Design of Antenna System

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In this paper, we describe design of onboard antenna system for STICS.

1 Introduction

STICS is a system for personal satellite communication, using an S-band communication satellite with a large deployable antenna. When the project started, only basic information such as the antenna model and aperture size was decided for the antenna system to be mounted on a satellite in STICS. On the other hand, detailed information such as F/D and the coverage area of the antenna to be mounted on a satellite was required for designing. Therefore, we created the basic design of the antenna system, with a view to putting this research to practical use. This is the main topic of this paper.

First, it was a prerequisite to use a defocus-feed type phased array antenna in the primary radiator, and to mount one deployable reflector with a 30 m class aperture. This purpose requires design of a reflector that enables coverage of the entire service area considered, and particularly, the ratio of the Focal length to the aperture Diameter (F/D) had to be appropriate. On the other hand, there is an F/D value feasible for the satellite-mounted antenna, and we sought the optimum value considering these issues.

This paper first gives several examples of the numerical calculation of relationships between F/D, coverage area, antenna gain, etc. Based on the results of that study, we describe the baseline of the antenna for STICS. Finally, based on the baseline, we discussed the primary radiator element arrangement method and optimization of the spacing.

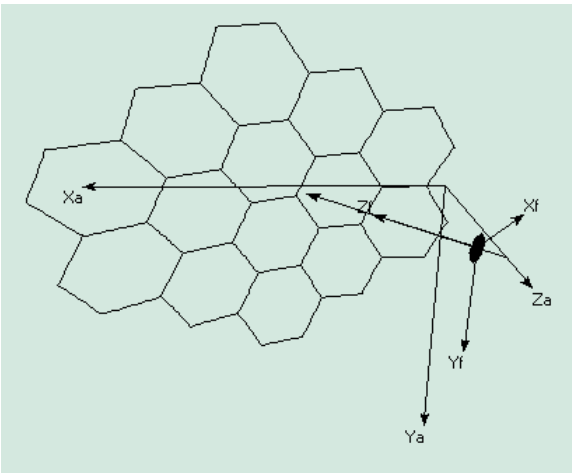


Fig. 1 Antenna configurations

2 STICS antenna beam directional characteristics

2.1 Factors used in the calculations

In the first calculation example, we used the parameters in Table 1 that would be for STICS. The antenna diameter used for projection towards the boresight of the inscribed circle of the reflector is 27 m, assuming that the antenna shall be mounted on the east side of the satellite as shown in Fig. 1. We optimized the amplitude and phase distribution of excitation for forming beams, to maximize the peak

Table 1 Specification of calculation

Satellite location	132° E
Boresight direction	130° E 28° N (Around Okinawa)
Locations of LDR	On-orbit East side
Frequency	2.0 GHz
Shape of Refector	14 Modules
Electric Aperture Diameter	27 m
Focal length	10.8 m(F/D=0.4) ～21.6 m(F/D=0.8)
Offset Angle	50.3°
Number of Element	127
Radiation Characteristics of feed elements	$\cos^{2.4}\theta$
Polarizations	Circular
Defocus length	0～15% of Focal length

gain in the specified direction. We moved the primary radiator slightly from the focal position towards the reflector side, so that the beams could be formed easily, and this value was defined as the defocus length, and changed 0% to 15% of the focal length.

2.2 Calculation results

For an indication of the beam steer area, when the defocus length was taken as 10% and F/D as 0.4, 0.6, and 0.8, Fig. 2 shows the approximate area where the formation of beams is possible, when the satellite beam was directed towards north, south, east and west (area in which the beam can be formed with a beam size similar to the beam size towards the boresight direction with an area gain of at least 47 dBi). As shown in the figure, the area in which a beam can be formed is approximately ± 3 degrees when F/D = 0.4, approximately ± 2.5 degrees when F/D = 0.6, and approximately ± 2 degrees when F/D = 0.8.

2.3 Selecting the optimum parameters

In order to study the results of Fig. 2 in more detail, using F/D and defocus length as the parameters, we calculated the peak gain characteristics in each direction by moving to the east (Fig. 3), and EIRP allocable to the beam (Fig. 4). Here, "EIRP allocable to the beam" has the following meaning.

In this study, for the maximum peak gain in each direction, we optimized not only the phases of each of the 127 elements, but also their amplitude (power). As a result, the power fed to each element is not equal; instead, the power distribution depends on the beam direction. As an example,

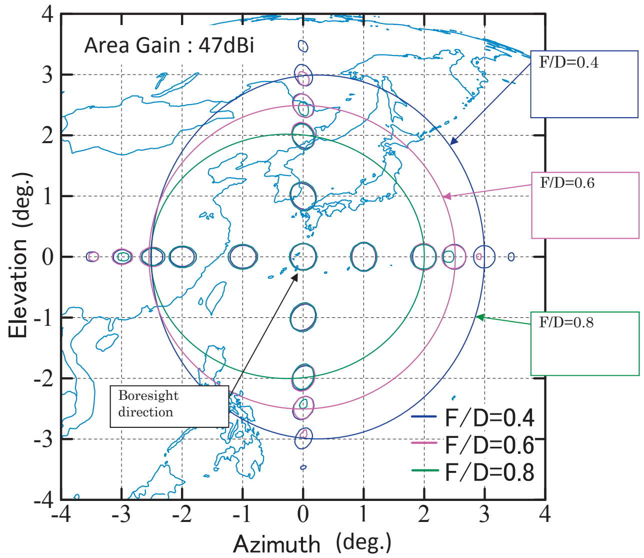


Fig. 2 Beamforming area

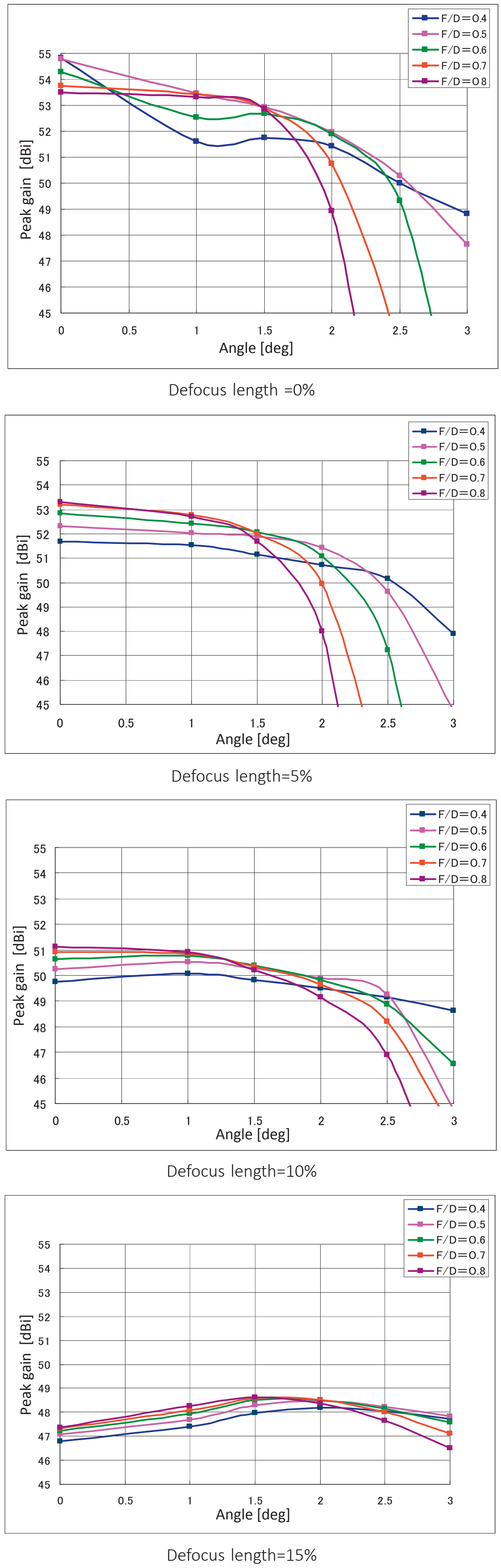
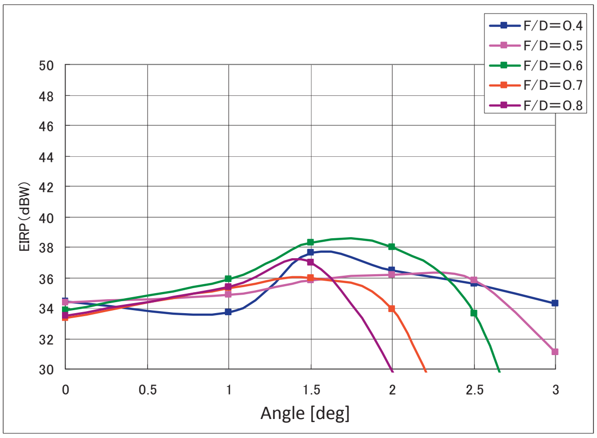
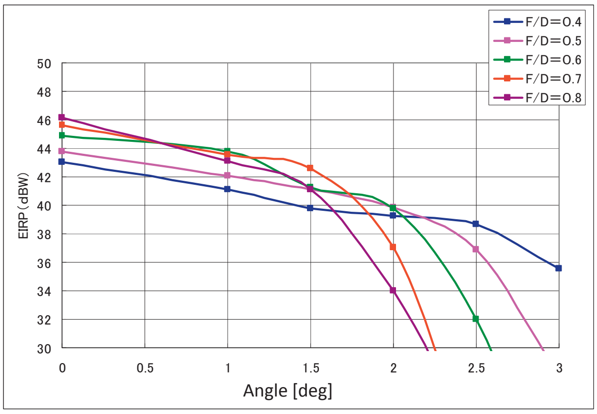


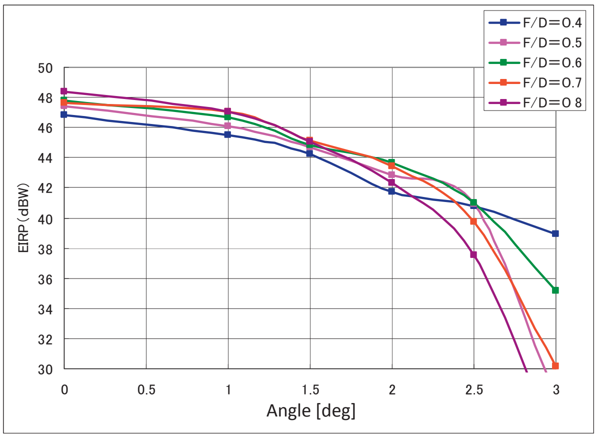
Fig. 3 Peak gain as a function of beam angle (F/D and defocus length are parameters)



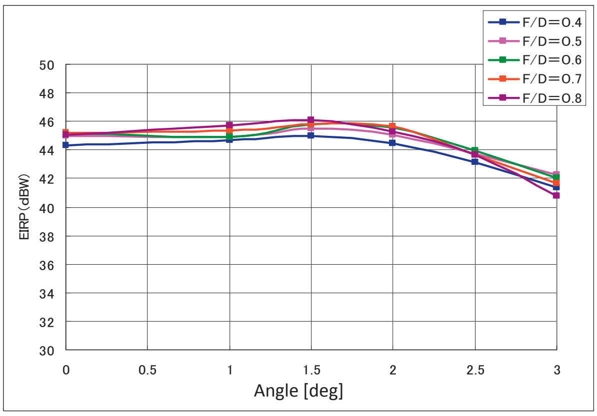
Defocus length =0%



Defocus length=5%



Defocus length =10%



Defocus length =15%

Fig. 4 Maximum EIRP as a function of beam direction (F/D and defocus length are parameters)

Fig. 5 shows power distribution to 127 elements in beam direction at 2.5 degrees to the north, south, east and west, and the boresight (the power is greater where the color is closer to red). As a result, the total power transmitted to 1 beam (= max SSPA power × number of elements) cannot all be allocated, and the sum of the SSPA output of all the elements having distribution is limited. Consequently, the EIRP allocable to the beams in each direction is defined as

EIRP allocable to the beams
= peak gain of beam + sum of the power distribution to each element.

Particularly, even if the antenna gain of the transmitting antenna is high, the allocable EIRP is small (few elements contribute to beam forming) and not many channels can be contained in the beam, so this is an important parameter for selecting the optimum parameters of a transmission antenna. Further, this study was done by using EIRP with total transmitted power (sum of the power of 127 elements) normalized to 1 W (= 0 dBW) (for example, if the total transmitted power = 1 kW, add 30 dB to the result of this study). On the other hand, in the case of the receiving antenna, to reduce the EIRP required for terrestrial terminals, higher mounted antenna gain must be given priority regardless of the number of contributing elements.

The following trends are qualitatively observed from Figs. 2 and 3.

- When the direction is roughly within 1.5 degrees, the greater the F/D, the higher the peak gain and allocable EIRP.

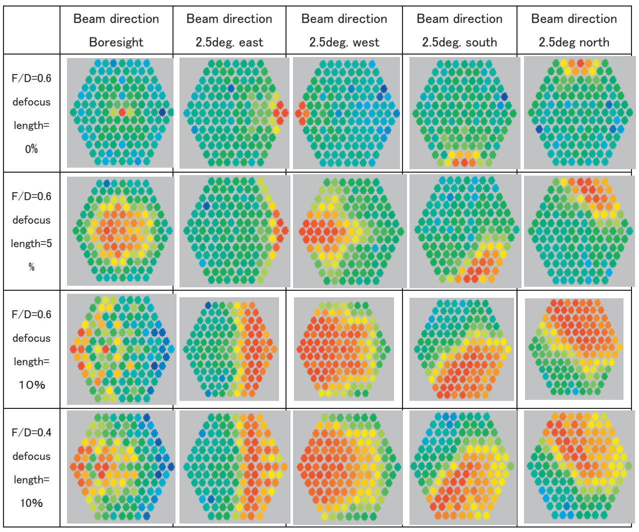


Fig. 5 Amplitude distribution of feeding element (127el.) (Red shows high power)

  - When the defocus length is 5% to 10%, and F/D = 0.8, then compared to 0.4, the peak gain is approximately 1.5 dB higher, and EIRP is 2 to 3 dB higher.
- When the direction is roughly 1.5 degrees or greater on the outer side, contrary to the above, the smaller the F/D, the higher the peak gain and allocable EIRP.
  - To form a decent beam at 2.5 degrees, F/D should be less than 0.6, and for a beam at 3 degrees, F/D should be less than 0.4.
- The smaller the defocus length, the greater the peak gain and allocable EIRP, overall.
  - However, if the defocus length is small, the sudden drop in gain of the beam on the outer side and drop in EIRP will make it difficult to form a beam.

The above results show that it is necessary to decide the optimum parameters by considering the condition of the service area, the antenna gain, the maximum number of channels per beam, and sharing for transmission and reception, but for a moderate service area and gain, F/D is expected to be 0.5 to 0.6 and the defocus length around 10%.

3 Study to reduce the feed array diameter

We evaluated the optimum F/D and optimized offset angle for the satellite/terrestrial integrated mobile communication system. When the beam forming area is ± 2°, offset angle of 60° and F/D = 0.4 were found to be the optimal values for achieving the minimum feed array diameter. This value is smaller than the F/D value in ETS-VIII (F/D = 0.8), and it was also confirmed to exhibit better characteristics than ETS-VIII. The details of this evaluation result are given below.

3.1 Study on beam forming

We studied the optimum F/D and offset angle on the deployable reflector plane with the minimum feed array for the service area required on the user side (hereinafter referred to as the “beam forming area”). Further, as the offset angle and F/D have a 1:1 relationship, once either of them is determined, the other is consequently determined.

The study described here was done using aperture diameter 30 m, beam diameter 0.4°, and EOC gain 47 dBi. Figure 6 shows the area when Osaka is in the boresight direction, and the maximum beam scan angle (beam forming area) is changed. Figure 7 shows the relation between the feed array diameter and the offset angle, when the beam forming area is changed. It was found that when the beam forming area is large, a large feed array diameter is required. If we draw a comparison with the same offset angle, we can see that the feed array diameter is approximately proportional to the beam forming area. In a geometrical analysis, given that the beam forming area is defined as δ, one can see that the feed array diameter is proportional to tan δ, and they also have a similar relationship in wave analysis. We see a tendency that the feed array diameter was the smallest when the offset angle ranged between roughly 60° to 70°, and when the beam forming area is larger, the minimum offset angle was somewhat larger. Also, since the F/D (focal length/ aperture diameter) is determined uniquely from the offset angle, we took F/D on

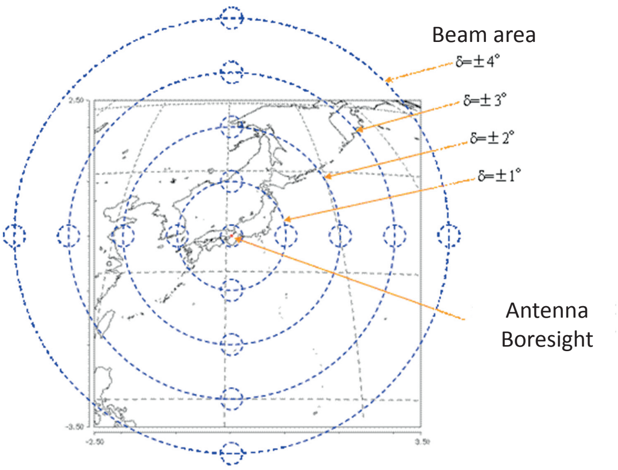


Fig. 6 Beamforming area

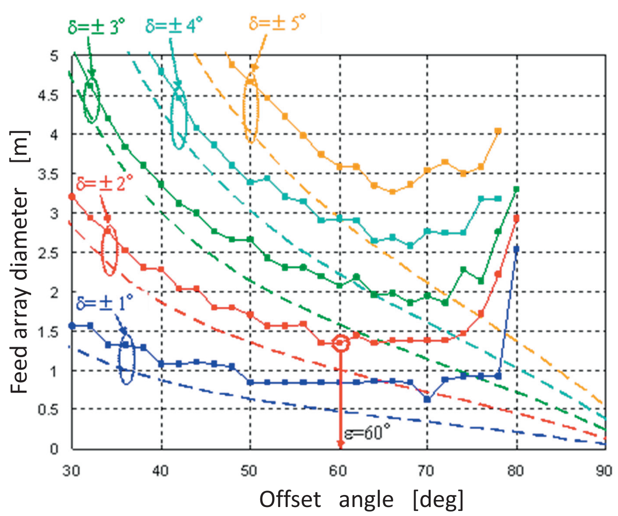


Fig. 7 Feed array diameter as a function of offset angle (when beamforming area is changed)

the horizontal axis in Fig. 8 (D = 30 m constant). When the offset angle is big, the focal length becomes small, so a big offset angle corresponds to a small F/D. Consequently, when the beam forming area δ = ±2°, an offset angle of 60° was selected, which corresponds to 0.36 F/D[1][2].

Here, the reflector plane was designed to meet the condition of minimizing the feed array with a view to ease mounting of the feed array and reducing the number of elements. On the other hand, from the structural viewpoint of the reflector, if the focal length is short, the curvature of the reflector plane becomes large (reflector is deep), and if the offset angle is big, the physical reflector plane becomes larger compared to the electric aperture diameter viewed from the direction of the antenna boresight. This is explained in Fig. 9. From a comprehensive perspective, it is necessary to study the optimal shape of the reflector[3]–[8].

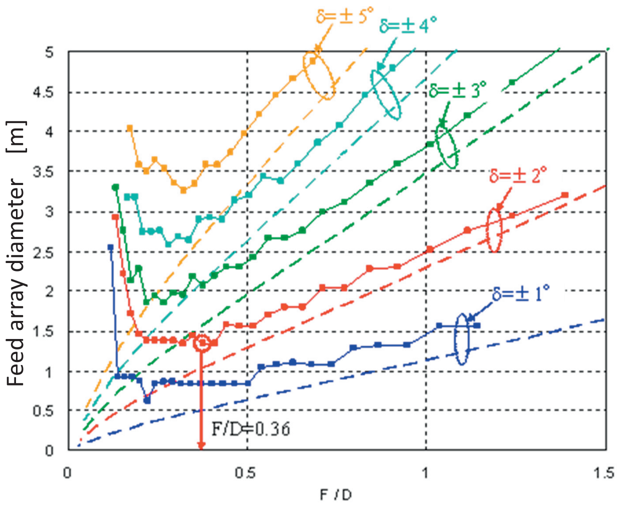


Fig. 8 Feed array diameter as a function of F/D (when beamforming area is changed)

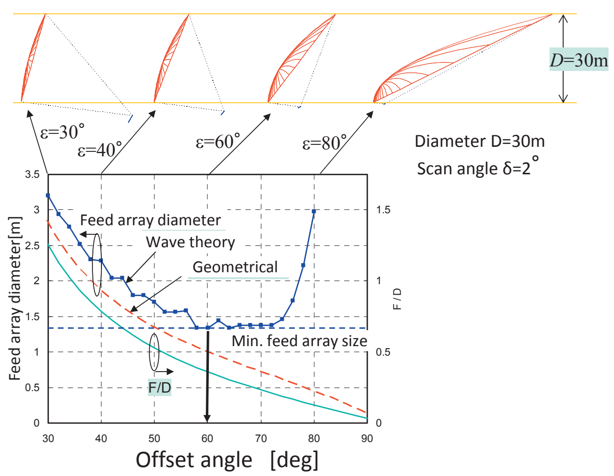


Fig. 9 Optimization of offset angle and F/D and its reflector shape

In the study described in this section, the defocus length was set to 0, so the feed method was akin to cluster feed. As a result, a small number of elements were required to form a beam, which could pose a problem from the viewpoint of redundancy.

4 Electrical feed section baseline

From the above study example, we found that various organizations engaged in developing power feeding systems (satellite development manufacturers, satellite communications vendors, JAXA, NICT, etc.) reached a consensus on the following points regarding STICS.

Table 2 shows the baseline. For the coverage area, it was ± 2° (minimum value) and ± 4° (target value). Also, in either case, the coverage in Minami-Tori-shima (Marcus Island) will be a problem, so it is necessary to consider this. According to the study in Section **3**, electrically, a suitable F/D is roughly 0.36 to 0.4, but the F/D verified for ETS-VIII is 0.8, and if it is cut down to 0.4 at a stroke, it could cause

Table 2 Baseline for primary feed

(1) Cover area	±2°(Min), ±4°(Target value) Considering Minamitorishima
(2) F/D	0.6
(3) Electric Aperture Diameter	27 m
(4) Defocus length	0.5~1 m
(5) Area of pattern compensation	More than 1 beam
(6) Antenna Gain	Min. 47 dBi. (49 dBi is appropriate for designed value.)
(7) Number of feed elements	Max.(127/130/144)elements
(8) Inter-element distance	Min.120 mm(should find optimum value by considering realization)
(9) Antenna gain difference between land or sea	Gain of land and sea should be same due to usage of same mobile terminal antenna. Difference of channel capacity can be considered
(10) Sidelobe-level	
(10-1) C/I level of sidelobe due to STICS system	>20 dB
(10-2) Sidelobe level due to neighbor frequency band	TBD
(11) EIRP	Total transmission power of satellite is around 2 kW. In case of emergency disaster, these satellite resources can be concentrate at the specific beam.
(12) G/T	Around 21 dB/K
(13) Radiation Characteristics of feed elements	$\cos^{1.7}\theta$ (electric field for d=120 mm)

a problem in satellite mounting. That means, as shown in Fig. 9, the curvature of the reflector would be abnormally large, so the structure for storage on satellite becomes poor, which is predicted to be highly risky for deployment. Consequently, we decided to assume 0.6 F/D in subsequent studies. Further, the defocus length taken was between 0.5 m and 1 m. Antenna gain was taken as 49 dBi, considering a margin from 47 dBi for the STICS link budget. If the number of feed elements is large, the number of SSPA increases, thereby affecting the feasibility of the satellite, so it would be better to keep the number of feed elements as small as possible; in consideration of this, we set the maximum number to about 144. We decided to not set differences for the required gain on land areas vs. sea areas, because terrestrial antennas can be used for both land and sea. However, we decided to set differences in the channel capacities (bandwidth) for land and sea, to ensure feasibility.

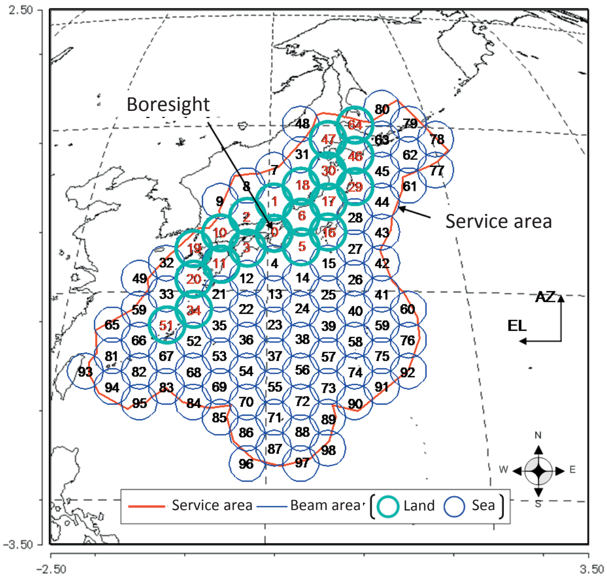


Fig. 10 Service area and beam allocation

5 Optimization study for aperture area of the primary radiator

5.1 Preconditions

In keeping with the baseline of Section **4**, when the defocus length was taken as 0.8 m, in order to optimize the structure of the primary radiator (particularly its aperture area) and to satisfy the required values of beam characteristics, the number of primary radiator elements must be reduced as much as possible to bring down the cost of the digital components described later. Therefore, for the primary radiator for sending and receiving with an optimized aperture area, we evaluated the element diameter, inter-element spacing and array arrangements[9][10].

5.2 Study details

With the aim of further improving antenna performance in order to develop a high density, compact satellite-mounted phased array feeding system for transmission and reception presuming 100 elements and 100 beam class, we studied the radiation elements for both sending and receiving with the aperture area optimized to the area defined by the array inter-element spacing. The flow of evaluation of the sending/receiving radiating elements through the optimized aperture area is explained in this subsection, based on the preconditions of Subsection **5.1**.

To reduce the weight mounted on the satellite and the complexity of the control circuit, we studied the minimum number of elements in the array arrangement (triangular arrangement and square arrangement) of the entire feed array, and the inter-element spacing. In that regard, the study was conducted on 99 beams in Japan's main islands and its exclusive economic zone shown in Fig. 10 (land: 20 beams, sea: 79 beams; in this study, no distinction was made between the land and sea areas). The area shown in Fig. 10 had around 100 beams, so the diameter of each beam is 0.4 deg., and the beam interval is 0.346 deg. thus forming a regular triangular arrangement. The satellite has a geostationary orbit of 136° of east longitude, and the front direction of the antenna (boresight) has the beam towards Osaka (east longitude 135.5°, north latitude 34.6°). Each element of the feed array is determined to meet the target of minimum gain of the reception frequency in each beam.

Based on the study of the baseline for the feeding system in Section **4**, the antenna type was assumed to be the array feed parabola antenna of de-focus feed shown in Fig. 11. The aperture size corresponding to the beam diameter was 27 m, F/D was 0.6 for the offset parabolic reflector, and the feed array was located in the defocus position on the reflector side, 0.8 m from the focal point on the reflector. The array arrangement formed a triangle and a square. The elements in this study were a patch antenna with a square cavity, and the arrangements were presumed to be a regular triangle with inter-elemental space, and an isosceles triangle and square with no inter-elemental space. In Figure 11, W is the distance between the centers of elements, and it is the sum of the inner diameter of cavity Wc + thickness t. We studied with Wc ranging from 120 mm to 220 mm.

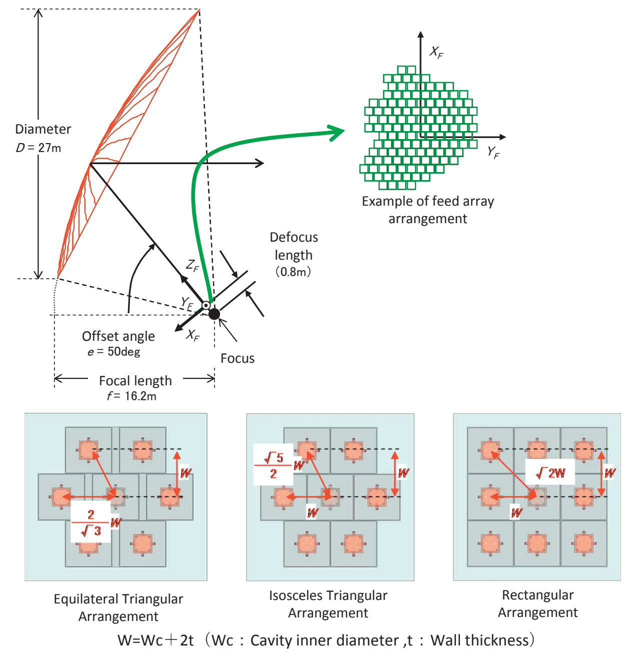


Fig. 11 Array feed reflector antenna

W = Wc + 2 t (Wc: Cavity inner diameter, t: thickness)

The flow of the study is described next. Steps 1 to 3 are studied according to the respective element arrangements and the inter-element spacing[10][11].

In the first step "(1) Study the outline of an element antenna," calculate the pattern of elements in array form corresponding to the elemental arrangement and inter-element spacing. First, make a schematic design of the shape of the elements to obtain maximum gain from the area occupied by the elements, to calculate the array element pattern after arranging the elements in the array.

Next, as step "(2) Optimize the excitation coefficient of the feed array," calculate the pattern of excitation through the reflector of each element, using the array element pattern calculated in step 1. Synthesize the excitation pattern of each element, to optimize the excitation coefficient of each element for achieving the target gain in each beam direction.

Next, as step "(3) Optimize the number of feed array elements," determine the minimum number of elements for obtaining the required gain. In the study done in step 2, the beams are formed by using a sufficiently large number of elements, but remove the elements that have a small excitation amplitude, and decide the minimum number of elements that can obtain the target gain in each beam. Consider the entire feed array as the sum of sets of elements of the beams, to calculate the total number of elements in the smallest feed array that can obtain the target gain in each beam.

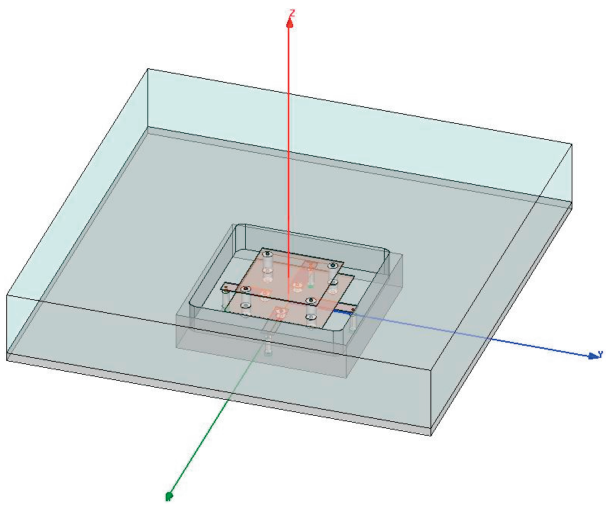


Fig. 12 Model of patch antenna with cavity

Next, in step "(4) Determine the optimum element diameter," determine the optimum element diameter (inter-element spacing and element arrangement) for minimizing the number of feed array elements.

5.3 Feasibility study of radiation elements

Here, we shall study the feasibility of the transmitting/receiving radiation elements for maximum gain from inter-element spacing (element diameter). The antenna efficiency here is defined by the ratio of the physical aperture area per element defined by the specified inter-element spacing and element arrangement, to the effective aperture area specified by the directional gain of the pertinent element, and the directional gain is the value when the contiguous elements are in an array form.

(1) Study of antenna element

Figure 12 shows the structure of a close-coupling-fed patch antenna with parasitic-element and cavity. The cavity width is Wc, and if it is large, the physical aperture area becomes large, and with the increase in directional gain, the effective aperture area also increases. Figure 13 shows the relation between Wc at this time and the directional gain as well as the antenna efficiency. Here the radiation efficiency is the ratio of the directional gain calculated from the physical aperture area per element defined by the inter-element spacing and element arrangement specified in array state (hereinafter called "physical aperture area gain"), to the directional gain of a single element. The study here is an evaluation of the element unit, and so to be exact, it is different from the definition of the antenna efficiency shown earlier in this section. However, the gain of the array form by element coupling and overlapping of the effective aperture area (when inter-element spacing is small) tends to be small compared to the value of a single element, so it was determined to be valid in the primary evaluation. Figure 13 shows that when Wc is 170 mm or more, higher than 70% antenna efficiency cannot be obtained. Consequently, the first candidate of cavity width is 160 mm[12].

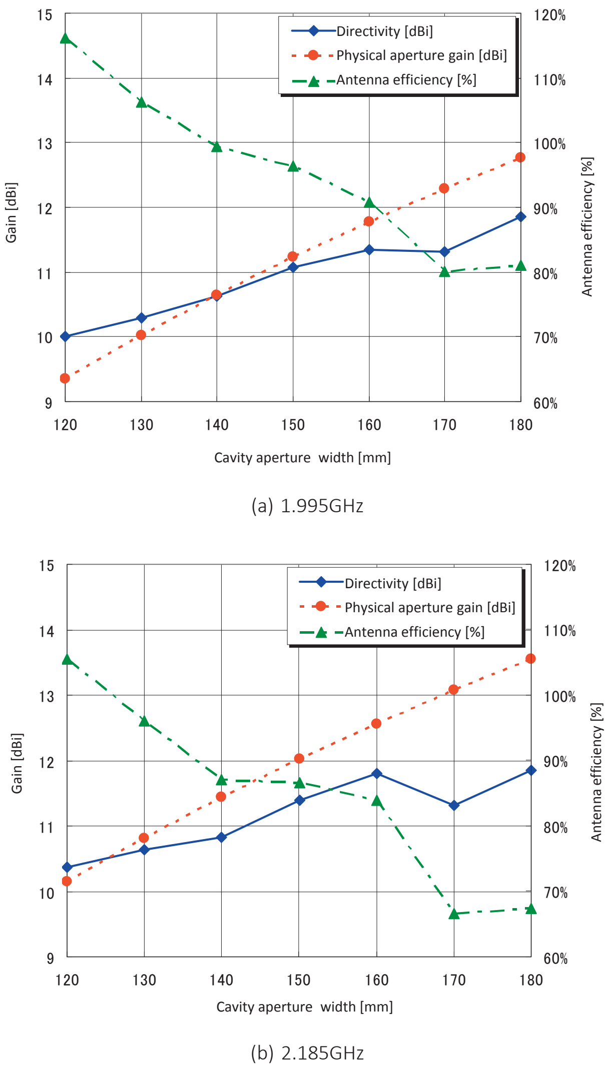


Fig. 13 Directivity and antenna efficiency vs. cavity width

(2) Study in array form

Next, we evaluate the gain in array form when Wc = 160 mm. Figure 11 shows three types of element arrangements: regular triangle, isosceles triangle and square array. Table 3 shows the antenna efficiency in each element arrangement. The spacing between the adjacent elements in only the regular triangle arrangement is larger than the other arrangements, so the antenna efficiency drops, but in all of these element arrangements, the antenna efficiency in array form is 70% or higher, showing that the value is satisfactory when Wc = 160 mm.

5.4 Study of the optimum element diameter, inter-element spacing and arrangements

The optimum array diameter for minimizing the total number of elements in feed array (inter-element spacing and element arrangement) is determined in this subsection.

Prepare the feed array by arranging the elements studied in the previous subsection, and calculate the radiation pattern through the reflector when each element unit of the feed array is excited. Synthesize the reflector mediated excitation pattern of each element, to numerically optimize the excitation coefficient (amplitude, phase) of each element, for achieving a target gain higher than the minimum gain in each beam.

Use the excitation pattern analyzed in the previous paragraph as the excitation pattern of each element. The excitation pattern of elements is generally symmetric, so use the average pattern in the circumferential direction, of the excitation pattern on a cut plane with 15° spacing.

Standardize the entire antenna gain including the reflector, by integrating the excitation pattern of the co-polarized wave of the entire feed array. Also, integrate the pattern of the co-polarized wave and the cross polarization waves in a single element, to calculate the polarization loss. In the previous subsection, the absolute value of the radiation pattern is the directional gain, and a loss of 0.5 dB is

Table 3 Calculation result for directivity and antenna efficiency in array condition

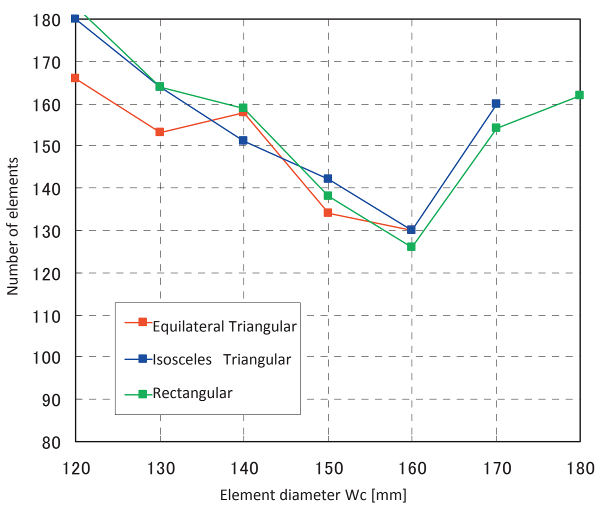
	1.995GHz			2.185GHz		
	Directivity [dBi]	Aperture area gain [dBi]	Antenna efficiency [%]	Directivity [dBi]	Aperture area gain [dBi]	Antenna efficiency [%]
Rectangular	11.40	11.75	92.2	11.62	12.54	80.9
Equilateral Triangular	11.30	12.38	78.1	11.87	13.17	74.2
Isosceles Triangular	11.11	11.75	86.3	11.66	12.54	81.6

considered as the feed circuit loss of a circular excitation circuit or other such circuits, or the reflection loss of elements, or the coupling loss with contiguous elements.

Next, determine the minimum number of elements for obtaining the required gain. In the study done in the previous stage, the beams are formed by using a sufficiently large number of elements, so remove the elements that have a small excitation amplitude, and decide the minimum number of elements that can obtain the target gain in each beam. Consider the entire feed array as the sum of the sets of elements of all the beams, to obtain the total number of elements in the smallest feed array that can obtain the target gain in each beam.

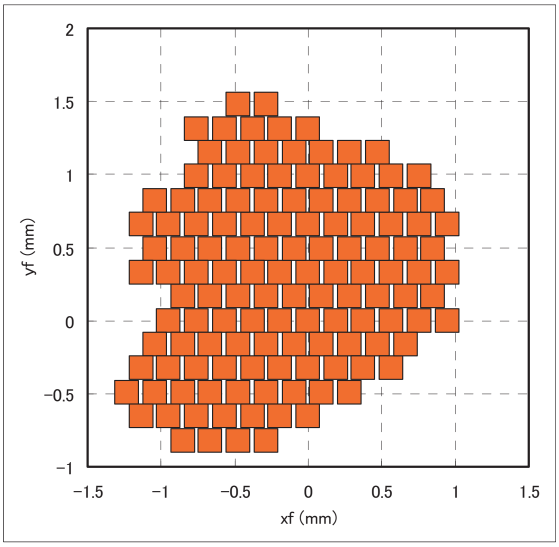
Also, do the above study on the respective element arrangements and element diameters, to determine the optimal element diameter for minimizing the number of feed array elements.

Figure 14 shows the number of elements in the feed array of each element arrangements (regular triangle, isosceles triangle, and square) for inter-element spacing (element diameter). "-" indicates that the target gain was not achieved. At this time, the target gain was taken as 47 dBi in the RX band (1,995 MHz). The beam range (coverage area) corresponds to the feed array size in the array fed reflector antenna, and if the element diameter is

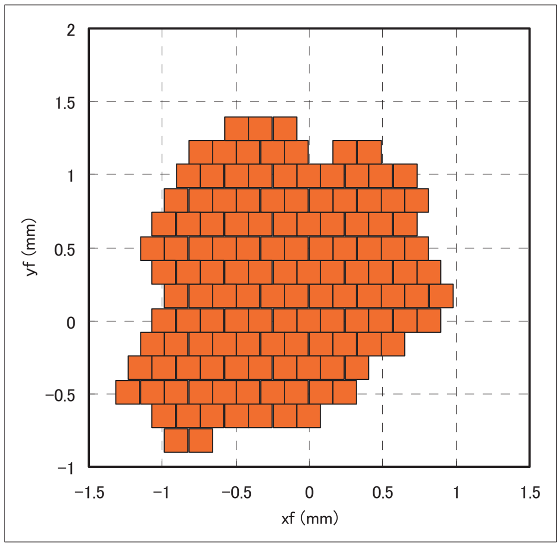


Diameter Wc (mm)	Equilateral Triangular	Isosceles Triangular	Rectangular
120	166	180	183
130	153	164	164
140	158	151	159
150	134	142	138
160	130	130	126
170	–	160	154
180	–	–	162
200	–	–	–
220	–	–	–

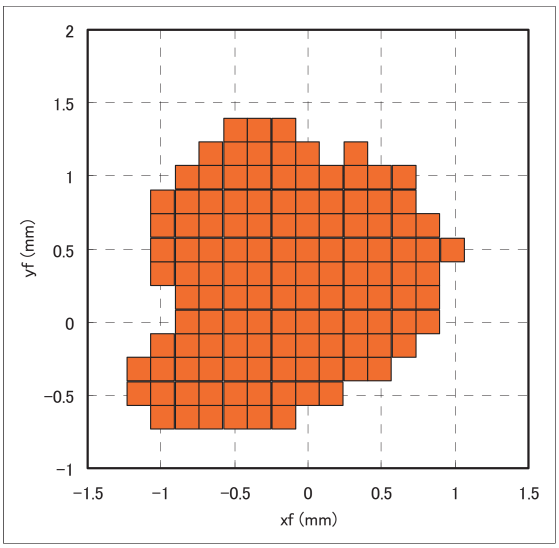
Fig. 14 Number of element vs. element diameter



(a) Triangular arrangement (130elements)



(b) Isosceles triangle arrangement (130elements)



(c) Rectangular arrangement (126elements)

Fig. 15 Element arrangement for Wc = 160 mm

Table 4 Result of electrical characteristics

Item	Analysis	Measurement
Return loss	> -19.3 dB	> -16.7 dB
Polarization	LHCP	LHCP
Peak gain (Directivity)	1.995 GHz: 11.1 dBi 2.185 GHz: 11.5 dBi	1.995 GHz: 10.9 dBi 2.185 GHz: 11.4 dBi
Efficiency (Include loss of feed line)	–	1.995 GHz: -0.40 dB 2.185 GHz: -0.21 dB
Angular range of axial ratio less than 3dB	1.995 GHz: 66° 2.185 GHz: 50°	1.995 GHz: 74° 2.185 GHz: 46°

Table 5 Antenna efficiency and directivity estimation considering difference of calculation and measurement

	1.995GHz			2.185GHz		
	Directivity [dBi]	Aperture area gain [dBi]	Antenna efficiency [%]	Directivity [dBi]	Aperture area gain [dBi]	Antenna efficiency [%]
Rectangular	11.20	11.75	88.1	11.52	12.54	79.0
Equilateral Triangular	11.10	12.38	74.5	11.77	13.17	72.5
Isosceles Triangular	10.91	11.75	82.4	11.56	12.54	79.8

large, the number of elements corresponding to the size of the same feed array (number of elements for forming beams in the same range) is small. However, the gain corresponding to the exclusive area of each element (antenna efficiency) drops if the elements shown in the previous subsection are large, so in Fig. 14, when Wc = 160 mm or longer, the number of elements become larger or the target gain cannot be achieved. Particularly, the regular triangle arrangement satisfies the target gain with a small number of elements when the element diameter is small, because of the spacing between the elements. But if the element diameter is large, the antenna efficiency is lower than the other element arrangements and the target gain cannot be achieved, even if the number of elements in the feed array is increased. In any of these element arrangements, when the element diameter Wc = 160 mm, the number of elements in the feed array was the least. Figure 15 shows the element arrangements when Wc = 160 mm.

Based on these results, a prototype of the radiation element with Wc = 160 mm was made. Figure 16 shows a photo of this prototype.

Also, Table 4 shows the measurement result of the reflection and radiation characteristics of the prototype radiation element, along with the comparison of the calculation values.

The measurement value of the directional gain compared to the calculated value had a difference of 0.2 dB when it was 1.995 GHz, and 0.1 dB when it was 2.185 GHz. In this prototype, evaluation by actual measurement of the array element pattern could not be done, but when we considered the difference from the calculated value in a single antenna mentioned above in the calculated value of the array element pattern, the result was as shown in Table 5. From this result, it is estimated that the target of antenna efficiency of 70% or higher can be achieved.

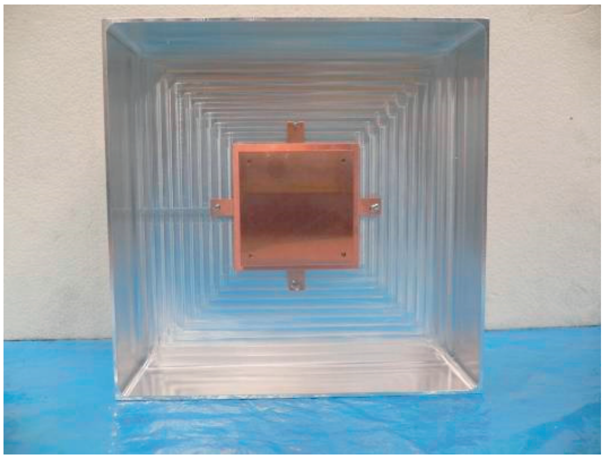


Fig. 16 Outer view of primary feed

6 Conclusion

In this paper, we first did several studies on the numerical calculation of the relation between F/D, coverage area and antenna gain. Based on their results, the baseline of the antenna of STICS was studied, to set the minimum value of the coverage area as ± 2°, and ± 4° as the target value. The standard F/D was set to 0.6.

Finally, based on the baseline, the primary radiator element arrangement method and the optimization of the spacing were studied, which showed that when the defocus length is 0.8 m, the optimal elements had inter-element spacing = 160 mm.

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