PAPER

Simple Switched-Beam Array Antenna System for Mobile Satellite Communications

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SUMMARY This paper presents a simple antenna system for land vehicle communication aimed at Engineering Test Satellite-VIII (ETS-VIII) applications. The developed antenna system which designed for mounting in a vehicle is compact, light weight and offers simple satellite-tracking operation. This system uses a microstrip patch array antenna, which includes onboard-power divider and switching circuit for antenna feeding control, due to its low profile. A Global Positioning System (GPS) receiver is constructed to provide accurate information on the vehicle's position and bearing during traveling. The personal computer (PC) interfaces as the control unit and data acquisition, which were specifically designed for this application, allow the switching circuit control as well as the retrieving of the received power levels. In this research, the antenna system was firstly examined in an anechoic chamber for S parameter, axial ratio, and radiation characteristics. Satisfactory characteristics were obtained. As for beam-tracking of antenna, it was examined in the anechoic chamber with the gain above 5 dBic and the axial ratio below 3 dB. Moreover, good received power levels for tracking the ETS-VIII satellite in outdoor measurement, were confirmed.

key words: *antenna system, ETS-VIII, satellite-tracking, microstrip patch array antenna, outdoor measurement*

1. Introduction

The potential market for mobile communications provided by satellite systems has triggered the development of a range of operational systems and conceptional designs either for domestic or global communications purposes. Most of them are developed for voice, data, facsimile, and paging communications in North America [1] and in Europe [2] yet in Japan [3] including for land, maritime and aircraft applications. As one of the mission satellite technologies, the Japan Aerospace Exploration Agency (JAXA) has launched satellite called ETS-VIII, as one of the largest geostationary S-band satellites in 2006. The ETS-VIII was conducted for various experiments in Japan and surrounding areas to verify mobile satellite communications functions. The mobile communication technologies adopted by ETS-VIII are expected to benefit our daily life in the field of communications, broadcasting, and global positioning [4]. In addition, this satellite communications system will help rescue efforts in disaster areas by allowing us to collect information more promptly, especially if ground communications facilities are damaged or in areas without advanced communications infrastructure. Here, we are concerning on the antenna system for land vehicle satellite applications.

In mobile satellite communications, an antenna model is expected to be able to respond to changes in the direction of a mobile object. Several antennas were able to meet mobile satellite antenna requirements have been extensively investigated, are widely available in the literature include the conical beam antennas by using wire antennas such as quadrifilar or bifilar helix [5]–[8], drooping dipole [9] or even the patch antenna in higher mode operation [10], [11] and the satellite-tracking antennas [12]. The attractive feature of the former antenna design is that, as the radiation is omnidirectional in the conical-cut direction and the beam is broad in the elevation plane, satellite-tracking is not necessary. However, the antennas offer typical gain about 0–4 dBi [3], [13] because of the isotropy in the conical-cut direction. Since the target minimum gain is more than 5 dBi in the overall azimuth coverage area at specified elevation angles (Table 1), with such typical gain will not satisfy the specification and the target. Therefore, a beam-tracking antenna was selected to suit the target. As for the beam-tracking antenna, it generates a directional beam and the beam can be deflected towards the satellite direction while the azimuth of the mobile station changes. Although such antenna type needs a tracking system, owing to the generation of directional beam, high transmission rate communications are possible.

Most recent antenna systems for vehicles are impractical since their design, based on mechanical steering, makes them extremely bulky. This type of antenna system has high power consumption as well as low tracking-speed owing to the use of the electric motors responsible for mechanical steering [14]–[17]. An alternative solution is a planar phased array antenna which perform beam steering by electronic means [18]–[20]. However, the use of phase shifters for beam forming is quite expensive owing to the large number of them are required. Such phase shifters, need to be properly designed in order to avoid the beam squinting in which the beam direction may differ considerably at the receive and transmit frequencies.

Various antennas for mobile satellite communication system aimed at ETS-VIII land vehicle applications have been developed [21], [22]. The performances of the antenna

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[22] have been experimented in outdoor environment by use of a pseudo-satellite station. Furthermore, the triangular array antenna [23] which was connected with a separate switching circuit [24] has been tested in anechoic chamber to evaluate the beam-switching of the array antenna. As for the antenna system, such design was examined for beam-tracking was reported in [25]. However, owing to large cable loss, it worsened the antenna characteristic, more complex structure and dimensionally took volume. So, the antenna configuration was not effective in terms of compactness, less loss and easiness for installation. From the point of view of antenna system design, such configuration is not effectively applied for future system miniaturization and costly in implementation, is considered. Yet, the absolute gain and the axial ratio were difficult to be confirmed. As for the automatic-tracking performance was quite slow with some problems such as circuit control and particular sensor limitation. Hence, the robust antenna system which avoids the aforementioned problems is considered. Yet, the faster and simple beam-tracking with less error is expected. Moreover, since the antenna will be installed on the car roof shown in Fig. 1, the investigation of the effects of ground plate and radome to the antenna performance are also required.

This paper is mainly to realize the overall antenna system and establish a mobile communication through the satellite by designing smaller and more compact antenna, developing a satellite-tracking program which utilizing GPS receiver or gyroscope sensor, and data acquisition program which utilizing spectrum analyzer for outdoor measurement using the signal from the satellite. First, in order to minimize the bulky antenna system, a new structure of active integrated patch array antenna was proposed and developed without phase shifter circuit, to realize a light and low profile antenna system with more in reliability and high-speed beam scanning possibility. Then, the antenna system was built by the proposed antenna which its beam-tracking characteristics was determined by the control unit as the vehicle's bearing from a navigation system (either gyroscope or GPS receiver). Here, the antenna system will be installed in a vehicle and communicate with the satellite by tracking it during traveling as a concept of our system depicted in Fig. 1. In this research, we thoroughly evaluate the beam-tracking performance of the antenna and also the influence of ground plate and radome when it was mounted to the antenna structure. Therefore, following the antenna was measured for some basic antenna characteristics such as S parameter, axial ratio and radiation characteristics, the antenna system was tested in the anechoic chamber for beam-tracking including by not mounting the ground plate and radome and by mounting them. Furthermore, the outdoor measurement using signal from the ETS-VIII satellite was also performed for immobile-state measurement on a testing-rig to confirm the beam-tracking performance which has been tested in the anechoic chamber measurement. Their results are discussed in this paper.

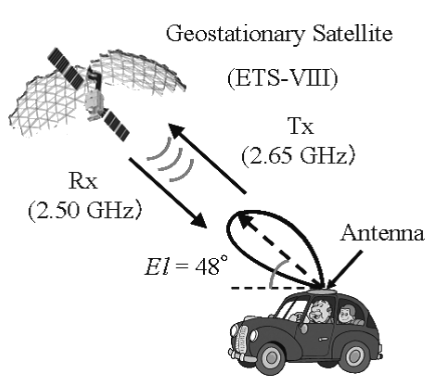


Fig. 1 Concept view of antenna system for ETS-VIII applications.

2. Antenna System Description

2.1 Specifications and Targets

The specifications and targets of the antenna are shown in Table 1. The ETS-VIII was providing voice/data communications with satellite mobile terminals in the S-band frequency (2.5025 GHz and 2.6575 GHz for reception and transmission, respectively). The polarization was left-handed circular (LHCP) for both transmission and reception units. As this antenna was assumed to be used in Tokyo and its vicinity, the targeted elevation angle was set to 48°. In our system, the antenna beam was expected to be steered towards the satellite and cover the whole azimuth space by more than 5 dBic and less than 3 dB for the gain and the axial ratio, respectively.

Table 2 shows the link budget for land vehicle aimed at field experiment using the ETS-VIII satellite. The link budget was made according to the report [26] that the Large Deployable Reflector (LDR) antenna of ETS-VIII satellite could not be used due to improper situation at Power Supply of Low Noise Amplifier (PS-LNA). For that reason, the present experiment was performed by using High Accuracy Clock (HAC) receiving antenna with gain 25 dBi instead of 43.80 dBi of LDR antenna. Therefore, the concept in Fig. 1 could not be achieved due to lack of equivalent isotropically radiated power (EIRP) for uplink from small antenna to the satellite. Instead of small antenna, a parabola antenna was set as a ground station transmitter for uplink. As a result of the link budget, the targeted vehicle antenna gain for

Table 1 Specification and targets of the antenna.

Specifications		
Frequency bands	Transmission (Tx)	2655.5 MHz ~2658.0 MHz
	Reception (Rx)	2500.5 MHz ~2503.0 MHz
Polarization	LHCP for both Tx and Rx	
Targets		
Angle range	Elevation (El)	48° (Tokyo) ±10°
	Azimuth (Az)	0° ~ 360°
Minimum gain	5 dBic	
Maximum axial ratio	3 dB	

Table 2 Link budget.

Link parameter	Forward Link	
Up Link		
Frequency (GHz)	Ground Station	2.6575
Tx power (Watt)		1.00
Tx EIRP (dBW)		20.90
Received level (dBW)		−172.48
Satellite antenna gain (dBi)	Satellite	25.00
Satellite G/T (dBK)		−8.40
C/N_0 (dBHz)		47.72
Down Link		
Frequency (GHz)	Satellite	2.5025
Tx power (Watt)		40.00
Tx EIRP (dBW)		55.02
Received level (dBW)		−137.91
Vehicle antenna gain (dBi)	Vehicle	5.00
Feed loss (dB)		1.70
Tracking loss (dB)		3.00
Vehicle G/T (dBK)		−22.92
C/N_0 (dBHz)		64.77
Results		
Total C/N_0 (dBHz)		47.64
Bit rate (kbps)		8.00
Required C/N_0 (dBHz)		45.83
Margin (dB)coded-BPSK		1.81

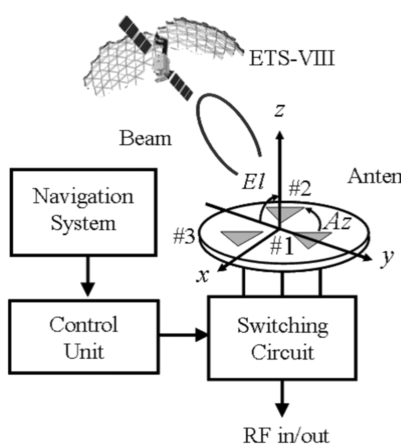


Fig. 2 Antenna system configuration.

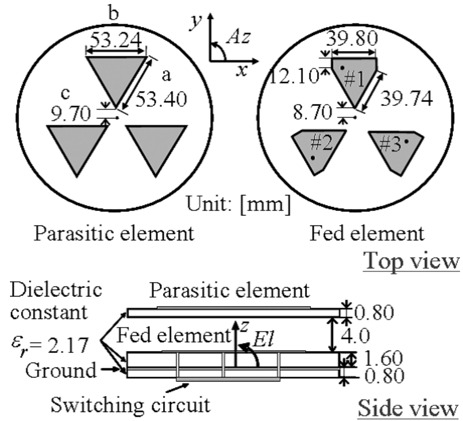
8 kbps of voice data transmission rate should be more than 5 dBic. Additionally, the link was inserted loss in the reception due to the feeding and tracking loss by 1.7 dB and 3 dB, respectively. The switching circuit and power divider circuit were attached on the antenna to control each feeding part of the antenna, thus the circuit loss was considered less than 1 dB. With the total C/N_0 47.64 dBHz and required C/N_0 45.83 dBHz, communication between transmitter and receiver through the ETS-VIII satellite can be established with margin 1.81 dB for coded-Binary Phase Shift Keying (BPSK). However, the quality of communication channel at the reception (land mobile) was sufficiently designed at 64.77 dBHz.

2.2 System Architecture

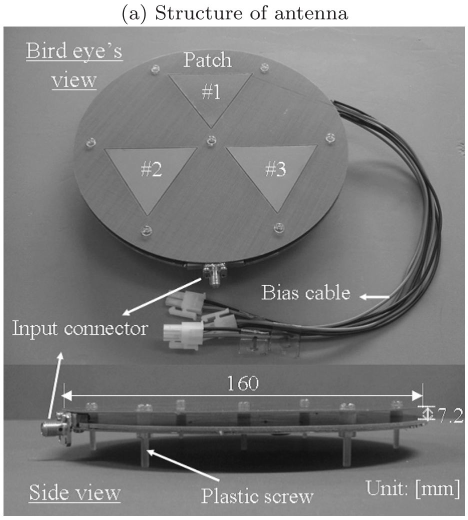
Figure 2 depicts a satellite-tracking system built with the beam switching method. As shown in this figure, the localization of the satellite is determined, based on the location and travelling direction of the mobile station by use of currently available car navigation systems and gyroscope, and the appropriate beam direction is selected. Then the signal emitted by the tracking unit is received and by appropriately controlling the activation of the feedings of each element, through the switching circuit used to control the feeding of the antenna, the beam is switched in three directions in the azimuth plane and the satellite can be followed. Since the antenna system utilizes the gyroscope, the satellite-tracking can be kept as the GPS satellite is out of sight. In order to realize the beam-steering capability, the designed array antenna were 120° sequentially physical rotated and set with an equal distance between each elements following a circular path. With such alignment, in case each element was fed in-phase, by sequentially rotating them, their relative phase was physically shifted. Such a sequential rotation ensures the generation of circular polarization. As a result, a beam was generated in the elevation direction with the direction of the created beam being shifted in the azimuth plane by −90° from the element that is turned off [22]. By successively turning off the feeding source of each antenna element, the whole azimuth range can be scanned by step of 120°. For example, when turning off element #1 located in $Az = 90°$, a beam was created in the azimuth direction $Az = 0°$. Similarly, if element #2 or #3 was turned off, the beam was generated in the direction $Az = 120°$ or 240°, respectively.

Structure of the developed array antenna is pictured in Fig. 3. The array antenna was composed of three pentagonal patch antennas which excited directly from the feeding network on the beneath of the construction. In the top of the construction was put three isosceles triangular patches as parasitic elements to enhance bandwidth of the antenna. In order to match with 50 Ω input feed, air gap was inserted at the area between the fed elements and the parasitic elements. The design makes possible the excitation of two near-degenerate orthogonal modes of equal amplitudes and 90° phase difference for left-handed circular polarization (LHCP) operation. Good axial ratio performance can be obtained by adjusting position of the feeding point, air gap height, and parasitic element dimension. Due to the satellite problem, this time, we developed and tested the antenna for reception only, however the antenna design is possible to arrange the transmission element on the same layer by specified interval for compactness.

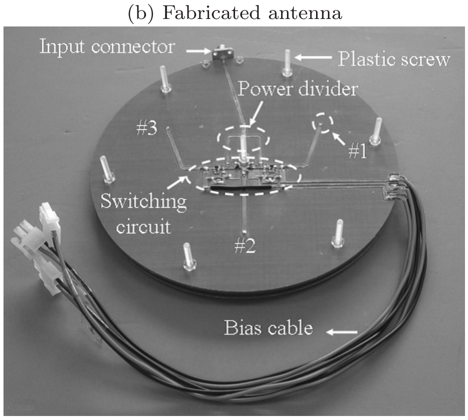
Owing to loss minimization such as feeding loss in antenna design is required, a power divider and a switching circuit was embedded on the array antenna, which was mounted on the backside of the antenna. The circuit is functioned as a feeding control of the array antenna. The mounted circuit composed of a divider and a Double Pole Triple Throw (DP3T) which proposed in [24] as pictured in Fig. 3(c). The measurement of insertion loss and isolation were less than 0.80 dB and more than 35 dB at frequency 2.5025 GHz, respectively, were confirmed. The phase difference was less than 1° between two active-output ports of the circuit.



(a) Structure of antenna

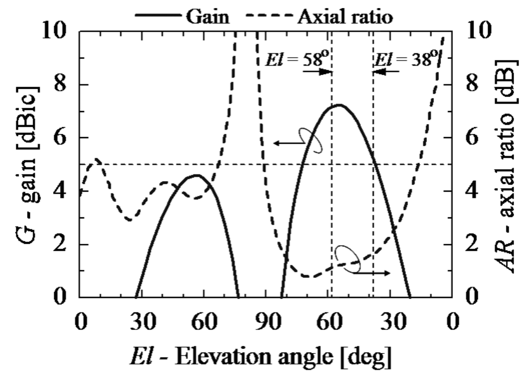


(b) Fabricated antenna

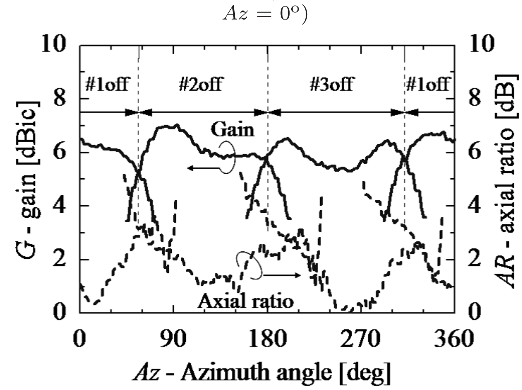


(c) Mounted-switching circuit

Fig. 3 Developed antenna structure.



(a) Elevation-cut performance (for #1off whose main beam at $Az = 0^o$)



(b) Conical-cut performance ($El = 48^o$)

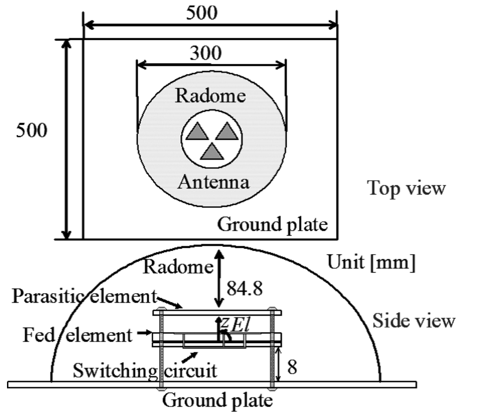
Fig. 4 Radiation characteristics of antenna.

3. Results and Discussion

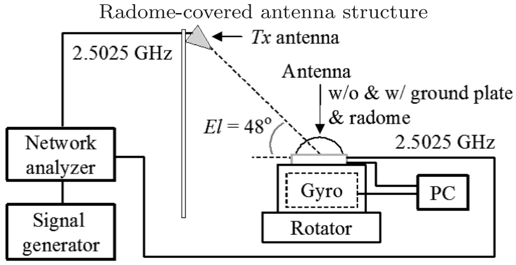
3.1 Basic Antenna Measurements

Having designed and manufactured the components of the system, we thoroughly tested each one before it was incorporated into the overall design. The first testing performed involved the array antenna. Two kinds of measurements were performed namely the basic measurement which tested at the anechoic chamber and outdoor environment on a testing-rig for immobile-state measurement. The basic measurement involved S parameter, axial ratio and radiation pattern measurements. The measured array antenna showed good reflection coefficient at the target frequency 2.5025 GHz. The impedance bandwidth ($|S_{11}| < -10$ dB) was approximately 9.5% which was more than what was required for ETS-VIII applications.The axial ratio was approximately 1 dB at frequency 2.5025 GHz for an elevation angle $El = 48°$ of the target elevation between antenna and satellite. Moreover, the 3 dB axial ratio bandwidth gave about 1.6% which satisfied the requirement.

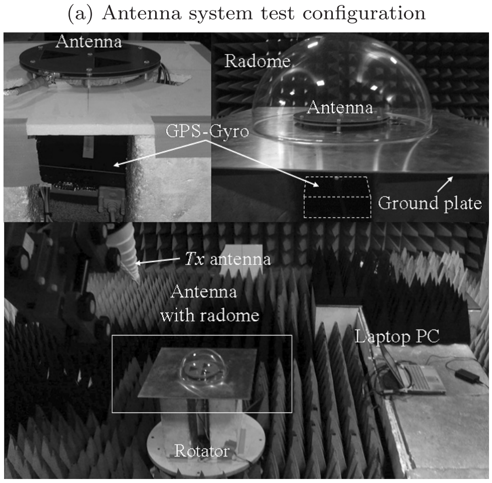
As for radiation pattern, Fig. 4(a) shows the radiation characteristics of the array antenna in the elevation-cut plane when element #1 was switched off. The antenna main beam was generated at $Az = 0°$ which is shown at the right side of the figure. Same manner was obtained in case of #2off and #3off whose beam occurred at $Az = 120°$ and $Az = 240°$, respectively. The result showed here is when the array elements mounted by the switch circuit. Note that the gain more than 5.2 dBic and the axial ratio less than 1.7 dB met the requirements for elevation angle $El = 38° - 58°$ which the approximation of elevation range from the satellite considering the Japanese archipelago from northern to southern. It was also confirmed that the gain 6.6 dBic and the axial ratio 1.2 dB at $El = 48°$. The measurements were taken at fre-



Radome-covered antenna structure

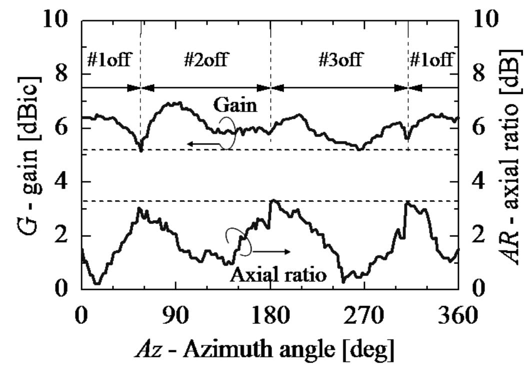


(a) Antenna system test configuration

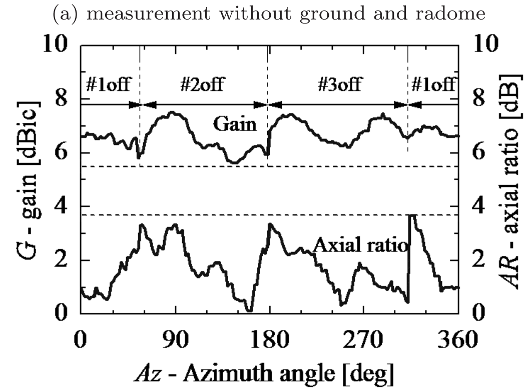


(b) Photograph of measurement

Fig. 5 View of measurement in anechoic chamber.



(a) measurement without ground and radome



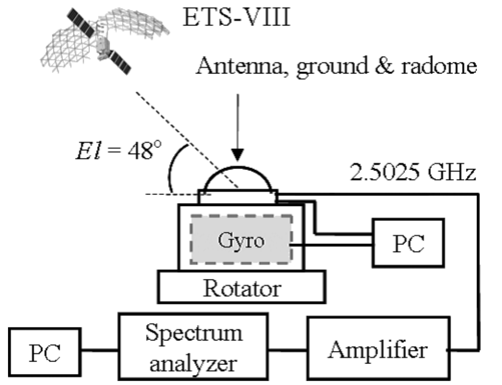
(b) measurement with ground and radome

Fig. 6 Beam-tracking performance in anechoic chamber measurement.

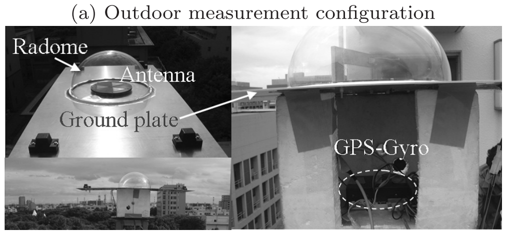
quency 2.5025 GHz. Figure 4(b) shows the measurement results of gain and axial ratio for each of three antenna beams in the azimuth plane at $El = 48°$. Small difference among each antenna beam-shape is observed. Such unsymmetrical property is considered due to the phase difference effect of the switching circuit and dimensionally discrepancy antenna fabrication. However, the 5 dBic-coverage in the 360° of the conical direction was satisfied enough. Moreover, the beam is possibly switched at minimum gain 5.2 dBic and the axial ratio below 3 dB is possibly to be obtained for automatic beam-tracking.

3.2 Antenna System Measurements

Once all the required components of the system were developed and individually examined, testing of the completed array antenna was performed in the anechoic chamber. As for this antenna system measurement, the transmitting (Tx) antenna was employed as though a satellite and the array antenna as a receiving antenna, as illustrated in Fig. 5(a). The antenna was covered by the radome and put on the ground plate since in the next outdoor mobile measurement the antenna will be located on the car roof as well as to avoid mechanical restriction or weather hindrance like snow, wind, and rainfall. The antenna was put 8 mm upper from the ground plate to avoid the switching circuit of the antenna on the rear-side touches the ground plate which may cause a shorted-circuit due to the bias cables connections. The measurement evaluated the capability of the array antenna allowing the beam automatically switched pursuing the Tx antenna. In order to realize such measurement we developed a simple application program on the PC to control the antenna beam by use of a gyro sensor of GPS receiver unit. The measurement circumstance is viewed in Fig. 5(b) where the array antenna was employed without a ground plate and a radome (upper-left) and with both of them (upper-right). Due to the chamber's height constraint, the measurement when ground plate installed was carried out in Fresnel region by 10λ distance which considered the guideline in [27]. Such measurement was carried out to grasp the influence of ground plate and radome on the antenna performance specifically the gain and the axial ratio. However, in order to reduce worse characteristics of the antenna, this time we used a hemisphere radome due to its less impact on the axial ratio performance, yet it was insignificant effect on the gain

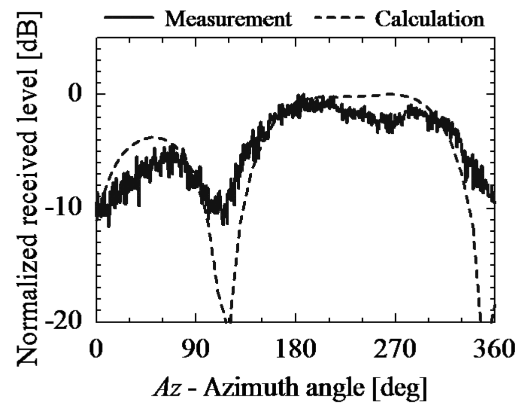


(a) Outdoor measurement configuration

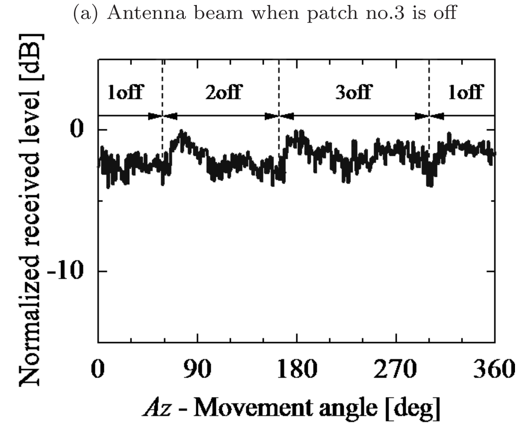


(b) Photograph of measurement on a testing-rig

Fig. 7 View of outdoor measurement.



(a) Antenna beam when patch no.3 is off



(b) Satellite-tracking

Fig. 8 Satellite-tracking performance in outdoor measurement.

characteristics.

The beam of the antenna was generated by a mechanism that consists of switching off one of the radiating elements as reported in Sect. 2.2 where the tested results is depicted in Fig. 4(b). Figure 4(b) represents the beam-switching characteristics in manual operation that was each beam (#1off, #2off and #3off) was separately measured. Having performed a manual beam measurement as shown in Fig. 4(b), we decided at which point we wanted to switch each beam automatically by considering the gain value at the coincide point of each beam. Since the beam is possibly to be switched at minimum gain 5.3 dBic, we decided to switch at azimuth angle Az = 56°, 180°, and 312°. With such decision, the gain can be switched automatically at the aforementioned azimuth angles and the axial ratio for each beam satisfies below 3.2 dB to cover 360° conical-plane was confirmed. This tracking performance is depicted in Fig. 6(a). So, in fact, Fig. 6(a) describes the beam-switching characteristics in automatic operation where the beam was switched by itself as the azimuth angle changes to track the source antenna.

In order to grasp the differences of the antenna characteristics caused by ground plate and radome installed, Fig. 6(b) depicts the automatic beam-tracking when ground plate and radome installed. It is shown that the characteristics of each beam did not change drastically when the radome and ground plate are employed (Fig. 6(b)) compared to the only antenna structure (Fig. 6(a)), except the axial ratio owing to the scattering from the ground plate affected the incident phase onto the antenna. The effect of used-radome is considerably neglected since a hemisphere shape gave minimum scattering and its thin material provided less loss. From Fig. 6, it can be stated that the proposed system can control the beam of the antenna automatically in the azimuth direction which the gain more than 5 dBic and the axial ratio less than 3.2 dB, although when radome and ground plate employed the axial ratio rose around 0.5 dB higher at the coincide point.

Additionally, because when the ground plate installed the chamber measurement became in Fresnel region distance, in order to confirm the validity of the overall antenna system, the far field measurement was examined in the outdoor measurement using signal from ETS-VIII satellite as depicted in Fig. 7. The antenna system was tested for immobile-state measurement in Chiba area (El = 48°) on a testing-rig by considering unobstructed area to receive direct signal from the satellite. In this measurement, a spectrum analyzer (Agilent E4403B) was used to measure the received power signal from the satellite signal. In order to compensate the weak satellite signal, an amplifier (Agilent 83017A) was associated with the array antenna and thus the signal level could be increased to achieve an enough C/N_0. Measured result showed that C/N_0 was 47.30 dBHz with link margin 1.45 dB where sufficiently to make the satellite-tracking measurement.

The measurement of satellite-tracking for array antenna was performed as same as the antenna system test in the anechoic chamber, which can be carried out in manual as well as automatic beam-tracking. For this purpose, we took the received power level of the antenna during the rotation of antenna. Each of three generated antenna beams met the calculation results as shown in Fig. 8(a) as one of them. In order to evaluate the system, a gyro sensor of the GPS receiver was put on the beneath of the array antenna and connected to the PC for automatically beam-switching as shown in Fig. 7(b). By use of such devices, the satellite-tracking could be automatically operated with good received power level as depicted in Fig. 8(b). Moreover, three antenna beams were smoothly switched to the satellite for each beam-coverage in the azimuth direction.

4. Conclusions

A simple switched-beam vehicle-mounted mobile-satellite-array antenna system has been presented. System components discussed include the array antenna, the switching system to activate two elements of the array, and a satellite-tracking system. Both of basic and antenna system measurement in anechoic chamber were examined where satisfactory performances have been recorded. The basic measurement included S parameter, axial ratio, and radiation pattern of array antenna and insertion-loss and isolation of switch circuit-power divider. The system measurement involved beam-tracking performance in anechoic chamber testing where satisfactory result was obtained. Furthermore, the antenna system has also been examined using signal from the ETS-VIII satellite for immobile-state measurement on the testing-rig. Without any obstacles present, the system was able to correctly track the satellite by considering the orientation of rotation of the antenna.

The overall design of the system has been effectively small and possibility in low cost due to the small and thin integrated-antenna with simple and inexpensive electronic-tracking system. These features make the system developed very promising for trends of mobile satellite communications in the near future technology.

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