研究論文

Feasibility Study on New SPS Concept Utilizing Multiple Satellites in Formation Flight

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Abstract

Space-solar Power Station (SPS) with 1GW class power generation is conventionally configured with a gigantic monolithic antenna, say, 1km in diameter, for the microwave transmission. This configuration seems quite advantageous in terms of the beam efficiency to concentrate the transmission (Tx) energy around its beam axis, but requires very high breakthrough technologies to the capacity of launch vehicle, the design and construction of the deployable space structure, and/or the design of robotics for the in-orbit assembly of space structure, all of which arise from the scale of space structure. In order to alleviate these difficulties, a new SPS concept utilizing multiple satellites, each of which has a relatively small Tx antenna, discretely allocated in orbit and constructing formation flight, is proposed. To validate the feasibility of the new concept, the beam efficiency of two-dimensional hexagonal antenna array, each of which is 200m in diameter, as a possible limit of the existing technology to manufacture the deployable space structure, is analyzed as a function of adjacent distance of satellites within a range of meters to hundreds of meters. The intention of this study is to enhance the square array analysis made by us and JAXA under the study contract by JAXA in 2004. The result is summarized in a form of the rectenna site diameter enclosing 95% of Tx energy, corresponding 95% beam efficiency of the antenna array, and enhanced to the discussions how to optimize the satellites geometry to minimize the rectenna site size. We also study the sensitivity of the optimized satellites geometry against the fluctuation of adjacent distance due to the orbit control error of satellites. Based on this sensitivity analysis, we further enhance our discussions to the feasibility of formation flight from the space technology viewpoint.

Keywords: SPS, Gigantic transmission antenna, Formation flight, Multiple satellites, Antenna array

1. Introduction

The conventional SPS system with 1GW class power generation is configured with a gigantic antenna for the microwave transmission(1)~(4), say, 1km in diameter with phased array antenna consisting of several hundreds million of element antennae which weighs more than 10,000t. It therefore needs a large number of launches to the low earth orbit (LEO), the in-orbit assembly by robotics or the extra vehicle activities (EVA), the in-orbit verification tests, and re-orbiting the gigantic space structure from LEO to the final orbit. The feasibility of this system concept, however, seems extremely challenging from the space technology viewpoint. The most fundamental premise, which would have led this concept, is thought to be the radiation pattern of the antenna. It is because the monolithic and huge antenna, by the nature, can provide good beam efficiency, or in other words, can concentrate Tx energy around the beam axis and allow a smaller rectenna site.

Recently, various studies have been carried out to construct the satellites formation flight in orbit(5)~(7). One application of the formation flight to SPS is to separate the sun-pointing reflector from the antenna to avoid mechanical and electrical connections, but it still uses the gigantic antenna(8). If multiple SPS satellites, each of which is smaller scaled and equips relatively smaller antenna, in formation flight can provide good beam efficiency, it would change the stream of SPS development from its start point.

With this motivation, we studied the radiation pattern and the beam efficiency of two-dimensional antenna array by the electro-magnetic simulation, assuming 1GW transmission from the geostationary earth orbit (GEO), in formation flight. Each antenna has relatively smaller diameter and the adjacent distance (distance between each pair of adjacent antennae) is assumed within a range of meters to hundreds of meters. The

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simulation covers both square and hexagonal array geometries, and searches whether, or not, there is any optimized adjacent distance to maximize the beam efficiency and to minimize the rectenna site size. The comparison study of beam efficiency between new and conventional concepts is also made.

We also validate the optimized adjacent distance of satellites or the maximized beam efficiency has a low sensitivity against the adjacent distance fluctuation. Based on this, we further enhance our discussion to the orbit selection and the feasibility of orbit control of the satellites to maintain the formation flight.

2. System Configuration and Features

2.1 System Configuration

Fig. 2.1 shows an example of flight configuration of Multiple Satellites SPS (MSS) in formation flight. In order to establish the beam forming control to all antennae, the distribution of source frequency signal to all satellites is necessary to maintain the in-phase coherency among all satellites. By this means, a large-scale "Phased Array" system consolidating multiple satellites can be created with no mechanical and no electro-conductive connections among satellites.

Each satellite consists of satellite bus system, sun-tracking mirror, fixed focusing mirror, hybrid solar-cell panel, and connection truss structure as s shown in Fig. 2.2.

The sun-tracking mirror collects the solar light and guides it to the fixed focusing mirror with a concave reflector. It focuses the solar light to a certain density on hybrid solar-cell panel, the density of which is most efficient for solar cells on the hybrid solar panel to generate a maximum electric power. The panel is a sandwich structure comprising a solar cell skin facing the deep space side, intermediate circuits structures, and the phased array antenna skin facing toward the earth. The intermediate circuits structures house DC to RF conversion circuits, phase shifters, and amplifiers. The solar light is first converted to DC at the solar cells on the solar skin panel, second converted to RF at the intermediate circuits structure, and then transmitted as the microwave energy from the phased array antenna to the earth.

Each satellite can be launched separately to each respective orbit to construct the formation flight by maintaining each relative position to the others, and transmits microwave energy to the ground under the united beam forming control.

2.2 Features of SPS with Multiple Satellites

Table 2.1 shows the comparison of features of MSS and the conventional Single Satellite SPS (SSS). As clearly explained in Table 2.1, MSS has advantages arising from the smaller sized structure than SSS, but has two disadvantages, which are on the beam efficiency performance and the formation flight difficulty.

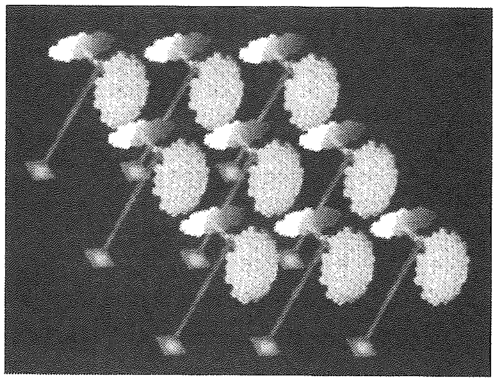


Fig. 2.1 An example of flight configuration of MSS in formation flight

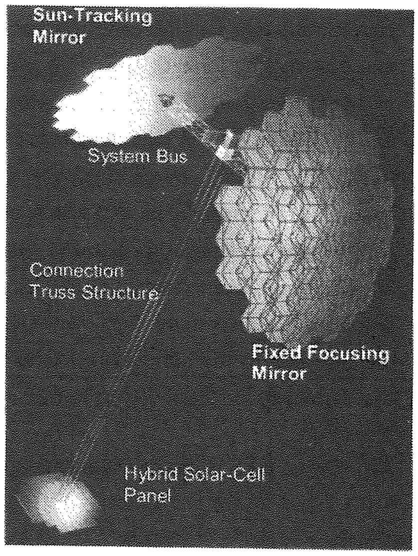


Fig. 2.2 Configuration of one satellite

Table 2.1 Features of MSS in comparison with SSS

Items	MSS	SSS
In orbit structure deployment	Mid to easy (mid and small size structures)	Difficult (In orbit robotics assembly may be needed)
Start of power transmission	Early stage (each launch)	After structure completion
Mission expandability	Mid to easy (more launches)	Difficult
Mission upgradability	Mid to easy (sequential permutation)	Difficult
Mission life	Long (sequential permutation)	Up to single satellite life
Attitude controllability	Easier (relatively smaller size)	Difficult (larger disturbances due to huge size)
Beam efficiency	Worse? (grating nature)	Good
Satellite navigation & System Operation	Difficult? (formation flight)	Easy (one satellite)

In order to overcome the former difficulty, quantitative simulations to improve the beam efficiency of MSS by finding an optimized geometry of satellites are made and detailed in Section 3. To alleviate the latter difficulty, the orbit selection not only to ease the formation construction with less fuel consumption, but also to allow the continuous energy supply to one rectenna site on the earth is are studied and described in Section 4.

3. Beam Efficiency of SPS with Multiple Satellites in Two-Dimensional Geometry

3.1 Analysis Modeling of One Antenna

In order to model MSS as uncomplicated as possible, the analysis model is considered follows.

(1) Each antenna aperture is equal to all antennae and far larger than the wavelength.

(2) Antennae are allocated on one plane two-dimensionally with a constant spacing far larger than the wavelength.

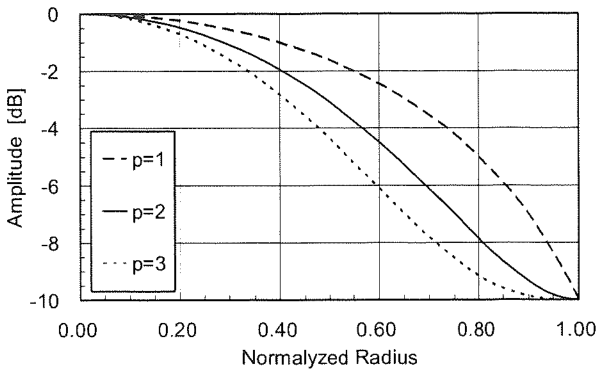
(3) All antennae transmit the microwave power with an equal power to all antennae under united beam forming control for the coherent combination.

When the phased array transmission from the above configuration is considered, significant level of grating lobes should be produced in the radiation pattern. The peak level of grating lobes tends to be restricted by the envelope of radiation pattern produced by a single antenna aperture of one power generation satellite (PGS). Bearing this in mind, even MSS should have each antenna aperture as large as possible, in order not to spread the grating lobes to a wider angle. As this may weaken MMS's advantages, however, we selected 200m in aperture diameter, as a practical upper limit of the deployable space structure, to study the radiation characteristics of MSS.

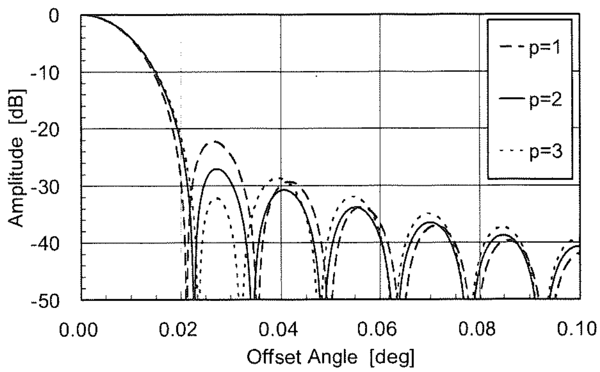
As for the assumption of aperture amplitude distribution, we select $(b+(1\text{-}r^2)^p)/(b+1)$ aperture distribution. Where, b and p are parameters to determine edge taper level, and r is a normalized aperture radius. Fig. 3.1 shows the aperture amplitude distribution, radiation pattern and beam efficiency of one 200m diameter antenna, having edge taper level of −10 dB, determined by choosing b=0.462. At this taper level, we choose p=2 for the further simulation, because the subtended half angle at 95% beam efficiency becomes minimum at this value as shown in table 3.1 and Fig. 3.1(c). The beam efficiency η over subtended half angle ψ is defined as follows.

$$\eta = \frac{\int_0^{2\pi}\int_0^{\psi}\left|E_s(\theta,\phi)\right|^2 \sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi}\left|E_s(\theta,\phi)\right|^2 \sin\theta d\theta d\phi} \qquad (1)$$

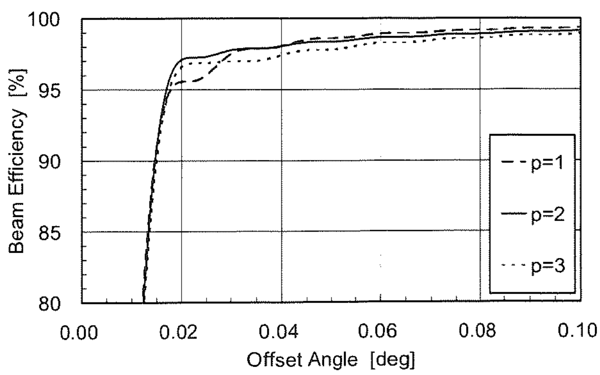
Where, E_s means electric field intensity, θ, ϕ are co-latitudinal and longitudinal angles in spherical coordinate system.



(a) Aperture amplitude distribution



(b) Radiation pattern



(c) Beam efficiency

Fig. 3.1 Aperture amplitude distribution, radiation pattern and beam efficiency of one MSS antenna (aperture dia.: 200m).

Table 3.1 Subtended half angle for 95% beam efficiency.

Edge Level	p=1	p=2	p=3	p=4	p=5
0dB (b=0.000)	0.0580	0.0580	0.0580	0.0580	0.0580
-10dB (b=0.462)	0.0179	0.0170	0.0176	0.0188	0.0350
-20dB (b=0.111)	0.0171	0.0183	0.0201	0.0225	0.0258
-30dB (b=0.033)	0.0174	0.0195	0.0221	0.0247	0.0274
-40dB (b=0.010)	0.0176	0.0203	0.0227	0.0253	0.0278

unit:deg.

3.2 Two-Dimensional Analysis

In order to construct MSS formation flight, two types of two-dimensional array geometry of PGSs are assumed. One is a square array shown in Fig. 3.2, and the other is a hexagonal array shown in Fig. 3.3.

Fig. 3.4 shows the calculated radiation pattern and beam efficiency of MSS with square array geometry with 25 circular antennae as a function of parameter L, distance between adjacent antennae. In the square array, total area of 25 each antenna apertures, each 200min diameter, can be equal to that of 1km diameter single monolithic antenna. As assumed in Section 3.1, Tx power from each PGS is 40MW(=1GW/25) constant. The radiation pattern and beam efficiency of 1km diameter single antenna with the uniform aperture amplitude distribution are shown in Fig. 3.4. This is to make a fair comparison with MSS having the uniform power generation in all PGS.

From the results of two-dimensional analysis shown in Fig. 3.4, it is clear that the beam efficiency of MSS varies as a function the adjacent antenna distance (L) which corresponds to the PGS spacing on a center-to-center basis.

3.3 Optimized Array Allocation

When the beam efficiency is fixed as a design target, say, 95%, the rectenna site diameter (D), which encloses 95% of Tx energy, can be obtained by the following equations as a function of the distance of adjacent antennae.

$$\eta(N, L, \psi) = 0.95 \qquad (2)$$
$$D = 2L_0 \sin\psi \qquad (3)$$

Where, N is the number of antennae, L is the adjacent distance, ψ is the subtended angle which encloses 95% energy, and L_0 is the altitude of the orbit.

Using equations (2) and (3), the response of rectenna site diameter as a function of the distance of adjacent antennae, L, and the number of antennae, N, is calculated for square and hexagonal arrays. In this calculation, the diameter of each antenna is fixed as 200m, and L and N are dealt as variables. This model can mean either (1) the Tx power of each PGS varies, when the total Tx power is fixed as 1GW and N changes, or, (2) the total Tx power varies, when the Tx power of each PGS is fixed as 40MW and N changes. In any case, since the purpose of analysis is to discuss how to maximize the beam efficiency (percentage of the Tx power utilization), this modeling should maintain its role. Fig. 3.5(a) and (b) show the calculation results for the square and hexagonal array geometries, each respectively. From these figures, it is found that local minimums of the rectenna site diameter enclosing 95% energy repeatedly appear as a function of L and the minimums also vary as a function of N.

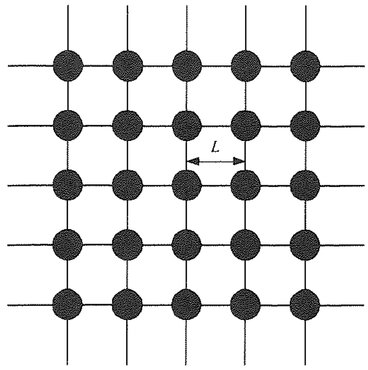


Fig. 3.2 Square array

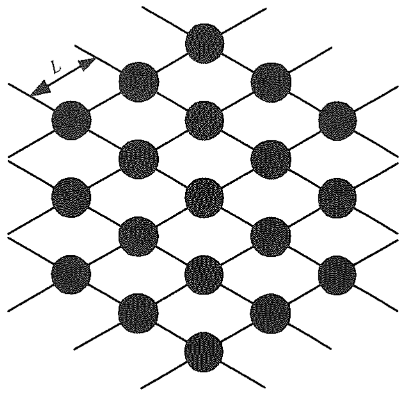
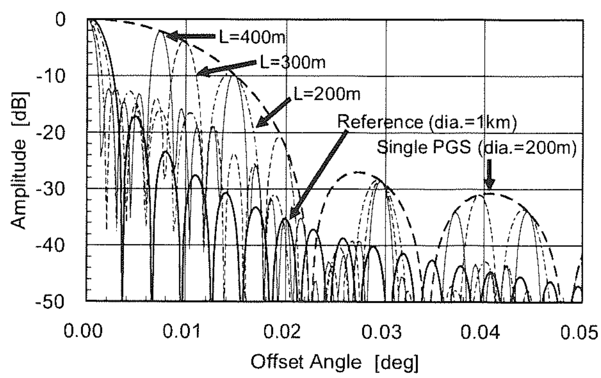
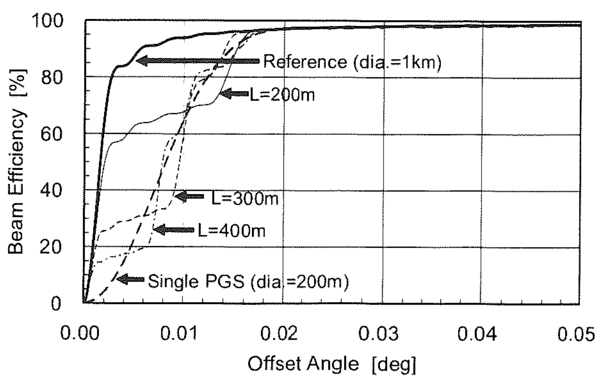


Fig. 3.3 Hexagonal array



(a) Radiation pattern



(b) Beam efficiency

Fig. 3.4 Radiation pattern and beam efficiency of MSS (N =25, square array)

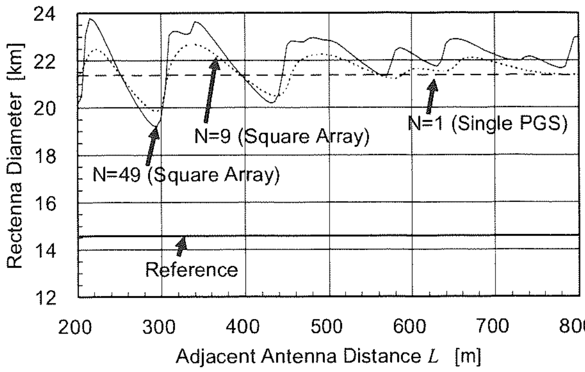
This former phenomenon can be explained as follows. The beam efficiency (enclosed energy) of MSS can be obtained by the power integral of the main, grating and side lobes, to the extent necessary. These lobes are, by nature, included in the envelope of radiation pattern of a single antenna of one PGS. The beam efficiency is mainly governed by the number and radiation power of grating lobes existing in the integration area. If we discuss the number of lobes included in the main lobe of one PGS and integrate them to obtain a certain beam efficiency, for easier understanding, the number of lobes existing in the main lobe shown in Fig 3.4(a) are two, three and four, when L=300m, 400m, and 500m, each respectively. On the other hand, the beam width of each lobe, or the radiation power in each lobe, decreases according to the increase of L. This is because the base line of the beam interference among all PGSs increases. Furthermore, a grating lobe existing just outside the first null point changes its height when it moves toward the null point according to the increase of L. Combining these three effects, it seems reasonable that the total radiation power included in the main lobe of one PGS shows a gradually fluctuated dull response according to the increase of L, and the local minimums repeatedly appear at the distances where the grating lobe outside the null point is included in the main lobe.

The latter reason can be explained as follows. If one grating lobe is produced at a certain subtended angle with an adjacent distance, the optical path length differences at the center of all apertures are $2n\pi$ (n=0, ±1, ±2, · · ·). Since the ratio of the aperture diameter over the adjacent distance(=D/L) is constant, the position of the grating lobe is kept unchanged, even when increasing the number of apertures. Concurrently, the ratio of the peak of the grating lobe over that of side lobes around it should be increased, because the equivalent total aperture of beams becomes larger. This means that the beam efficiency tends to be more dependent on the inclusion of grating robe in the integration area, and the local minimum values become improved distinctly.

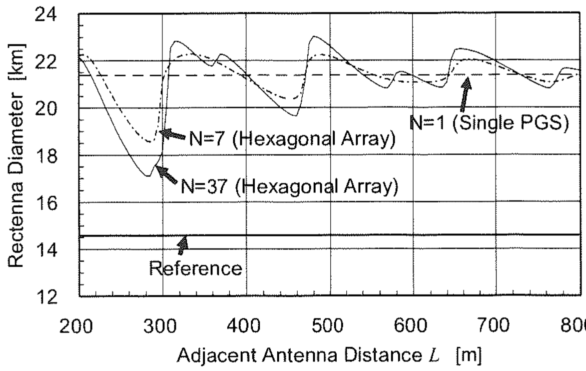
From Fig. 3.5, the following points are obtained.

(1) Distance (L) to minimize rectenna site diameter enclosing 95% energy is approximately 290 m, when each antenna diameter is 200m in both array geometries. Even when N is small, the local minimums clearly exist.

(2) The minimized rectenna site diameter at the square and hexagonal arrays is 1.32 times and 1.17 times as large as that at 1km diameter reference system, each respectively. The hexagonal array shows better local minimums, because it includes more apertures within a certain radius of array than the other, so that the number of grating lobes also increases.



(a) Square array



(b) Hexagonal array

Fig. 3.5 Response of 95% energy enclosing rectenna site diameter as a function of distance of adjacent antennae and number of array

4. Feasibility Study from Orbit Control of Satellites

4.1 Orbit

In order to supply the microwave power on a steady basis, the orbit suitable for MSS to construct the formation flight should be near GEO. One of the candidate orbits is so-called, Record Plate Orbit (RPO)[9] with GEO as a cluster center orbit.

In RPO, each satellite maintains a constant distance from the center satellite in the cluster center orbit. In the formation flight in RPO, multiple satellites in the formation show 360 degrees revolution with respect to the cluster center satellite at every orbiting. This orbit can be chosen by setting the eccentricity and inclination of orbit as per the following equations[9].

$$i_j = i \pm \Delta i \quad (4)$$

$$\Delta i = \frac{\sqrt{3}}{2}\frac{R}{a} \quad (5)$$

$$e = \frac{\Delta i}{\sqrt{3}} \quad (6)$$

Where, i_j is the inclination angle of the RPO, i is the inclination angle of the cluster center orbit (in GEO, i =0), Δi is the offset angle of RPO from the center orbit, a is the semimajor axis of cluster center orbit (in GEO, a =36000 km), R is the constant distance from the cluster center and e is the eccentricity of RPO.

In order to explain the RPO, Hill coordinate system, as shown in Fig. 4.1, is introduced[9]. Aligning x axis to the radius vector, y axis to the tangential line, and z axis parallel to the orbit momentum vector in the orbit normal direction, the satellite motion relative to the cluster center satellite can be expressed by the following equations.

$$\begin{aligned} x &= -ae\cos M \\ y &= 2ae\sin M \\ z &= \pm\sqrt{3}x \end{aligned} \qquad (7)$$

Where, M is the mean anomaly.

If there is no perturbation in RPO and the cluster center orbit, the relative motions of satellites in the formation flight can be maintained with no additional adjustment. Practically, however, the satellites will receive the following perturbations and the shape of formation will be deformed consequently.

- earth gravitational potential (J2, J4)
- gravitational pull of the moon
- gravitational pull of the sun
- radiation pressure by the sun
- atmospheric drag

In the orbit as high as GEO, the perturbation should contain so small components of the high spatial frequency that the shape of formation can be rather deformed homogeneously with a low time frequency. Therefore, RPO should be therefore a very promising candidate to minimize the fuel consumption to provide the above orbit control[10]~[12].

4.2 Satellites Allocation in Orbit

We choose the hexagonal array geometry, because it can provide a better beam efficiency as described in Section 3. Fig. 4.2 and Table 4.1 show one example of the geometry. Maintaining the hexagonal array, the concentric allocation of satellites preferred by space technology is also attainable. Overall configuration of the SPS with multiple satellites in formation flight will be as shown in Fig. 4.3. In this case, each PGS transmits 37MW power, assuming 1GW SPS.

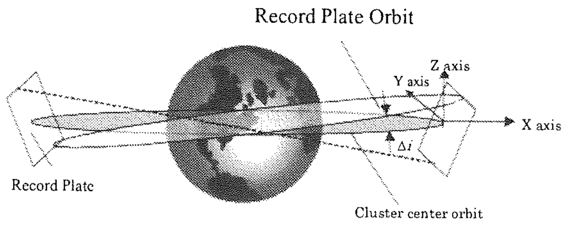


Fig. 4.1 Hill coordinate systems and RPO

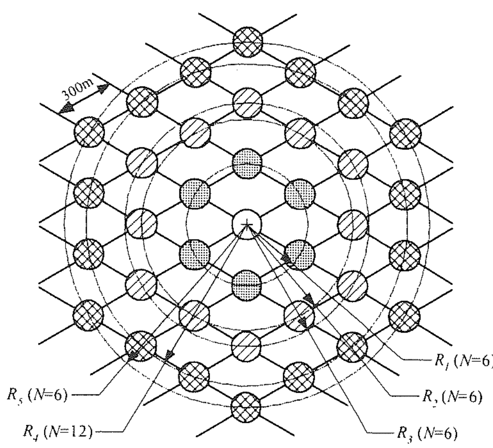


Fig. 4.2 One example of satellites allocation (Hexagonal array) in RPO

Table 4.1 Relationship between number of satellites and the distance from the center satellite of Fig.4.2.

Distance from the center satellite	Number of satellites
R_0= 0.0 m	1
R_1=300.0 m	6
R_2=519.6 m	6
R_3=600.0 m	6
R_4=793.7 m	12
R_5=900.0 m	6
Total	37

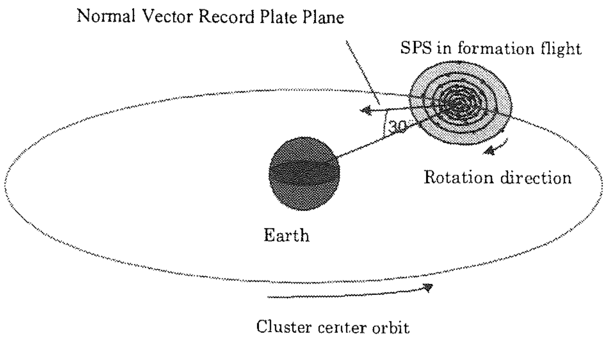


Fig. 4.3 Multiple satellites in formation flight

4.3 Controllability of Satellites in Formation Flight

When constructing formation flight with a few satellites, the centralized control system has been applied generally. If we expand this system to the formation flight of MSS, the cross-link communication between the center satellite and other satellites should become so busy that the computation load at the center satellite would be increased proportionally to the square of the distributed autonomous system the distributed autonomous system has been studied as a possible solution. If the distributed autonomous control system is applied to RPO, the effectiveness not only to simplify the cross-link communication, but also to reduce the fuel consumption are confirmed in several papers(10)(13)(14).

The next subject is the controllability of relative motions of satellites. The Autonomous Formation Flying sensor (AFF) is already studied and developed by Jet Propulsion Laboratory, and it can achieve the relative position knowledge of ±1cm and the attitude knowledge of ±1arcminute(15). Using these numbers, the control error of the relative position of satellites at our formation flight scale can be within 1m range. Assuming isotropic deformation, this error would not degrade the optimized beam efficiency, thanks to the little sensitivity of the beam efficiency as shown in Fig. 3.5. Assuming the random fluctuation of satellites, 1m-position error to the in-plane direction and the off-plane direction on the record plate, the phase error due to each position error is only 7.2 degrees and 5.1 degrees, respectively. This phase error seems harmless to establish grating lobes as planned for the positive utilization. We therefore believe the SPS with multiple satellites in formation flight is a promising candidate from the orbit control viewpoint as well as the beam efficiency viewpoint.

5. Conclusion

New SPS concept utilizing multiple satellites in formation flight, MSS, is proposed. As a result of the comparison study, MSS is confirmed to posses a lot of advantages over the conventional gigantic system in terms of feasibility of the space structure readiness, and the better mission expandability and upgradability, but to posses two disadvantages arising from the grating lobes generation and the formation flight difficulty. In order to resolve the former disadvantages, the method to utilize the grating lobes positively and improve the beam efficiency by optimizing the distance of adjacent satellites in formation flight is developed. In order to resolve the latter disadvantage, the feasibility of formation flight in RPO utilizing the distributed autonomous control system and AFF developed by JPL is confirmed from the viewpoints to minimize the fuel consumption and to maintain the optimized satellites geometry due to orbit control errors.

In conclusion, we like to advocate that the new SPS concept utilizing multiple satellites in formation flight is a promising candidate to expedite the SPS program.

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