A Study of Low Side-lobe Beam Generation for Onboard Multi-beam Antenna

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In a handheld satellite phone system using a large onboard reflector and a phased array feed system, multi beams with low side-lobe level are important for frequency reuse. In the beam pattern design, a search method combining constraint points is usually used for obtaining an optimized set of excitation distributions of the feed system. This paper studies a simple method of deriving the excitation distributions for low side-lobe beams and evaluates the effectiveness and the limits of the method by computer simulation.

1 Introduction

In a satellite/terrestrial integrated mobile communication system that has to share a common frequency band, the generation of a number of low side-lobe beams each with a different orientation is one of the key technologies to make efficient re-use of frequencies for increasing the number of available communication channels. To generate such a number of different beams using an onboard antenna, a reflector antenna with a phased array feeder is commonly used. A phased array feeder provides an efficient way to modify beam shapes and directions and to suppress side-lobe by properly controlling the excitation distribution (amplitude and phase angle of radiation for each element) of the feeder elements.

Several methods are available to create a desirable radiation pattern from the reflector antenna, such as searching the optimum pattern of the phased array feeder's excitation distributions[2][3]. These methods attempt to find the excitation distribution that brings the radiation pattern most close to the desired shape under the constraint of several optimization conditions, or constraint points (i.e. gains in given directions). If the objective is limited to shaping of the main beam and lowering side-lobes in some peripheral beams, the desired radiation pattern can be reached by giving a relatively small number of constraint points.

A problem associated with these methods—i.e. search for the optimum solution under the condition of given constraint points—is the fact that the constraint points can only be determined through trial and error. That is, appropriateness of the constraint points can only be judged after the beam pattern calculation is completed. For a mobile satellite communication system that typically requires more than 100 beams, this trial and error approach is costly: the side-lobe patterns of the beams, which are different for each beam direction, must be suppressed below a certain criteria over a broad area. In this report, the author studies an automatic computational process of determining constraint points, and uses computer simulation to verify its validity for automatic generation of low side-lobe beam patterns in a multi-beam antenna system[4].

2 Baseline of discussion

2.1 Configuration of multi-beam antenna system

In this study, the author assumes satellite-based mobile phone systems that allow communications between unspecified locations, and integrated terrestrial/satellite mobile communication systems[1] that share common frequencies

Table 1 Link budget for the service link

Item	Unit	Uplink	Downlink
Frequency	GHz	2.0	2.0
Transmitting power	W	0.2	0.2
Feeder loss	dB	1.0	1.0
Transmitting antenna gain	dBi	0.0	47.0
Free-space loss	dB	189.6	189.6
Fading loss	dB	3.0	3.0
Receiving antenna gain	dBi	47.0	0.0
G/T	dB/K	19.7	-24.8
Receiving C/No	dBHz	47.7	50.2
Eb/No (10 kbps)	dB	7.7	10.2

with ground-based mobile phone systems. Table 1 summarizes a typical link budget between a satellite-based mobile phone and satellite (service link) that the author assumes in this study. To realize low power consumption, the transmission EIRP of the satellite-based mobile unit is assumed to have magnitude around 0.2 W. To enable voice communication with such a low power unit, the onboard antenna must have a gain of no less than 47 dBi. To realize such a high gain in the frequency band allocated to mobile satellite communications (2 GHz band), a large reflector with aperture size of approx. 30 m and a feeder system that is capable of generating more than 100 beams are required to cover the wide service area.

This study assumes the use of an onboard antenna system consisting of a large deployable parabolic reflector, a defocus phased array feeder, and a beam forming network (BFN) (see Fig. 1). Such an antenna system configuration has been actually mounted on the test satellite "Kiku 8"[3] and proved its validity. The feeder has N feeder elements each connected with a power amplifier at the transmitting side and a low-noise amplifier at the receiving side, and the excitation distribution of each element is controlled by the devices within the BFN connected to the feeder. With consideration given to such aspects as the reflector size (sufficient gain to cover a wide area), the amount of defocus and easy mountability on a satellite, the author uses the system parameters shown in Table 2 to proceed with the discussion on suppressing side-lobes.

2.2 Beam pattern calculation

The outline of the steps used to calculate the beam characteristics is shown below. The program used to perform these calculations was written in the C language.

① Generate a coordination data set that defines the parabolic reflector surface (generally spacing at a wavelength, but may vary depending on the precision and computation time requirements).

② Determine an excitation distribution for the phased array feeder (see the descriptions in the next section).

③ Irradiate the reflector by the primary radiation wave from more than one feeder placed with a

Table 2 Assumed onboard antenna parameters

Satellite position	136° east longitude
Reflector loading position	East side of the satellite body
Frequency	2 GHz
Reflector shape	Ideal paraboloidal surface
Equivalent electric aperture size of the reflector	30 m
Focal length	18 m (F/D = 0.6)
Offset angle	60°
Number of feeder elements	127
Feeder position	Shifted to reflector by 10% (1.8m) of focal length
Radiation pattern of the element	$\cos^2\theta$
Boresight direction	135° east longitude, 35° north latitude

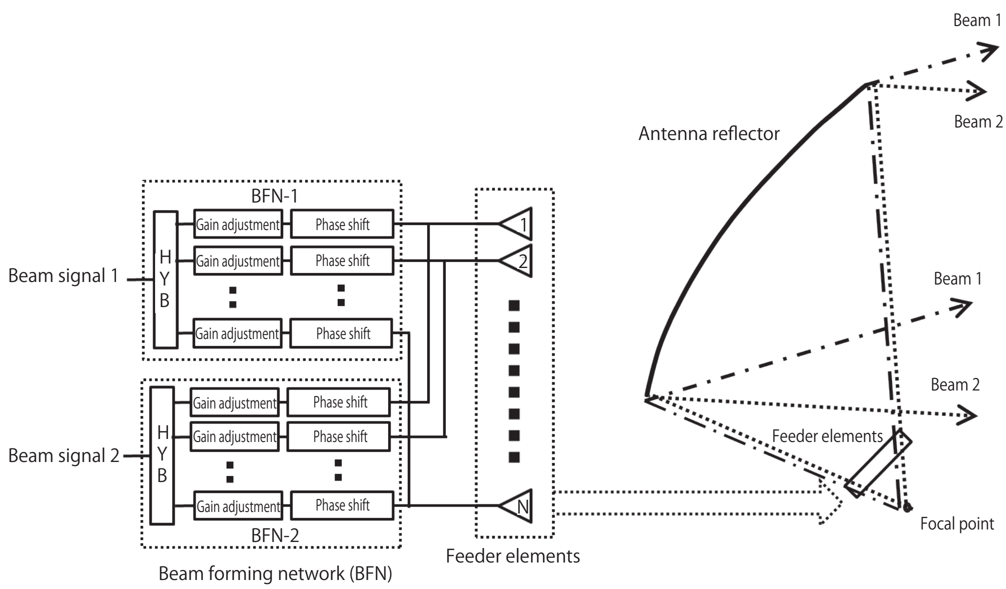


Fig. 1 Configuration of phased array feeder antenna system (a two-beam system)

certain displacement from the antenna's focal point. The amplitude and phase of each elemental radiation wave are determined in ②.

④ Based on the principles of physical optics, calculate a far field electromagnetic field by synthesizing all the contributions from tiny dipoles distributed on the reflector surface.

⑤ Illustrate the gain contour (beam pattern) in a coordinate of Az (azimuth) and El (elevation) angles.

3 Study for suppressing side-lobes

In this study, a search technique by the least-squares method is used to calculate the excitation distribution for the desired beam pattern. Search by least squares is an asymptotical approach to attain the optimum solution, in which the excitation distribution parameters (amplitude and phase) are repeatedly modified in an attempt to reduce the sum of squared differences between the constraint conditions (or constraint points, i.e. gain settings in given directions) and the calculation results. What is critical in this approach is how to configure the constraint conditions that most effectively reduce the side-lobe over a wide peripheral area.

In this study, the following steps are applied to determine the constraint points.

① Set an initial excitation distribution.

② Calculate the beam pattern corresponding to the given excitation distribution.

③ Search for any location in the external periphery of the main beam where a higher than specified side-lobe exists. Stop the attempt if no relevant location is found.

④ If a location is found in step ③, add one or more constraint points for further suppression of its side-lobe: one in said location, or more than one in the neighborhood of it. Then, iterate the search for the optimum excitation distribution using the new set of constraint conditions. When completed, return to ②.

This is a relatively simple iteration procedure in which new constraint points are repeatedly added to the major side-lobe position to reduce the magnitude of the side-lobe. Note, however, that this procedure does not guarantee gradual reduction of the side-lobe as desired. For example, addition of new constraint points may work negatively—i.e. strengthening of the side-lobe in other areas. If this happens, further addition of constraint points may become necessary over and over again to suppress the increasing trend. The author tests the validity of this procedure using computer simulations.

3.1 Initial values of excitation distribution

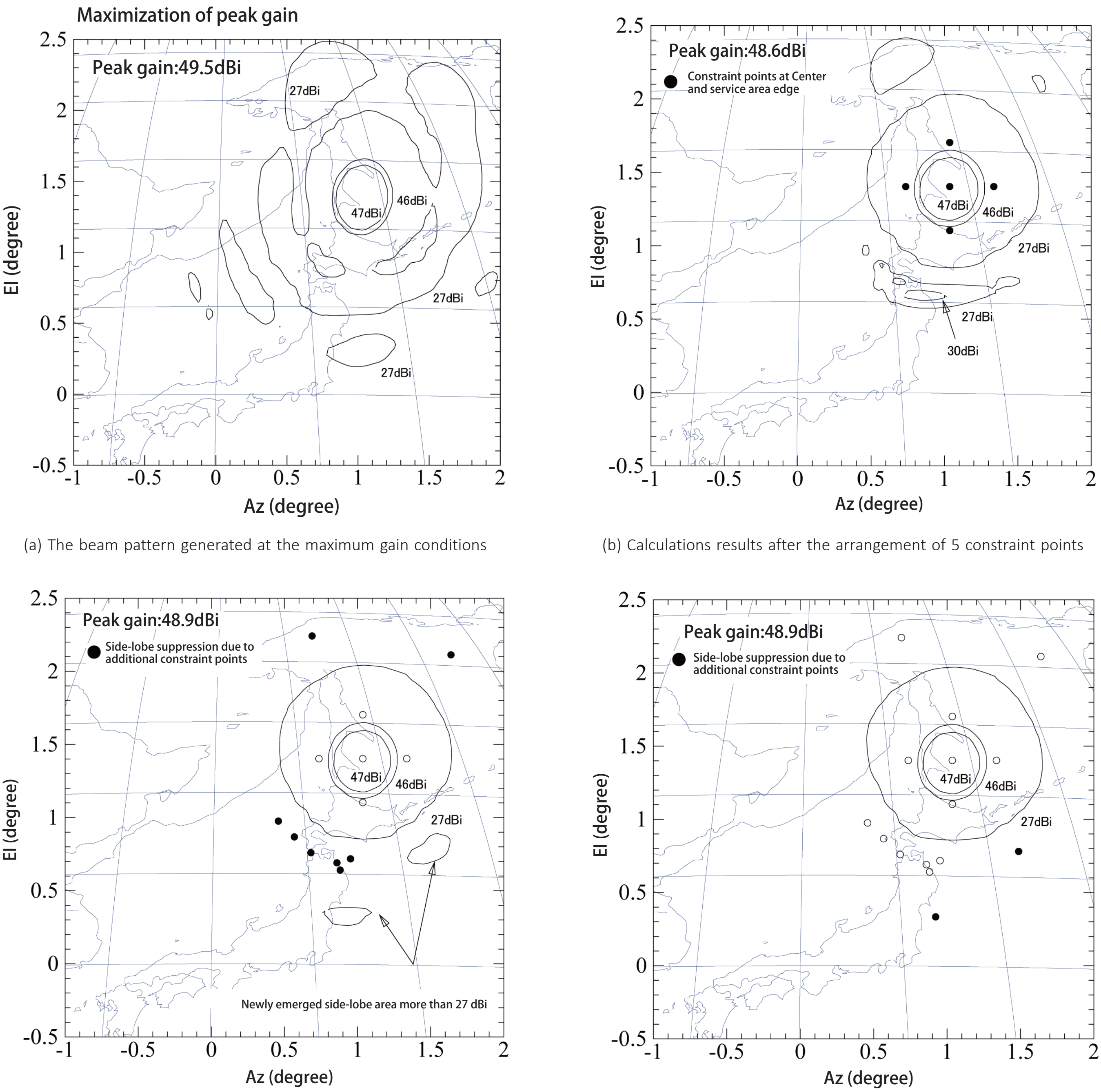
First, let us review the method to determine initial excitation distribution. References [2] and [3] do not contain a concrete description of initial value settings, and presumably they assume a uniform excitation distribution. In this study, the search begins using an excitation distribution that maximizes beam gain in a given direction. Such an excitation distribution can be uniquely determined using the Maximum Ratio Combining Method[4] (MRCM). During the search, the gain generally shows a tendency to decrease from the maximum value as the excitation distribution undergoes modifications. However, a beam pattern without heavy gain loss can be achieved if the constraint conditions are met relatively quickly.

Figure 2 (a) shows an example of the gain maximization calculation. This figure shows the resultant beam pattern when calculations are made aiming at maximizing gain in the direction toward Hokkaido area (Az = 1.04°, El = 1.4° from the boresight direction: Akashi city). The gain in the target direction is 49.5 dBi, and gain values greater than or equal to 47 dBi were obtained within a ± 0.2° range around it. Note, however, that the gain contour in the low-gain area—in the area where gain is lower by 20 dB compared to the value of 47 dBi—indicates a distorted spread outward as well as strengthening of external side-lobes. As this example indicates, the gain maximization approach can achieve excellent antenna performance within the service area (main beam), but needs improvements in the side-lobe characteristics.

3.2 Constraint points setting to lower side-lobes

The target for lowering side-lobes should be decided considering the required performance of the satellite communication system. In this study, the author sets the following objectives taking the link budget (Table 2) into account as well as each objective's feasibility.

- The target gain that determines the service area is set as 47 dBi (referred to as the boundary *gain*)
- The lower antenna gain area around the service area should be as narrow as possible. The area is referred to as the *peripheral domain* and is defined as the area that falls in the gain range between the boundary gain (47 dBi) and a specified value (27 dBi in this study).
- The antenna gain in all areas except those described



(a) The beam pattern generated at the maximum gain conditions

(b) Calculations results after the arrangement of 5 constraint points

(c) Calculations results by further adding 8 constraint points

(d) Calculation result after the addition of last two constraint points

Fig. 2 Process to suppress side-lobe: initial pattern settings and subsequent addition of constraint points (copyright(c) 2008 IEICE)

above should be suppressed equal to or below a specified level (27 dBi in this study). The target area is called the *off-axis domain*.

In the following paragraphs, the author verifies the attainability of the objectives, by manually stepping forward through the procedures for setting constraint points described at ① to ④ in the beginning of this section.

(1) Constraint points in the periphery of the main beam

First, a set of constraint points to define the location of the beam's center position and service area is arranged. The beam center is directed, as described above, to Hokkaido, and 4 constraint points are located on the left, right, top and bottom of the center, each at an angle of 0.25° from the center, to define the extent of the service area. The objective gain at the center is set to 51 dBi (slightly higher than the actual maximum gain obtained by MRCM), and the gain at the boundary is defined to be 47 dBi. Note that constraint points for the defining area boundary are located at an angle of 0.25° which is wider than the value obtained by the MRCM (± 0.2°) because, in a system that uses a reflector antenna, a wider main beam is known to lower peripheral side-lobes.

Using the excitation distribution described in the previous section as an initial distribution, search by the least-squares method is carried out under the constraint conditions described above. The calculations result in the beam pattern shown in Fig. 2 (b). The beam is generated in the specified direction, and the peak gain is less than the maximum gain by approx. 0.2 dB. The peripheral domain around the main beam has been narrowed down as expected. However, the results still come short of the desired beam pattern: considerable broadening yet remains and local strengthening of side-lobes is observed. As the next step, an attempt is made, in line with the iteration procedures proposed in this study, to suppress the side-lobes.

(2) Additional constraint points

Search by the least-squares method is performed again after placing additional constraint points to suppress side-lobe strength—one at the side-lobe peak and several on the periphery (in the figure shown, 8 constraint points are added). Figure 2 (c) shows the results of recalculation. The side-lobe in the area that contains added constraint points is reduced, as expected, to the level of 27 dBi or below, and the high intensity area on the periphery of the main beam is almost restricted within the near circular domain around the beam center.

However, the addition of new constraint points generated two new unexpected high side-lobe areas in the off-axis domain. Again, new constraint points are added in these peak positions for further optimization. As shown in Fig. 2 (d), recalculation successfully suppressed side-lobe intensity in the off-axis domain to 27 dBi or less without invoking new high side-lobe emergences. The peak gain at

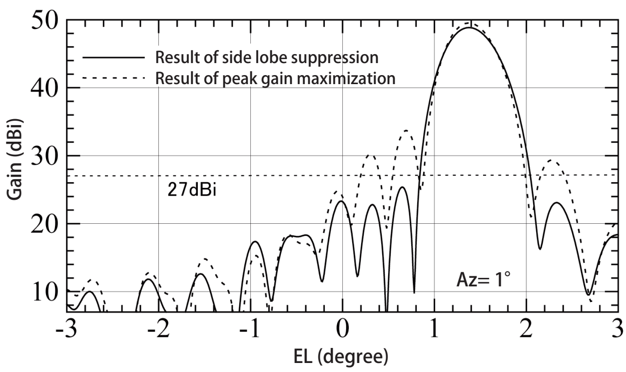


Fig. 3 Cross-sectional plot (Az=1°) of Fig.2 (a) and (d) (copyright(c) 2008 IEICE)

this stage is 48.9 dBi, or 0.6 dB lower than the maximum value. Figure 3 shows a cross-sectional view of (a) and (d) in the EI direction (at Az = 1°). Although the main beam width shows a slight spread, side-lobes are successfully suppressed.

4 Automatic generation of multiple beams with suppressed side-lobes

In the previous section, it was verified that the procedures for setting constraint points produce an effect of suppressing side-lobes for arbitrarily specified beam directions. As only one example is insufficient to draw a general conclusion, the same approach was applied to a more complex situation—automatic side-lobe suppression in a system with more than 100 beams.

4.1 Side-lobe suppression of multi-beam antenna

In this section, the author attempts an automatic generation of excitation distributions for multiple beams with low side-lobe characteristics. Each beam direction is arranged at 0.4° intervals within a range between Az ± 3°and El ± 3° from the boresight direction. As a result, approx. 270 beams are the objects to be processed. The beam is considered unattainable if: the boundary gain cannot attain 46 dBi during the process, or more than 10 iterations of constraint point addition failed to satisfy the given requirement of side-lobe suppression.

Figure 4 shows the flow of the automatic calculation process. In this process, only one constraint point is added in each of the iterations at the point where the off-axis antenna gain shows a peak over the desired side-lobe criteria—in contrast to several points on the “periphery” in the manual procedure described previously. This restriction—only one addition at a time—makes the automatic settings for computation much easier.

Figure 5 shows the low side-lobe pattern created automatically. The total number of beams thus generated was 160 out of 270 objects. In the central part of the service area, beams were generated so that they intersect with each other at the specified boundary gain (47 dBi), and even the periphery beams (2° off axis from the boresight) maintained a generally high enough boundary gain (≧ 46 dBi). The side-lobe levels of the beams were all successfully suppressed to the level of 27 dBi or less. From these results, it can be concluded that the procedures to define constraint points reported here provide an effective approach for multi-beam antenna design.

A commercially available PC with a 1 GHz clock running Windows XP™ was used for these computations. It took 1 to 2 minutes of calculation for one beam, depending on the number of iterations required to reach the desired side-lobe conditions. Thus, nearly half a day was required to process all 270 directions.

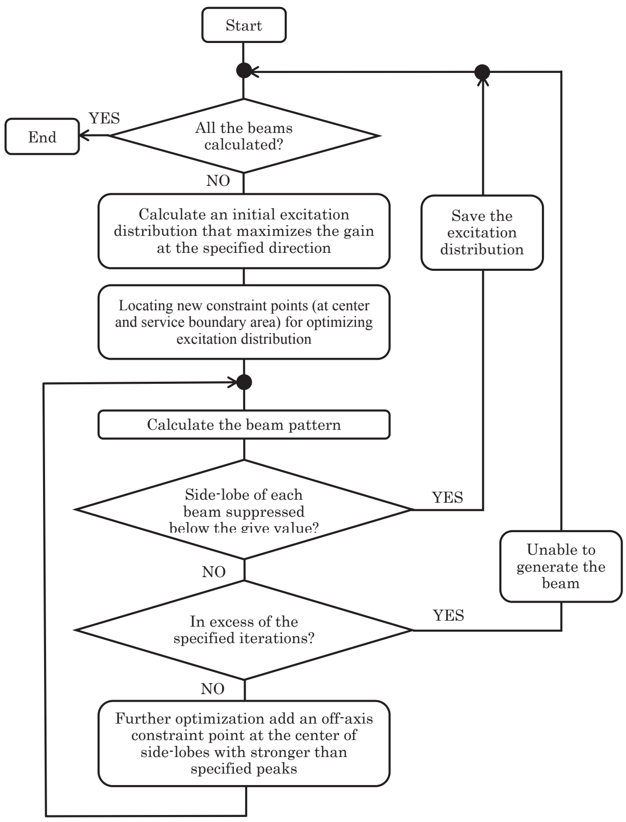


Fig. 4 Flow chart for automatic generation of multiple beams (copyright (c) 2008 IEICE)

4.2 Performance limitations

To probe the limit of side-lobe suppression with the procedures described in the report, attempts are made to automatically generate the beam with more stringent side-lobe suppression levels (≦25 dBi, ≦23 dBi) than the instance described above (27 dBi). Figure 6 shows the envelope of the beam area with gain higher than that at the boundary (a slightly relaxed level, 46 dBi, is used).

As evidenced by this figure, the lower the side-lobe settings, the more difficult it is to generate a beam with a large direction angle. Examination of the processing results indicates that the following reasons hindered successful generation of the beams.

- Large beam direction angles, notwithstanding the use of a gain maximization method, hinder generation of a beam that satisfies the given boundary gain.
- Excessively strict settings on the side-lobe level render it impossible to achieve satisfactory suppression even with the addition of constraint points.

It is yet uncertain whether this indicates a limitation of the antenna system, or if there is room to improve the constraint point setting approach. This question is left open for future investigation.

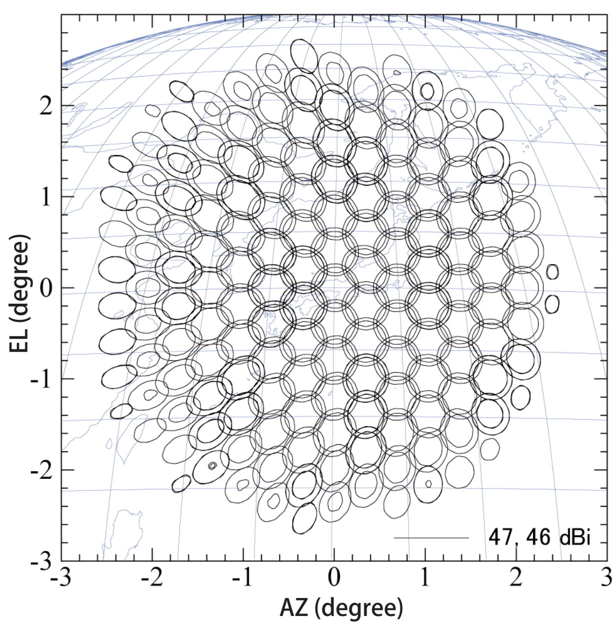


Fig. 5 An example of multi-beam configuration by automatic generation and side-lobe suppression (copyright (c) 2008 IEICE)

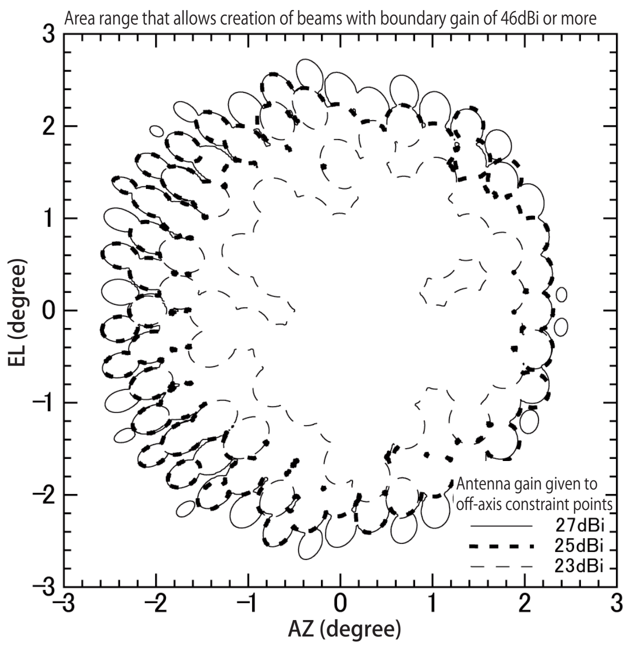


Fig. 6 Envelope of the outermost beams for different constraint point gains: 27, 25 and 23 dBi (copyright (c) 2008 IEICE)

5 Conclusions

The author studied the method to suppress side-lobes of the beams emitted from an onboard antenna equipped with a large reflector and phased-array feeder. The author approached this problem by reviewing procedures used to calculate excitation distribution, and checked the validity of this approach using computer simulations. This approach was applied to a 30 m onboard multi-beam antenna system, and proved its potential to generate a number of beams with low side-lobe level within the desired service area. Future problems to be tackled include detailed validation of this approach to clarify both its limitations and potentials for improvement.

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