IMMC 2017 Region of Zhonghua Problem B

RESEARCH ON THE EFFICIENCY AND EFFECTIVENESS OF COOPERATIVE TRANSMISSION FOR MULTI-ORBITAL SATELLITES

1. Background

Earth satellite is an important part of our information infrastructure. Nowadays due to the global climate change, major applications such as disaster prevention and mitigation, emergency rescue, ocean navigation, navigation and positioning, air freight, aerospace control, etc. are playing increasingly major roles, especially for the acquisition of structured data in large spatial and temporal scales, which has become an indispensable tool in these applications.

2. Description

A *Geostationary Earth Orbit/Geosynchronous Equatorial Orbit* (GEO) satellite, i.e. earth geosynchronous orbit satellite, is a satellite whose orbital plane coincides with Earth's Equatorial Plane. The altitude of the orbit is at 35786 km from Earth, and the orbital period of the satellite matches the rotation of Earth on its axis (one sidereal day) of approximately 23 hours 56 minutes and 4 seconds. Regardless of the orbital perturbation, satellites operating in geostationary orbits can pass over the same location every day over a given point of the planet's surface, and those orbits are usually used by communication and meteorological satellites.

For more detailed introduction to GEO, please refer to: `https://en.wikipedia.org/wiki/Geosynchronous_orbit`

The orbit of a *Polar Satellite* has an inclination of 90° to the equator, and its altitude is approximately 720-800 km. When in operation, a polar satellite can arrive at the space above Antarctica and Arctic. Sun-synchronous Orbit or Helio-synchronous Orbit is a satellite orbit whose orbital plane has a fixed orientation relative to the sun. Its orbital inclination is very close to 90 degrees, and its orbital altitude is mostly in the range of 600-800 km. Such a satellite passes nearly above both poles of Earth, and therefore its orbit is also called *Near-Polar* sun-synchronous Orbit, Polar Orbit and Sun-Synchronous Orbit are all Low Earth Orbit (LEO) and satellites performing global scale observations and applications such as meteorology, positioning, resources, reconnaissance, etc. are all LEOs.

For more detailed introduction to polar orbit, polar satellite, and sun synchronous orbit, please refer to:

`https://en.wikipedia.org/wiki/Polar_orbit`
`https://en.wikipedia.org/wiki/Polar_(satellite)`
`https://en.wikipedia.org/wiki/Sun-synchronous_orbit`

Geostationary Earth Orbit Satellite can perform continuous real-time surveillance on certain designated regions. However, since its distance from the earth surface is relatively large, satellite-carrying sensors do not have enough precision and resolution, and hence the surveillance capability is limited. Therefore, Low Earth Orbit Satellites, among those include Chinese high resolution satellites such as GF-series and meteorological satellites such as FY-3, US satellites such as NOAA-18-19, NPP and EOS, have been used extensively to perform remote sensor observations so as to increase the measurement accuracy and resolution.

Geostationary Earth Orbit Satellites can relay continuous real-time communication with receivers on different locations on Earth, while Low Earth Orbit Satellites circle around Earth, and their communication can only succeed during the state of "over the top" or via the continuous relay by other satellites.

Satellite orbital parameters: Based on Kepler's Laws, the orbits of satellites are elliptic around the Earth. This elliptical orbit can be described using 6 orbital elements. For example, in Figure /reffig:Orbit, we use a non-rotational equatorial earth-centered coordinate system XYZ as reference, the 6 orbital elements are: semi-major axis α, eccentricity e, inclination i, argument of periapsis ω, longitude of the ascending node Ω, the time of perihelion passage τ. In any given time t, the orbital satellite positions can be determined by these 6 parameters.

(1) **inclination** i: vertical tilt of the elliptical orbit of satellite with respect to the reference plane – Earth's equatorial plane.
(2) **semi-major axis** α: this is a parameter that confirms the size of the orbit. For circular orbits, it is the radius of the circle; for elliptical orbits, this is the semi-major axis.
(3) **eccentricity** e: this is a parameter that confirms the shape of the orbit. When $e = 0$, the orbit is a circle, when $0 < e < 1$ it is an ellipse.
(4) **longitude of the ascending node** Ω: this is a parameter to confirm the orbital plane, as an angle measured on the Equatorial Plane from the equinox to the ascending node (the point where satellites will pass though on the Equatorial Plane from the Southern Hemisphere to the Northern Hemisphere)
(5) **time of perihelion passage** τ: the time where the satellite is passing through the closest point on the central object around which it orbits.
(6) **argument of periapsis** ω: defines the orientation of the ellipse in the orbital plane, as an angle measured from the ascending node to the periapsis (the closest point the satellite object comes to the primary object around which it orbits) and this is also referred to as the angle between the line of ascending node and the line of perigee.

For more detailed introduction to orbital elements, please refer to:

`https://en.wikipedia.org/wiki/Orbital_elements`

Optical Inter-satellite Links, or OISLs, refer to the development of interconnected laser communications or visible light communication in outer space satellites. This can increase connectivity, and expand coverage, boost business demands and flexibility. But optical

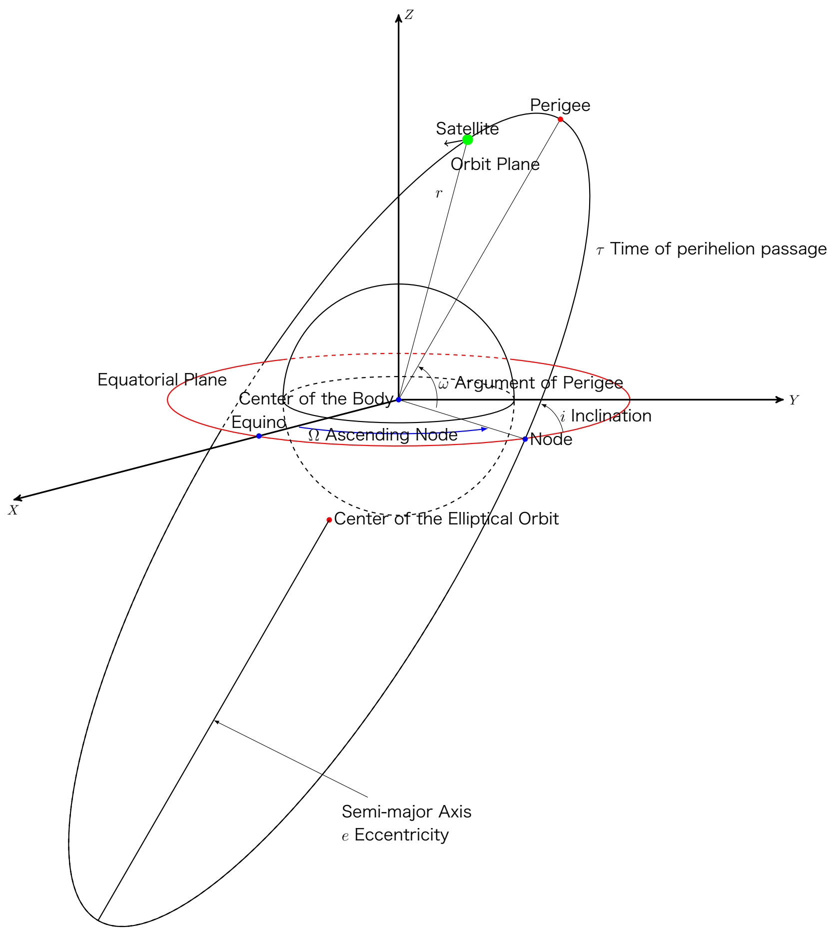

Figure 1. An Orbit of a Satellite

communication signals can only transverse along straight lines, and when there is blockage, no signals can be passed through. For example, as demonstrated in Figure 2, the red-colored linked path between LEO C and LEO A is blocked by blockage M2, therefore signals can only pass through LEO B to arrive at LEO A.

For more detailed information on optical communication in space, please refer to:
`https://en.wikipedia.org/wiki/Free-space_optical_communication`
`https://en.wikipedia.org/wiki/Laser_communication_in_space`

Research on the efficiency and effectiveness of the synergy of multi-orbital satellites: From the aforementioned description, the geostationary earth orbit can maintain real-time continuous communication with the receivers on Earth, and Low Earth Orbit Satellite

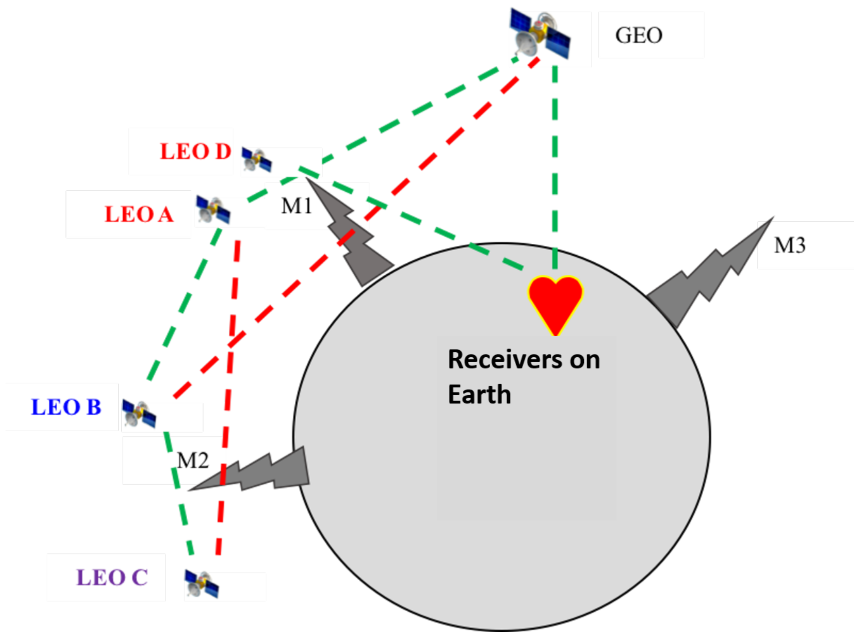

FIGURE 2. Laser Link Communication

orbits around Earth, and their communication with receivers on Earth can only fulfill during the state of "over the top" or via the continuous relay by other satellites. In order to realize the data retrieved from the satellites, we always would hope that it can be transmitted to the receivers on Earth as soon as possible for processing, please design the optimal transmission mode.

3. Questions

(1) Select a Polar Satellite and a Geostationary Earth Orbit Satellite, plus one receiver on Earth, please find the time and spatial region for direct data transmission from the Polar Satellite to the receiver on Earth (line-of-sight transmission). Do the same for relay data transmission in which data are first transmitted from the Polar Satellite to the GEO Satellite, which then relay them to the receiver on Earth.

(2) Efficiency and effectiveness are important criteria for remote sensing. Thus minimizing the time lapse from the time data are collected by the Polar Satellite to the time the receiver on Earth receives the data is a priority in remote sensing. Please find the maximum time lapse in both scenarios in Question 1. Namely, find the time lapse from the time data are collected by the Polar Satellite to the time the receiver on Earth receives the data in both the direct transmission model and the replay through GEO Satellite model.

(3) Assume that in order to enhance the transmission efficiency and effectiveness we have the luxury to add one more relay Polar Satellite to the system. Design an orbit model for the new Polar Satellite (determine its position at any one time as well as the phase difference between it and the original Polar Satellite), so that the total time lapse for data transmission is minimized over a whole day using the combination of direct and relay (through the GEO and the additional Polar Satellites) transmission.

Assumption: Earth is approximately round and spherical, and that the high mountains on earth will block the transmission of the line-of-sight propagation of the electromagnetic waves. For details of the orbital elements of satellites, please visit:

`http://celestrak.com/satcat/search.asp`