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Design Optimization of Phased-Array-Fed Reflector Antennas for Mobile Communication Satellites

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A satellite antenna system for satellite communications requires high gain and effective transmission power use. To satisfy these requirements, we studied a phased-array-fed reflector antenna for multiple beams, particularly the optimization method to design antenna parameters and to determine the array weight distributions for high gain, low side-lobe levels, and efficient amplifier use. The results of our analytical study and experiment model test clarified the electrical performance and verified the optimum design method. We also studied the effects of the weighting error, given to the optimized weighting distribution, which have a significant effect on the antenna performance.

Nomenclature

a = antenna element's diameter, mm
D = aperture diameter of offset parabolic reflector, mm
F = focus length of offset parabolic reflector, mm
f_i = frequency ($i = 1, 2, 3, 4$), Hz
L = offset length from reflector's focus to feed array, mm
s = element spacing, mm
θ_{off} = offset angle of offset parabolic reflector, deg
λ = wavelength, mm

Introduction

COMMUNICATION satellites using a geostationary orbit (GEO) provide low-cost personal communication services. A satellite system with high gain and high transmission power is required for personal communications with handheld terminals using GEO satellites. A multibeam antenna with a large deployable reflector is one key technology available to achieve this high gain. Using pattern synthesis to generate low side-lobe patterns to reuse limited frequency resources is important. Furthermore, beam scanning and beam shaping flexibility are required for future satellite communications and will produce new applications.

This paper focuses on an antenna system that realizes the requirements and advanced functions just noted. The Mobile Satellite[1] and the Asia Cellular Satellite System,[2] using a cluster-fed reflector antenna, adopted a hybrid matrix power amplifier system to achieve power flexibility. However, based on a tradeoff study on increasing the number of beams and controlling the beam direction, we selected a phased-array-fed reflector antenna. This antenna has the following advantages over a conventional cluster-fed reflector antenna:

1) The number of feed elements is independent of the number of beams. Therefore, many beams can be generated with a smaller primary feed array.

2) The beam shape and direction can be changed.

3) Lower power amplifiers are acceptable for high transmission power generation because of the larger number of element antennas in phased-array-fed reflector antennas compared to cluster-fed antennas.

The authors have reported the design procedure of a phased-array-fed antenna.[3] However, the design details and the electrical performance have not been studied yet. Therefore, the purposes of this study are 1) to develop a weight optimization method that determines the optimum weight distributions of a feed array to realize a low side-lobe pattern for each beam and to achieve flexible power transmission, allowing transmission power to be changed beam-by-beam according to traffic conditions; 2) to optimize the antenna parameters, especially important parameters such as element spacing and the location of the feed array, which are studied in detail; and 3) to clarify the electric performance and to verify the design effectiveness by analysis and measurements of an experiment model.

The phased-array-fed antenna with two types of weight distributions is described: One consists of the same amplitude and individual phase weight distributions for beams. This type is designed using the new weight optimization method and is verified by measurements. The other consists of individual amplitude and phase weight distributions for beams. The latter type is designed by a conventional method. The antenna achieves high gain and low side lobe.

Design of Phased-Array-Fed Reflector Antenna

Requirements and Parameters

To realize personal communications with handheld terminals, a transmit multibeam antenna for satellite communications must provide high coverage gain and beam isolation for coverage areas where the same frequency is used. To satisfy these requirements, the system must be able to maximize the coverage gain where traffic is concentrated, achieve a coverage gain exceeding 42 dBi [the gain of an isotropic radiator is defined to be unity (=0 dBi)], realize frequency reuse every three beams, and provide beam isolation exceeding 20 dB.

We studied the phased-array-fed reflector antenna system to obtain these functions. The aperture diameter of the reflector is assumed to be 108.3λ (= 13 m). The frequency band is 2.5 GHz. The phased-array feed is composed of feed elements, amplifiers, beam-forming networks (BFNs), etc. The feed system is shown in Fig. 1. Each BFN excites each beam weighting. A beam allocation with 10 beams is assumed, as shown in Fig. 2. The coverage diameter of each beam is 0.6 deg. Frequency reuse of three frequencies is assumed; the same frequencies are assumed for use in coverage areas 1, 4, and 7; areas 2, 5, and 8; and areas 3, 6, and 9.

By setting the same amplitude weight distribution for the beams in the phased-array feed, it is possible to use the transmission

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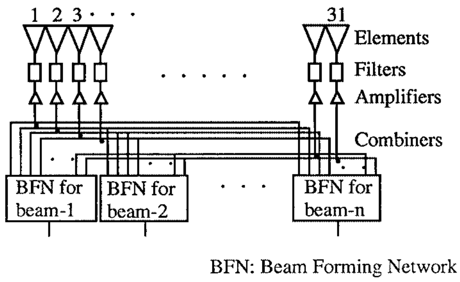


Fig. 1 Array feed system.

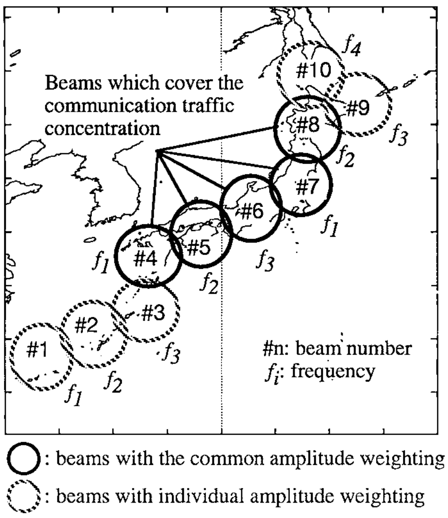


Fig. 2 Assumed beam allocation.

power effectively and to change the output power among the beams according to traffic changes. When each beam has individual amplitude weighting distribution and the same output power, the output power in each element antenna needs the largest in beams. But each element has the ability to radiate part of the prepared power. Therefore, the five coverage areas 4 to 8, where communication traffic is concentrated, are set at the same amplitude weight distribution and optimized by setting only the phase weight distributions. These beams are shown by circles with a solid curve in Fig. 2. Coverage areas with less communication traffic are set using individual amplitudes and phase weight distributions. These beams are shown by circles with an oblique line in Fig. 2.

Weight Optimization Method for Array Feed

The following two guidelines are proposed for the design of weight distribution:

1) For all beams whose communication traffic is extremely large, the same amplitude weight distribution is set up, and the individual phase distributions are optimized to generate the desired radiation patterns.

2) For beams that serve only a small number of users, the amplitude and phase weight distributions are optimized individually.

The design algorithm according to the first guideline is explained subsequently. First, we calculate the initial weight distributions using the directional constraint minimum power (DCMP)[3] method for individual beams to fix the amplitude distribution and to optimize the phase distributions. In the DCMP method, a higher gain is achieved by setting the directional constraint condition, and the sidelobe level in areas where the same frequency is used is suppressed by the power minimization approach. Second, the amplitude weight distribution, which is common for crowded beams, is calculated by averaging the amplitude weights obtained in the previous step. The amplitude weight distribution is then optimized by the least-mean-square (LMS) approach, under the condition that the phase weight distribution of each beam is not changeable. Finally, because the amplitude weight distribution obtained in the second step is not changeable, only the phase distribution of each beam is optimized

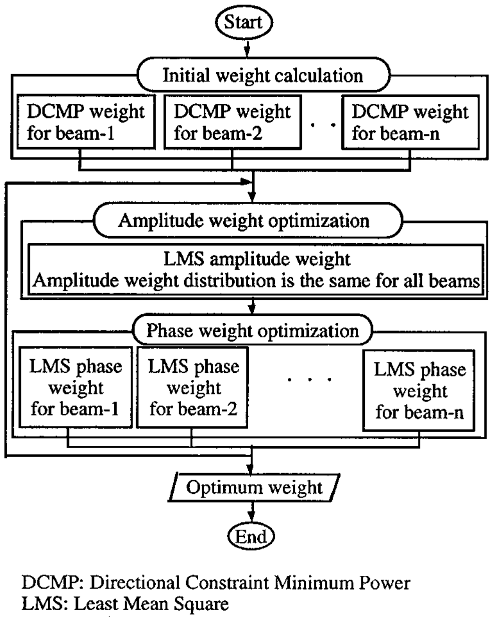


Fig. 3 Flowchart of the weight optimization algorithm.[3]

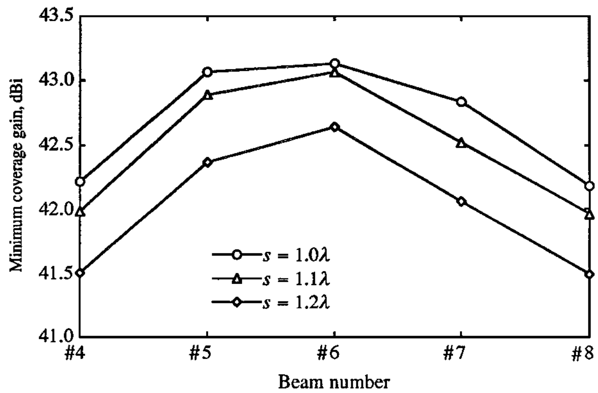


Fig. 4 Minimum gain in beam coverage with element spacing.

by the LMS.[4] The flowchart of the weight optimization algorithm is shown in Fig. 3. The second and third steps are repeated several times until the antenna requirements are achieved.

Design of Antenna Parameters

A large deployable reflector for a satellite is launched in the stowed state and deployed in orbit. Thus, a small reflector curvature is preferable. $F/D = 0.8$ was selected as a design parameter. The array is composed of 31-element antennas for an easier division of power. They are arranged in triangular positions. The diameter of each element antenna is assumed to be 1.0λ. Figure 4 shows the coverage gain with the spacing of the element antennas. The coverage gain is maximum when the spacing is 1.0λ. The spacing of the elements was 1.0λ.

The location of the feed array is closely related to the range of beam scanning. The shorter the distance from the reflector focus to the reflector center, the higher the boresight gain is. The higher the gain at a wide scan angle, the longer the distance is. In Fig. 5, the minimum-coverage gain is compared with different distances from the reflector focus. Figure 4 indicates that higher gains are generally achieved at distances from 800 to 1000 mm. When the distance is 1000 mm, there are small differences in the magnitude of the amplitude weight in all element antennas. Therefore, L is 1000 mm (8.3λ). Figure 6 shows the antenna configuration and parameters. To operate amplifiers at high efficiency, the common amplitude weight is chosen from three steps, 0, -3, and -6 dB; some types of amplifiers with different output powers may be used.

As a result of this design, the coverage gain from beam 4 to beam 8 was more than 42.0 dBi, and the beam isolation exceeded

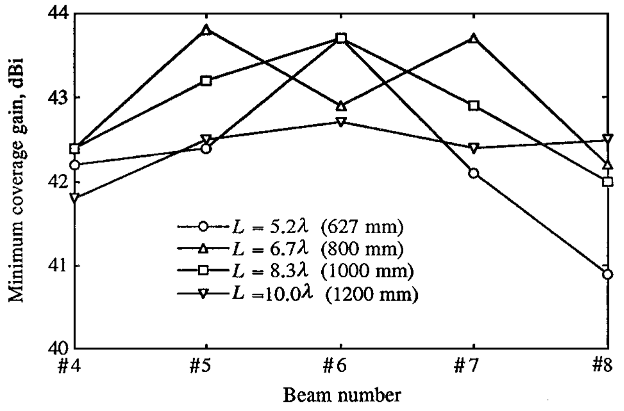


Fig. 5 Minimum gain in beam coverage with defocus length.

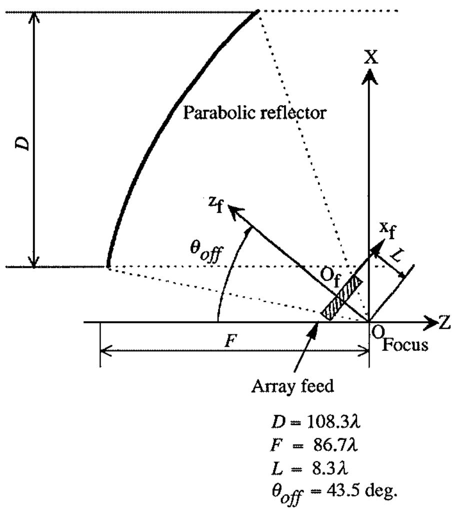
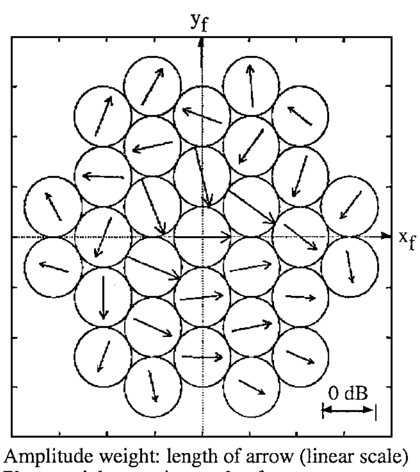


Fig. 6 Configuration of array-fed reflector antenna.



Amplitude weight: length of arrow (linear scale)
Phase weight: rotation angle of arrow

Fig. 7 Example of optimized weight distribution; beam 4.

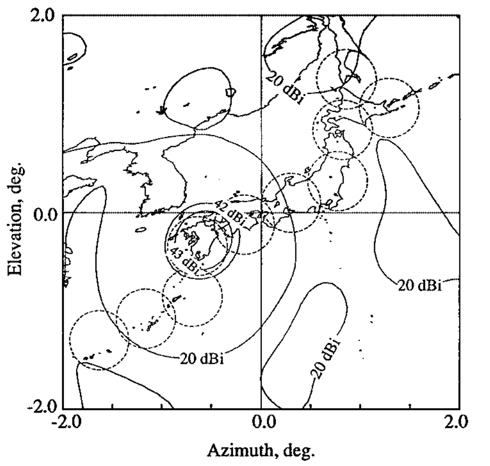


Fig. 8 Example of analyzed radiation pattern; beam 4.

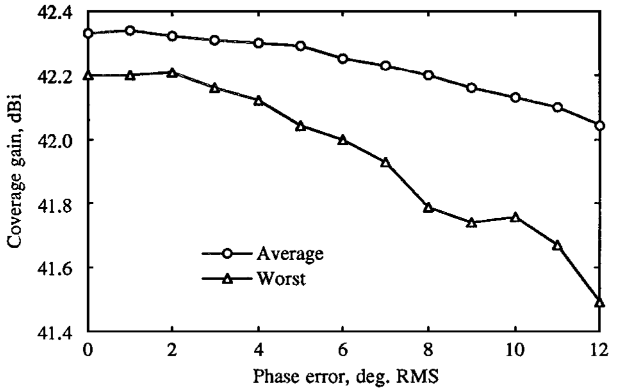


Fig. 9 Coverage gain with weighting error; amplitude weighting error = 0.7 dB rms.

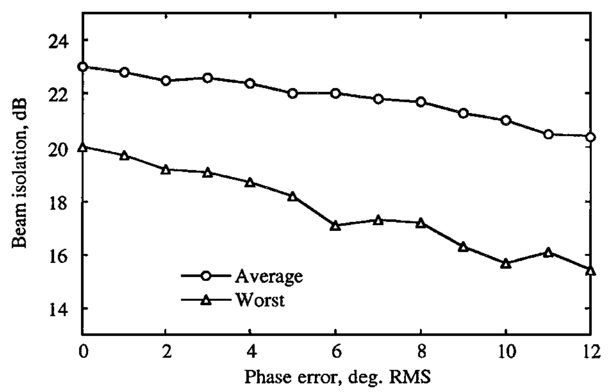


Fig. 10 Beam isolation with weighting error; amplitude weighting error = 0.7 dB rms.

23 dB in frequency reuse beams. The coverage gain of the beams with individual amplitude weighting from beams 1 to 3 and 9 and 10 was over 40.0 dBi. Except for beam 1, the coverage gains were more than 41.8 dBi. Figures 7 and 8 show examples of the optimized amplitude weight distribution for crowded beams and their radiation patterns. By using this weighting distribution, it is possible to keep the transmission power constant and to save amplifier output power when the transmission power is freely changed due to traffic.

Analysis of the Weighting Error of the Array Feed

We studied the weighting error, which is given to the optimized weighting distribution, because it has a significant effect on the antenna's performance. Figures 9 and 10 show the minimum coverage gain and beam isolation with the phase weighting distribution error when the amplitude weighting distribution error is assumed to be 0.5-dB rms. The calculation was performed 200 times for each distribution error. The amplitude weighting distribution error was assumed to be 0.5-dB rms, and the phase weighting distribution error was assumed to be 11-deg rms; the coverage gain degraded about 0.2 dB, and the beam isolation worsened from 3 to 5 dB. In the worst case, the beam isolation worsened to 16 dB.

Design Verification

The optimization design method was verified using the experiment model of the feed array system, and we established the measurement and estimating method of the phased-array feed. We measured the primary feed pattern using the near-field measurement

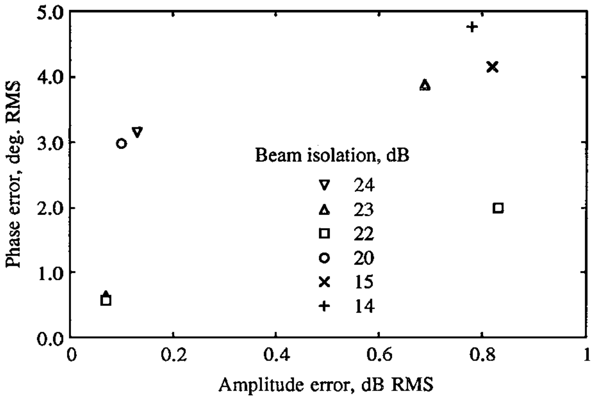


Fig. 11 Measurement of beam isolation with weighting error.

system. The secondary radiation pattern was estimated using the primary feed pattern that was measured.[5] The aperture-field distribution of the primary feed was calculated from the measured feed pattern, and the secondary pattern was calculated using the aperture distribution.

The experiment model was composed of a 31-element phased-array feed and BFNs; it did not include filters and amplifiers because of the separating effect of these components. This experimental feed array system generated only four beams. These four beams were formed by four individual BFNs, where the weight distribution of three beams (the fixed beams) was fixed and the weight distribution of only one beam (the scanning beam) was changeable. In the fixed beams for coverages 4, 6, and 7, the coverage gain exceeded 42.0 dBi, and the beam isolation between coverages 4 and 7, where frequency reuse was assumed, was over 20 dB. The shape and direction of the scanning beam can be changed by adjusting its weight. In the scanning beam, which scans from coverages 4 to 8, the coverage gain was over 42.0 dBi, and the beam isolations between coverages 4 and 7 and between coverages 5 and 8 were similarly over 20 dB. We obtained close agreement between the designed secondary patterns and the calculated patterns, which are calculated using the measurements of the primary feed patterns.

Figure 11 shows the measurement of the beam isolation with weighting distribution errors. The weighting error was bigger and the beam isolation degraded quickly to less than 15 dB. This result agrees with the worst analysis, when an amplitude error is 0.7-dB rms and a phase error is 5-deg rms, as shown in Fig. 10.

Conclusion

We studied a phased-array-fed reflector antenna for a communications satellite using a GEO satellite system and developed a weight optimization method for effective amplifier power usage. We investigated whether the optimized antenna design met the requirements. The element antennas' spacing and the position of the array feed, which are important parameters for antenna performance, were studied in detail. We also studied the effects of the weighting error, generated by the optimized weighting distribution, which have a significant effect on the antenna performance. The secondary radiation patterns were evaluated using the primary feed measurement results, and close agreement was obtained. This study demonstrates that the antenna design procedures are effective.

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