EGERTON UNIVERSITY

EEEN 567 – SATELLITE ENGINEERING

HIGHLY ELLIPTICAL ORBIT (HEO) SATELLITE SYSTEMS – STUDY GUIDE/REVISION

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1. INTRODUCTION

The primary advantage of Geostationary Earth Orbit (GEO) satellites is their fixed position relative to the Earth. However, this comes at a major cost: high latency and poor coverage of polar regions. HEO solves the specific problem of providing continuous, high-latitude coverage.

The key Motivation for HEO satellites is to provide long-duration communication and observation services over the Earth's polar regions (above ~55-60° latitude), where GEO satellites are below the horizon and ineffective.

2. ORBITAL MECHANICS FUNDAMENTALS OF HEO

2.1 **Kepler's Laws of Planetary Motion:** These are the foundation.

1. **First Law:** Orbits are elliptical, with the primary body (Earth) at one of the two foci.
2. **Second Law (Law of Equal Areas):** A line segment joining a satellite and Earth sweeps out equal areas during equal intervals of time. **This is crucial for HEO.** It means the satellite moves slowest at apogee and fastest at perigee.
3. **Third Law:** The square of the orbital period is proportional to the cube of the semi-major axis. This determines how long one orbit takes.

2.2 Key Orbital Parameters for HEO:

- **Apogee:** The point in the orbit farthest from Earth. For HEO, this is strategically placed over the service area (e.g., Northern Europe, Russia, Canada).
- **Perigee:** The point in the orbit closest to Earth. This is over the opposite hemisphere.
- **Eccentricity (e):** A measure of how "stretched" the ellipse is. e = (distance between foci) / (length of major axis). For HEO, **e is close to 1** (e.g., 0.6 - 0.75). A circular orbit has e=0.
- **Inclination (i):** The tilt of the orbital plane relative to the Earth's equator. Critical HEO orbits have specific inclinations to ensure apogee is always over the same latitude.
- **Argument of Perigee (ω):** The angle from the ascending node to the perigee point. For a useful HEO, this is set so that apogee occurs at a high northern (or southern) latitude.
- **Orbital Period (T):** Typically, a **12-hour or 24-hour period** is chosen. A 12-hour period is common for the Molniya orbit, allowing two satellites to provide near-continuous coverage (one is active while the other is moving through perigee).

3. TYPES OF HEO ORBITS

Not all elliptical orbits are useful. Two are particularly important:

3.1 Molniya Orbit is the classic HEO with the following parameters:

- **Inclination: 63.4 degrees**. This is a "critical inclination." At this angle, the perturbation of the orbit due to the Earth's oblateness (J2 effect) causes the argument of perigee (ω) to remain stationary. This keeps the apogee locked at a high latitude. Without this, the apogee would drift, making the orbit useless for consistent coverage.

- **Eccentricity:** ~0.72
- **Period:** 12 hours (semi-major axis ~26,600 km).
- **Apogee Altitude:** ~39,300 km (similar to GEO altitude).
- **Perigee Altitude:** ~500-1,000 km.
- **History:** Developed by the Soviet Union for communications across their vast northern territory.

3.2 Tundra Orbit:

A Tundra orbit is a specialized type of highly elliptical, geosynchronous orbit with a 24-hour period and a critical inclination of 63.4 degrees, designed so that its apogee is fixed over a desired high-latitude region. This configuration causes the satellite to move very slowly near its apogee altitude (approximately 47,600 km), appearing to "hover" for more than 8 hours over the same area, such as North America or Europe, while it races through its low perigee (about 25,200 km) over the opposite hemisphere. The key advantage over a 12-hour Molniya orbit is this extended dwell time, which allows a constellation of just two or three Tundra satellites to provide near-continuous coverage, making it highly efficient for applications like satellite radio (e.g., SiriusXM) and communications services targeting high-latitude populations.

- **Inclination:** 63.4 degrees (same critical inclination as Molniya).
- **Period: 24 hours**. This is a "geosynchronous" elliptical orbit.
- **Eccentricity:** ~0.25

The satellite moves even more slowly at apogee. A single satellite can provide coverage for over 8-9 hours. A constellation of two or three satellites can provide truly continuous coverage.

4. SYSTEM DESIGN & CHALLENGES

4.1 Space Segment

- **Power Systems:** The satellite experiences extreme variations in solar flux. Near perigee, it's close to Earth and may enter the Earth's shadow (eclipse) frequently. Near apogee, it's in sunlight for long periods. The **power subsystem** (solar panels, batteries) must be designed to handle these long eclipse periods and rapid charging cycles.
- **Thermal Control:** The temperature variations are severe. The satellite is baked by the sun at apogee and experiences rapid temperature changes near perigee. Robust thermal management is essential.
- **Propulsion (Station Keeping):** While the orbit is stable against drift in argument of perigee, other orbital parameters still need correction (e.g., counteracting atmospheric drag at perigee). This requires a propulsion system, consuming fuel and limiting satellite lifetime.

4.2 Communication Payload & Link Budget

- **Large Range Variation:** The distance from a ground station to the satellite changes dramatically—from ~1,000 km at perigee to ~40,000 km at apogee. This causes a **huge variation in path loss** (~32 dB difference! Path Loss α 20*log10(distance)).

- **Link Budget Calculation:** You must perform a dynamic link budget. The **Effective Isotropic Radiated Power (EIRP)** and **Gain-to-Noise-Temperature ratio (G/T)** of the satellite and ground station are not constant. Systems often require:
  - **Automatic Gain Control (AGC)** on the receivers.
  - **Variable power output** from the transmitters.
- **Doppler Shift:** The high radial velocity of the satellite, especially near perigee, causes a significant Doppler shift in the carrier frequency. The communication system must track and compensate for this frequency shift.

4.3 Ground Segment

- **Tracking Antennas:** Ground antennas cannot be fixed. They must be steerable to track the satellite's large apparent movement across the sky, especially during the ~4-8 hours it is near apogee.
- **Handovers:** To provide continuous service, a constellation of 2-3 HEO satellites is used. As one satellite moves away from apogee, the ground station must perform a **handover** to the next satellite that is entering its apogee phase. This requires precise timing and network management.

5. ADVANTAGES AND DISADVANTAGES

Advantage	Disadvantage
Excellent high-latitude coverage	Complex ground segment (tracking antennas required)
Lower latency over poles than GEO (shorter path)	Complex satellite systems (power, thermal, comms) to handle orbit variation
GEO-like "quasi-stationary" behaviour at apogee	Van Allen Radiation Belts: The orbit passes through these belts, requiring radiation-hardened electronics.
Can be cheaper to launch than GEO (lower energy to reach perigee)	Orbital slots are limited (e.g., specific arguments of perigee) to avoid interference.

6. DIFFERENCE BETWEEN MOLNIYA & TUNDRA ORBIT SATELLITES

The main differences are their orbital periods and coverage: Molniya orbits have a 12-hour period and cover two opposite regions of the Earth, while Tundra orbits are geosynchronous with a 24-hour period and provide coverage for one fixed, high-latitude region over the course of a day. Molniya orbits use a 3-satellite constellation to achieve continuous coverage, while a single Tundra satellite can provide coverage for its designated region.

Feature	Molniya Orbit	Tundra Orbit
Orbital Period	**12 hours**	**24 hours**
Orbital Period vs. Earth's Rotation	**Semi-synchronous, meaning it completes two orbits per day**	**Geosynchronous (synchronous with Earth's rotation)**

Ground Track	**Three satellites cover a 180-degree longitude swath over a hemisphere**	**A single satellite covers a fixed, narrow region at the North or South Pole**
Apogee Location	**Located over a specific high-latitude region**	**Located over a single fixed region of the Earth at high latitudes**
Constellation **Size**	**Requires a constellation of three satellites for continuous coverage**	**Can operate with a single satellite for a specific regional coverage goal**
Altitude	**Generally lower altitude**	**Generally higher altitude**
Primary Use	**Communication and remote sensing for high-latitude areas in both hemispheres**	**Communications for specific, single regions in high-latitude regions**

6. APPLICATIONS

1. **Communications:** Military communications (US, Russia), satellite radio (SiriusXM uses an inclined HEO-like constellation).
2. **Earth Observation:** Spy satellites, weather monitoring of polar regions.
3. **Scientific Missions:** Astronomy satellites (e.g., INTEGRAL) use HEO to spend long periods outside the Earth's radiation belts.

7. STUDY QUESTIONS & EXERCISES

7.1 Conceptual

Explain why an inclination of 63.4° is so critical for a Molniya orbit. What problem does it solve?

7.2 Calculation

A Molniya orbit has a perigee altitude of 500 km and an apogee altitude of 39,300 km. Calculate the semi-major axis, eccentricity, and orbital period. (Earth's radius = 6,371 km, $\mu_{Earth} = 3.986 \times 10^{14}$ m^3/s^2).

7.3 Link Budget

The distance to a HEO satellite varies from 7,000 km to 44,000 km. Calculate the difference in free-space path loss (in dB) for a 10 GHz signal between these two points.

7.4 System Design

Propose a block diagram for a ground station receiver that can handle the large signal level variations and Doppler shift from a HEO satellite. What key components would you include?

7.5Comparison

Create a table comparing GEO, MEO (e.g., GPS), and HEO orbits in terms of altitude, period, advantages, disadvantages, and primary applications.