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Satellite Trajectory and Types of Orbits

Alimjonov Islom, Siddikov Khayitbek, Salimov Farkhodjon
Students of TSTU, faculty of aviation transport engineering

Abstract: The main goal of studying the above topic is to get acquainted with the general information currently learned about the trajectories of satellites and the types of their orbits. To study the general characteristics of the orbit, how satellites move in each type of orbit and for what purpose. To evaluate each orbit from a scientific point of view and from an economic point of view, depending on the emerging benefits in different fields.

Keywords: Kepler's work, LEO, MEO, Polar orbit, GEO, Sun-synchronous orbit, Transfer orbits, Highly eccentric orbit, Lagrange points, Heliocentric orbit.

Introduction: Kepler's pioneering work on orbital mechanics laid the groundwork for modern space exploration, and today, Europe honors that legacy through its advanced space program and the European Spaceport, where a diverse array of rockets are deployed to reach various orbits, supporting missions to Earth, the Moon, the Sun, and beyond. An orbit describes the curved trajectory an object takes around another due to gravitational forces, resulting in a dynamic interplay where objects with mass attract one another. When two bodies have enough momentum, they can enter into an orbit; typically, smaller bodies orbit larger ones, as seen in our Solar System where the Moon orbits the Earth, and the Earth-Moon system, in turn, orbits the Sun.[1]. This gravitational interaction causes not just the orbits themselves but also subtle movements in the larger bodies, as they are influenced by the gravitational pull of their orbiting companions, exemplified by the tidal effects the Moon has on Earth's oceans. The Solar System's formation began approximately 4.6 billion years ago with a massive swirling cloud of dust and gas bound by gravity. As the core of this cloud grew denser, it collapsed under its own weight, igniting to form the Sun. Surrounding this newly formed star, the remaining materials continued to spin and, influenced by centrifugal forces, flattened into a disc known as the solar nebula.

Materials.

The Sun's gravitational pull kept the gas, dust, and ice in orbit, leading to the development of a ring-like structure that would eventually evolve into the planets, moons, and other celestial bodies we observe today. As the particles within the solar nebula began to settle and coalesce, they gradually merged into larger bodies, much like rolling snowballs, ultimately forming the planets, comets, asteroids, and moons in our Solar System but not Earth's Moon. This shared process of formation from the same rotating cloud of dust accounts for the fact that all the planets orbit the Sun in the same direction and within a roughly aligned orbital plane, reflecting their common origin. When rockets launch satellites, they place them into orbit by first ascending above Earth's atmosphere, where denser air no longer significantly slows them down. This process is analogous to throwing a ball from a tall tower: the initial push from the rocket's engines gives the satellite the necessary speed to begin its orbit, similar to how a throw sets the ball on a curved path towards the ground. Once in space, gravity takes over, maintaining the satellite's orbit around Earth much like it keeps the Moon circling our planet, ensuring that it continually falls toward Earth while simultaneously moving forward at a sufficient speed to remain in orbit. When an object is thrown from a tall tower with sufficient speed, it can travel along a curved path that matches the curvature of the Earth, allowing it to fall around the planet indefinitely essentially achieving orbit. In the vacuum of space, where air friction is absent, gravity can maintain the satellite's orbit with minimal ongoing assistance once it is correctly launched. This capability allows us to leverage satellite technology for various applications, including telecommunications, navigation, weather forecasting, emergency response, and astronomical observations, enhancing our understanding and connectivity in the modern world.[2].

Research and methods: Upon launch, satellites and spacecraft are positioned in specific orbits around Earth or set on trajectories for interplanetary travel, which allows them to orbit the Sun instead. The selection of an optimal orbit is influenced by various factors tailored to the mission's objectives, such as the desired coverage area, altitude, and the particular requirements for data collection or communication. For instance, geostationary orbits provide continuous coverage over specific regions on Earth, while low Earth orbits are ideal for Earth observation and data collection, ensuring that the spacecraft can effectively achieve its intended goals.[3].[4].

1. Low earth orbit
2. Medium earth orbit
3. Polar orbit
4. Sun-synchronous orbit
5. Geostationary orbit
6. Transfer orbits and geostatsionary transfer orbit
7. Highly eccentric orbit
8. Lagrange points
9. Heliocentric orbit

Low Earth orbit (LEO) refers to orbits that are relatively close to Earth's surface, typically at altitudes below 2,000 kilometers, influenced by the presence of the Van Allen belts and the challenging environment they create. Satellites are generally restricted from flying below about 180 kilometers due to atmospheric drag, which affects their stability and operational efficiency. In contrast, commercial airplanes operate at altitudes around 12 kilometers, making even the lowest LEO more than ten times higher than typical aircraft flight levels, illustrating the vast difference in operational space between satellites and airplanes. LEO satellites offer advantages due to their proximity to Earth, including high-resolution satellite imaging capabilities and easier access for astronauts, as seen with the International Space Station's (ISS) orbit. At approximately 7.8 km per second, LEO satellites also complete an orbit in about 90 minutes, resulting in the ISS circling the Earth roughly 16 times daily. LEO communications satellites typically operate in constellations, enabling them to provide seamless coverage around the Earth through coordinated networks of multiple satellites. This approach also extends to observation and navigation missions. Notably, the Ariane 5 has successfully delivered heavy payloads, such as the Automated Transfer Vehicle (ATV), to the ISS multiple times, while the upcoming Ariane 6 is expected to continue this role, facilitating resupply missions to both Earth and lunar space stations.

Medium Earth orbit (MEO) encompasses a wide altitude range between Low Earth Orbit (LEO) and Geostationary Orbit (GEO), typically situated above the Van Allen belts. Similar to LEO, MEO satellites have flexibility in their orbital paths, allowing for diverse applications across various missions, including navigation, communications, and Earth observation, benefiting from the trade-offs between coverage area and latency. MEO is notably employed by navigation satellite constellations, such as the European Galileo system, which offers global navigation services. By providing simultaneous coverage over vast areas, Galileo enables users to access information necessary for tasks like tracking air traffic and providing smartphone-based directions. This extensive network of interlinked satellites in MEO plays a crucial role in facilitating modern navigation technologies.[5].

Polar orbits are a subcategory of Low Earth Orbit (LEO), characterized by altitudes between 200 and 1000 km. Distinguishing themselves from conventional east-west orbits, polar satellites travel from approximately one pole to the other, often deviating by as much as 10 degrees in latitude, rather than following a direct path over the poles. Polar orbits are highly effective for achieving comprehensive global Earth coverage, as satellites in these orbits can view every part of the planet over time. By traveling 'up' and 'down' relative to Earth's surface while the planet rotates beneath them, these satellites ensure that they can capture data from all geographic areas, making them ideal for applications such as environmental monitoring, reconnaissance, and mapping.

Sun-synchronous orbits (SSO) are specialized polar orbits that enable satellites to maintain a consistent position relative to the Sun, allowing them to pass over the same geographic location at the same local time each day. This synchronization enhances the comparability of imaging data by minimizing variations in light and shadows, making it particularly useful for monitoring environmental changes, predicting extreme weather, and addressing long-term issues like deforestation and sea-level rise. Typically situated at altitudes between 600 to 800 km, satellites in SSO can achieve speeds of around 7.5 km per second, often achieving a constant dawn or dusk trajectory for optimal illumination conditions.

Results.

Satellites in **geostationary orbit** (GEO) are positioned above Earth's equator, orbiting in sync with the planet's rotation at an altitude of approximately 35,786 km and traveling at a speed of about 3 km per second. This alignment allows GEO satellites to appear stationary over a fixed point on Earth, making them especially valuable for telecommunication purposes, as antennas on the ground can remain aimed at a constant location. Additionally, GEO is beneficial for weather monitoring, providing continuous observation of specific regions to track and analyze evolving weather patterns and trends over time. Geostationary orbit (GEO) satellites offer a unique advantage in terms of coverage, allowing them to see a larger portion of the Earth's surface due to their high altitude. With three evenly spaced satellites, they can provide near-global coverage, making them ideal for applications that require continuous observation of large areas. This is particularly useful for the European Data Relay System (EDRS) program, which utilizes a constellation of GEO satellites to relay data and information between non-GEO satellites, spacecraft, and ground stations that may have limited or intermittent connectivity. This ensures that Europe remains connected and online at all times, even with satellites in lower orbits that may have reduced visibility from the ground.

Transfer orbits are specialized trajectories used to transition satellites from one orbit to another, as they typically cannot be launched directly into their final orbits. When rockets like Ariane 6 launch satellites, they often place them in a temporary transfer orbit, such as a geostationary transfer orbit (GTO) for those destined for geostationary orbit (GEO). In this scenario, the satellite subsequently uses onboard propulsion to maneuver into its final orbit. Orbits can exhibit different shapes or 'eccentricities'; a perfectly circular orbit maintains a constant distance from Earth's surface, while a highly eccentric orbit causes the satellite to vary its distance, moving closer and farther from the planet during its journey. In transfer orbits, satellites or spacecraft maneuver using their onboard engines to transition from an orbit of one eccentricity to another, allowing them to adjust not only their altitude but also aspects like orbital inclination and semi-major axis. After liftoff, the launch vehicle follows a designated trajectory, depicted in yellow, and releases its payload into an elliptical orbit, illustrated in blue. This elliptical orbit has two key points: the apogee, which is the farthest point from Earth, and the perigee, which is the closest point. These features enable the satellite to efficiently reach higher or lower operational orbits as needed. To reach geostationary orbit (GEO), a satellite typically achieves circularization at its apogee by firing its engines, effectively transforming the elliptical orbit into a stable, circular geostationary one, as depicted in red on the diagram. This process not only places the satellite in its intended orbit but also allows it to counteract any inclination imparted by its launch location. When launching from a non-equatorial site, like Kourou, or from a farther-removed location such as Cape Canaveral, the satellite may require additional maneuvers to correct its orbit and ultimately reach the desired geostationary equatorial orbit, potentially using more eccentric transfer orbits like the 'Supersynchronous' transfer orbit.

Discussion.

Orbits, like individuals, can exhibit a wide range of **eccentricities**, with a spacecraft in a highly eccentric orbit experiencing significant variations in its distance from celestial bodies, approaching them at high speeds before retreating into the depths of space. Eccentricity is quantified on a scale from zero to one, where a perfect circle has an eccentricity of zero, while highly eccentric orbits approach, but never reach, one. A score of one indicates a parabolic trajectory, allowing an object to escape gravitational attraction, and values above one represent hyperbolic trajectories, indicating sufficient velocity for escape. Comets, such as Halley's Comet with an eccentricity of 0.967, exhibit these highly eccentric orbits around the Sun, taking millions of years to complete their journeys, predominantly residing in the cold outer Solar System and often unable to withstand the intense heat during their brief passages near the Sun. Highly Elliptical Orbits (HEO) are advantageous for missions requiring prolonged observations of Earth or space from elevated altitudes, such as ESA's upcoming SMILE mission, which aims to investigate the interactions between the solar wind and Earth's magnetosphere by spending extended time away from Earth to monitor large-scale processes. Additionally, HEO serves as a useful transfer orbit for interplanetary missions or for satellites aiming to reach geostationary orbit (GEO), particularly when launching from sites that are significantly north of the equator, like Cape Canaveral or Baikonur.[6].

Lagrange, or libration points, are areas in space where the gravitational forces of two large masses, like the Sun and Earth or Earth and Moon, create a balance, allowing various orbits to exist. Spacecraft that require precise stability and minimal interference, such as deep space astronomical missions like Gaia and Euclid, benefit from positioning themselves at these Lagrange points, as proximity to Earth can hinder their operations due to light, radiation, and shadow complications, even from distant orbits like geostationary orbit (GEO). For space observatories and telescopes aiming to capture images of faint cosmic objects, being near Earth is particularly disadvantageous, as the planet's infrared emissions and reflected sunlight can obscure the detection of distant galaxies, much like trying to observe stars during broad daylight on Earth.

Some missions operate in **heliocentric orbits**, allowing them to travel alongside Earth and other planets in their orbits around the Sun, which is beneficial for studying various celestial bodies, including the Sun, planets, moons, comets, and asteroids, as it liberates spacecraft from Earth's gravitational influence. To achieve a heliocentric orbit, spacecraft must first reach escape velocity to break free from Earth's gravity, typically using powerful launch vehicles, after which they can adjust their trajectories using their onboard engines. ESA's Solar Orbiter is one such mission, positioned 42 million kilometers from the Sun, enabling it to study the star up close while viewing its poles, while the Rosetta mission utilized a heliocentric path to investigate comet 67P/Churyumov-Gerasimenko, and future missions like Comet Interceptor are also set to leverage heliocentric orbits for exploring distant celestial bodies within our Solar System.[7].

Conclusion. Understanding satellite orbits is fundamental to space mission design, balancing factors like altitude, inclination, and orbital perturbations to optimize mission objectives. Low Earth Orbit (LEO) satellites excel in high-resolution applications but require constellations for comprehensive coverage, while Geostationary Earth Orbit (GEO) offers extensive coverage for essential services like weather monitoring but faces limitations in signal delay and resolution.

Challenges such as orbital debris and the need for occasional maneuvers due to perturbing forces necessitate careful planning and innovative strategies, particularly as emerging concepts involve constellations of small satellites and exploration of cislunar space, highlighting the critical need for sustainable practices in future space endeavors. If we continue to develop at this rate with active use of orbits, several more orbits that we need in the future will be discovered and the current orbits will be used more widely. New orbits may be discovered to monitor not only Earth's orbits but also other planets.

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