PAPER Special Section on Satellite Communication Technologies in Conjunction with Main Topics of JC-SAT2008

Realization of Simple Antenna System Using ETS-VIII Satellite for Land Vehicle Communications

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SUMMARY This paper presents a realization of a simple antenna system for land vehicle satellite communication that is tested in experiments conducted on the Engineering Test Satellite-VIII (ETS-VIII). The developed antenna system which was mounted onto a vehicle roof is compact, light weight with simple satellite-tracking operation. In order to realize compact antennas, an onboard-power divider and switching circuit for antenna feeding control are mounted under the array antenna. A Global Positioning System (GPS) module is used to provide accurate information on the vehicle's position and bearing during travelling. A personal computer (PC) is used as the control unit and data logger, which was specifically designed for this application, allow the switching circuit control as well as the retrieving of the received power levels and error rate. The field tests reported in this paper mainly address the tracking performance of the proposed antenna system. Satisfactory results were obtained. Good received power levels and bit error rate (BER) for tracking the ETS-VIII satellite were confirmed. Furthermore, in order to grasp the environmental factors that impact the quality of land vehicle communications, we carefully captured data at obstacles such as buildings, foliages, utility poles and highway overpasses. The results showed blockage and shadowing was confirmed. Additionally, when the antenna was tested at the inclined-road for simple propagation characteristics in elevation direction, stable reception of the satellite signals was realized.

key words: *antenna system, land vehicle satellite communication, ETS-VIII, satellite-tracking, field experiment*

1. Introduction

In the last decades, 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 3 tons-weight geostationary S-band satellite called ETS-VIII in December 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. The satellite is missioned for 3 years experiment test and has been using in some kind of field experiments. Here, we are concerning on field experiment test by use of our developed antenna system for land vehicle satellite applications.

Most of the recent developed antenna systems for vehicle-based antenna design are huge and bulky which the antenna was mechanically steered high-gain design. 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 [5]–[9]. An alternative solution is a planar phased array antenna which perform beam steering by electronic means [10]–[12]. 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.

This paper provides a simple antenna system for land mobile satellite communications particularly aimed at ETS-VIII applications. In order to minimize the bulky system, an active integrated patch array antenna is developed with no phase shifter circuit, realizing a light and low profile antenna system which has reliable operation and high-speed beam scanning performance. The antenna system was built by an array antenna, whose beam tracking characteristics is determined by the control unit as the vehicle's bearing from a navigation system (Global Positioning System (GPS) module) is updated in real time. Here, the antenna system was installed onto a vehicle roof and was expected to communicate with the satellite by tracking it during travelling as shown by the system concept depicted in Fig. 1.

Following the antenna was measured for some basic antenna characteristics such as S parameter, axial ratio and radiation characteristics, the antenna system was also tested in the anechoic chamber for beam-tracking characteristics. However, we do not discuss the aforementioned results. In this paper, we thoroughly concerned to evaluate the antenna system in the field experiment using signal from the ETS-VIII satellite.

Manuscript received March 16, 2009.
Manuscript revised July 10, 2009.

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DOI: 10.1587/transcom.E92.B.3375

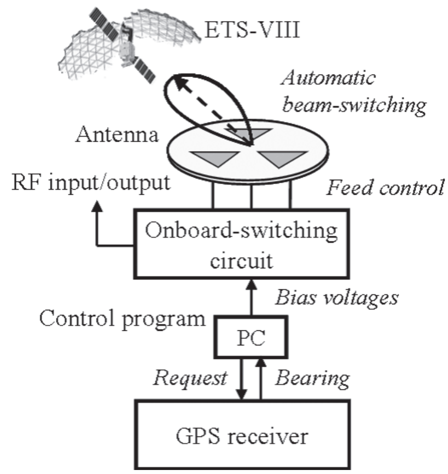


Fig. 1 Antenna system configuration for ETS-VIII land vehicle applications.

Most of field measurement derived from the satellite were propagation measurements [13]–[15] by use of omnidirectional or directional antennas. However, they employed huge and bulky antenna which had some diffulties when it is employed into a small car. Yet, the satellite-tracking characteristics for directional antenna [15] did not be reported for various movements of vehicle in the azimuth direction owing to vehicle movement property. Even though the multibeam antenna [16] has been proposed and performed for various measurements, however, in case of the automatic beam tracking under line of sight (LOS) condition when the vehicle traced a circular path, due to wrong selection the tracking was failed at certain azimuth angles which degraded the received signals and lost the coverage. Moreover, the communications link performances such as bit error rate (BER) did not be evaluated yet.

We carried out the field experiment into two main experiments i.e. the received power level measurement and the data communication measurement. For the received power level measurement, we carried out the experiment for satellite-tracking in direct wave environment and propagation characteristics at obstacles area such as buildings, roadside-trees, utility poles and highway overpasses. Finally, a simple data communication experiment was performed in direct wave area to confirm the link quality of our developed antenna system.

2. Antenna System Description

2.1 Specifications of Antenna

The specifications of the developed 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 1 Specification of antenna.

Frequency 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	
Angular characteristics		
Angle range	Elevation (El)	48° (Tokyo) ±10°
	Azimuth (Az)	0°~ 360°
Minimum gain	5 dBic	
Maximum axial ratio	3 dB	

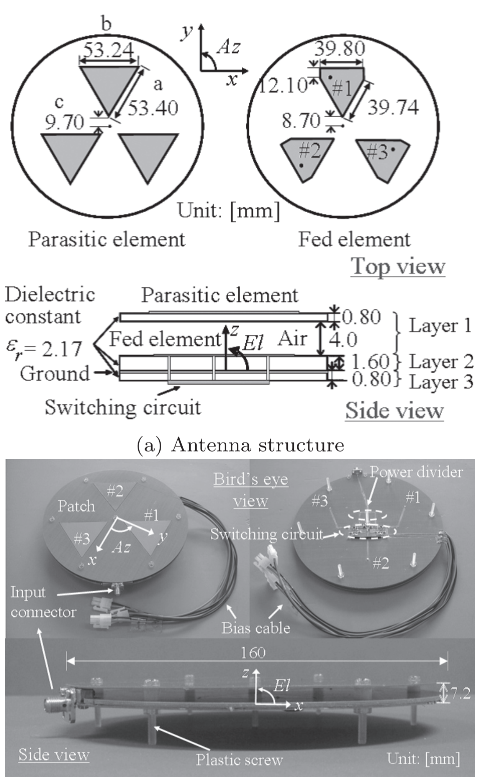
2.2 System Architecture

In order to realize the beam-steering capability, the developed 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 [17]. 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.

Figure 1 describes a satellite-tracking system built with the beam switching method. The antenna system works associated with the control unit, hence the tracking-algorithm is expected allowing the antenna beam automatically steered. The tracking-algorithm was simply developed regardless the signal of satellite. As for beam-forming of array antenna, the personal computer provides three bias voltages to switch on and off the P-I-N diodes of the circuit (switching circuit in Fig. 2) and thus two elements of the array are correctly fed and specified beam is created. For automatic beam switching, by considering the orientation of the vehicle, a control program on PC decides a correctly-generated beam among three selectable-beams. As the satellite lies at southern from Japan area, the beam is invariably controlled at the south direction.

Structure of the developed array antenna is pictured in Fig. 2. The antenna was composed of three layers, i.e. the parasitic elements with air gap (layer 1), the fed elements (layer 2) and the switching circuit (layer 3). The fed elements were three pentagonal patch antennas [18] which excited directly from the feeding network on layer 3 of the construction. In the top of the construction was put three isosceles triangular patches as parasitic elements to enhance bandwidth and gain 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 [18], [19]. Due to the satellite problem, we developed and tested the antenna for reception only, however the antenna design is possible to arrange the transmission elements on the fed and the parasitic elements at the same layer by specified interval thus antenna compactness can be achieved.

In order to minimize a feeding loss in antenna design, 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 power divider and a Double Pole Triple Throw (DP3T) switching circuit. 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. The antenna performances were reported in [19].



(a) Antenna structure

(b) Fabricated antenna

Fig. 2 Developed antenna for realization of system.

3. Realization Antenna System in Field Experiment

3.1 Experimental Configuration

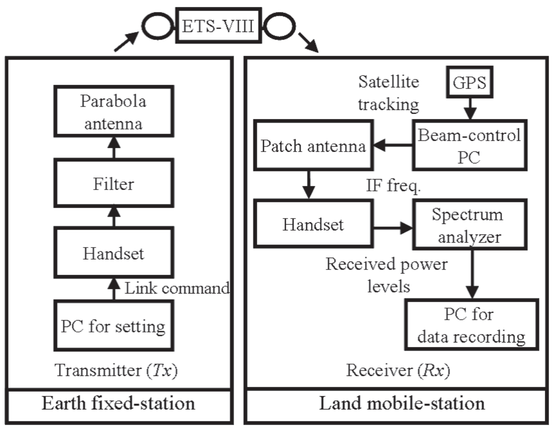
Table 2 shows the link budget for land vehicle aimed at ETS-VIII application. The link budget was made according to the report [20] that the Large Deployable Reflector (LDR) antenna of ETS-VIII satellite could not be used due to improper situation at Power Supply of Low Noise Amplifier (PS-LNA). For 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.

In this link budget, the system was built for forward link from the transmission (earth fixed-station) to the reception (land mobile-station) through the ETS-VIII satellite. In the same manner, the return link could be calculated in the same results. As a result of the link budget, the targeted antenna gain for 8 kbps of data transmission rate should be more than 5 dBic. Additionally, the link is 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 are attached on the antenna to control each feeding part of the antenna, thus the circuit loss is 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. This time, we performed the field experiment without correction-code transmission, thus the margin is decreased to be 0.30 dB. However, the quality of communication channel at the reception (land mobile-station) is sufficiently designed at 64.77 dBHz.

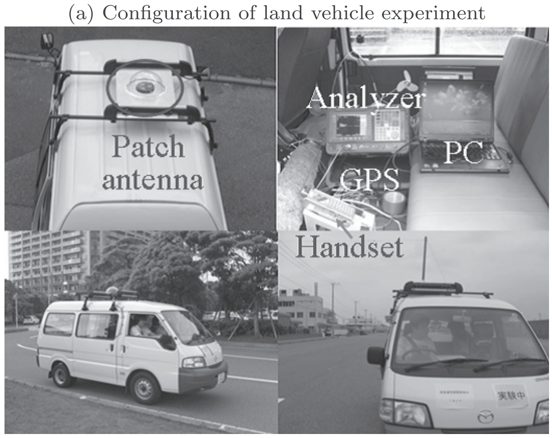
In this field experiment, we measured the received

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



(a) Configuration of land vehicle experiment



(b) Photograph of experiment (at receiver)

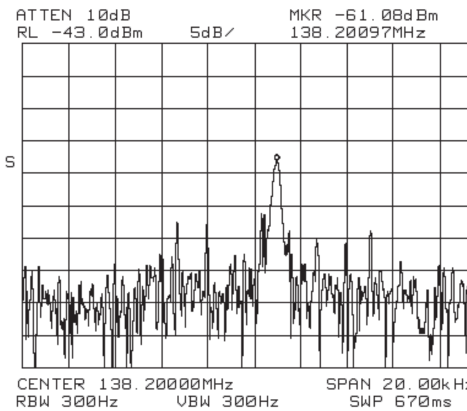
Fig. 3 Configuration of field experiment.

power level of the array antenna at some different areas for direct wave area and obstructed areas like buildings, foliages, utility poles and highway overpasses. The experiment configuration and circumstance are described in Figs. 3(a) and 3(b), respectively. An unmodulated continuous wave of LHCP at 2.65 GHz was transmitted from the earth fixed-station through the ETS-VIII satellite and received by a land mobile-station into which the developed antenna system was mounted. The received power level was measured from intermediate frequency (IF) output from handset terminal into which connected the patch array antenna. With the PC the received power level can be recorded.

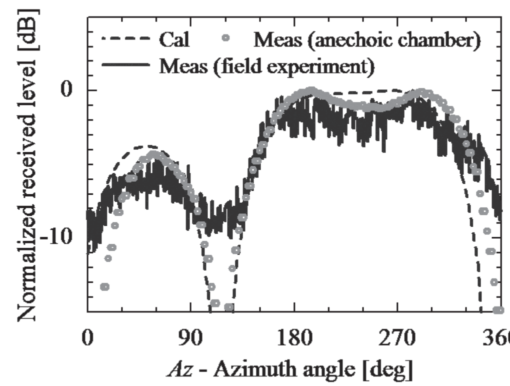
3.2 Experiment Results

3.2.1 Measurement for Satellite Tracking

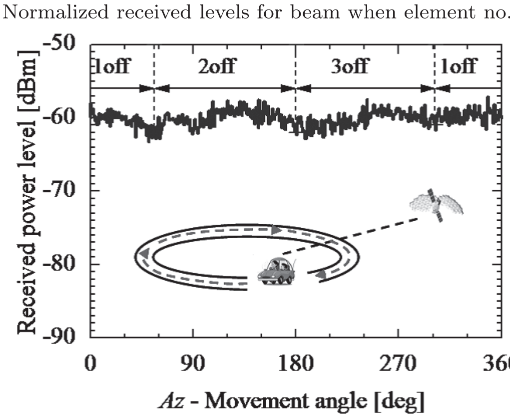
The measurement was performed in direct wave area by using a spectrum analyzer (Agilent E4403B) to retrieve the IF signal amplitude. The example of recorded spectrum of IF output is depicted in Fig. 4(a). Yet, by setting the spectrum analyzer in zero span at specified frequency, the received power level can be recorded. One of three beams of the patch array antenna is depicted in Fig. 4(b). The experiment result tends to agree with the calculation even though small differences are observed. We performed the antenna by using the aluminum ground plate which was installed under the antenna (Fig. 3(b)). Such plate affected the antenna performance especially the beam. Small difference existed, particularly the beam-shape and the beam-width. However, such differences did not significantly worsen the received signal of the antenna.



(a) Example of the IF signal spectrum



(b) Normalized received levels for beam when element no.#3 off

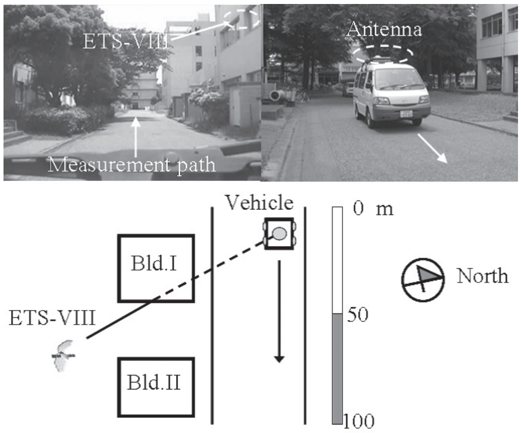


(c) Automatic satellite-tracking performance

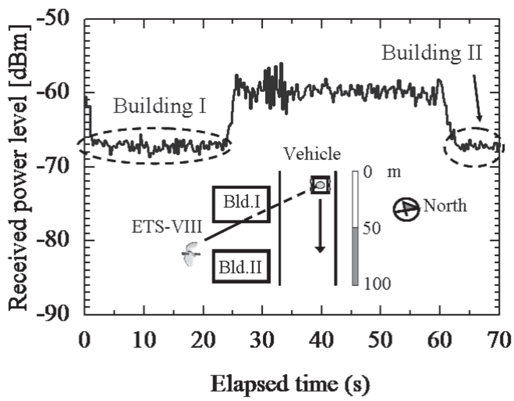
Fig. 4 Measured received power levels at line of sight (LOS) area.

As for the C/N_0, it can be calculated by the following formula [21], [22]:

$$C/N_0 = (\text{signalpower}) - (\text{noisefloor}) + (10\log\text{RBW}) \quad (1)$$

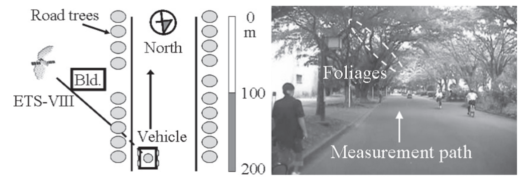


(a) Photograph of measurement at blocking area

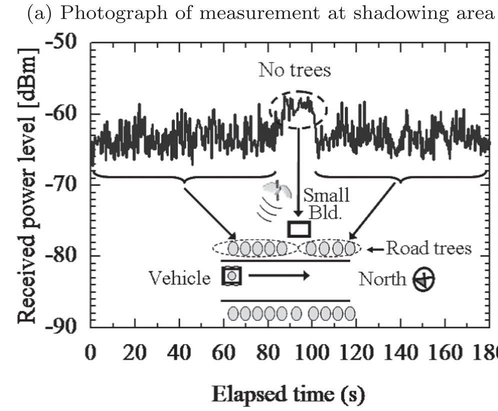


(b) Measurement result

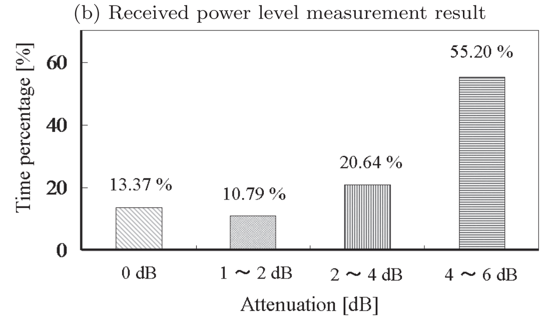
Fig. 5 Blockage signal measurement at buildings area.



(a) Photograph of measurement at shadowing area



(b) Received power level measurement result



(c) Time percentage of attenuated signal by roadside-trees

Fig. 6 Blockage signal measurement from roadside-trees.

By considering the received power level averaged by −60 dBm and noise floor −83 dBm as described in Fig. 4(a), the C/N_0 can be calculated as:

$$C/N_0 = (-60\,\text{dBm}) - (-83\,\text{dBm}) + (10\log(300\,\text{Hz})) \tag{2}$$

yields C/N_0 approximately 47.77 dBHz and thus the link margin achieved 1.94 dB can be obtained.

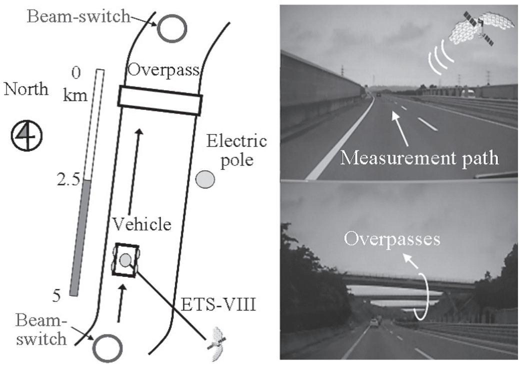
The land vehicle measurement was mainly tested to evaluate the satellite-tracking of antenna system. While the vehicle was travelling the beam of the antenna electronically steered pursuing the ETS-VIII satellite associated with vehicle's orientation. Three antenna beams are smoothly switched to the satellite for each beam-coverage in the azimuth direction.

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). Having known the coincide point of gain for each beam as well as the satellite position relative to the land mobile-station (in Chiba area, the satellite was at Az = 170° relative to North as 0° and El = 48.10°–48.20°), the rule of beam switching was decided. The beam can be switched automatically at the specified azimuth angles to cover 360° of conical-plane. This satellite-tracking performance is depicted in Fig. 4(c). The good received power levels was obtained to track the satellite during land-mobile travelling yet when the beam switching happened.

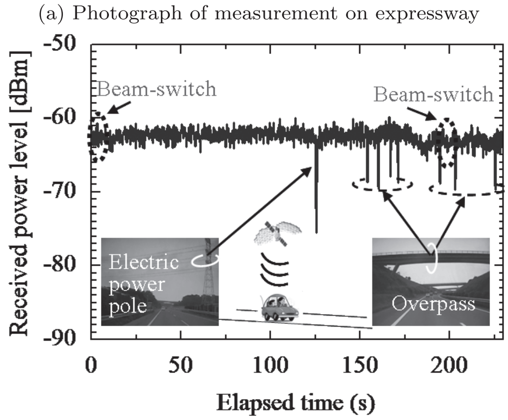
3.2.2 Measurements in Obstacles Areas

We thoroughly evaluated the effect of obstacle objects namely buildings, foliages of trees, utility poles such as electricity power poles, and highway overpasses or bridge roof, to the received level qualities of the antenna. Figure 5(a) shows the circumstance of the experiment at buildings area. There were two high buildings on the test field which expected to block the signal from the satellite. The vehicle travelled on straight path at bearing = 99.30° when element no.#2 was switched-off. From Fig. 5(b), it can be stated that high buildings decreased the signal from the satellite became same level with noise floor and thus it could not be detected well as a received signal. If it happens for too long period, the satellite communication link will be disconnected.

We also examined the blockage of roadside-trees to the antenna. The experiment was carried out in summer season since there were dense foliages which considered to affect the performance of the received power level. As shown in

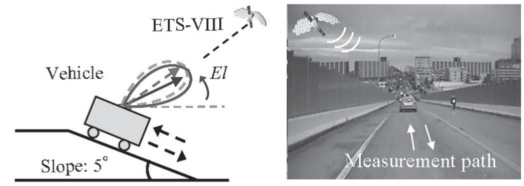


(a) Photograph of measurement on expressway

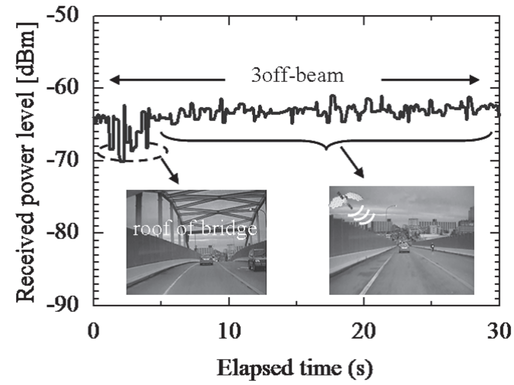


(b) Measurement result

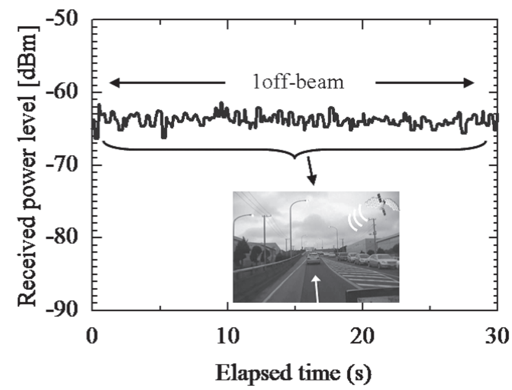
Fig. 7 Measurement on expressway.



(a) Photograph of measurement at inclined-road



(b) Measured result of downward-movement



(c) Measured result of upward-movement

Fig. 8 Measurement at inclined-road.

Fig. 6(a), the measurement was performed on straight path which the satellite at the left side of the figure. The vehicle travelled at bearing = 189.30° when element no.#3 was switched-off. Unlike the blockage of buildings, the foliages of roadside-trees were less effect to the received signal even though they barred by an average 3–5 dB, decreasing the well-received signal. It is obvious shown in Fig. 6(b) when we compare to the direct wave signal. Figure 6(c) shows the time percentage of attenuated signal due to the roadside-trees blockage. From this figure, it can be stated that almost 75% of the satellite signal was approximately attenuated by 2–6 dB at the dense foliages area.

In order to grasp the antenna system whether it can be used in normal land mobile applications, we thoroughly experimented the system on expressway and ordinary road. The field experiment of expressway was carried out in Chiba prefecture area (El = 48°) between Kisarazu-kita and Soga interchange by speed 70–80 km/h, as shown in Fig. 7(a). With almost no obstacles present, such as electric power poles and highway overpasses or bridges, the received signals gave well-received and yet the beam-switch happened at the beginning and the last measurement path. It was also been confirmed that the signal drastically dropped in very short time (0.2–0.4 s) when the vehicle passed the overpass or bridges as shown in Fig. 7(b).

The array antenna had radiation characteristics in the elevation direction [18], so thus it is required to confirm with the real environment for vehicle application. Therefore, we tested the antenna system at incline-road in Chiba prefecture shown in Fig. 8(a). The vehicle passed on the 5°-inclined road at bearing = 222° relative to the North. The speed of movement was constantly kept 40 km/h without any beam-switch happened during movement i.e. when element no.#1 was switched-off for upward-movement and element no.#3 was switched-off for downward-movement. Figure 8(b) shows an example of the received signal levels for downward-measurement. From the result, it can be stated that the received signal tended to increase by an average 0.5 dB. The reason is the antenna has a peak gain at El = 60° and it increases as the elevation-angle increases, while the measurement was held at El = 48°. Downward-movement means increasing the elevation thus increasing in received power level. On the other hand, as for the upward-measurement the received power level tended to decrease by an average 0.4 dB as confirmed from Fig. 8(c).

Table 3 Link setting for bit error rate (BER) measurement.

Link setting for BER measurement	
Link access technique	FDMA
Frequency (UL/DL)	2.65/2.50 GHz
Channel bandwidth	12.5 kHz
Bit rate	8 kbps
Target BER	10^{-4}
Modulation technique	BPSK
Transmitted data	PN-code

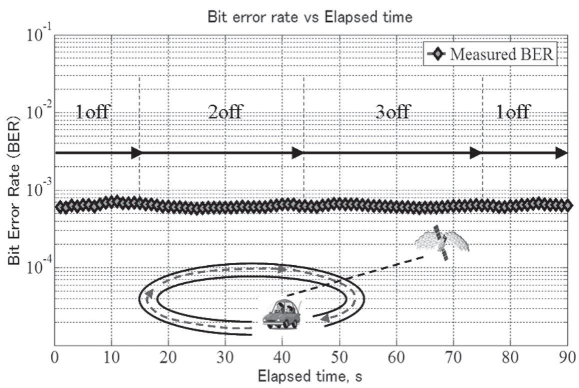


Fig. 9 Bit error ratio (BER) characteristics on satellite-tracking.

3.2.3 Measurement for Bit Error Rate (BER)

In the mobile satellite communications, bit error rate (BER) measurement was rarely reported. Therefore, we tested the BER characteristics besides the propagation measurements. In this paper, the measurement was carried out in line of sight (LOS) area to evaluate the performance of satellite-tracking. A binary-phase shift keying (BPSK)-modulated pseudo-noise sequences (PN-code) was transmitted from the earth fixed-station through the ETS-VIII satellite and received by a land mobile-station into which the antenna system present. The measurement used a BER analyzer (Anritsu MD6420A) to retrieve the BER value of the antenna system was measured from interface board which connected to the BER analyzer from the handset terminal. We set the communication link to be 8 kbps. The detail of data communication link setting is listed in Table 3. The satisfactory BER value in 10^{-4} as predicted in link calculation was confirmed.

The measurement path was performed in the same manner in Sect. 3.2.1 for satellite tracking, however we evaluated only for BER value. As shown in Fig. 9 the BER performance was kept stable in range 5 to 7×10^{-4} and yet the beam-switching happened. With such results, mobile satellite communications could be established between our antenna system and earth fixed-station through the ETS-VIII satellite.

4. Conclusions

Realization of simple antenna system for land mobile satellite applications has been experimentally tested, was presented. Antenna system components discussed include a patch array antenna integrated by a switching circuit and a satellite-tracking system, which mounted onto a vehicle roof. Following the satisfactory performances of anechoic chamber measurement, the antenna system was examined in field experiment using signal from the ETS-VIII satellite for land vehicle applications. We thoroughly evaluated the antenna system for satellite-tracking. Without any obstacles present, the system was able to correctly track the satellite by considering the orientation of vehicle which retrieved from GPS module.

From the experiment, we considered and tested the environment influences to the received signal, in particular when buildings, dense foliages of roadside-trees, utility poles and highway overpasses present. The results show the blockage and shadowing happened which attenuated the received signal. Furthermore, we tested the antenna system on the incline-road for elevation-characteristics test. Slight fluctuation tended in received power was confirmed. Finally, the BER performance has been carried out for satellite-tracking with satisfactory result in 10^{-4} was clarified.

Due to the overall design of our antenna system has been effectively small and possibility in low cost, the developed antenna system make it very promising for future mobile satellite communications.

Acknowledgements

The authors wish to express their gratitude to Mr. Shin-ichi Yamamoto from the National Institute of Information and Communications Technology (NICT) for his valuable helps. We also wish to thank to the NICT and the Japan Aerospace Exploration Agency (JAXA) for Research Collaboration.

This work was supported in part by the Strategic Information and Communications R&D Promotion Programme (SCOPE) for Grant-in-Aid for Scientific Research (Project no.061203004).

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