 - Detects radiation in Visible, Near-IR, and Far-IR bands
 - Visible images: sunlight reflected from Earth/clouds
 - IR images: temperature of cloud tops & Earth's surface
- Radiometer Types:
 - Imagers → capture cloud patterns & surface features
 - Sounders → measure vertical temperature & moisture profiles

Weather Forecasting Satellite Payload

- Examples:
 - INSAT-3 Series:
 - VHRR (Very High Resolution Radiometer):
 - Visible: 2 km resolution
 - IR & Water Vapour: 8 km resolution
 - CCD (Charge Coupled Device) Camera:
 - Visible (0.63–0.69 μm), Near-IR (0.77–0.86 μm), Short-wave IR (1.55–1.70 μm)
 - 1 km resolution
 - Meteosat Satellite:
 - VHRR payload

Earth Observation Satellite Payloads

- Main Payloads:
 - High Resolution Visible (HRV) Cameras
 - Multispectral Scanners (MSS)
 - Thematic Mapper (TM)
- Function:
 - Capture **light & heat** reflected/emitted from **land and oceans**
 - Contain information about **living and non-living features**

Earth Observation Satellite Payloads

- **Process:**
 - Sensors pick up radiation data
 - Images digitized onboard
 - Transmitted to Earth stations
 - Processed → useful maps, resources & environmental information
- **Applications:**
 - Land use & vegetation mapping
 - Ocean studies
 - Natural resource monitoring
 - Environmental & climate studies

Scientific Satellite Payloads

- Purpose: To study space, planets, stars, and cosmic phenomena
- Payloads vary with mission objectives
- Examples:
 - Astronomy Satellites
 - Telescopes → collect light from stars
 - Spectrographs (UV 120–320 nm) → analyze star radiation
 - Planetary Exploration Satellites
 - Plasma Detectors → study solar wind & radiation belts
 - Magnetometer → detect planetary magnetic fields
 - Gamma Spectrometer → measure surface rock radioactivity
 - Neutral & Ion Mass Spectroscopes → analyze atmospheric & surface particles
- Applications:
 - Space science research
 - Planetary atmosphere & surface studies
 - Cosmic radiation and magnetic field investigations

Reference

- Anil K. Maini, Varsha Agrawal, *Satellite Communications*, Wiley India Pvt. Ltd., 2015, ISBN: 978-81-265-2071-8.