ICAST2014 #030

Development of a smart reconfigurable reflector prototype for an extremely high frequency antenna

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Abstract

A prototype of a space-borne smart reconfigurable reflector whose reflector surface can be changed intentionally using surface adjustment actuators has been developed, and its performance was evaluated through experiments. The smart reconfigurable reflector was designed as a sub-reflector of a space antenna for observations in the extremely high frequency band and is used for correcting the path length errors in the antenna system caused by surface deformations of the main reflector. It consists of a solid surface, supporting members, and surface adjustment actuators. The surface adjustment actuator is a key part of the smart reconfigurable reflector and consists of a piezoelectric stack actuator and a displacement magnifying mechanism. In order to investigate the performance of the actuator, functional tests were performed. The results indicate that the actuator has a stroke more than 0.9 mm with an accuracy of 0.01 mm and a force more than 90 N. The control accuracy was much better than the required surface accuracy for an EHF antenna system. The effectiveness of the developed reflector system was demonstrated through numerical simulations and shape modification experiments. In order to clarify the effectiveness of the developed smart reconfigurable reflector for the antenna system, the performance of the antenna system equipped with the smart reconfigurable reflector was evaluated. It was observed that the received power changed while changing the surface shapes of the smart reconfigurable reflector, and the changes in the power increased with an increase in applied voltage. The experimental results corresponded to the performance expected from the numerical simulation and indicated that the antenna performance was adequately controlled as expected. These results clearly indicate that the smart reconfigurable reflector system is effective for a future antenna system used for observations in the extremely high frequency band.

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1. INTRODUCTION

High-accuracy reflector antennas are necessary for future satellite missions. For example, antenna systems observing celestial objects at the extremely high frequency band (EHF / Frequency range: 30–300 GHz) are required for future scientific space missions. Reconfigurable reflector systems are good candidates to realize such high-performance space antennas[1)]. In reconfigurable reflectors, the surface shapes of the reflectors are controlled by surface adjustment actuators. A high accuracy antenna can be constructed by correcting surface errors using the reconfigurable reflector. Clarricoats and Zhou demonstrated the feasibility of the reconfigurable reflector antenna system[1)]. However, their antenna system was a conceptual model and it was not suitable for usage in space.

Among many studies on shape control of a reflector antenna, only a few space-borne reconfigurable reflector systems have been developed and investigated[2-4)]. Fang et al. developed a 2.4 m engineering model equipped with 84 PVDF actuators and investigated the adaptive surface control of the membrane reflector[2)]. Datashvili et al. developed laboratory models of reconfigurable reflectors that employed a carbon fiber reinforced silicon (CFRS) surface for communication satellites and investigated their mechanical properties[3)]. They also investigated the RF properties of the CFRS material. However, flexible reflectors were employed in these studies; therefore, they were not suitable for an antenna operated in an EHF band. Bradford et al. developed an active composite reflector panel equipped with MFC actuators to correct wavefront errors in the reflector and its feasibility was demonstrated[4)]. Although this active composite reflector panel was applicable for an antenna operated in an EHF band, the reflector that employed this composite panel has not been developed.

Moreover, these studies mainly focused on the structural aspect of the system and paid less attention on the performance of the antenna system. In addition, the reconfigurable reflector systems were assumed to be employed as the main reflectors in these studies. Recently, main reflectors need to be deployable to obtain a large aperture. Installing actuators to a deployable reflector can cause difficulties in their electric wiring. Furthermore, these actuators can cause thermal deformation of a main reflector that is exposed to the space environment because of the differences in thermal expansion ratios. Therefore, a reconfigurable main reflector has many disadvantages.

Therefore, in this study, a prototype of a space-borne reconfigurable sub-reflector has been developed, and its performances, including antenna performance, are evaluated through experiments. It is assumed that the reconfigurable reflector system is employed as a non-deployed sub-reflector and used in a thermally stable condition. Smart structures are employed in the reconfigurable reflector; therefore, we name the reconfigurable reflector system as a “smart reconfigurable reflector.” The smart reconfigurable reflector will be used for correcting the path length errors in the antenna system caused by surface deformations of a main reflector.

The smart reconfigurable reflector employs a solid aluminum surface as a reflector surface to enable operation in the EHF band. The shape of the reflector surface can be changed intentionally by using surface adjustment actuators. Key parts of the reflector such as surface adjustment actuators and solid surface are designed and their performances are evaluated. Further, a demonstration experiment of the antenna system is performed in order to evaluate the effectiveness of the developed smart reconfigurable reflector. The changes in received power of radiowaves from a satellite are measured while the shape of the smart reconfigurable reflector is changed. The performance as the reconfigurable antenna system is demonstrated through these experiments.

2. HIGH ACCURACY ANTENNA SYSTEM EQUIPPED WITH A SMART RECONFIGURABLE REFLECTOR

In order to achieve a high accuracy optical system, a reflector antenna system equipped with a smart reconfigurable sub-reflector is proposed. Figure 1 shows a schematic representation of the high accuracy antenna system. Path length errors due to surface errors of the main reflector are compensated by using the smart reconfigurable sub-reflector that minimizes the total path length errors. Because of these controls, the antenna gain that was decreased by the surface error of the main reflector is recovered.

Reflectors of EHF antennas used for radio astronomy require their surface accuracy to be better than 0.5–0.05 mm RMS depending on the observation frequency. Accordingly, the control accuracy of the actuators in the smart reconfigurable reflector is required to be much smaller than the required surface accuracy. We set the requirement for control accuracy of the actuators to be 0.01 mm and that for the stroke to be 1 mm (100 times of the control accuracy).

Antenna surface errors have to be measured for shape control of the high accuracy antenna system. It is assumed that radio holographic analyses[5)] and photogrammetry measurements[6)] are applied to diagnose the surface errors of the antenna system. These measurement methods are also investigated along with the proposed high accuracy antenna system[7)].

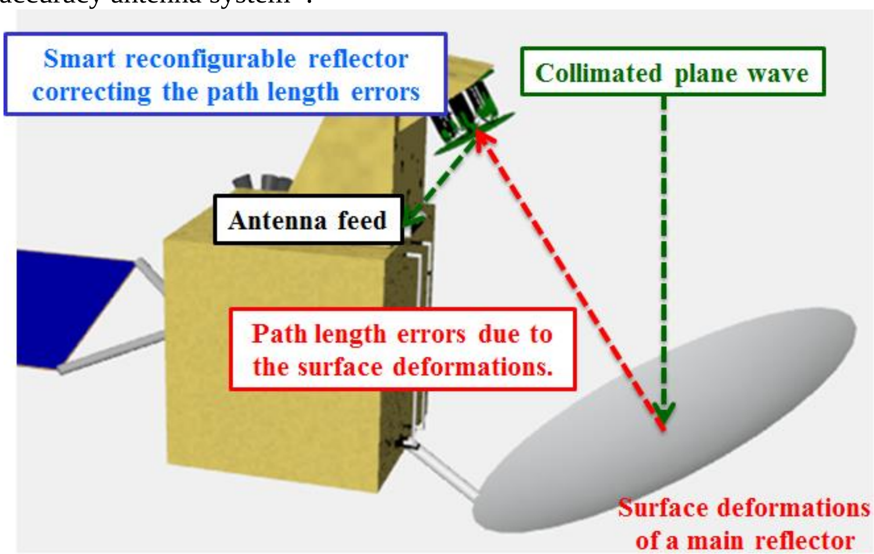


Figure 1. High accuracy antenna system equipped with a smart reconfigurable reflector

3. PROTOTYPE OF A SMART RECONFIGURABLE REFLECTOR

3.1 Outline of the prototype

Figure 2 shows a schematic representation of the prototype. The specifications of the prototype are summarized in Table 1. The smart reconfigurable reflector was designed as a sub-reflector of a space antenna and was used for changing the path length errors in the antenna system. It consists of a solid surface, a supporting column, a base plate, and surface adjustment actuators. The solid surface is employed as a reflector surface to meet the requirements for an EHF antenna. The shape of the solid surface is given as

$$z = \sqrt{0.03894\left(1 + \frac{r^2}{0.02693}\right)} - 0.19733 \quad (1).$$

Here, r and z denote cylindrical radial and axial coordinates, respectively.

The surface shape is actively deformed according to the command. It has been demonstrated that some deformation modes are barely achieved using the solid reflector that has a uniform thickness and no slits[8)]. Therefore, the solid surface with slits was developed[9)]. A schematic representation and a photograph of the solid surface are shown in Fig. 3. It has six slits to achieve target shapes (defocus mode and trefoil mode) when the surface is actively deformed by the surface adjustment actuators.

Table 1. Specifications of the prototype of the smart reconfigurable reflector

Category	Specifications
Solid surface	Hyperbolic aluminum reflector with slits Diameter: 200 mm Thickness: 0.5 mm
Surface adjustment actuator	Piezoelectric actuator (Piezomechanik GmbH, PSt 150/10/100 VS15) +Displacement magnifying mechanism
Amplifier	Input: 0–10 V Output: 0–150 V

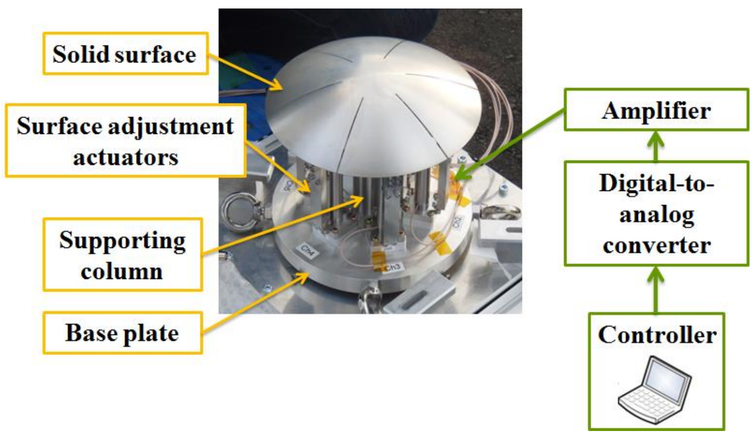
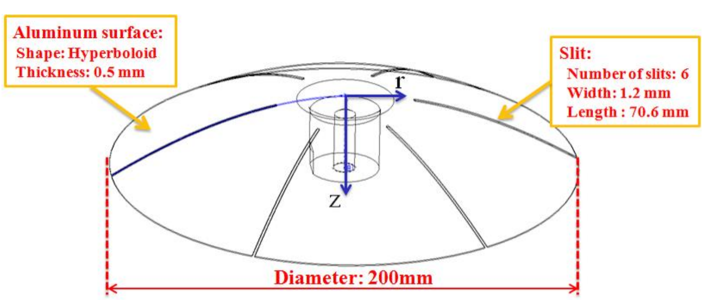
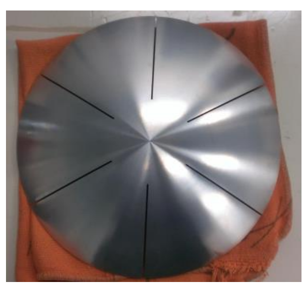


Figure 2. Prototype of the smart reconfigurable reflector



Schematic representation



Photograph

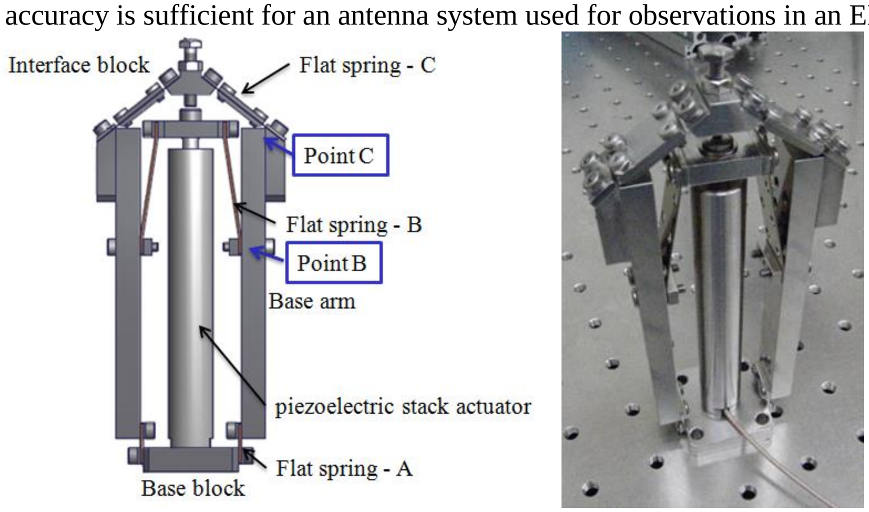
Figure 3. Hyperbolic aluminum reflector with slits

3.2 Surface adjustment actuator

A schematic representation and a photograph of the surface adjustment actuators are shown in Fig. 4. The surface adjustment actuator consists of a piezoelectric stack actuator (Piezomechanik GmbH, PSt 150/10/100 VS15) and a displacement magnifying mechanism developed in-house. The displacement magnifying mechanism is actuated by the piezoelectric stack actuator, and it magnifies the input displacement by approximately 10 times. The process of magnification is as follows:

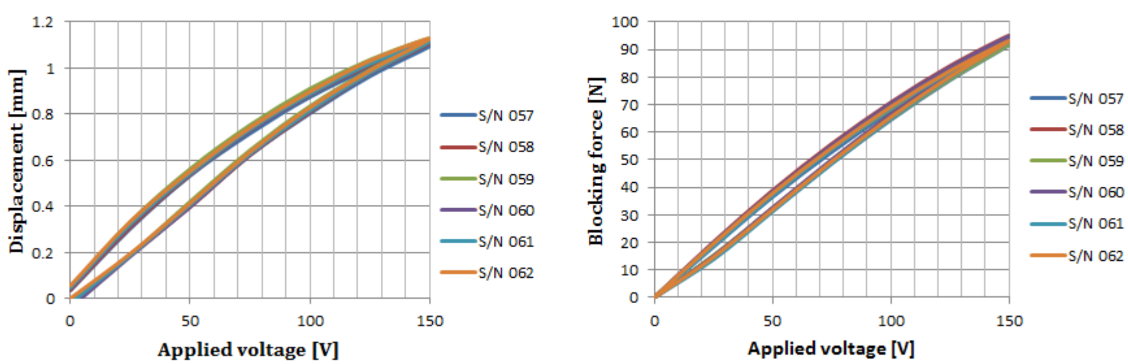
[A] Base arms are tilted to the inside by the elongation of the piezoelectric stack actuator, and the displacement at point B is enlarged based on the geometrical relationships of the stack actuator, flat spring B, and the base arm.
[B] The leverage mechanism makes the displacement at point C larger than that of point B.
[C] The direction of the displacement is changed using flat spring C and interface block for output.

Some functional tests were performed to investigate the performance of the actuators. Figure 5 shows the relation between the displacements and the applied voltages, and those between the blocking forces and the applied voltages. The results indicate that actuators have strokes more than 1 mm with an accuracy of 0.01 mm and blocking forces of more than 90 N. These performances satisfy the requirements. The observed control accuracy is sufficient for an antenna system used for observations in an EHF band.



Schematic representation　　　　Photograph

Figure 4. Surface adjustment actuator



(a) Displacement versus applied voltage　　(b) Blocking force versus applied voltage

Figure 5. Performance of surface adjustment actuators

3.3 Shape modifications of a smart reconfigurable reflector

In order to evaluate the performance of the smart reconfigurable reflector, numerical simulations and shape modification experiments were carried out. Figure 6 shows the analysis model, and the positions of the actuators are illustrated in Fig. 7. Shape modifications of the reflector were simulated by the commercial FEM code ABAQUS. Figure 8 shows the experimental setup. The developed prototype was set in a temperature-controlled booth and the shape modifications of the reflector surface were measured using a laser displacement sensor on a dual-axis slider.

The defocus and trefoil modes have been set as target modes, which are to be achieved on the reflector surface. Nominal output of the actuator has been set as 0.6 mm, which is 60% of maximum stroke. The outputs of the actuators to achieve the target mode shapes are summarized in Table 2. Figures 9 and 10 illustrate the results of numerical simulations and those of the experiments, respectively. Deformations along z-axis (Fig.3) are plotted in these figures. Contoured plot in Fig.10 is drawn from discrete measurements (20 x 20 grid, 10mm spacing) for easy comparison. It can be observed from these figures that the shapes of the target modes were achieved adequately through shape modification using the smart reconfigurable reflector. Differences between simulated and experimental results were caused by the differences between the model of analysis and the developed prototype.

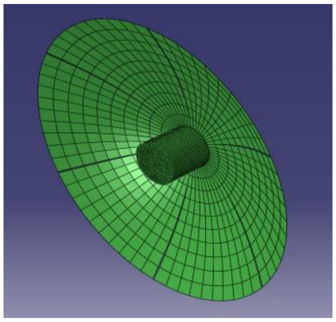


Figure 6. Model of analysis

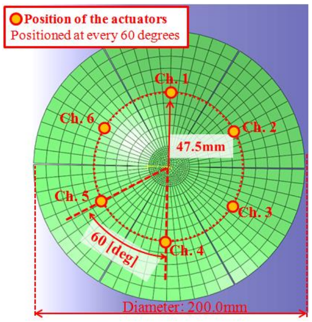


Figure 7. Position of the actuators

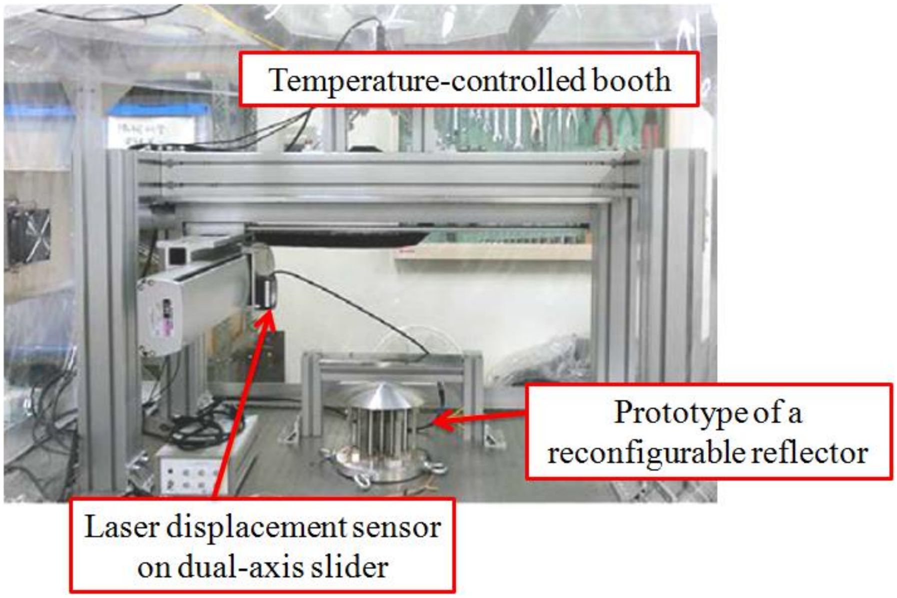
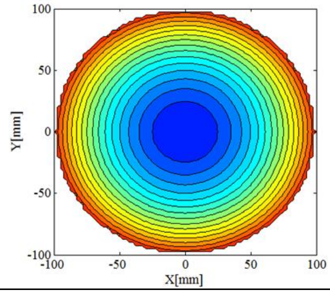
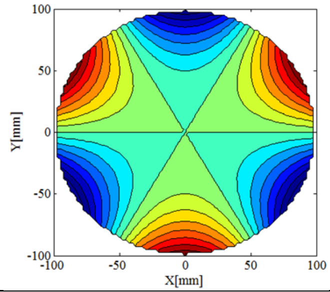
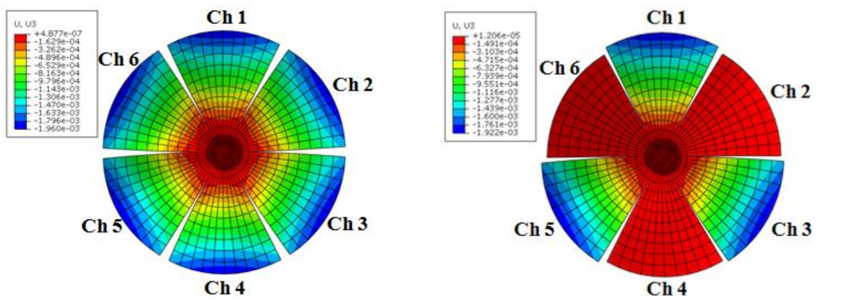


Figure 8. Experimental setup for evaluation of shape modifications.

Table 2. Outputs of actuators to achieve the target mode shapes

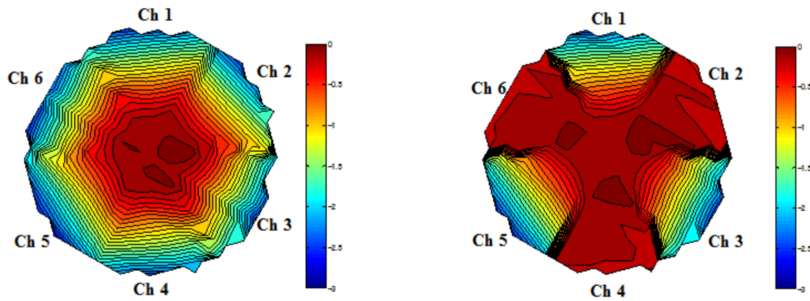
Mode	Defocus	Trefoil
Mode shape		
Output of actuator: Ch.1	0.6[mm]	0.6[mm]
Output of actuator: Ch.2	0.6[mm]	0.0[mm]
Output of actuator: Ch.3	0.6[mm]	0.6[mm]
Output of actuator: Ch.4	0.6[mm]	0.0[mm]
Output of actuator: Ch.5	0.6[mm]	0.6[mm]
Output of actuator: Ch.6	0.6[mm]	0.0[mm]



Defocus mode
(Max. Deformation: 1.96 mm)

Trefoil mode
(Max. Deformation: 1.92 mm)

Figure 9. Simulated results of shape modifications



defocus mode
(Max. Deformation: 2.60 mm)

Trefoil mode
(Max. Deformation: 2.48 mm)

Figure 10. Experimental results of shape modifications

4. DEMONSTRATION EXPERIMENT OF THE ANTENNA SYSTEM

Performance of the antenna system equipped with the smart reconfigurable reflector was experimentally evaluated in order to demonstrate the effectiveness of the developed smart reconfigurable reflector. Figure 11 shows the prototype of an antenna system with the prototype of the reconfigurable secondary reflector. Schematic representation of the experimental setup for performance evaluation of the antenna system is illustrated in Fig. 12. In the experiment, radiowaves from IPSTAR, which is a communications satellite of Thaicom Public Company Limited, were received by the antenna and their power was measured while changing the surface shapes of the smart reconfigurable reflector. The frequency of the radiowaves was approximately 20 GHz. The measured radiowaves were analyzed using a spectrum analyzer. Figure 13 shows one example of the analyzed data.

The ratios of the received signals to the background noises are summarized in Fig. 14. It is observed from this figure that the ratios were changed because of the changes in the surface shape of the reconfigurable reflector while the applied voltage was increased. The surface errors were estimated using Ruze's equation[10)] from the measurement results and they are summarized in Fig. 15. An RMS surface error calculated by the result of the numerical simulation was also plotted. The experimental results corresponded to the performance expected from the numerical simulation. These results indicate the antenna performance was adequately controlled as expected.

The observed changes in the received power measurements were obvious in these experiments. Furthermore, actuator's control accuracy of 0.01mm verified in the functional tests explained in section 3.2 was much better than the required surface accuracy for an EHF antenna system. Therefore, the results of this demonstration experiment are applicable to the antenna system operated at over 30 GHz, although the frequency of the radio wave used in these experiments was lower than EHF band.

(a) Prototype of highly precise antenna (φ1500 mm)

(b) Smart reflector on prototype of highly precise antenna

Figure 11. Prototype of an antenna system with reconfigurable secondary reflector.

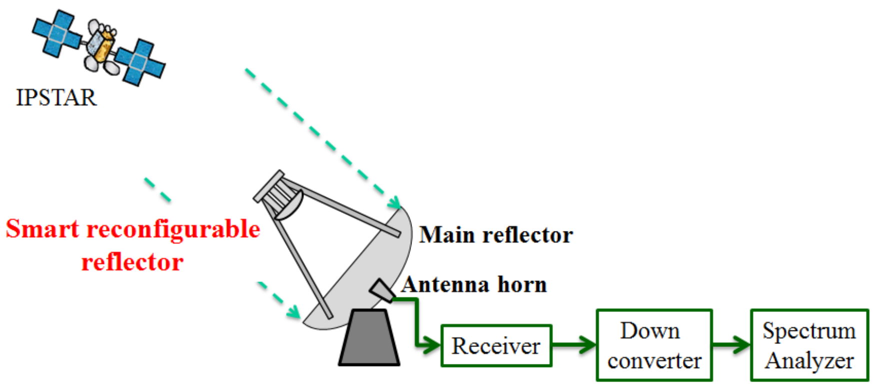


Figure 12. Schematic representation of experimental setup

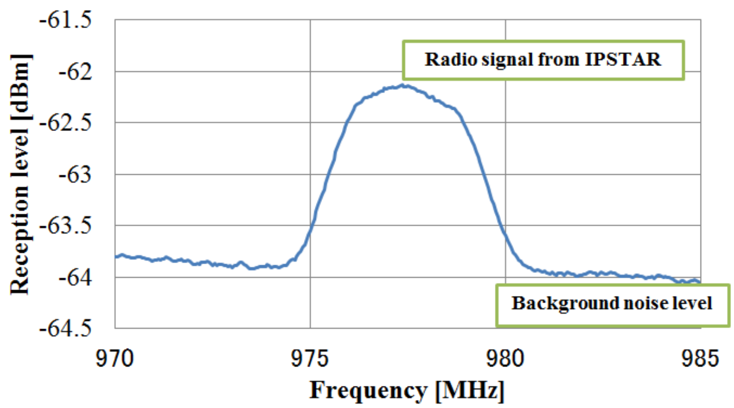


Figure 13. Example of received signals

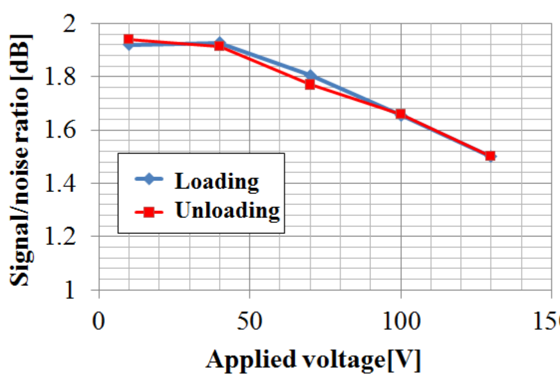


Figure 14. Changes in reception level caused by the surface shape modification of the smart reconfigurable reflector

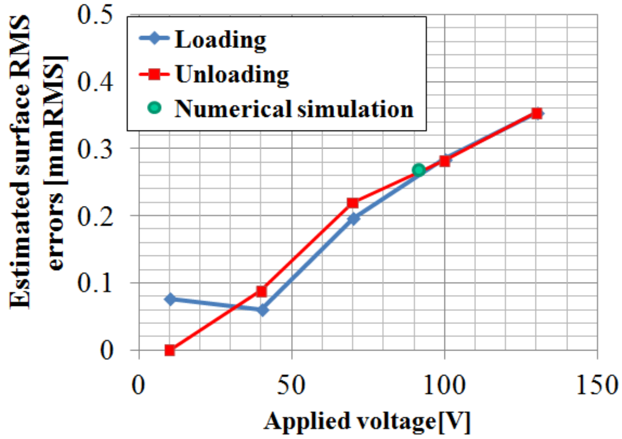


Figure 15. Estimated surface errors of the smart reconfigurable reflector

5. CONCLUSION

A prototype of a space-borne smart reconfigurable reflector whose reflector surface can be changed intentionally by using surface adjustment actuators was developed, and its performance was evaluated through experiments. It consists of a solid surface, supporting members, and surface adjustment actuators. Prototypes of surface adjustment actuators were developed and their performances were investigated. The surface adjustment actuator consisted of a piezoelectric stack actuator and a displacement magnifying mechanism that was developed in-house. Some functional tests were performed and their results indicate that the actuators had strokes more than 1 mm in accuracy of 0.01 mm and blocking forces of more than 90 N. The observed control accuracy was sufficient for an antenna system used for observations in the EHF band.

Some numerical simulations and experiments of shape modification were carried out. The shapes of the target modes were achieved adequately by the shape modification of the smart reconfigurable reflector. Performance of the antenna system equipped with the smart reconfigurable reflector was experimentally evaluated to demonstrate the effectiveness of the developed smart reconfigurable reflector. The ratios of the received signals to the background noises were changed because of the changes in surface shape of the reconfigurable reflector as increasing voltage was applied to the actuators. The experimental results corresponded to the performance expected from the numerical simulation and indicated that the antenna performance was adequately controlled as expected. These results clearly demonstrate the feasibility of high accuracy antenna systems equipped with a smart reconfigurable reflector for future missions.

ACKNOWLEDGMENTS

This study was supported by the “Research and development on high accuracy large space structure systems” in the “Science and engineering experiments of strategic development and research” of ISAS, JAXA.

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