STATION-KEEPING METHODS FOR TWO BROADCASTING SATELLITES IN THE SAME GEOSTATIONARY POSITION

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ABSTRACT

Three station keeping methods to keep twin geostationary satellites avoiding collision hazards and mutual occultations within a given longitudinal tolerance are introduced. They are named "Longitude Separation Method", "Synchronized Method", and "Eccentricity Separation Method". Taking into account orbit determination errors, manoeuvre errors and so on, the operational station keeping tolerance and manoeuvre execution intervals are investigated numerically for the Japanese twin broadcasting satellites, BS-2a and BS-2b. Then an actual operation result of the "Synchronized Method" applied for BS-2 is introduced. From this result, this method is ascertained to be useful for sharing the geostationary ring more efficiently.

Keywords: Geostationary Satellite, Station Keeping, Collision, Occultation, Twin Satellites, Relative Node, BS-2.

1. INTRODUCTION

More than one hundred satellites are operating on the geostationary ring at approximately 36,000 km above the earth's equator. In order to utilize it more efficiently, station and frequency assignments have been discussed with much effort, and some satellites had already been deorbited from the geostationary ring after their mission lives.

This paper introduces three methods sharing the geostationary ring more efficiently to keep twin satellites in a limited region preventing from collision hazards and mutual occultations.

The motion of a geostationary satellite is studied first. After that, three station keeping methods are investigated dynamically from the operational point of view under the condition of no radio interference. Then, three methods are examined numerically for the Japanese twin broadcasting satellites, BS-2a and BS-2b.

Finally, an actual operation result of BS-2 is reported. These satellites were launched on January 23, 1984 (BS-2a) and February 12, 1986 (BS-2b) and placed on the same geostationary orbit with the sub-satellite longitude at 110 deg E.

2. MOTION OF GEOSTATIONARY SATELLITE

It is convenient to describe a satellite position in a three dimensional, rectangular coordinates system when discussing a geostationary satellite motion. Fig. 1 shows the coordinates system, where r-axis corresponds with the radial direction, λ-axis the east longitude, and ϕ-axis the north latitude, and the origin is a centre of station.

The motion of the geostationary satellite is approximated in this coordinates system as follows (Ref.1).

$$r = a(1 + e \cos f) - r_s \quad (1)$$

$$\lambda = \Omega + \omega + f - \theta_g - \lambda_s \quad (2)$$

$$\phi = i \sin (\omega + f), \quad (3)$$

where

a : semi-major axis

e : eccentricity

i : orbital inclination

Ω : right ascension of ascending node

ω : argument of perigee

f : true anomaly

r_s: geostationary radius

θ_g: Greenwich sidereal time

λ_s: station longitude.

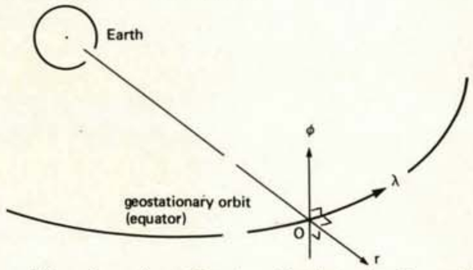

Fig. 1 Coordinates System to Describe Satellite Position

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By neglecting all perturbing forces, the satellite motion can be drawn as shown in Fig. 2, because all orbital elements except f are constant. This elipse locus can be regarded as the daily motion of the geostationary satellite.

Fig. 3 shows the projection of the satellite motion onto the r - λ plane which corresponds to the equatorial plane.

The orbital elements, however, are varied due to perturbations, such as nonsphericity of the earth's gravity, luni-solar attraction, solar radiation pressure, and so on. When discussing the orbital elements' evolution, the following equinoctial elements, instead of the usual Keplerian elements, are convenient in order to avoid the singular point where e or i is equal to zero.

a : semi-major axis

λ : sub-satellite longitude

$$\vec{e} \equiv \begin{pmatrix} \xi \\ \eta \end{pmatrix} = \begin{pmatrix} e \cos(\Omega + \omega) \\ e \sin(\Omega + \omega) \end{pmatrix} \tag{4}$$

$$\vec{i} \equiv \begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} \sin i \cos \Omega \\ \sin i \sin \Omega \end{pmatrix} \fallingdotseq \begin{pmatrix} i \cos \Omega \\ i \sin \Omega \end{pmatrix} \quad (\because i \fallingdotseq 0 \text{ deg}). \tag{5}$$

where $\vec{e}$ and $\vec{i}$ are called eccentricity vector and inclination vector respectively.

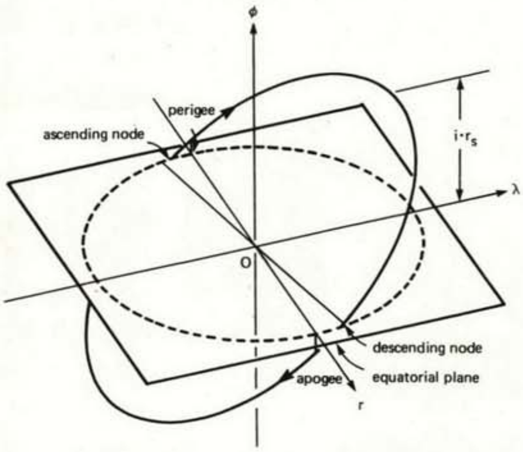

Fig. 2 Daily Motion of Geostationary Satellite

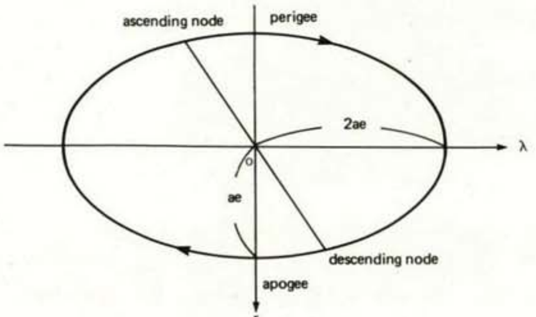

Fig. 3 Projection of the Motion to Equatorial Plane

Among the perturbing forces, the earth's triaxiality mainly affects to a and λ, the solar radiation pressure to $\vec{e}$, and the earth's oblateness and the luni-solar gravity to $\vec{i}$. Fig. 4 to Fig. 6 describe the evolution of mean orbital elements by these perturbing forces.

In order to keep a satellite in a required region, a and $\vec{i}$ should be controlled periodically. As a result of the manoeuvre of a, $\vec{e}$ is also changed. The magnitude of $\vec{e}$ ($|\vec{e}|$) determines the amplitude of the daily oscillation along the λ-axis as shown in Fig. 3. Therefore, e should be kept as small as possible. For this purpose, the manoeuvre execution time of longitude station keeping is chosen so that the direction of $\vec{e}$ changed by the manoeuvre becomes opposite to its drift motion direction caused by the solar radiation pressure.

Such an eccentricity-keeping method is called the "Sun-synchronized Method" or "Sun-pointing Method" (Ref. 2). By this method, eccentricity can be kept smaller than the radius of the natural drift motion of $\vec{e}$ caused by the solar radiation pressure.

3. THREE STATION KEEPING METHODS

This section introduces three longitude station keeping methods for avoidance of collision hazards and mutual occultations between two geostationary satellites located almost on the same position.

The conditions to avoid the collision between two satellites are given as

$$\Delta r \equiv | r_1 - r_2 | > \varepsilon_r \tag{6}$$

or

$$\Delta \lambda \equiv | \lambda_1 - \lambda_2 | > \varepsilon_\lambda \tag{7}$$

or

$$\Delta \phi \equiv | \phi_1 - \phi_2 | > \varepsilon_\phi, \tag{8}$$

where subscripts 1 and 2 denote satellites, ε_r, ε_λ, and ε_ϕ are permissible minimum distances between two satellites along the three coordinates axes. When either equation (7) or (8) is satisfied, mutual occultation of two satellites cannot occur.

Three possible longitude station keeping methods are investigated in turn. They are named "Longitude Separation Method", "Synchronized Method", and "Eccentricity Separation Method".

The "Longitude Separation Method" is the simplest idea such that the given longitude tolerance is divided into two regions and each satellite is kept in a respective region. Fig. 7 shows the operation image of this method, which indicates that it is possible to control the satellite positions independently. In this method, the operation is simple, but the manoeuvre execution interval, on the other hand, is the shortest among the methods because of its narrowest tolerance.

To extend this interval, another method, called the "Synchronized Method" is proposed such that operational longitude tolerance of two satellites is overlapped and station keeping manoeuvres for them are carried out sequentially. The operation image of this method is depicted in Fig. 8. From the operational point of view, however, simultaneous manoeuvres sometimes cause problems

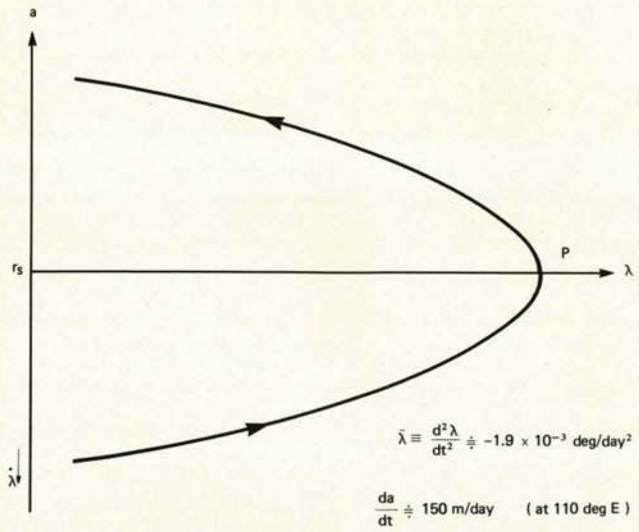

Fig. 4 Semi-Major Axis and Longitude Evolution

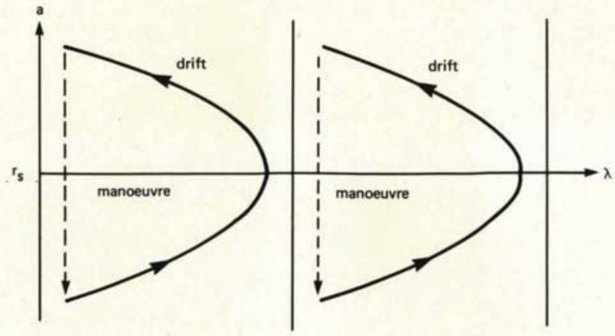

Fig. 7 Longitude Station Keeping Method (1)
(Longitude Separation Method)

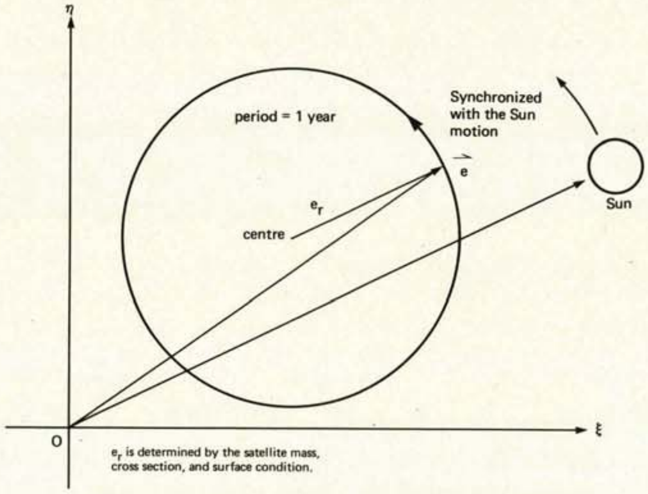

Fig. 5 Eccentricity Vector Evolution

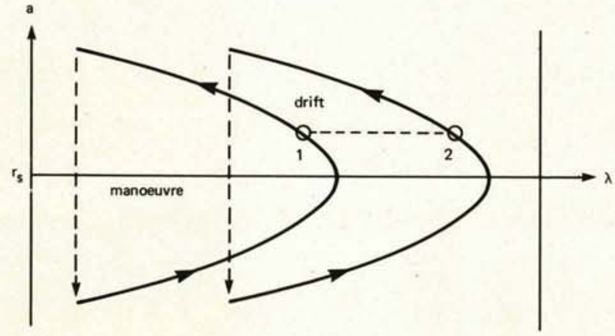

Fig. 8 Longitude Station Keeping Method (2)
(Synchronized Method)

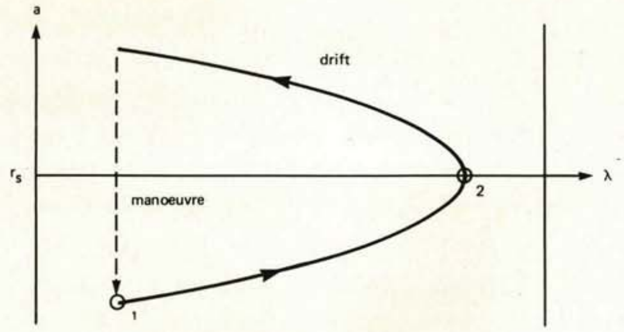

Fig. 9 Longitude Station Keeping Method (3)
(Eccentricity Separation Method)

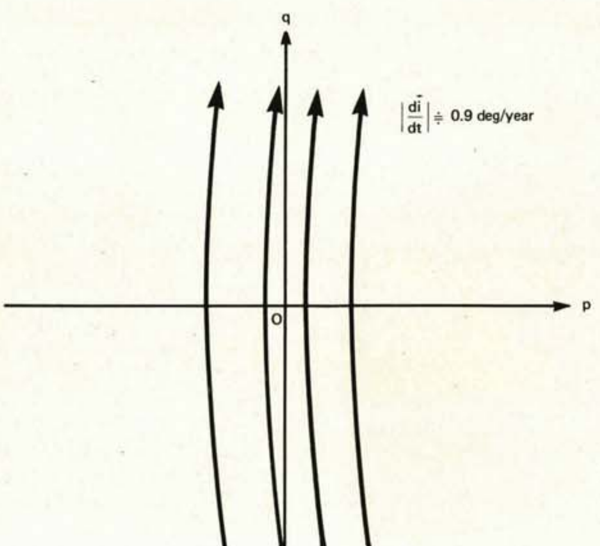

Fig. 6 Inclination Vector Evolution

related to assignment of equipments and scheduling of operators. This is a disadvantage of the "Synchronized Method".

The "Eccentricity Separation Method", the third method, solves this problem by shifting the drift motions of two satellites mutually by a half period of manoeuvre cycle, though they move on a same locus of drift motion. This method is drawn in Fig. 9, which indicates that $\Delta\lambda$ becomes zero twice during one keeping cycle. If $\Delta\phi$ is also zero at that time, mutual occultations occur. Moreover, if Δr also reaches zero at the same time, collision hazards occur.

In the third method, it is very difficult to avoid mutual occultations perfectly even if additional manoeuvres are done because of orbit determination and manoeuvre errors, though occultation probability is extremely small.

There is, however, a possible operational way to escape collision. There are two points where one orbit crosses the other orbital plane and $\Delta\phi$ becomes zero. These points are called "relative nodes". Therefore, it is possible to avoid collision by keeping $\Delta\lambda$ larger than ε_r around the relative nodes. This can be realized by separating the eccentricity vectors of two satellites along the direction of relative nodes.

As the inclination vector drifts almost along the q-axis according to time elapsing as shown in Fig. 6, the relative nodes are oriented almost in the same direction as the q-axis. This means that if the eccentricity vector would be separated along the η -axis as depicted in Fig. 10, collision hazards could be avoided at the relative nodes.

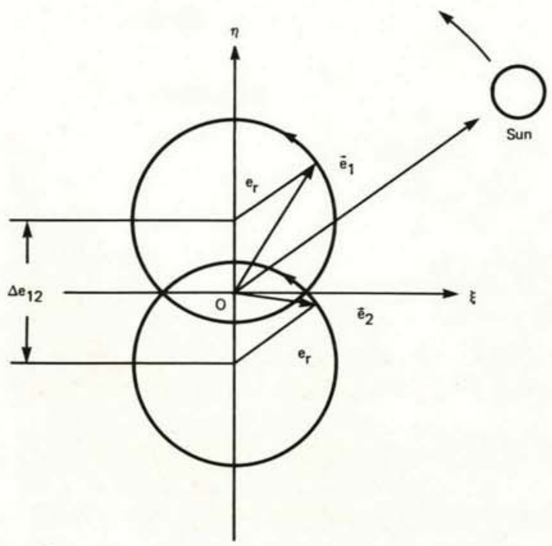

Fig. 10 Eccentricity Vector Separation

4. OPERATIONAL INVESTIGATION OF THREE METHODS

Three methods mentioned in section 3 are investigated in detail, especially from the point of view of manoeuvre execution interval.

4.1 Longitude Separation Method

This is the ordinary operation method except for the narrow keeping tolerance. The operational keeping tolerance is determined by taking into account the following items.

- orbit determination error in longitude: $\Delta\lambda_D$
- orbit determination error in semi-major axis : Δa_D
- rate of manoeuvre magnitude error : ε_m
- amplitude of daily oscillation along λ-axis due to eccentricity : $\Delta\lambda e$
- longitudinal margin for optimizing the manoeuvre time : $\Delta\lambda w$

Among them, Δa_D and ε_m are to be converted into a longitudinal error $\Delta\lambda_E$ at the point P in Fig. 4 where drift direction changes. $\Delta\lambda_E$ is described, when they are independent, as

$$\Delta\lambda_E = \frac{3}{2}\sqrt{\frac{\mu}{r_s^5}}\,\{\Delta a_D{}^2 + (\Delta a_m\cdot\varepsilon_m)^2\}^{1/2} \times \frac{N}{2} \tag{9}$$

where μ is the geogravitational constant, Δa_m the manoeuvre magnitude in the semi-major axis, and N the manoeuvre execution interval.
Considering the above mentioned margins, operational station keeping tolerance $\Delta\lambda_{OP}$ is given in Fig. 11, where $\Delta\lambda_{EW}$ is the given tolerance for station keeping.
In this case, $\Delta\lambda_{OP}$ is given by,

$$\Delta\lambda_{OP} = \Delta\lambda_{EW} - \{2(\Delta\lambda_D + \Delta\lambda_e) + \Delta\lambda_W + \Delta\lambda_E\}. \tag{10}$$

Other important relations between parameters are

$$\Delta\lambda_e = 2\,(e_r + \Delta e_r) \tag{11}$$

$$\Delta\lambda_W = |\,\ddot{\lambda}\,| \times \frac{N}{2} \tag{12}$$

$$\Delta a_m = \frac{2}{3}\sqrt{\frac{r_s{}^5}{\mu}}\cdot|\ddot{\lambda}|\cdot N \tag{13}$$

$$\Delta\lambda_{OP} = |\,\ddot{\lambda}\,| \times \frac{N^2}{8} \tag{14}$$

where e_r is the radius of mean eccentricity keeping circle, Δe_r the deviation of eccentricity from the circle due to manoeuvre and perturbations, and $\ddot{\lambda}$ the acceleration of longitude drift. In this method, the central eccentricity of its keeping circle is zero.

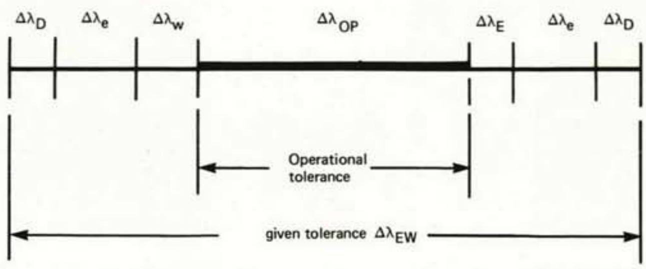

Fig. 11 Operational Keeping Tolerance (1)

4.2 Synchronized Method

In addition to the former discussion, the longitude separation distance between two satellites being kept on synchronized loci, defined as $\Delta\lambda_{12}$, is to be investigated for this method. This distance is determined by considering the following items,

- relative daily oscillation due to the eccentricity difference : $\Delta\lambda_{de}$
- longitude deviation by manoeuver error after one manoeuvre cycle : $\Delta\lambda_m$.

These parameters are given by

$$\Delta\lambda_{de} = 2 \ \Delta e \qquad (15)$$

$$\Delta\lambda_m = \frac{3}{2}\sqrt{\frac{\mu}{r_s^5}} \cdot \Delta a_m \cdot \varepsilon_m \cdot N \qquad (16)$$

where Δe is the difference between eccentricities of two satellite orbits. In order to avoid near miss, the distance between two nominal loci of drift motion must be greater than

$$\Delta\lambda_{12} = \Delta\lambda_{de} + \Delta\lambda_m \ . \qquad (17)$$

As the daily oscillation by the perturbations and the orbit determination error can be regarded as the same for both satellites, they are not taken into account for $\Delta\lambda_{12}$.
The result of these discussions is shown in Fig. 12, and $\Delta\lambda_{OP}$ for each satellite is given as

$$\Delta\lambda_{OP} = \Delta\lambda_{EW} - \{2(\Delta\lambda_D + \Delta\lambda_e) + \Delta\lambda_W + \Delta\lambda_E + \Delta\lambda_{12}\} \qquad (18)$$

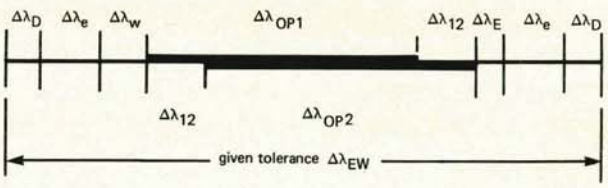

Fig. 12 Operational Keeping Tolerance (2)

4.3 Eccentricity Separation Method

The operational tolerance of this method is also given by Fig. 11, though magnitude of the tolerance and $\Delta\lambda_e$ are greater than those of the "Longitude Separation Method". In this case, the maximum eccentricity is greater than those of other methods, because the eccentricity vector is shifted from the optimum point.

One more important discussion item here is the separation distance of eccentricity vectors of two satellites. In order to avoid the collision, the separation distance should be greater than

$$\Delta e_{12} = \frac{(\Delta a + \Delta a_m + \varepsilon_r)}{r_s} + \Delta e, \qquad (19)$$

where Δa is the difference of semi-major axes when $\Delta\lambda$ is less than ε_λ. Therefore, in this case, $\Delta\lambda_e$ becomes

$$\Delta\lambda_e = 2\{(e_r + \Delta e_r) + \Delta e_{12}/2\} = \{2(e_r + \Delta e_r) + \Delta e_{12}\} \qquad (20)$$

and $\Delta\lambda_{OP}$ is given by equation (10).

4.4 Numerical examination for BS-2

The twin Japanese broadcasting satellites, BS-2, are placed on the geostationary orbit at 110 deg E and the given station tolerance in longitude is 0.2 deg. The acceleration of longitude drift $\ddot{\lambda}$ at 110 deg E is about -1.9×10^{-3} deg/day^2.
Other parameters assumed for BS-2 are,

$$e_r = 2 \times 10^{-4}$$

$$\Delta e_r = 1 \times 10^{-4}$$

$$\Delta\lambda_D = 0.005 \text{ (deg)}$$

$$\Delta a_D = 50 \text{ (m)}$$

$$\varepsilon_m = 5\%.$$

Under these conditions, operational tolerance $\Delta\lambda_{OP}$ and manoeuvre interval N are calculated for three methods in the following.

For the "Longitude Separation Method", the given tolerance is equally divided into two regions, so that the station keeping tolerance is 0.1 deg for each satellite. The relation between $\Delta\lambda_{OP}$ and N depicted in Fig. 13 shows that the maximum $\Delta\lambda_{OP}$ is 0.012 deg which gives a manoeuvre interval of 7 days.
In the case of "Synchronized Method", additional parameters are assumed as,

$$\Delta e = 1 \times 10^{-4}$$

$$\Delta a_m = 2.2 \text{ (km)},$$

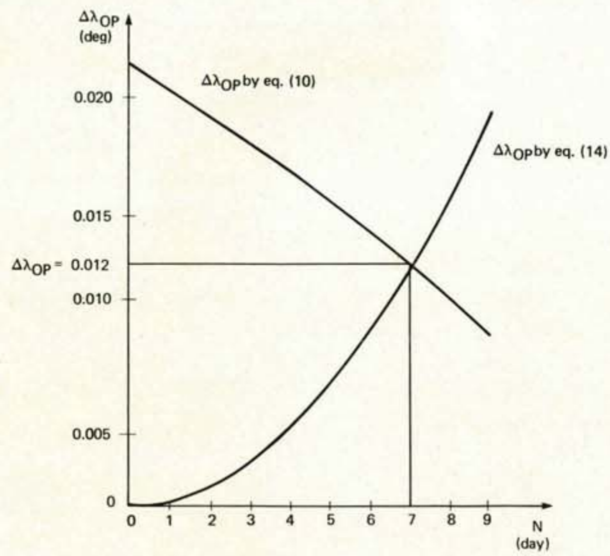

Fig. 13 Relationship between $\Delta\lambda_{OP}$ and N (Longitude Separation Method)

so that the separation distance between two loci of drift motion becomes

$$\Delta\lambda_{12} = 0.033 \text{ (deg)}.$$

When the manoeuvre interval is 15 days, $\Delta\lambda_{OP}$ is maximized and its value is 0.063 deg.

For the "Eccentricity Separation Method", the eccentricity can be kept within 3×10^{-4} from the keeping centre. When

$$\Delta a = 2 \text{ (km)}$$

$$\varepsilon_r = 1 \text{ (km)},$$

the separation distance of eccentricity vector Δe_{12} must be greater than 2.3×10^{-4} and $\Delta\lambda_e$ becomes 0.048 deg. For this case, $\Delta\lambda_{OP}$ of 0.066 deg and N of 16 days are the maximum values.
These results are shown in Table 1 and Fig. 14, and they seem to be acceptable for actual operations.

Table 1 $\Delta\lambda_{OP}$ and N for Three Methods

Method \ Parameters	$\Delta\lambda_{OP}$ (deg)	N (days)
Longitude Separation Method	0.012	7
Synchronized Method	0.063	15
Eccentricity Separation Method	0.066	16

5. ACTUAL OPERATION RESULT OF BS-2

The actual operation result of BS-2 is reported in the sequel. Two BS-2 are being operated by Telecommunications Satellite Corporation of Japan (TSCJ) since July 12, 1986 and the "Synchronized Method" is adopted as the station keeping method.

At the west boundary of station, 0.060 deg is set as the margin whose details are,

$$\Delta\lambda_D = 0.010 \text{ deg}$$

$$\Delta\lambda_e = 0.035 \text{ deg}$$

$$\Delta\lambda_W = 0.015 \text{ deg}.$$

$\Delta\lambda_{12}$ becomes 0.035 deg, assuming that

$$\Delta\lambda_{de} = 0.015 \text{ deg}$$

$$\Delta\lambda_m = 0.020 \text{ deg}.$$

The margin for east boundary is 0.055 deg, because

$$\Delta\lambda_D = 0.010 \text{ deg}$$

$$\Delta\lambda_e = 0.035 \text{ deg}$$

$$\Delta\lambda_E = 0.010 \text{ deg}.$$

Under these conditions, the station keeping tolerance $\Delta\lambda_{OP}$ for each satellite becomes 0.050 deg and the corresponding manoeuvre execution interval is 14 days. These values are less than these in Fig. 14, because 2 weeks of manoeuvre interval is operational. As the result, the operational keeping region for BS-2a is limited by 109.960 deg E and 110.010 deg E, and that of BS-2b by 109.995 deg E and 110.045 deg E as shown in Fig. 15.

The manoeuvre execution time of BS-2 is chosen to keep the local sun time of the satellite within 18 h ±3 h for adopting the "Sun-synchronized Method", and time difference of two satellites' manoeuvres should be greater than 1 hour for operational preparation.

Moreover, BS-2 are controlled to keep the distance between two satellites greater than 10 km considering the worst case of orbit determination error. When this distance is estimated to become less than 10 km by manoeuvre execution error, an additional manoeuvre will be scheduled immediately to eliminate the danger of collision.

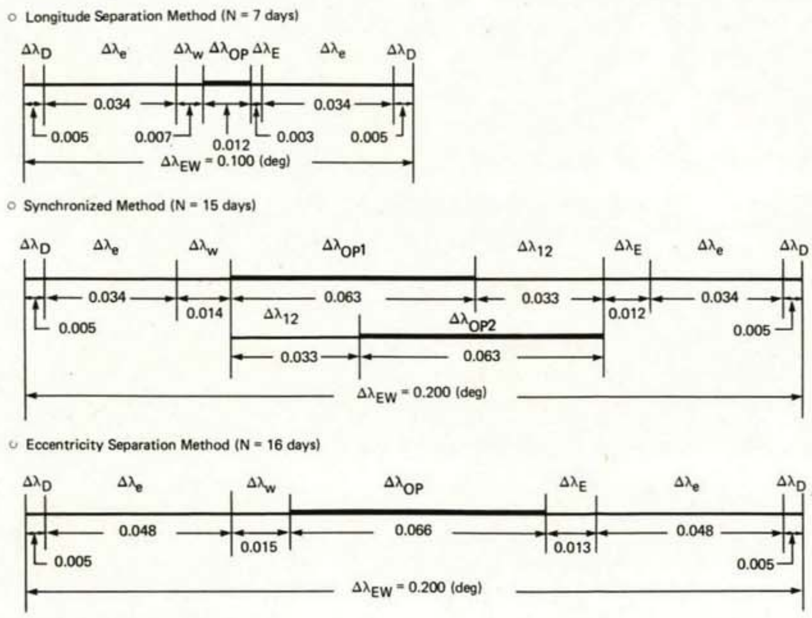

Fig. 14 Applied Example for BS-2

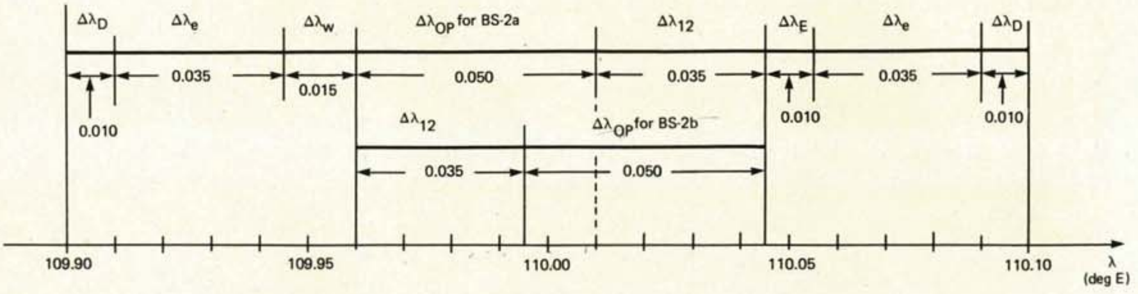

Fig. 15 Operational Keeping Boundary for BS-2

The sub-satellite longitude evolution of BS-2 from August 21, 1986 to September 19, 1986 is depicted in Fig. 16, where each satellite is not always kept in the respective region mentioned above because of manoeuvre execution error.

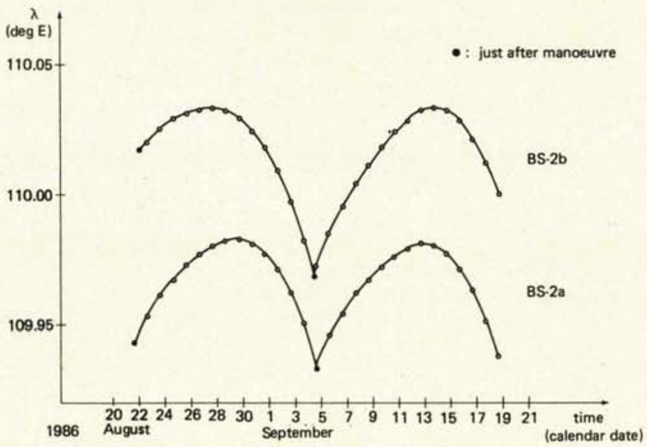

Fig. 16 Sub-Satellite Longitude Evolution of BS-2

6. CONCLUSION

Three operational methods to keep twin geostationary satellites within a limited region are introduced. They are named "Longitude Separation Method", "Synchronized Method", and "Eccentricity Separation Method". These three methods are examined numerically for Japanese twin broadcasting satellites, BS-2, from the operational point of view. And as an actual example, the keeping result for BS-2 is introduced. Judging from the result, the "Synchronized Method" is very effective for sharing the geostationary ring more efficiently.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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