ECE 514E – RADAR & SATELLITE ENGINEERING

INTRODUCTION TO SATELLITES – STUDY GUIDE/REVISION

I. INTRODUCTION

What is Artificial Satellite?

An artificial satellite is a human-built object intentionally placed into orbit around Earth (or another celestial body). Satellites extend human capabilities for communication, observation, navigation, and scientific research beyond the confines of the planet. Discussion in this guide is restricted to artificial satellites. We shall therefore drop the adjective ‘artificial.’

Generations of Satellites

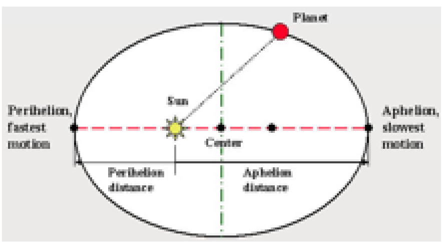
- **Sputnik 1 (1957):** First satellite (USSR), sparked the space race.
- **Explorer 1 (1958):** First US satellite.
- **Key Milestones:** Syncom 3 (1st geosynchronous comms sat, 1964), TIROS-1 (1st weather sat, 1960), GPS constellation development (1970s-1990s).

Why Satellites?

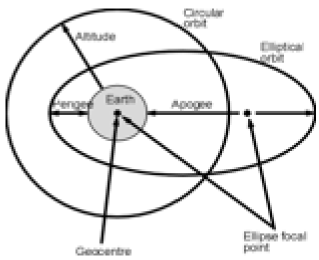
1. **Global Coverage:** View large areas, connect remote locations.
2. **Persistence:** Continuous observation/communication over fixed points (GEO).
3. **Unique Perspective:** Earth observation, astronomy, space environment monitoring.
4. **Ubiquitous Services:** TV/Radio broadcast, internet, GPS, weather forecasting, disaster monitoring.

II. ORBITAL MECHANICS FUNDAMENTALS (EE RELEVANCE: TIMING, POSITIONING, LINK BUDGETS)

- **Kepler's Laws:**
    1. **First Law:Elliptical Orbits:** Satellites orbit in ellipses with the central body (Earth) at one focus.



(a) Original Observations of Kepler



(b) Extension of Kepler to artificial satellites

Figure 1: Description of satellite orbits (Perihelion (Perigee), Aphelion (Apogee), Altitude, etc)

2. **Second Law: Equal Area:** Line connecting satellite to Earth sweeps equal areas in equal times (satellite moves faster at perigee, slower at apogee).

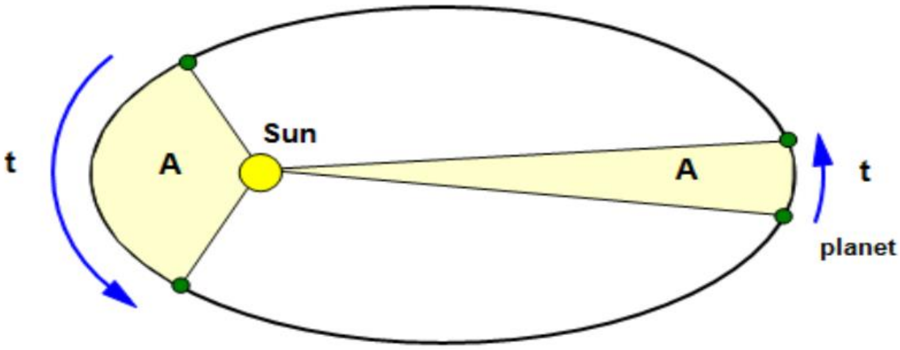


Figure 2: Kepler's second Law: A line joining the Sun and a planet sweeps out equal areas in equal time (t)

3. **Third Law: Harmonic Law:** Orbital period squared (T^2) proportional to semi-major axis cubed (R^3): $T^2 \propto R^3$ (For circular orbits: $T = 2\pi\sqrt{(a^3/\mu)}$, where μ = Earth's gravitational parameter ≈ 3.986×10^5 km^3/s^2).

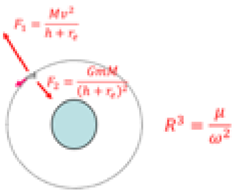


Figure 3: Kepler's third Law:

- **Newton's Law of Universal Gravitation:** $F = G * (m_1 * m_2) / r^2$ (Explains centripetal force causing orbit).
- **Key Orbital Elements:** Define size, shape, and orientation of orbit (Semi-major axis, Eccentricity, Inclination, RAAN, Argument of Perigee, True Anomaly).

III. COMMON ORBIT TYPES

1. **Low Earth Orbit (LEO):** 160 - 2000 km. **Pros:** Low latency, lower launch cost, high resolution (imaging). **Cons:** Short orbital period (~90 mins), small coverage area, high atmospheric drag (needs station-keeping). *EE Relevance:* Requires large constellations for continuous coverage (e.g., Starlink, Iridium), complex handoff management, lower power links.
2. **Medium Earth Orbit (MEO):** ~2000 - 35,786 km (GPS ~20,200 km). **Pros:** Good coverage balance, longer period than LEO (~12 hrs). **Cons:** Higher latency than LEO.

   EE Relevance: Primary domain for GNSS (GPS, Galileo, GLONASS, BeiDou). Precise timing is critical.

3. **Geosynchronous Orbit (GSO):** Orbital period = Earth's sidereal rotation period (~23h 56m 4s). Circular orbit at this period.
4. **Geostationary Orbit (GEO - *Subset of GSO*):** Circular GSO orbit directly above the equator (0° inclination). **Pros:** Satellite appears stationary over one point on Earth; constant coverage over ~1/3 Earth; simple ground antenna pointing. **Cons:** High altitude (~35,786 km) = high latency (~250 ms RTT), high launch cost, lower resolution (imaging), coverage limited near

poles. *EE Relevance:* Dominates TV broadcast, weather satellites (full disk), fixed satellite services (FSS). High-power transmitters needed. Critical for uplink/downlink station design.

5. **Highly Elliptical Orbit (HEO):** e.g., Molniya (63.4° inclination), Tundra. **Pros:** Long dwell time over high latitudes (e.g., Russia, Arctic). **Cons:** Complex tracking required.

   EE Relevance: Requires sophisticated ground antenna tracking systems.

IV. SATELLITE SUBSYSTEMS (EE CORE FOCUS)

1. **Communication Payload:**
   - **Transponder:** The core repeater unit.
     - **Receiver:** Captures weak uplink signal (e.g., 14 GHz Ku-band, 30 GHz Ka-band). *EE Focus:* Low Noise Amplifier (LNA - critical NF!), Mixers (Frequency Conversion), Demodulators.
     - **Frequency Converter:** Shifts signal frequency (e.g., uplink 14 GHz → downlink 12 GHz). *EE Focus:* Local Oscillators (LO - stability!), Mixers, Filters.
     - **Transmitter:** Amplifies and retransmits signal to Earth. *EE Focus:* High-Power Amplifier (HPA - TWTA, SSPA), Waveguides, Antenna Feed Network.
   - **Antennas:** *EE Focus:* Gain, Beamwidth, Polarization (Linear - H/V; Circular - RHCP/LHCP), Coverage Patterns (Global, Spot Beams - phased arrays becoming common). Shaped reflectors, Horn antennas, Array antennas.
2. **Bus:**
   - **Electrical Power Subsystem (EPS):** *Critical EE Domain!*
     - **Sources:** Solar Arrays (Photovoltaic Cells - Si, GaAs; Efficiency, Degradation in radiation), Radioisotope Thermoelectric Generators (RTGs - deep space).
     - **Storage:** Rechargeable Batteries (NiCd, NiH_2, Li-ion - charge/discharge cycles, depth of discharge, thermal management). Crucial for eclipse operation.
     - **Power Conditioning & Distribution (PCU/PDU):** Regulation (e.g., 28V or 100V Bus), DC-DC Converters, Battery Charge/Discharge Management, Load Switching. *EE Focus:* Efficiency, Reliability, Regulation Stability.
   - **Attitude Determination and Control System (ADCS):** *EE Focus:* Sensors (Sun Sensors, Star Trackers, Earth Sensors, Gyros, Magnetometers), Actuators (Reaction Wheels, Magnetorquers, Thrusters), Control Algorithms (PID, State-Space).
   - **Command and Data Handling (C&DH):** *EE Focus:* Onboard Computer (Rad-Hard Processors, FPGAs), Telemetry (TM - sensor data downlink), Telecommand (TC - control uplink), Data Buses (MIL-STD-1553, SpaceWire), Memory (Rad-Hard).
   - **Propulsion System:** Adjusts orbit (Station-Keeping) and attitude. *EE Focus:* Thruster control valves (solenoids), Pressure/Temperature sensors, Power switching for electric propulsion (Hall Effect Thrusters, Ion Thrusters).
   - **Thermal Control System (TCS):** Maintains components within operating temps. *EE Focus:* Thermistors, Heaters (resistive elements), Control Loops, Radiator surface properties.

- **Structure:** Mechanical skeleton. *EE Focus:* Vibration/isolation for sensitive components.

V. SATELLITE APPLICATIONS (DRIVING EE REQUIREMENTS)

1. **Telecommunications:** DTH TV/Radio, VSAT networks, Mobile Satellite Services (MSS - voice/data), Trunking, Backhaul, Broadband Internet (LEO constellations). *EE Focus:* Modulation (QPSK, 8PSK, QAM), Multiple Access (FDMA, TDMA, CDMA), Coding (FEC - Turbo, LDPC), High-Frequency RF design, Beamforming.
2. **Earth Observation (EO) / Remote Sensing:**
   - **Optical:** Multispectral/Hyperspectral Imaging, Panchromatic Imaging. *EE Focus:* CCD/CMOS detectors, Radiometric calibration, Image processing.
   - **Radar:** Synthetic Aperture Radar (SAR - all-weather/day-night). *EE Focus:* Microwave signal generation, Pulse compression, Doppler processing, High-speed data handling.
   - *Applications:* Weather, Agriculture, Forestry, Disaster Management, Mapping, Environmental Monitoring.
3. **Global Navigation Satellite Systems (GNSS):** GPS, Galileo, GLONASS, BeiDou. *EE Focus:* Precise atomic clocks (Rb, Cs, H-Masers), Spread Spectrum signals (CDMA), Signal processing (correlation, acquisition, tracking), Receiver design (chip-scale), Timing synchronization.
4. **Scientific:** Astronomy (Hubble, JWST), Space Physics (Van Allen Probes), Planetary Science. *EE Focus:* Ultra-sensitive detectors (low-noise), Precision instrumentation, High-data-rate downlinks.
5. **Military/Government:** Reconnaissance, Secure Comms, Early Warning, SIGINT. *EE Focus:* Anti-jamming (AJ), Low Probability of Intercept (LPI) waveforms, Encryption hardware, Secure C&DH.

VI. KEY DESIGN CHALLENGES & CONSIDERATIONS (EE PERSPECTIVE)

- **Harsh Environment:** Radiation (TID, SEE - requires Rad-Hard components/systems), Vacuum (outgassing, thermal management), Atomic Oxygen (erosion), Micrometeoroids & Debris (shielding).
- **Power Constraints:** Limited generation (Especially during eclipse), Finite storage (battery mass/volume). *EE Imperative:* Maximize efficiency at all levels (components, circuits, systems).
- **Thermal Management:** No convection in vacuum; relies on conduction/radiation. Thermal design is integral to EE design (component derating).
- **Reliability & Redundancy:** Extremely high reliability required (no repair possible!). Redundant paths, fault tolerance, rigorous testing (HALT/HASS).
- **Mass & Volume Constraints:** Directly impact launch cost. Drives miniaturization (SMD, ASICs, SoCs) and integration.
- **Link Budget:** *Fundamental EE Analysis!* Accounts for all gains and losses between transmitter and receiver: Received Power (dBm) = Transmit Power + Gains - Losses (Includes EIRP, Path

Loss (Free Space Path Loss - FSPL), Atmospheric Losses, Rain Fade, Antenna Gains, System Losses). Determines achievable data rate (Shannon-Hartley) and required Eb/No.

- **Cost:** Launch, hardware (Rad-Hard!), ground segment, operations. Drives commercial viability.

VII. MODERN TRENDS

- **Small Satellites (SmallSats):** Cubesats (1U, 3U, 6U, 12U), Microsats (<100 kg). *EE Impact:* COTS components (radiation risk trade-off), miniaturization, standardization, rapid development.
- **Mega-Constellations (LEO):** Thousands of satellites (Starlink, OneWeb, Kuiper) for global broadband. *EE Challenges:* Spectrum management, interference mitigation, complex networking/routing, massive ground station networks, collision avoidance.
- **Advanced Payloads:** Digital Transponders (Flexible channelization, beamforming), Software-Defined Payloads (reconfigurability), AI/ML onboard processing (e.g., data reduction, anomaly detection).
- **Electric Propulsion (EP):** Higher efficiency than chemical thrusters (lower mass fuel). *EE Focus:* High-power processing (> kW), PPU design.
- **Laser Communications (LaserCom/Optical ISL):** Higher data rates than RF, smaller antennas. *EE Focus:* Precision pointing/tracking, sensitive detectors (APDs, SPADs), modulation (PPM, DPSK).
- **Reusable Launch Vehicles (RLVs):** Reducing launch costs (SpaceX Falcon 9/Starship).

VIII. KEY TAKEAWAYS FOR EES:

Satellites are complex systems where electrical engineering is paramount. Success requires deep understanding of RF/microwave systems, digital signal processing, power electronics, control systems, embedded systems, and the unique constraints of the space environment. The field is rapidly evolving with smallsats, constellations, and advanced payloads creating exciting opportunities