Orbital sequence and configurations for the communication satellite system using heliocentric orbits

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Abstract － Most of the communication satellites are now operated in Geostationary Orbit (GEO) because satellites in GEO are stationary at one point in the sky when seen from the ground and the antennas on the ground can be fixed. GEO, however, has some problems. For instance, the satellites in GEO cannot cover the middle latitude area where most of the people live. The number of the satellites is also limited in GEO. For these reasons, a new communication satellite system for one-way communication using heliocentric orbits is proposed. This system covers the relatively high latitude area. This paper will present an overview of the system and orbital analysis in order to show the feasibility of this system from the point of view of the sequence of the orbits.

太陽周回軌道を用いた通信衛星システムのための軌道シーケンスおよび衛星配置

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概要 － 従来の通信衛星の多くは，静止軌道（GEO）上で運用されている．GEO には，軌道上の衛星が地上から見て空の一点に静止しているという利点がある一方，人口の多い中緯度以北の地域のカバーが難しい，衛星の配置数に限りがあるといった問題もある．そこで，一方向通信を対象とし，北半球を一括でカバーすることのできる，太陽周回軌道を用いた通信衛星システムが現在提案されている．本稿では，本システムの概要を示し，軌道解析を行うことにより，システムの実現性を示す．

1. Background

Communication satellites are used in a variety of fields such as television broadcasting, Internet services, satellite positioning systems, and so on. Most of the communication satellites are operated in Geostationary Orbit (GEO). GEO is a kind of circular orbits, whose altitude from the ground is approximately 36,000 km (Fig.1), and its orbital period is equal to that of the Earth's rotation. Therefore, satellites in GEO look stationary when seen from the ground. This characteristic is the main reason why GEO is usually utilized as the orbit of communication satellites. The antennas on the ground can be fixed in one direction. However, there are some problems in GEO. Since GEO exists above the Equator, satellites in GEO cover only low

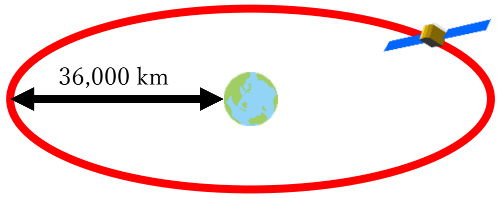

Fig. 1 Geostationary Orbit

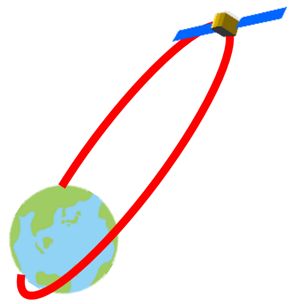

Fig. 2 Molniya Orbit

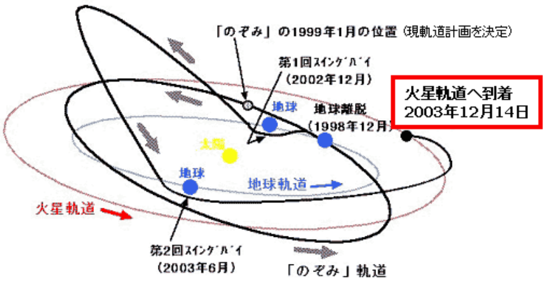

Fig. 3 The transfer orbit of PLANET-B[1]

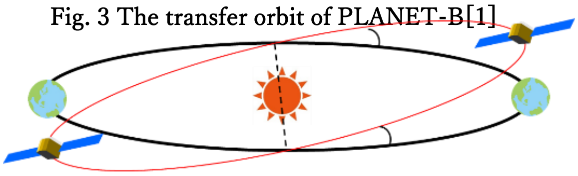

Fig. 4 The heliocentric orbit
for communication satellite system

latitude areas. It's difficult to cover relatively high latitude area such as Japan, Europe, the US and so on. The capacity of this orbit is also limited because of the increase of the number of geostationary satellites. Therefore, a communication satellite system using alternative orbits is now required.

A Molniya orbit is a type of satellite orbit designed to provide communications and remote sensing coverage over high latitude areas. It is a highly elliptical orbit, whose inclination is 63.4 degrees and period is 12 hours. However, satellites in this orbit are not stationary when seen from the Earth. The satellites move in the sky and have time when they are invisible in one day. This orbit also crosses the Van Allen radiation belt, causing a short life of the satellites.

On the other hand, a heliocentric orbit is now proposed as an orbit for communication satellite system. It is inspired by PLANET-B mission, Nozomi.

Nozomi is a Mars-orbiting aeronomy probe launched by ISAS in 1998. On its way to Mars, it conducted a swing-by at Earth so as to put itself into a heliocentric orbit, whose inclination is different from that of the ecliptic plane and period is about one year. Because of the characteristics of that orbit, Nozomi approached Earth again about half year later. At that time, it conducted the second swing-by at Earth. During this period, Nozomi was visible from the northern hemisphere because its position had been kept near Earth and in the north pole direction.

The characteristics of Nozomi's orbit are utilized in the proposed communication satellite system. I propose a communication satellite system using heliocentric orbits, whose inclination are different from that of the ecliptic plane and periods are one year, that is, synchronized with that of the Earth's revolution around the sun. This system covers the relatively high latitude area, which includes Japan, Europe, the US, and so on. This paper will present the feasibility of this system by conducting an orbital analysis.

2. Overview of the system

First of all, I will present the overview of the communication satellite system I propose. This system conducts one-way communication, such as television broadcasting, satellite positioning services, and so on. This system covers relatively high latitude areas which have large population. Three satellites compose the system. Each of the three satellites has an orbit, whose inclination is different from that of the ecliptic plane and period is equal to that of the Earth's revolution around the sun. The longitude of the ascending node is different with each other. Because of these orbits, at least one of the satellites is visible at all time when seen from the ground.

3. Conditions of the system

I set the conditions for this system in order to conduct the orbital analysis.

Since this system performs one-way communication, time delay is not a big matter. Because of that, I do not set the upper limit of the distance between the satellites and Earth.

From the point of view of the gravity of the Earth, because the radius of the Sphere of Influence of Earth is calculated as 930,000 km [2], I set the lower limit of the distance as 1,000,000 km. The perturbation of the Moon is not considered this time.

This system covers the relatively high latitude area of the northern hemisphere which has large population and it is hard for the usual system to cover. I assume that this system covers the north of the Tropic of Cancer (23.5° N). Therefore, I set the declination of the satellites as +66.5°~ +90°.

4. Orbital analysis

I conducted an orbital analysis under the conditions I set. I will explain the sequence for the orbital insertion below.

First, three satellites are launched at the same time using one rocket in order to save the cost for the launch. They are put into a one-year orbit, that is, they approach Earth again in one year at the launching point. At that time, each of the three satellites uses Earth gravity assist maneuver. I named each of them as Sat1, Sat2, and Sat3. I will explain each of them below.

Sat1 conducts Earth swing-by in order to change the inclination and the semimajor axis of the orbit. Sat1 changes the inclination in order to keep its position in the north pole direction. The reason why Sat1 needs to change the semimajor axis is that it can change the orbital period by changing the semimajor axis as you can see in the equation below.

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

a: semimajor axis, μ: gravitational constant

By changing its orbital period, Sat1 can shift the timing of crossing the ecliptic plane and can avoid the effect of the Earth gravity. If Sat1 does not change its orbital period, Sat1 will approach Earth in half a year and will be affected by the gravity of Earth. It will be difficult to maintain its orbit. In some days after the swing-by, Sat1 conducts ΔV in order to equalize the semimajor axis of the orbit with that of Earth.

Sat2 also conducts Earth gravity assist in order to put itself into a 1.4-year orbit. It approaches Earth again in 1.4 years at a point which is different from the launching point. Sat2 then conducts the second swing-by in order to change the inclination and the semimajor axis of the orbit. The sequence after that is same as that of Sat1. By conducting these two Earth gravity assists, Sat2 can shift the longitude of the ascending node from that of Sat1 by 150°.

The sequence of Sat3 is basically same as that of Sat2, but Sat3 is put not into 1.4-year orbit but into 2.5-year orbit. Sat3 can shift the longitude of the ascending node from that of Sat1 by 160°.

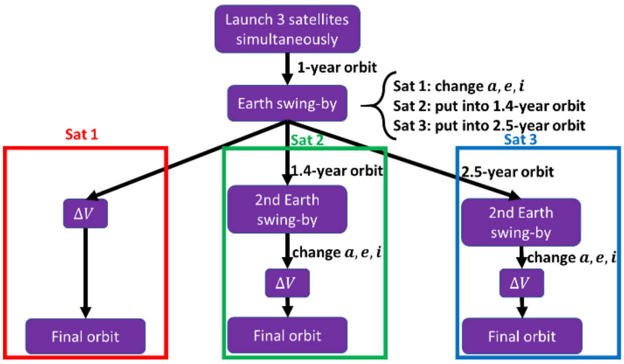

Fig. 5 The sequence of the orbit insertion

Based on the above, I conducted the numerical simulation to search for solutions that satisfy the conditions all year round. The variables I used are :

- $C3 = v_\infty^2$
- Distance from the Earth to the perigee at the swing-by r_p
- Angle between the incoming trajectory plane and the ecliptic at the swing-by θ
- The timing of ΔV

I change these variables under the conditions I set.

5. Result of the numerical simulations

Fig.6~8 show the result of the numerical simulations I conducted.

Fig.6 shows the overview of the orbits of the three satellites and Earth. As you can see, each of the satellites' orbits is inclined from the ecliptic plane and the longitude of the ascending node is different from each other.

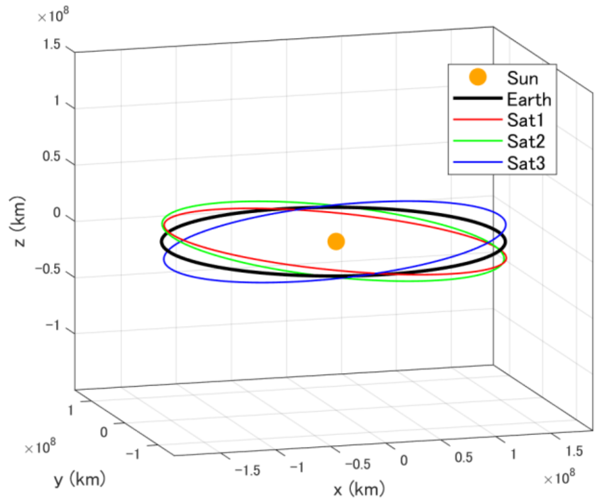

Fig. 6 Overview of the orbits

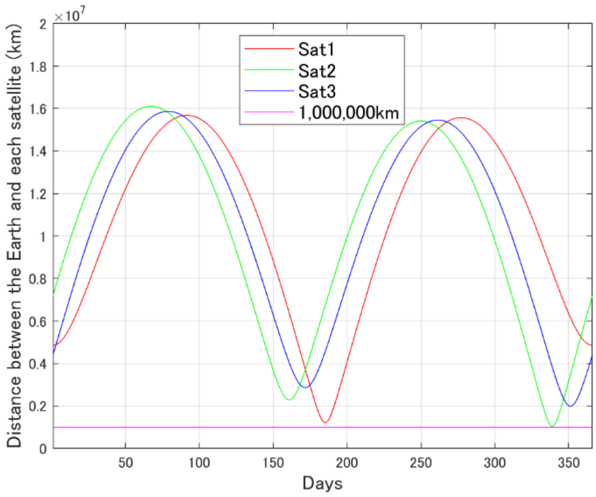

Fig. 7 Distance from the Earth

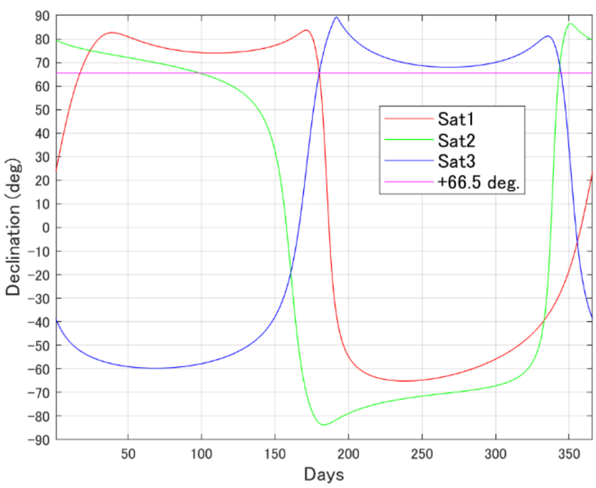

Fig. 8 Declination

Fig.7 shows the change of the distance between each of the satellites and Earth in one year. Each of them satisfies the condition that the lower limit of the distance is 1,000,000 km. The distance is at most 16,000,000 km, 0.107 AU.

Fig.8 shows the change of the declination of the satellites when seen from Earth. At least one of the three satellites satisfies the conditions that the declination should be +66.5°~ +90° all year around.

C3 is calculated as $9.71 \mathrm{km}^2/\mathrm{s}^2$ from the numerical simulation. If I assume the launch using H2A, the payload should be 2,000 kg from Fig.9. Since I also assume that the three satellites are launched simultaneously in this system, each of the wet mass of the satellites should be 650 kg. Each of the required ΔV is calculated as $137\,\mathrm{km/s}$ (Sat1), $137\,\mathrm{km/s}$ (Sat2), $58.7\,\mathrm{km/s}$ (Sat3). I can calculate the required mass of the fuel from the Tsiolkovsky rocket equation:

$$\frac{M_{\mathrm{dry}}}{M_{\mathrm{wet}}} = \exp\left(-\frac{\Delta V_{\mathrm{total}}}{g I_{\mathrm{sp}}}\right)$$

M_{dry} : Dry mass of the satellite

M_{wet} : Wet mass of the satellite (includes fuel mass)

g : Standard gravity

I_{sp} : Specific impulse

If I assume the required ΔV is $137\,\mathrm{km/s}$ (the highest of the three) and the chemical propulsion with an $I_{sp} = 300$ s, the dry mass of the satellite (M_{dry}) is calculated as 620 kg and the mass of the required fuel as 30 kg.

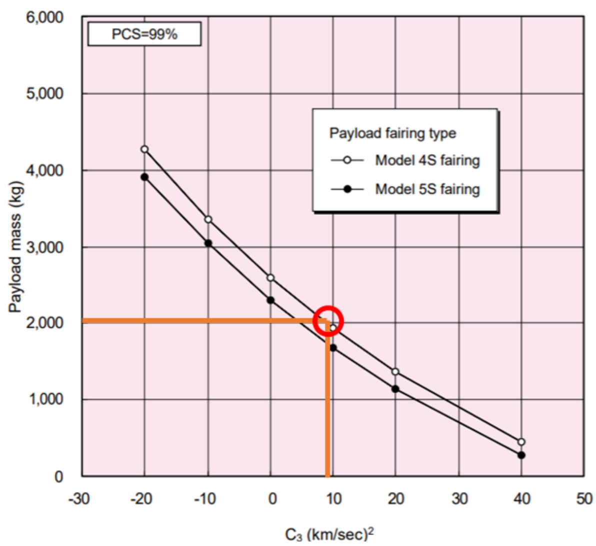

Fig. 9 Launch capability for earth escape mission (H2A202)[3]

6. Summary

I presented the overview of the communication satellite system using heliocentric orbits. This system conducts one-way communication and covers the north of the middle latitude area, which has large population.

I conducted an orbital analysis of this system and the result is that this system satisfies the conditions all year around by using three satellties.

I conclude that this system will be feasible in terms of orbital mechanics

On the other hand, the quality of communication is not considered in this analysis. It is necessary to check whether it is possible to maintain the quality of communication at the distant position from Earth in the future.

7. Reference

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[2]半揚稔雄，ミッション解析と軌道設計の基礎，現代数学社, 2014

[3]MHI Launch Services, “H-IIA User’s Manual Ver.4.0 February 2015”