Error Correction Experiment of Radiation Pattern of Large Reflector Antenna

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The reflectors of large antennas of equipped on communication satellite are very complex and radiation pattern of antenna can be affected by surface error and distortion. With these large antennas, thermal distortion error especially can have serious implications, causing orbit beam direction errors, distortion of beam shapes, and increasing sidelobe levels.

This chapter describes the experimental results with the REV (Rotating element Electric field Vector) method measured at multi earth stations using ETS-VIII (Engineering Test Satellite VIII) and we verified the evaluation of limited reflector information (rotation) for correction of weight of array elements and radiation pattern.

1 Introduction

Experiments revealed that the beam orientation of an antenna of ETS-VIII changes daily[1][2], which is caused by the thermal distortion of the reflector. For future large satellite antennas, it is hence necessary to design an in-orbit antenna beam control with the thermal distortion caused beam pattern variation being taken into account.

In this paper, technological problems of large antennas are examined, the distortion of the actual reflector of ETS-VIII is estimated, and a method of correcting the radiation pattern is studied. Also, as an application experiment, the distortion estimation of the reflector and the correction of the radiation pattern are conducted with REV (rotating element electric field vector) method using multiple earth stations. We will show the results and discussions below.

2 Technological problems of large satellite antennas

2.1 Requirements and current technologies of antennas

The largest requirement for future satellite antennas is that their aperture be large enough to reduce the load of terrestrial terminals (in order to make the terminals more compact and more energy saving). This requirement makes the beam width of the antenna radiation pattern narrower and hence the service area needs to be covered up with multiple beams, which requires an advanced function and performance.

Basic requirements to the satellite antennas are:

(1) High gain and high efficiency
(2) Low side lobe
(3) High beam pointing accuracy
(4) Easy forming of beam
(5) High power durability
(6) Low power consumption

These requirements are for large-capacity multi-beam communications. The antenna of ETS-VIII was developed to meet these requirements for terrestrial mobile satellite communications, various basic experiments were conducted to check the functions and performance in orbit, and technological tests were made to identify problems [1][2].

One of the problems found in the basic experiments of LDRA (large deployable reflector antenna) is the degradation (distortion of the beam shape, increase of the side lobe level, variation of the beam orientation, etc.) of the antenna radiation pattern due to thermal distortion of the reflector. The feeder mounted on ETS-VIII is of a phased array type and the beam shape, side lobe, and beam orientation can be corrected by changing the excitation distribution of the array.

On the other hand, NICT conducts research and development of a future communication system, i.e. satellite/terrestrial integrated mobile communication system (STICS)[3]. The aperture diameter of an antenna of this system is about 30m, which is about twice as large as that of ETS-VIII. The beam width of the new antenna is about half of that of ETS-VIII. In what follows, the future antenna of STICS is compared with the antenna of ETS-VIII.

Figure 1 shows the antenna parameters of STICS. The array feed is placed at dF=800 mm from the focal point toward the reflector and forms multi-beams. The antenna is an array-feed reflector antenna with a beam orientation control function and basically of the same type as the one used for ETS-VIII. Figure 2 shows an example of an allocation of about 100 beams, which covers all of Japan and the exclusive economic zone.

The antennas of ETS-VIII and STICS are compared in Table 1. The antenna of STICS has more beams and more feed circuits, which make the system complicated. For ETS-VIII, the beam forming network (BFN), which is a beam forming circuit, is made with an analogue circuit. However if it is applied to form 100 beams, the circuit would be very complicated. Therefore a digital circuit is used for BFN of STICS. For ETS-VIII, in consideration of the performance of SSPA (Solid State Power Amplifier), the feed element excitation amplitude is fixed to either of three amplitudes (20W for red, 10W for yellow, 5W for light blue) as in Fig. 3 and the array feed excitation distribution is determined by changing the phase. There are two output types of SSPA, 20W and 10W. For STICS, more flexible setting of excitation amplitude will be designed and 4 or 5 amplitudes will be available. In the future it is desired to have more SSPA output choices and more efficient SSPA. For (1) to (3) of the above basic requirements for the antennas, these requirements mean high performance and the development of high performance antenna is needed. The beam forming requirement in (4) can be satisfied by employing a phased array type of feed, which also allows easy beam orientation control. The power durability requirement in (5) is also met with the phased array type of feed, which disperses the power and enhances the durability than the other methods.

On the other hand, a future problem of the energy consumption issue (6) is to promote the efficiency of SSPA and optimize the selection of SSPA.

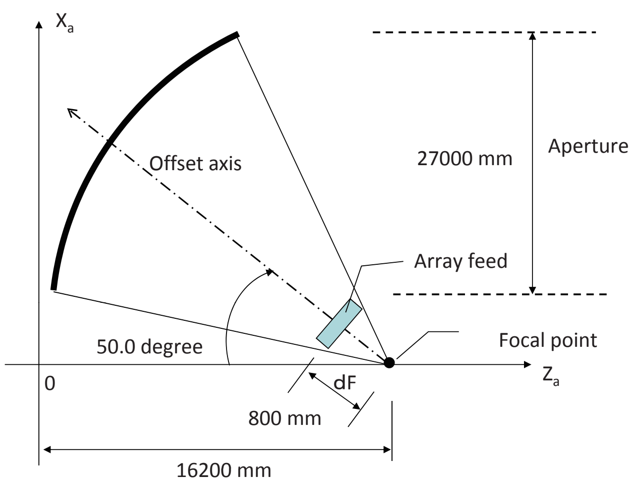


Fig. 1 Parameter of antenna

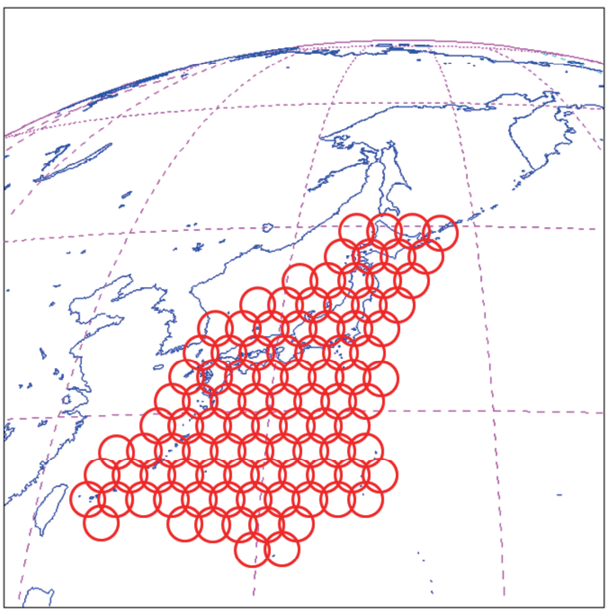


Fig. 2 Beam allocation

Table 1 Current and future technology of antenna

衛星	ETS-Ⅷ	STICS
Diameter of aperture(m)	13.0	27.0以上
frequency (GHz)	2.5/2.6	2.0
Beam width (degree)	0.7°	0.4°
Number of element	31	100
Number of beam	3	100
Polarization	Left-hand circular	circular
Number of antenna	2 (transmit and receive)	1 (common use)

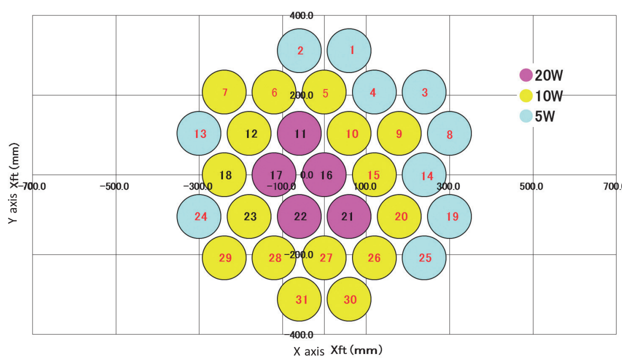


Fig. 3 Excitation amplitude distribution of feed elements

2.2 Technological problems of large antennas

Problems for future large antennas are not limited to the equipment development to satisfy the basic requirements shown in **2.1**. Actually, important problems for practical antenna development were found in the basic experiments of LDRA.

Major technological problems for antennas in orbit identified in the antenna pattern experiments of ETS-VIII are:

(1) The beam orientation varies daily due to the thermal distortion of the reflector.

(2) Due to the unknown shape of the reflector, the excitation weight of the feed for desired side lobe cannot be specified.

(3) Reflector shape error and feed excitation weight error cannot be separated from each other.

For the problem (3), the influence of the reflector distortion to the radiation pattern was not fully understood in designing ETS-VIII. It was considered that the reflector shape could be estimated by thermal distortion analysis and the shape was not adequately taken into account. Therefore these factors should be fully taken into account in future antenna development. However the problems (1) and (2) are more serious. Since the antenna aperture of STICS is twice as large as that of ETS-VIII, it is difficult to suppress the thermal distortion of the reflector. The larger the reflector is, the more difficult it is to overcome the problem.

Possible countermeasures against the reflector shape error are:

(1) Suppression of thermal distortion of reflector

(2) Estimation of thermal distortion and shape of reflecting in orbit

(3) In-orbit measurement of reflector shape

(4) On-ground estimation of reflector shape in orbit

The countermeasure (1) is not realistic as mentioned above. For the countermeasure (2), the estimation did not coincide with the actual results as mentioned in **2-2-1** for the fundamental experiment results for ETS-VIII, and the current shape estimation technology is not satisfactory.

On the other hand, although ETS-VIII does not have a function to realize (3), it would be useful if available. For this countermeasure, separation between the reflector shape error and feed weight error is needed. For example, a compact antenna is placed on an appropriate location near the array feed for the radio wave detection and the REV method (Rotating element Electric field Vector method)[4] is used to measure the excitation weight of the feed and then can be separated above errors. For (4), various methods can be considered and the possible methods should be examined in the future.

3 Study of reflector estimation

The basic experiments of LDRA revealed the thermal distortion of the reflector in orbit. However, the reflector distortion in orbit could not be estimated.

In the basic experiments, we tried to correct the excitation weight of each element with the REV method (phase and amplitude assigned to each element of the array feed) but failed because the excitation weight error included a reflector shape error and they cannot be analyzed separately. Since a system for the estimation of reflector shape in orbit is important for STICS, we used a reflector shape error estimation method for on-ground estimation of the in-orbit reflector shape. As an application experiment of ETS-VIII, a reflector error estimation experiment was conducted with the REV method by using multiple earth stations. In this experiment, ETS-VIII and more than one earth station were utilized to verify the effectiveness of the reflector shape estimation method.

3.1 Overview of REV method[4]

The REV method is a method of estimating the excitation weight of each array antenna element from a distant place. It measures a change in the received signal level and does not require a phase measurement. Since it measures only the level even in satellite-earth station measurements, the measurements are relatively easy. The principle of the method is explained here briefly. When an electric field radiates from N array elements of a satellite antenna is received, the electric field at the receiving point is expressed as a synthesis of the electric field vectors from the elements, denoted as E_0. As the excitation phase of an element of number n is changed, a new electric field E rotates from the original combined field E_0 as indicated by the dotted line in Fig. 4. The original electric field E_0 is determined with the current beam excitation weight applied to the level of each phase. In this original electric field the excitation phase of an element chosen by the REV method is changed (by a stepwise angle from 0 to 360 degrees), and the resulting synthesized electric field also changes. The ratio of the square of the new electric field E to that of E_0 can be expressed as a cosine function of the phaseΔ:

$$Q = \frac{|\mathbf{E}|^2}{E_0^2} = C_0 + C_1 \cos(\Delta + C_2) \tag{1}$$

After calculating C_0, C_1 and C_2, we obtain k and X in the following equations from the amplitude E_n and phase ϕ_n relative to those parameters of the original electric field.

$$k = \frac{E_n}{E_0} \tag{2}$$

$$X = \phi_n - \phi_0 \tag{3}$$

Here the subscription *0* indicates the original synthesized electric field. This operation is repeated over *N* elements.

In actual measurements, the timing of the phase change is adjusted and a spectrum analyzer is used to receive signals. The received signals have an error of the array feed and that of the reflector shape. In particular, the reflector of ETS-VIII is extremely large and hence the shape error could be as large as wavelength (120mm), which could cause 360° uncertainty.

3.2 REV method with multiple stations

Since measurement with a single station would cause a problem as mentioned above, the REV method with more than one station was studied. This method utilizes the fact that the excitation weight distribution obtained from the REVs received at the earth stations could change as the locations of the stations change. An evaluation function with some parameters is created and then minimized. The parameters should be the ones associated with the shape and other features of the reflector. For STICS, "Simulation Software for Correction of Large Antenna Beam Orientation Variation" was developed and used for the evaluation.

There are many parameters related to the reflector shape and they cannot all be taken into account for actual evaluation. It is therefore necessary to choose the parameters that essentially characterize the reflector shape. The following two functions were selected to be checked in the experiments:

(1) Beam orientation correction

(2) Side lobe reduction

The function (1) was chosen because of the importance of the beam orientation in forming multi beams and the function (2) was chosen since low side lobe is the most important factor to reuse frequency. Studies on the functions are explained below.

(1) Beam orientation correction

To calculate a beam shift, "Simulation Software for Correction of Large Antenna Beam Orientation Variation" rotates the reflector by angles of α_t and β_t and finds the angles at which the reflector fits its distorted shape. Here α_t and β_t are the angles of rotation about the offset axis (to the direction from the mirror center to the feed as in Fig. 1) and about the Ya axis, respectively, as shown in Fig. 5. The obtained α_t and β_t determine the position and shape of the reflector, from which one can calculate the beam shift. An evaluation function is defined for the evaluation of the phase.

The evaluation function is given to minimize the difference between the relative phase measured on the earth stations with the REV method and the one calculated:

Relative phase obtained in REV measurement: $P_r(m,i)$

Relative phase obtained in calculation: $P_S(m,i)$

The evaluation function is defined by

Evaluation function: $$\Delta f = \sum_{i=1}^{N}\sum_{m=1}^{M}\left(P_S(m,i) - P_r(m,i)\right)^2 \tag{4}$$

Here M is the number of the earth stations and N is the number of the elements. P_s and P_r change depending on the earth stations and the conditions under which the evaluation function is minimized give the parameters that we seek for each earth station.

The evaluation function Δf is minimized by changing αt and βt to obtain the solution, i.e. optimal α_t and β_t. In what follows the change of these parameters is called primary change.

(2) Sidelobe reduction

Since the reflector rotation give almost no influence to the sidelobe, it is difficult to correct the sidelobe level only by adjusting the parameters mentioned in (1). The error of the reflector that could increase the sidelobe is an error in the periodicity of the reflector surface. Therefore, parameters are assigned to each module of the reflector surface of ETS-VIII. As shown in Fig. 6, the reflector of ETS-VIII consists of 14 modules. The figure also shows the definition of the antenna coordinate system and the module coordinate system. The module coordinate system is parallel to the antenna coordinate system with different origin. The following parameters are given to each module.

θ: Angle from Z axis of module

ϕ: Rotation angle about Z axis

ΔZ: Displacement along Z axis

The evaluation function Δf is minimized with these parameters by utilizing Equation (4) to obtain optimal θ, ϕ, and ΔZ for each module. Then P_s is calculated from the parameters of the fourteen modules. Therefore the comparison of this P_s with P_r is made 14 times as many times as the comparison of the P_s calculated from the rotation angles in the beam orientation correction with P_r. In what follows the errors from these parameters are called secondary change.

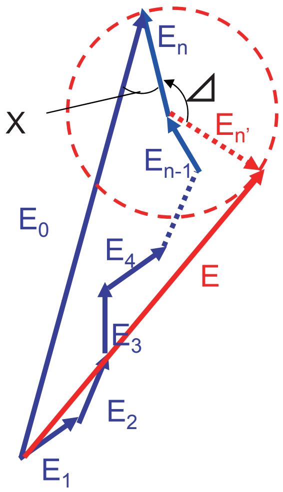


Fig. 4 Synthesized electric field for REV method

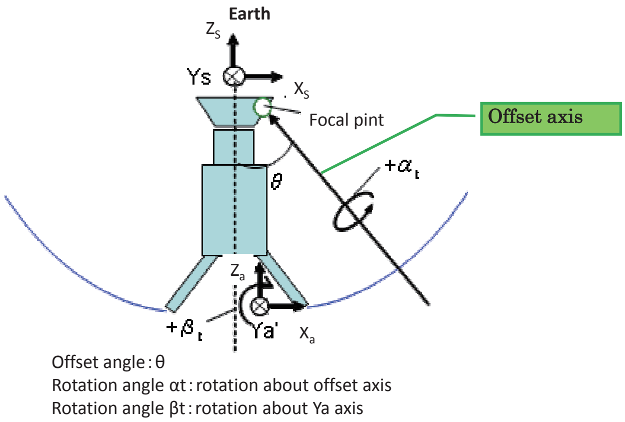


Fig. 5 Parameter for beam allocation correction

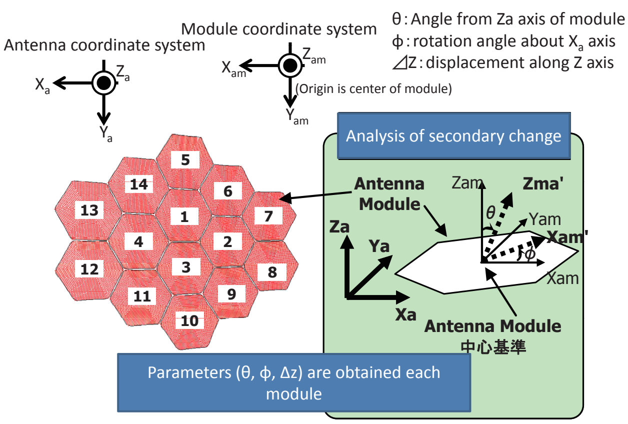


Fig. 6 Parameter for sidelobe reduction

3.3 Reflector shape estimation procedure

In this subsection, the procedure of actual experiment is explained. Figure 7 shows a flow of the reflector shape estimation. Although the figure is given for a beam orientation correction experiment, the procedure is the same for the sidelobe reduction. As shown in the figure, the radiation pattern measurement and the REV measurement are both conducted in the experiment. The pattern is measured to check the current radiation pattern. The two measurements are conducted successively since the successive measurements with a small time interval could reduce the influence from the time-varying thermal deformation. Then the relative phase P_r is derived from the data obtained with the REV method. Next the correction value is calculated. P_s is calculated from the initially given parameters α_t and β_t and the parameters are evaluated using the evaluation function. Then the resultant optimal parameters are used as the reflector shape data to conduct the pattern calculation and evaluate the beam orientation. Also for the correction, new excitation weight is calculated from these reflector shape data and used for the feed of ETS-VIII to conduct another pattern measurement and make evaluation.

3.4 Study on experiments

Here we summarize what was taken into account in the experiments.

3.4.1 Study on earth stations

The earth stations of NICT shown in Fig. 8 were used in the experiments. The stations were distributed over the country from Okinawa and Kyushu to Kansai and Kanto to cover the beam as widely as possible. The beam orientation

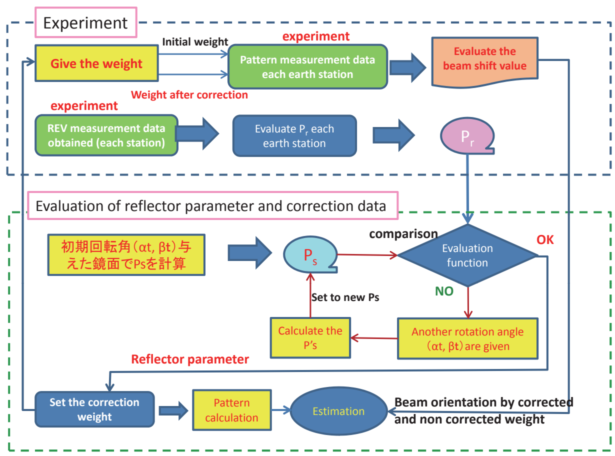


Fig. 7 Flow of reflector shape estimation

correction experiment and the sidelobe reduction experiment were conducted at different timings. Also, during these experiments, ETS-VIII did not make north-south control for the correction of the orbital displacement in the north-south direction and the satellite orbit, and hence the beam, could deviate in the northern or southern direction. The deviation grew with time. Since the experiment interval was about 1 year, the deviation was significantly large (causing about 0.3° angle deviation in the beam orientation) when the sidelobe reduction experiment was performed, and hence Okinawa station was added.

3.4.2 Study on evaluation beam

The antenna of ETS-VIII is an offset feed parabolic reflector antenna with a phased array feed. In contrast to ordinary direct-radiation array antennas, the beam from a single element is made narrow by the parabolic reflector and covers not the entire country but part of the country. Therefore the contribution (gain) from each element is dependent of the location. Figure 9 shows an example of radiation pattern of a single element. The pattern from the element 9 is calculated by setting the excitation amplitude weight of the element 9 in the element array in Fig. 3 to be 1 and that of the others to be 0. In the same manner the pattern from the element 13 is obtained by setting the excitation amplitude weight of the element 13 to be 1 and that of the others to be 0. The horizontal axis of the figure shows the azimuth direction angle and the vertical axis is the elevation direction angle. The values indicated by the contour lines show absolute gains. Let us take a look at the earth stations in Kyushu (Kita Kyushu station and Yamagawa station). The figure shows that the element 9 has a large gain in Kyushu, indicating that the beam receiving level should be high there. On the other hand the element 13 has a low gain in Kyushu and the beam receiving level should be low in Kyushu and high in Kanto.

In the experiments with the REV method, if the Kyushu beam is used then the beam receiving level in Kanto becomes lower and if the Kanto beam is used then the beam receiving level in Kyushu becomes lower. Since the beam level received at the stations thus varies largely depending on the stations, small variations in the REV cannot be detected. For example, when the earth station in Kitakyushu receives the Kyushu beam, the receiving level is extremely high. If the REV of the element 13 is measured in this situation, the pattern from the element 13 has a low gain at the Kitakyushu station as shown in Fig. 9 and a change in the REV due to a phase change cannot be detected. In other words, C_0 in Equation (1) is large but C_1 is too small (variation level lower than 0.05dB) to be detected.

The excitation amplitude was then changed from the one in Fig. 3 to the one shown in Fig. 10 to be used as excitation amplitude fed from SSPA of each device. The amplitude was set in two levels. Figure 11 shows a pattern with this amplitude and a uniform phase. This beam is called quasi-uniform beam. The gain is high in a wide area from Kyushu to Kanto. In the experiments the REV method is implemented with this beam used as original synthesized electric field E_0.

4 Experimental results

Experimental results are presented in this Section.

4.1 Experiment items

The experiments of the following two items were

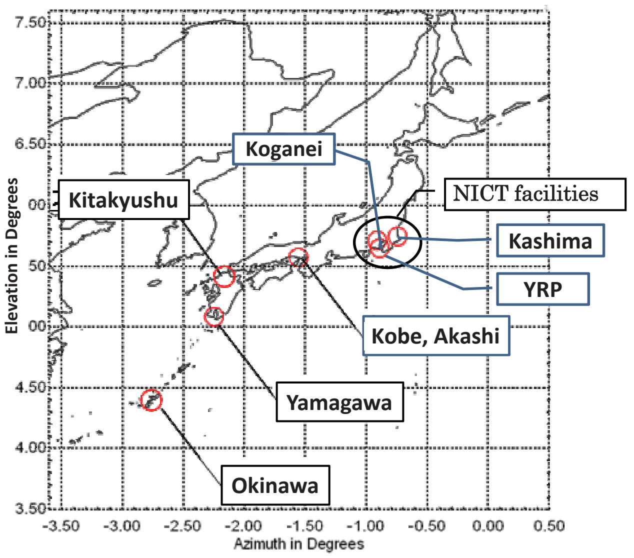
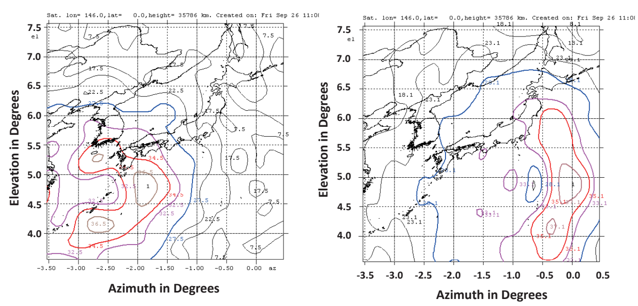


Fig. 8 Allocation of earth station



(a) Radiation pattern of element 9 (b) Radiation pattern of element 13

Fig. 9 Radiation pattern with one element excited

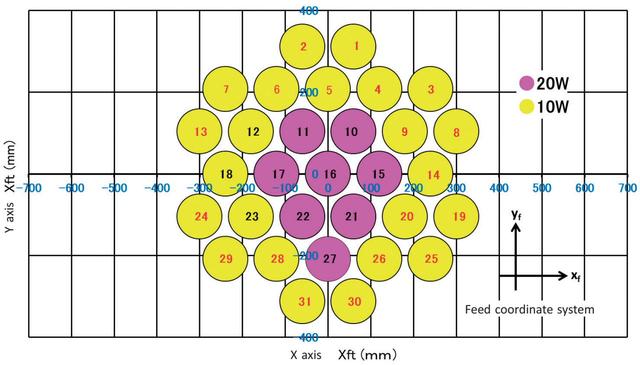


Fig. 10 Excitation amplitude of feed for REV measurement

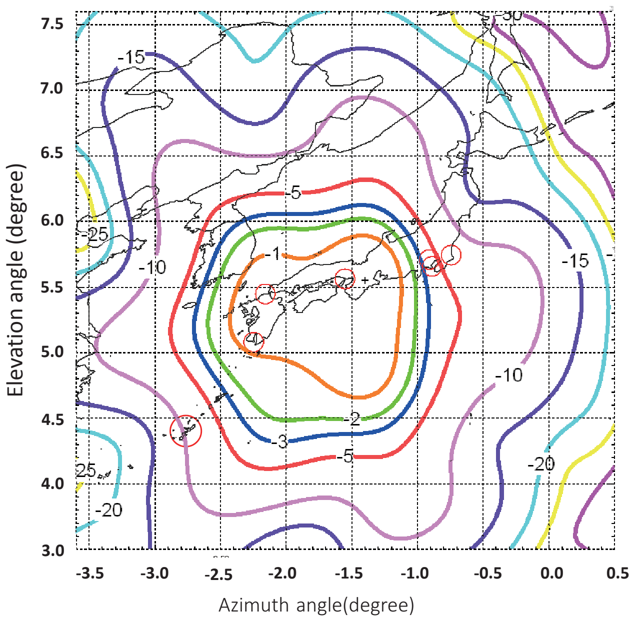


Fig. 11 Radiation pattern for REV method

conducted based on the pattern measurement results of ETS-VIII.

(1) Beam orientation correction experiments

The variation of the beam orientation of ETS-VIII was observed and the beam orientation correction experiments were conducted, as part of the basic experiments, by estimating the beam orientation[2]. In the basic correction experiments, the direction to which the beam orientation deviated was estimated to scan relative beams. But in this beam orientation correction experiment, if the actual beam position was shifted from an expected position, the reflector shape error and the feed excitation error were corrected to set the beam to the expected position.

(2) Sidelobe reduction experiments

In this experiment, as mentioned in Section **3**, the measured initial sidelobe level is used to identify a rotational error and a translational error (displacement along the Z axis of the antenna coordinate system) for each module, based on which a new excitation weight is provided to lower the sidelobe level.

4.2 Earth stations

The NICT related facilities in Fig. 8 were used as earth stations for the experiments. The beam orientation correction experiments and the sidelobe reduction experiments were conducted at different timings and with slightly different stations. The earth stations used for the experiments are shown below.

Beam orientation correction experiments: Kanto NICT related facilities (Koganei, Kashima, YRP), Akashi, and Yamagawa

Sidelobe reduction experiments: Kanto NICT (Kashima, YRP), Kobe, Kitakyushu, Yamagawa, and Okinawa.

4.3 Beam orientation correction experiments[5]-[8]

(1) Experiment overview

The experiments consist of pattern measurement and REV measurement. First the pattern was measured to find the current situation and then the REV method was used to measure the relative excitation amplitude and phase. Next, the shape of the reflector was estimated from the obtained REV data and a new feed element excitation weight was configured for another pattern measurement. We first used a quasi-uniform beam (in **3.4.2**) to check data availability and then made the beam orientation correction experiments. The experiments were performed in two steps.

- Check experiments (summer period: July 13 and 14, 2010)

In the experiments, the feasibility of the REV measurement at each station was checked. The formal REV experiments were planned to be performed in December 2010 in winter period. As in Fig. 8, for the planned winter experiments with earth stations for receiving signals from the satellite, the same earth stations as those for winter experiments were used and the data obtained at the stations were compared with each other. Figure 12 shows the measurement configuration.

ETS-VIII has REV commands in an on-board program (program built in the feed control computer) and uses them to specify the element number used for the REV experiments, phase change interval, and retention time of changed phase. The experiments used this function to use all of the thirty one elements.

The following points were taken into account during the experiments.

a. Since the signal receiving level changes from station to station, an HAC (high accuracy clock) antenna that could radiate a broad beam of radio waves for every station to receive the signals at the same level was used for the beam radiation. Then the signal levels at the station were compared to each other to correct the levels. The HAC antenna was installed at ETS-VIII for satellite positioning experiments and could handle 2.5GHz frequency. The beam angle was 7° or wider, almost covering entire Japan with a uniform gain.

b. To shorten the measurement time, the commands were arranged so that the beams from the thirty one devices could be transmitted automatically. This was done because the sunlight direction and hence the thermal distortion of the reflector changed with time and the time-varying influence from the distortion needed to be suppressed.

- Beam orientation correction experiments (winter period: December 6-10, 2010)

The same earth stations as in the summer period were used for the REV measurements. For the measurements, a quasi-uniform beam was used. Two beams, the Kyushu beam and the Kanto beam, were produced for the evaluation and the patterns were measured.

(2) Check of beam shift

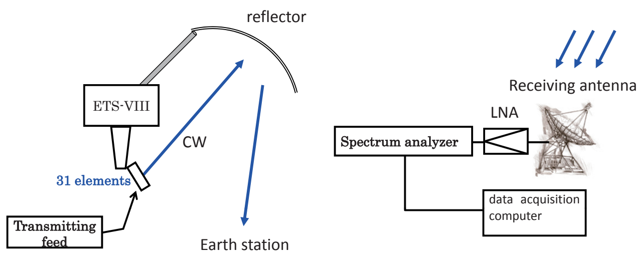
This experiment was conducted to check the pattern shift by estimating the actual shape of the reflector based on the measurement data obtained with the REV method. The REV measurements were made with multiple stations to estimate the distortion of the reflector. Recalculation based on the shape data confirmed the shift of the beam. The Kanto beam shifted by the azimuth angle 0.35° and the elevation angle 0.11° and the Kyushu beam shifted by the azimuth angle 0.30° and the elevation angle 0.10° toward east-northeast. The beam could thus be corrected by recalculating the excitation phases based on the reflector shape data. The results are shown in Fig. 13. The solid circle in the figure is the result calculated with the reflector data estimated from the REV data, indicating the beam shift. The dotted circle is the result calculated with a new excitation weight derived from this reflector data. In the figure, the sign of the angles are defined as:

Azimuth angle: Positive in eastern direction and negative in western direction

Elevation angle: Positive in northern direction and negative in southern direction.

Figures 14 and 15 show an example of the REV measurement results. The figures give raw data with no processing applied. Both the data, obtained at Yamagawa and Kashima stations, show cosine curves as functions of phase, where the horizontal axis is preset phase. The curves may not look like cosine curves since the received power is shown in logarithmic scale in the figure but they are actually cosine if presented in linear scale. The received power looks the same at the phase 180°. This is because the excitation phase was set to 180° for every device in the beam setting. When the REV measurement of each element uses a phase 180°, the phase of the preset beam, the received power level is therefore the same. Namely when the phase is changed to 180° in the REV measurement for an element, it coincides with the phase of the preset beam and gives the same power level. When the REV measurement starts, the onboard program changes the phase of the phase shifter at a preset step and time. The phase of the phase shifter starts from 0°. To make the starting phase clearer in the experiments, we set it to 180°. With a phase step 11.25°, the phase changes in 32 steps from 0° to 348.75°.

Through the development of Simulation Software for Correction of Large Antenna Orientation Variation for STICS, it was found that four or more earth stations were necessary[7]. As a result of a test with the antenna of



(a) Configuration of Satellite (b) Configuration of satellite

Fig. 12 Measurement configuration

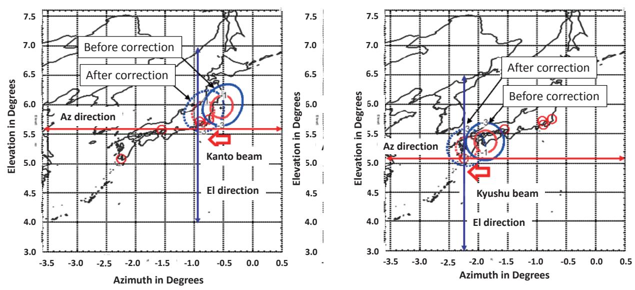


Fig. 13 Check and correction of beam shift

ETS-VIII, the necessity of four or more stations was confirmed. The test result is shown in Fig. 16, which compares the evaluation function values at different reflector rotation angles. The angle at which the function is zero or minimized is the one used as estimated angle. The angle βt about the Ya axis could be estimated with less than four stations since the angle is highly sensitive to the beam translation angle. However the angle about the offset axis is not that sensitive and four or more stations would be necessary for the estimation of the angle. In the present experiments the rotation axis was selected by taking into account the installation conditions of the ETS-VIII reflector. However in future experiments, rotation axes which are orthogonal to each other should be chosen in such a way that the rotation angles about them be more sensitive to the beam translation angle. The rotation direction of each axis is given in Fig. 5.

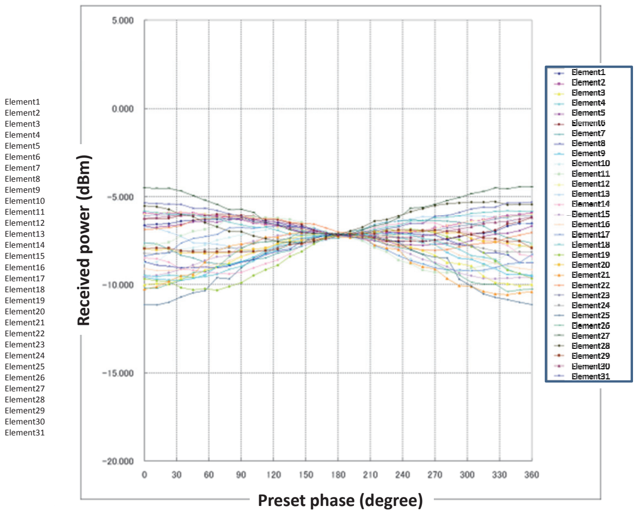


Fig. 14 Example of REV measurement results (Yamagawa station)

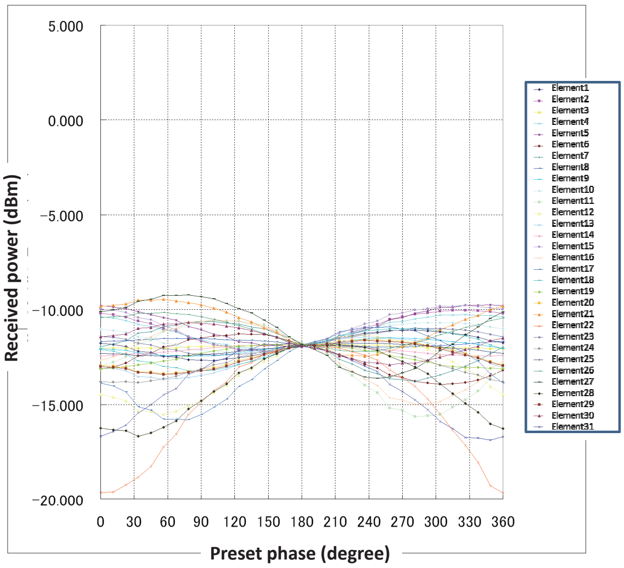


Fig. 15 Example of REV measurement results (Kashima station)

(3) Beam orientation correction experiments

Demonstration experiments for the beam orientation correction were conducted with the REV method. In the experiments, the following result of (2) was used to specify the amount of correction of the feed array elements.

Kanto beam: Azimuth angle +0.35°, elevation angle +0.11°

Kyushu beam: Azimuth angle +0.3°, elevation angle +0.1°

The beam can be corrected by compensating these shifts. Namely these values with their sign reversed are the estimated beam correction values.

Figures 17 to 20 show the results of the correction experiments based on the REV results. The beam shift amount, relative to the uncorrected beam position, is given by

Kanto beam: Azimuth angle -0.30°, elevation angle -0.05°

Kyushu beam: Azimuth angle -0.17°, elevation angle -0.01°

which is close to the estimated correction. Figures 21 and 22 are cut diagrams with the beam shift evaluated.

We conducted demonstration experiments of the beam orientation correction using the Simulation Software for Correction of Large Antenna Beam Orientation Variation for STICS. The results showed that the beam orientation could be estimated and corrected by using data obtained at multiple earth stations with the REV method.

4.4 Sidelobe reduction experiments

(1) Experiment overview

For the experiments, pattern measurements and REV measurements were conducted. The basic flow of the experiments is the same as that of the beam orientation control experiments. In the present experiments, however,

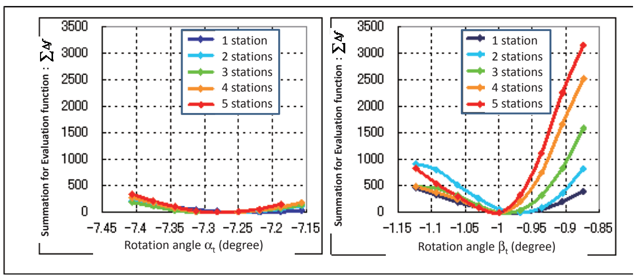
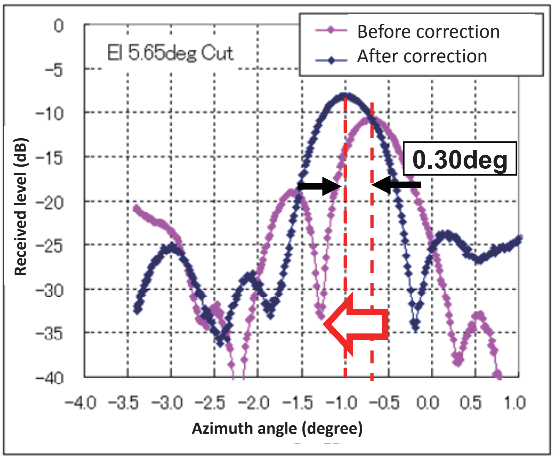


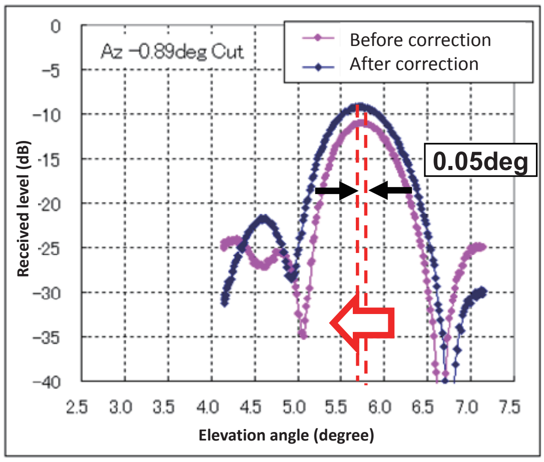
Fig. 16 Number of earth station and evaluation function

the correction data obtained from the result of the REV measurements conducted in the first step of the experiments were used to reconfigure the excitation weight and then the pattern measurements were performed. These were made in the same period. The experiments were conducted in summer and winter.



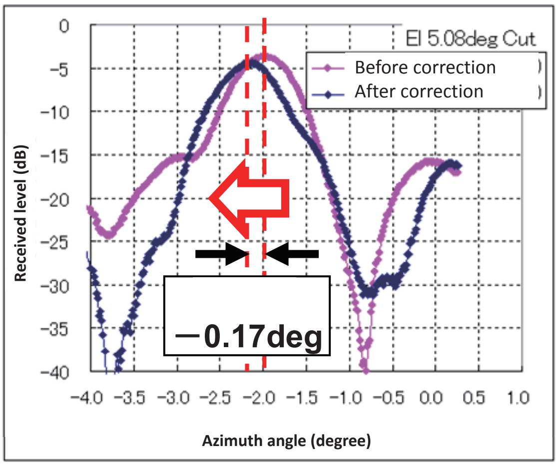
(a) Correction result of azimuth direction

Fig. 17 Beam orientation correction result of Kanto beam



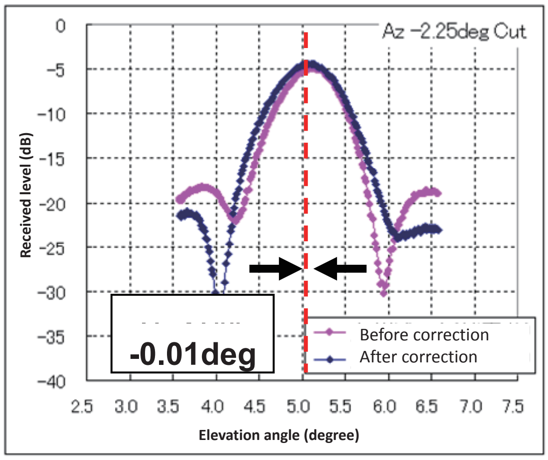
(b) Correction result of elevation direction

Fig. 18 Beam orientation correction result of Kanto beam



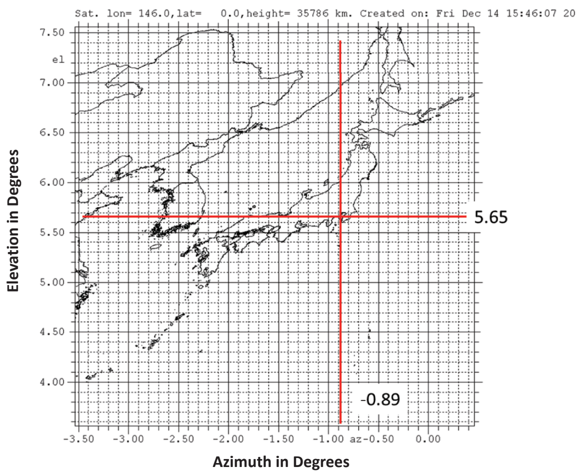
(a) Correction result of azimuth direction

Fig. 19 Beam orientation correction result of Kyushu beam



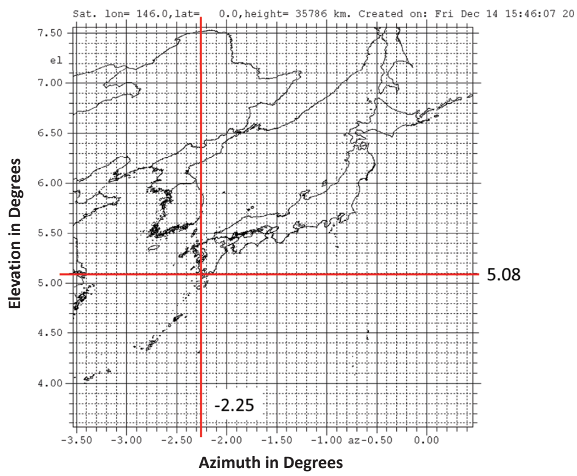
(b) Correction result of elevation direction

Fig. 20 Beam orientation correction result of Kyushu beam



(a) Cut planes of Kanto beam

Fig. 21 Cut diagrams with the beam shift evaluated



(b) Cut planes of Kyushu beam

Fig. 22 Cut diagrams with the beam shift evaluated

-Summer experiments: June 4-8, 2011

-Winter experiments: December 5-9, 2011

A beam from the satellite was simultaneously received by multiple earth stations and the excitation error was estimated based on the REV data of the stations. Then the reflector shape was estimated from the excitation error and a new excitation distribution was calculated. After reconfiguring the excitation weight, we compared and examined the resulting patterns.

(2) Experiment results

For the experiments, we focused on the Kyushu beam since it was highly symmetric and could be received by the earth stations in Kitakyushu, Yamagawa, and Okinawa to obtain high precision data. The experiments were made in summer and winter with different beam orientations. The beam orientation changed from season to season since the orbit of ETS-VIII varies with time. Namely the beam orientation slightly shifted north in summer and south in winter. This change had to be taken into account in the experiments. We therefore calculated the time and satellite position and performed measurements at an appropriate time during winter when the beam orientation became close to that in summer. The results are shown in Figs. 23 and 24.

It can be seen in the cut pattern in the azimuth direction that the side lobe values are higher than the calculated ones (ideal values). The calculated values were defined when the beam was set and were regarded as those of an expected pattern. For this pattern, actual thermal distortion of the reflector in orbit was not taken into account. The present experiments aimed to reduce the side lobe which was higher than expected. The star symbol in the figures indicates the location of the Kitakyushu earth station. The difference between the measurement value and the calculated one (ideal one) of the beam angle is given by:

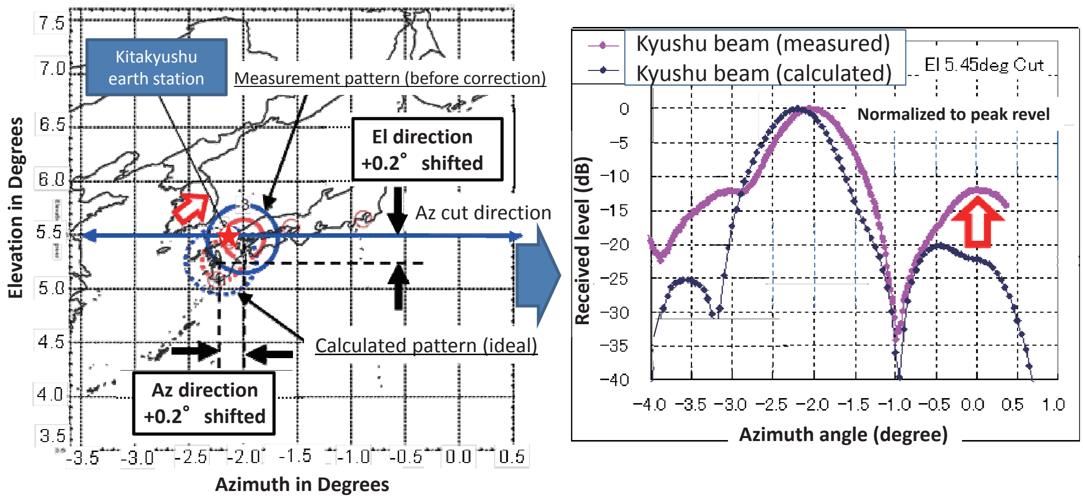


Fig. 23 Orientation of Kyushu beam in summer

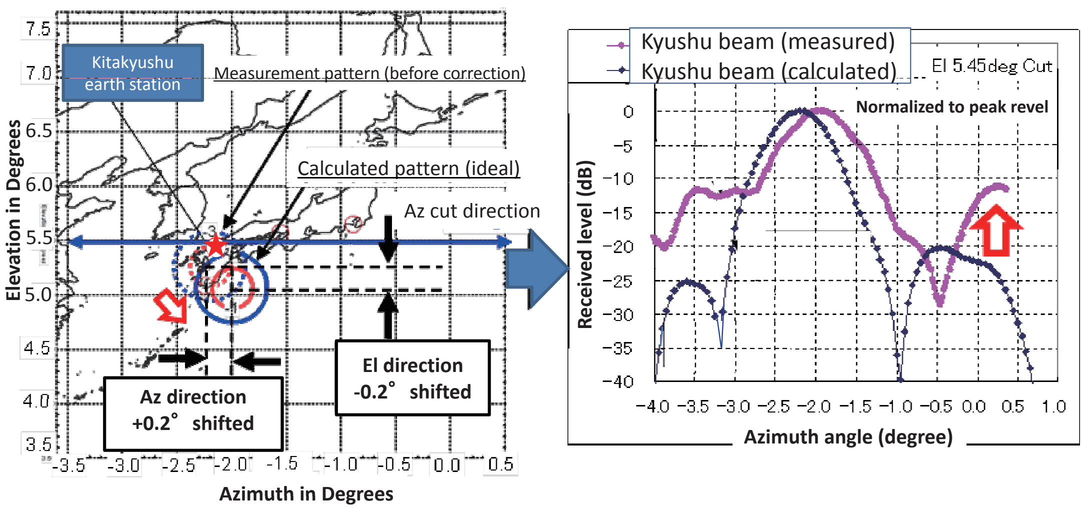


Fig. 24 Orientation of Kyushu beam in winter

Azimuth: About +0.2° in both summer and winter

Elevation: +0.2° in summer and -0.2° in winter

In the experiments, the pattern measurement and the REV measurement were made first in both summer and winter. Using the measurement data, we estimated the reflector shape and obtained the correction to the amplitude and phase of the feed excitation. Then the feed excitation amplitude and phase were reconfigured and a pattern measurement was made to compare the new and old patterns and verify the validity of the correction. Kyushu beam was used for the evaluation.

Figure 25 shows the summer results. The contour diagram on the left shows the calculated values of an ideal pattern. However the sidelobe in an area indicated by a circle was found to be high in the experiment. In order to reduce the sidelobe in this area, the REV method with multiple earth stations was used to estimate the reflector shape, derive the correction, reconfigure the feed excitation amplitude and phase, and compare the resulting pattern (corrected pattern) with the original one. The measurement result obtained at the Kitakyushu station is shown in the cut pattern diagram on the right. It can be seen in the cut pattern that the sidelobe was improved in the corrected data. The arrow direction in the contour diagram is the cut direction and the star symbol is the location of the Kitakyushu earth station.

Figure 26 shows the winter result. As in the summer result, the sidelobe was suppressed.

(3) Summary of experiment results

The sidelobe reduction experiments were conducted with the REV method using multiple earth stations and the sidelobe in the Kyushu beam was successfully suppressed. Under the same conditions in summer and winter, i.e. with the same earth stations, the same measurement system, and the same measurement procedure, the sidelobe reduction

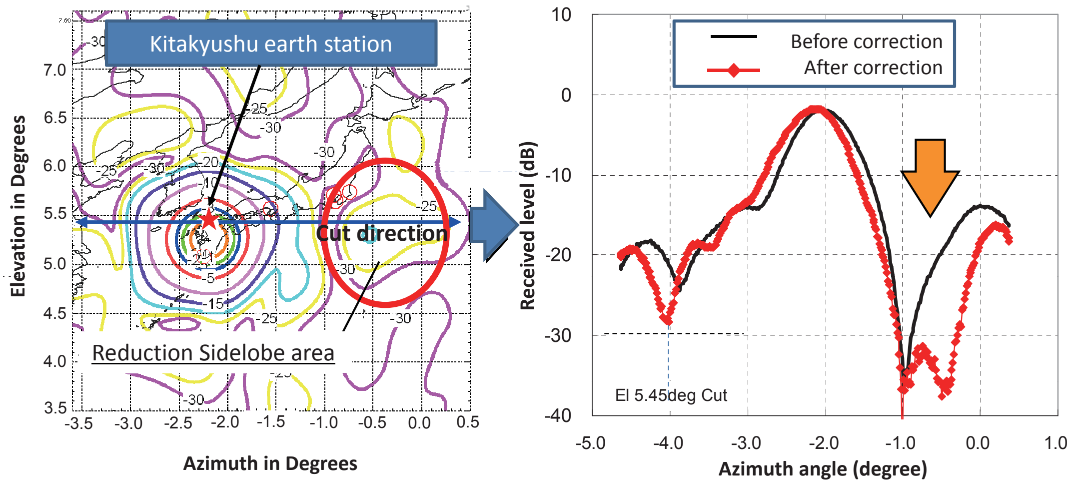


Fig. 25 Corrected pattern result of Kyusyu beam in summer

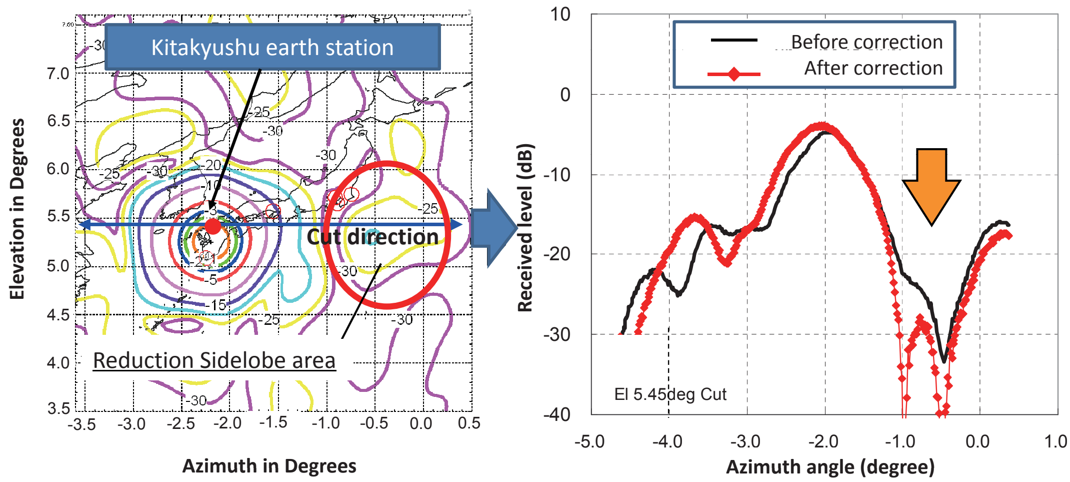


Fig. 26 Corrected pattern result of Kyusyu beam in winter

in the same area could be realized. Figure 27 shows the comparison of the results obtained in summer and winter. One can see in the figure that the data of the main lobe and sidelobe in summer and winter are almost the same. This result indicates that the reflector shape can be estimated if the multiple station REV method is used and the sidelobe can be suppressed based on this estimated shape.

The results were obtained only for the Kyushu beam and comprehensive study including other beams would be necessary for practical application. The Kyushu beam is relatively symmetric and has a high gain and hence the earth stations can be selected at appropriate locations. For the reflector shape estimation, more detailed characteristics of the reflector need to be taken account of to develop an evaluation program.

Since the REV measurement time was as long as 30 minutes and the processing of the obtained data also took time, the sidelobe cannot be controlled in real time. For practical control, this problem should also be solved.

4.5 Influence from termination of north-south control of satellite

During the experiment period, ETS-VIII had no north-south control and the position deviated from a formal orbit. The analysis in the experiments was made by taking into account the beam position shift due to the orbital deviation of the satellite. Figure 28 shows a difference in the Kyushu beam by about 0.37° between in summer and in winter. The shift in the azimuth direction was analyzed by comparing the received signals at Kitakyushu and Yamagawa stations (Fig. 29). The result indicated that the shift was 0.14°. The experiments in summer and winter used the same feed excitation weight for the comparison.

4.6 Remaining problems

The reflector shape estimation was found feasible

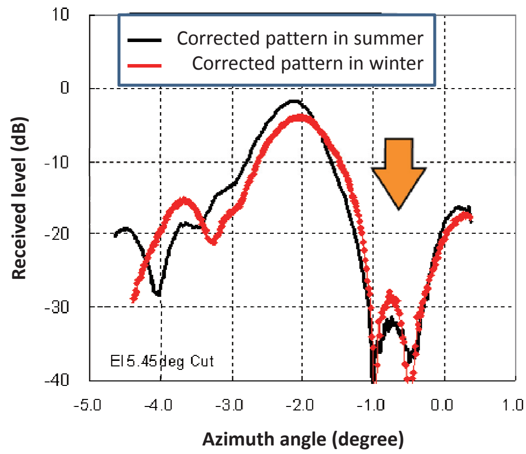


Fig. 27 Comparison of the experimental results of Kyushu beam obtained in summer and winter

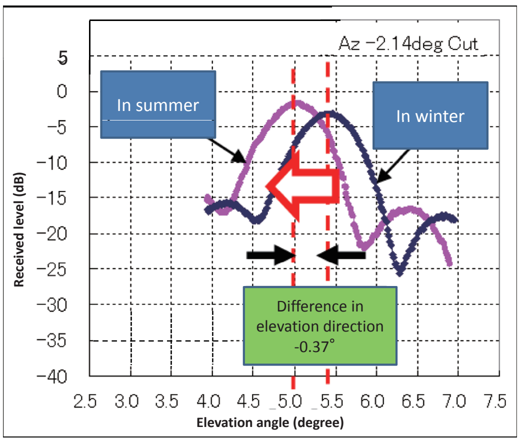


Fig. 28 Beam position difference of Kyushu beam between in summer and winter (measured at Kitakyushu earth station)

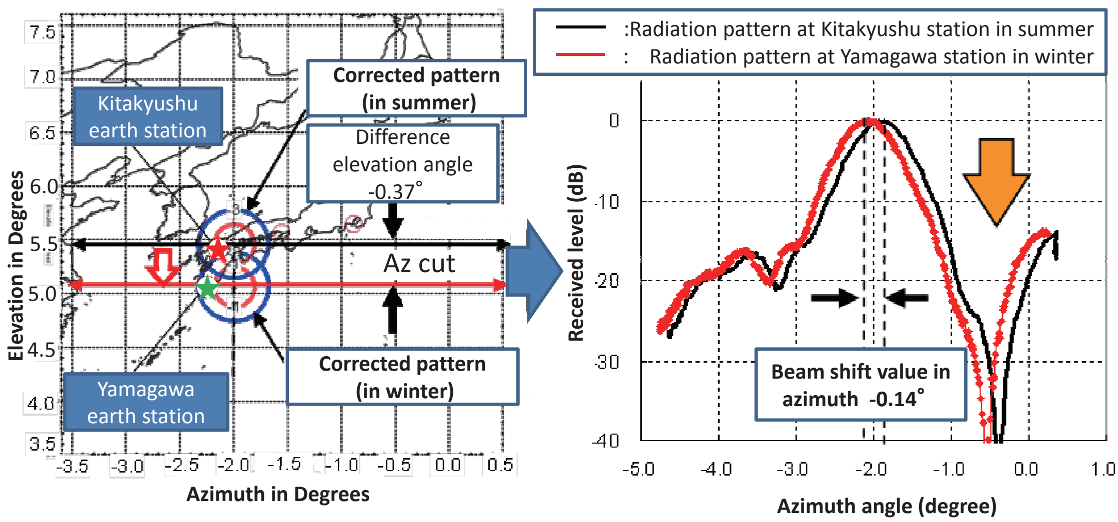


Fig. 29 Repeatability of Kyushu beam pattern between in summer and winter (azimuth direction)

through the in-orbit reflector shape estimation experiments with the REV method using multiple earth stations. However the reflector distortion was rather limited and only the rotation angles (α, β) of the reflector were used as reflector shape parameters in the beam orientation correction experiments and the rotation angle and translational shift of each module were used as parameters in the side lobe reduction experiments. These parameters, characterizing actual reflector distortion, had a large influence to the pattern. For more detailed beam control additional analysis would be necessary for the selection of the reflector shape parameters.

For STICS, a confirmation experiment of correcting radiation patterns by estimating the reflector shape distortion was conducted[9]. The present experiments employed the REV method but other methods of examining the reflector shape in orbit need to be studied.

5 Summary

Applicative experiments with ETS-VIII were conducted to identify technological problems of future antennas. Multiple earth stations distributed over the country were used to receive signals and the REV method was used for the evaluation. It was found as a result that the reflector shape could be estimated with the REV method if multiple stations were used. However the evaluation procedure is extremely difficult since it requires preparation of multiple earth stations, immediate evaluation of measurement results, selection of reflector parameters, reconfiguration of excitation weight, and immediate check of pattern. Therefore, real-time control will be necessary in future antenna designing, for which rapid measurement of reflector shape and feed excitation weight in orbit will be necessary to estimate the reflector shape and reconfigure the excitation weight immediately.

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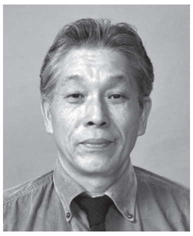

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