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Antenna System for Land Mobile Satellite Communications

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1. Introduction

Personal wireless communications is a true success story and has become part of people's everyday lives around the world. Whereas in the early days of mobile communications Quality of Service (QoS) was often poor, nowadays it is assumed the service will be ubiquitous, of high speech quality and the ability to watch and share streaming video or even broadcast television programs for example is driving operators to offer even higher uplink and downlink data-rates, while maintaining appropriate QoS.

Terrestrial mobile communications infrastructure has made deep inroads around the world. Even rural areas are obtaining good coverage in many countries. However, there are still geographically remote and isolated areas without good coverage, and several countries do not yet have coverage in towns and cities. On the other hand, satellite mobile communications offers the benefits of true global coverage, reaching into remote areas as well as populated areas. This has made them popular for niche markets like news reporting, marine, military and disaster relief services. However, until now there has been no wide-ranging adoption of mobile satellite communications to the mass market.

Current terrestrial mobile communication systems are inefficient in the delivery of multicast and broadcast traffic, due to network resource duplication (i.e. multiple base stations transmitting the same traffic). Satellite based mobile communications offers great advantages in delivering multicast and broadcast traffic because of their intrinsic broadcast nature. The utilization of satellites to complement terrestrial mobile communications for bringing this type of traffic to the mass market is gaining increasing support in the standards groups, as it may well be the cheapest and most efficient method of doing so.

In order to challenge the great advantages of mobile satellite communications, the Japan Aerospace Exploration Agency (JAXA) has developed and launched the largest geostationary S-band satellite called Engineering Test Satellite-VIII (ETS-VIII) to meet future requirements of mobile communications. The ETS-VIII conducted various orbital experiments in Japan and surrounding areas to verify mobile satellite communications functions, making use of a small satellite handset similar to a mobile phone. The mobile

communication technologies adopted by ETS-VIII are expected to benefit our daily life in the field of communications, broadcasting, and global positioning. Quick and accurate directions for example, can be given to emergency vehicles by means of traffic control information via satellite in the event of a disaster (JAXA, 2003).
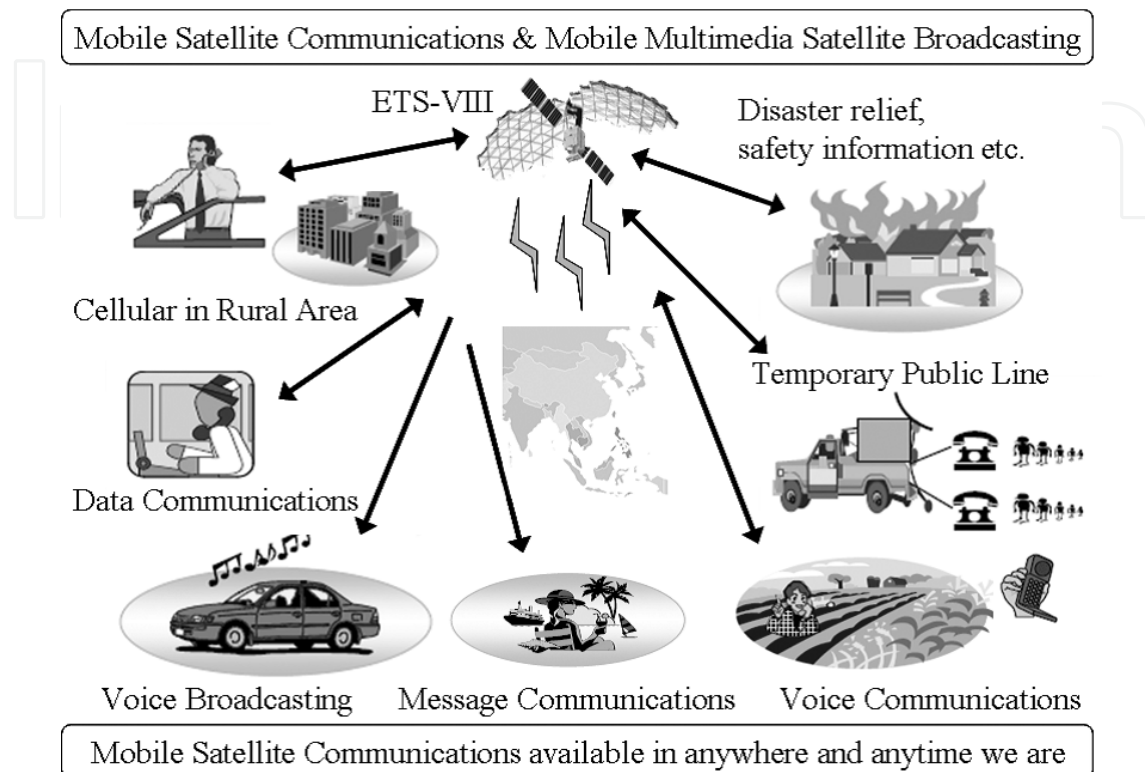

Fig. 1. Conceptual chart of mobile satellite communications and broadcasting system (JAXA & i-Space, 2003)

Figure 1 shows some of services made possible through the technological developments with the ETS-VIII. The mission of ETS-VIII is not only to improve the environment for mobile-phone based communications, but also to contribute to the development of technologies for a satellite-based multimedia broadcasting system for mobile devices. It will play as important role in the provision of services and information, such as the transmission of CD-quality audio and video; more reliable voice and data communications; global positioning of moving objects such as cars, broadcasting; faster disaster relief, etc (JAXA & i-Space, 2003).

In addition, nowadays as can be seen with the spreading of the GPS or the Electronic Toll Collection (ETC), the vehicular communications systematization is remarkable. From this phenomenon, in the near future, system for mobile satellite communications using the Internet environment will be generalized and the demand for on-board mobile satellite communications system as well as antenna is expected to increase. So far, we are enrolled in the experimental use of ETS-VIII and develop an onboard antenna system for mobile satellite communications, in particular for land vehicle applications.

In this chapter, we will figure out realization of an antenna system and establishing a mobile communication through a geostationary satellite by designing smaller and more compact antenna, developing a satellite-tracking program which utilizes Global Positioning System (GPS) receiver or gyroscope sensor, and data acquisition program which utilizes 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 is 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 is built by the proposed antenna which its beam-tracking characteristics is 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 travelling as a concept of the antenna system.

This chapter will be divided by several sections from the research background, antenna design, numerical results, chamber measurement verification, realization on overall antenna system design, and finally antenna system verification by conducting measurement campaign using the satellite.

This chapter is organized as follows. Section 2 will provide review of mobile satellite communications systems in particular its design parameters. An example of a link budget for a mobile satellite application is given. Section 3 describes designing issues on vehicle antennas for mobile satellite system from their mechanical and electrical requirements, and also their tracking functions. In this section, we also describe our proposed antenna system, especially aimed at ETS-VIII applications. Section 4 will focus on the planar antenna design for compactness and integrated construction. It provides details about the measurement results of some basic antenna performances, such as S_{11}, axial ratio and radiation pattern characteristics that compared with the numerical results which are calculated by use of moment method. Section 5 will describe about verification of all antenna system in laboratory test and experimentally confirm in outdoor immobile-state measurement to verify the satellite-tracking performances using gyro sensor system under pre-test for field measurement campaign. The effect of radome and ground plate also will be discussed. Section 6 will show various field experiments results by utilizing the satellite to verify the validity of our developed antenna system. Overall system is tested for its performance validity not only propagation characteristics but also bit error rate performance. Finally, the last section draws conclusions on the work, and provides scope and direction for promotion in the future applications.

2. Mobile Satellite System Communication

2.1 Mobile Satellite System Architecture

Figure 2 describes a typical design for mobile satellite communication system. Three basic segments: satellite, fixed and mobile earth station are included. A propagation path is added as another fourth segment owing to its importance factor that mainly affects the channel quality of the communication system. In land mobile satellite system, the most serious propagation problem is the effect of blocking caused by buildings and surroundings objects,

which cause losing the satellite signal completely. The second problem is shadowing caused by tree and foliage, resulting the signal attenuation. The other is multipath fading, which is mainly caused by surrounding buildings, poles and trees. However, such an effect can usually be ignored when the directional antenna is used since less reflected signals approach the receiver.
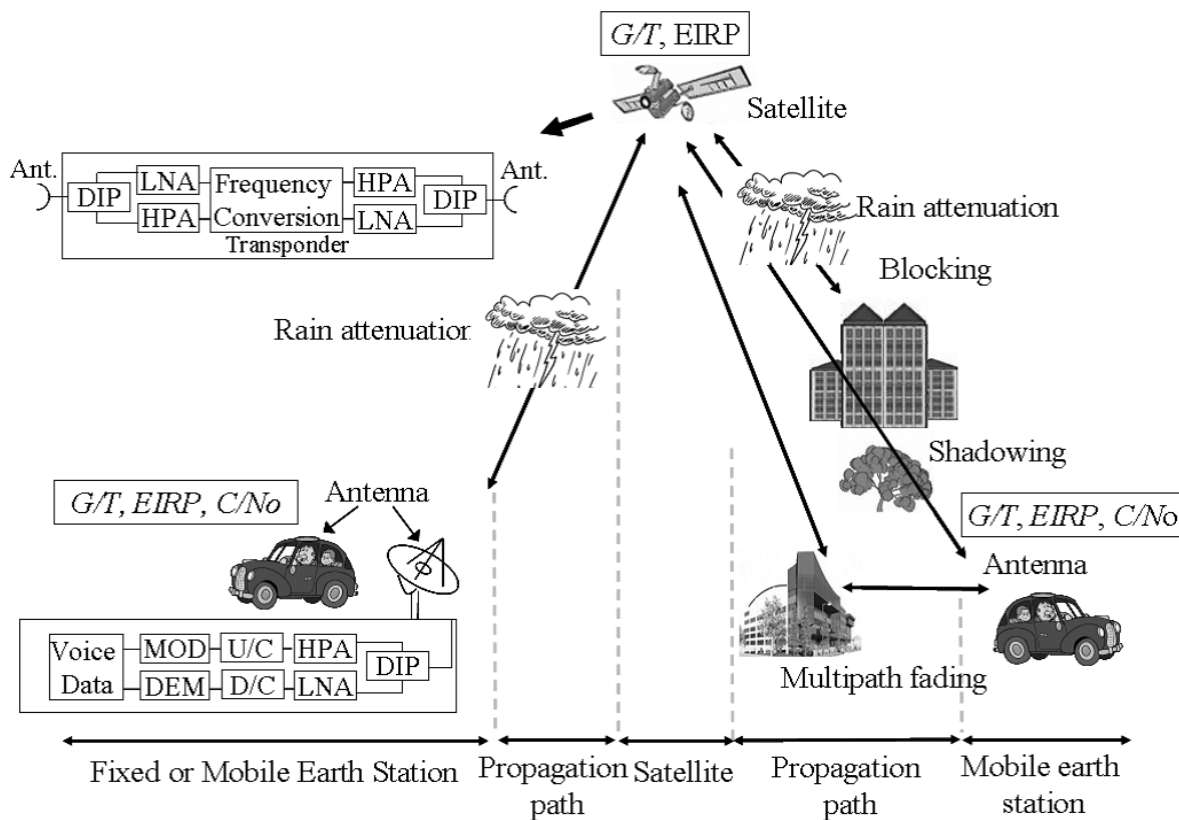

Fig. 2. Typical configuration of mobile satellite communications

Fixed or mobile earth station system consists of antenna, diplexer (DIP), up-converter and down-converter (U/C and D/C), high power amplifier (HPA) and low noise amplifier (LNA), as well as modulator (MOD) and demodulator (DEM). The satellite system is almost similar either for fixed or mobile earth station which can be constructed by antenna and up-converter and down-converter, called a transponder. Most of commercial satellites do not have modulator and demodulator. They only transmit a signal after converting its frequency and amplify the received weak signals, or usually called a bent pipe transponder or a transparent transponder.

2.2 Mobile Satellite System Link Parameters

Performance of mobile satellite system is characterized by three main parameters for link budget. Those parameters indicate the performance of three segments –namely satellite, fixed and mobile earth station– are G/T (ratio of antenna gain to system noise temperature or usually called figure of merit), effective isotropically radiated power ($EIRP$) and C/N_0 (ratio of carrier power to noise power density). The G/T and $EIRP$ denote the receiving and transmitting capabilities, respectively, of satellite, fixed earth station and mobile terminal. The C/N_0 indicates the quality of the communication channel.

The *G/T* is calculated from a value of *G* which means system gain at the input port to the Low Noise Amplifier (LNA). Consequently, the ratio of antenna gain to noise temperature at the input port to the LNA can be written as:

$$\frac{G}{T} = \frac{G_R}{T_a + T_0(L_f - 1) + T_R L_f} \quad \text{(dBK)} \tag{1}$$

where *G/T*: figure of merit, G_R: gain of receiving antenna, T_a: antenna noise temperature, T_0: physical temperature when the circuit immersed, T_R: receiver noise temperature, L_f: total loss of feed lines and components such as diplexers, cables, and phase shifters (if used). As for the transmitter, the *EIRP* is one of the important parameters to describe the capabilities of transmission. The *EIRP* can be expressed as:

$$EIRP = G_T \cdot P_T \quad \text{(watts)}$$
$$\text{or} \quad [EIRP] = [G_T] + [P_T] \quad \text{(dBW)} \tag{2}$$

where G_T: gain of transmitting antenna and P_T: transmitted power.
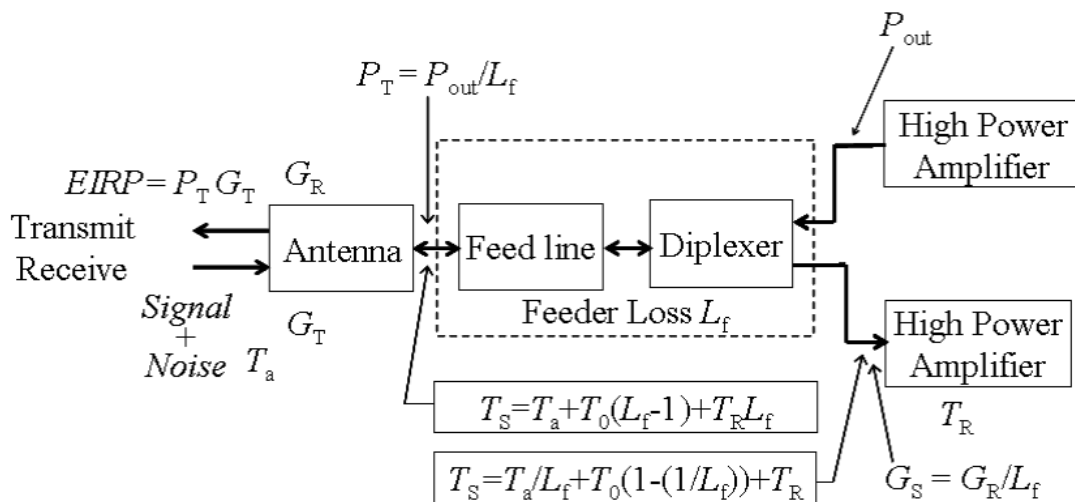

Fig. 3. Typical RF stage at earth station and satellite

In general, the radio frequency stages of earth station and satellite consist of antenna, feed line, diplexer, high power amplifier (HPA), and low noise amplifier (LNA), as shown in Fig. 3. From the figure, the ratio of input signal power (*C*) to noise power density (N_0) or simply called carrier to noise density ratio (C/N_0) at the input point to the antenna can be written as follows:

$$\frac{C}{N_0} = \frac{EIRP}{L_P}\left(\frac{G_R}{T_S}\right)\frac{1}{\kappa}$$
$$\left[\frac{C}{N_0}\right] = [EIRP] - [L_P] + \left[\frac{G_R}{T_S}\right] + 228.6 \tag{3}$$

where L_P: free space propagation, G_R/T_S: figure of merit, and κ : Boltzman's constant $(1.38 \times 10^{-23}$ watt/sec/K).

The total channel quality in the system is calculated by including the uplink and downlink channels, given by:

$$\left(\frac{C}{N_0}\right)_{Total} = \left(\frac{1}{\left(\dfrac{C}{N_0}\right)_{Uplink}} + \frac{1}{\left(\dfrac{C}{N_0}\right)_{Downlink}}\right)^{-1} \text{(dBHz)} \qquad (4)$$

In land mobile satellite communications, the gain of mobile station is quite smaller than the satellite has, allowing the total quality is dominated by the poor uplink and the total channel quality will never exceed the uplink quality no matter how much downlink quality is increased.

Once the system channel quality is calculated, the next is what kind of modulation scheme is suitable for communication. Mobile satellite communication system currently uses digital modulation schemes, such as π/4-QPSK, OQPSK, or MSK (Lodge, 1991); low-bit rate digital voice encoder-decoder of about 4.8 to 6.7 kbps, such as vector sum excited linear prediction (VSELP), low-delay code excited linear prediction (LD-CELP), adaptive differential pulse code modulation (ADPCM), regular pulse excited linear prediction code with long-term prediction (RPE-LTP); and powerful forward error correction (FEC) technologies.

Next, another most important performance parameter for mobile satellite modulation schemes is efficiency, which includes both power and bandwidth efficiency, since mobile satellite communication systems usually have limited availability of both power and bandwidth. The power efficiency is defined as the ratio of required signal energy per bit to noise density (E_b/N_0) required to achieve a given bit error rate (BER) over an additive white Gaussian noise (AWGN) channel, although in fact, mobile satellite communication channel is Ricean fading channel. However, let we deal with performance over AWGN for simplicity in design. The bandwidth efficiency is defined as ratio of information rate R [bit/s] and the required channel bandwidth B.

For analog signals (passband signals) C/N_0 is used in the same way as E_b/N_0 for digital (baseband signals). C and E_b are related by the bit rate by:

$$C = E_b \cdot R_b \qquad (5)$$

So, C/N_0 is:

$$C/N_0 = (E_b/N_0) \cdot R_b \qquad (6)$$

Due C/N_0 does not relate with bit rate, as increasing bit rate does not affect C/N_0 value, but E_b/N_0 get decreasing.

Some parameters besides efficiency as described earlier, such as immunity to nonlinearity, simplicity for implementation are also be considered for designing a simple and small mobile satellite modem. Table 1 shows comparison of several modulation schemes in terms of bandwidth, E_b/N_0 for *BER* 10^{-5}, non linearity immunity, and implementation simplicity for BPSK, QPSK, OQPSK, π/4-PSK, and MSK.

*   in normalized frequency offset from the center frequency
** A is highest value

Modulation scheme	Half-power Bandwidth*	Noise Bandwidth*	E_b/N_0 for *BER* = 10^{-5}	Nonlinearity Immunity**	Implementation Simplicity**
BPSK	0.88	1.00	9.6 dB	D	A
QPSK	0.44	0.50	9.6 dB	C	B
OQPSK and π/4-PSK	0.44	0.50	9.6 dB	B	C
MSK	0.59	0.62	9.6 dB	A	D

Table 1. Several digital modulation schemes for mobile satellite communications (Xiong, 1994)

Finally, we calculate the above mentioned parameters for link budget. Here, we design vehicle to vehicle communication via satellite for low rate data and voice communications. We assume that the data rate is 8 kbps by using a convolutional code with viterbi decoder, and 5.6 kbps PSI-CELP voice codec are suitable for conveying low data rate and voice signal from ground vehicle to another vehicle through the geostationary satellite. An example of link budget calculation is depicted in Table 2 below. From this example, by use of a large satellite antenna (i.e. very high gain antenna), we can design a small mobile earth station to enable development of a compact land vehicle communication.

Link parameter	Forward link	
Uplink		
Uplink frequency (GHz)		2.6575
T_x power (Watt)		1.00
Feed loss (dB)		1.70
Antenna gain (dBi)		5.00
T_x EIRP (dBW)	Vehicle	3.20
Tracking loss (dB)		3.00
Propagation loss (dB)		192.35
Received level (dBW)		- 190.25

Satellite antenna gain (dBi)	Satellite	43.80
Feed loss (dB)		2.60
Satellite G/T (dB/K)		14.04
System noise temperature (K)		520.00
Uplink C (dBW)		- 151.95
N_0 (dB/Hz)		- 201.44
Uplink C/N_0 (dBHz)		49.49
Downlink		
Downlink frequency (GHz)	Satellite	2.5025
T_x power (Watt)		40.00
Feed loss (dB)		2.60
Satellite gain (dBi)		43.80
Pointing loss (dB)		3.00
T_x EIRP (dBW)		54.22
Propagation loss (dB)		191.83
Received level (dBW)		- 138.71
Antenna gain (dBi)	Vehicle	5.00
Feed loss (dB)		1.70
Tracking loss (dB)		3.00
Satellite G/T (dB/K)		- 22.92
System noise temperature (K)		418.60
Downlink C (dBW)		- 138.41
N_0 (dB/Hz)		- 202.38
Downlink C/N_0 (dBHz)		63.97
Calculation Results		
Total C/N_0 (dBHz)		49.34
Bit rate (kbps)		8.00
E_b/N_0 (dB)		10.31
Coding gain (Convolutional code R=1/2, K=5, with Viterbi decoder and without interleaver) for BER=10^{-5}		5.00
Required C/N_0 (dBHz)		43.63
Margin (dB)		5.71

Table 2. Link budget calculation for land mobile satellite communication

3. Antenna System Design for Vehicle Application

3.1 Vehicle Antennas

In order to develop an antenna system for land vehicle application in mobile satellite communication system, considering the requirements of antenna properties both in mechanical and electrical characteristics is required. Thus, their characteristics are briefly explained in the following subsection.

3.1.1 Mechanical Characteristics

3.1.1.1 Compactness and Lightweight

Design of mobile antennas is required as compact and lightweight as possible to minimize the space and easy installation (Ohmori et al., 1998 & Rabinovich et al., 2010). However, a compact antenna has two major disadvantages in electrical characteristics such as low gain and wide beamwidth. Due to its low gain and limited electric power supply, it is quite difficult for mobile antennas to have enough receiving capability (i.e. *G/T*) and transmission power (i.e. *EIRP*). Nonetheless, such disadvantages of mobile terminals can be compensated by providing a satellite has a large antenna and huge power amplifier with enough electric power.

The second demerit is that a wide beam antenna is likely to transmit undesired signals to, and receive them from, undesired directions, which will cause interference in and from other systems. The wide beam is also suffered from multipath fading in land mobile satellite communication. Therefore, a directive sufficient-gain antenna is expected to prevent fading and interference.

3.1.1.2 Installation

Easy installation and appropriate physical shape are worthwhile requirements besides compactness and lightweight (Ohmori et al., 1998 & Rabinovich et al., 2010). The requirements antennas for cars or aircraft are different from shipborne which has enough space for antenna system installation. In case of cars, low profile and lightweight equipment is required. Aircraft antenna is required more stringent to satisfy aerodynamics standard such as low air drag (Ohmori et al., 1998). Our research concern on designing and developing a compact, lightweight and easy installation.

3.1.2 Electrical Characteristics

3.1.2.1 Frequency and Bandwidth

The Radio Regulations of International Telecommunication Union (ITU) regulates the satellite services including allocated frequency according to each region (three regions, i.e. Region 1: Europe, Russia, & Africa; Region 2: North & South America and Region 3: Asia). The typical frequencies allocated to mobile satellite communications are the L (1.6/1.5 GHz) and S (2.6/2.4) bands which being operated in the present, Ka (30/20 GHz) band and millimeter wave for future systems (ITU-R Radio Regulation, 2004).

The required frequency bandwidth is about 7% for L band, 10% for S band, and 40% for Ka band. This chapter provides an antenna for S band application with wide frequency bandwidth and will be discussed in the next subsection.

3.1.2.2 Polarization and Axial Ratio

In mobile satellite communications, circular polarized waves are used to avoid polarization tracking and Faraday rotation. When both satellite and mobile earth stations use linearly (vertical or horizontal) polarized waves, the mobile earth stations have to keep the antenna coinciding with the polarization. If the direction of the mobile antenna rotates 90º, the antenna cannot receive signals from the satellite. Even if circular polarization waves are

used, the polarization mismatch loss caused by the axial ratio has to be taken into account to link budget. Generally, we design a circular polarized antenna below 3 dB axial ratio (Sri Sumantyo et al., 2005).

3.1.2.3 Gain and Beam Coverage

Required antenna gain is determined by a link budget, which is calculated by taking into account the satellite capability and the required channel quality. The channel quality (C/N_0) depends on the G/T and the EIRP values of the satellite and mobile earth stations. Typical gains are shown in Table 3 according to their application at L band satellite communications.

Antenna	Typical Gain (dBi)	Typical G/T (dBK)	Typical antenna (dimension)	Typical service
Directional	20–24	-4	Dish (1mφ)	Voice, high speed data
	17–20	-8 to -6	Dish (0.8mφ)	Ship (Inmarsat-A,B)
Semi directional	8–16	-18 to -10	SBF (0.4mφ)	Voice/high speed data
			Phased array	Aircraft (Inmarsat-Aero)
	4–8	-23 to -18	Array (2-4 elements)	Ship (Inmarsat-M)
			Helical, patch	Land mobile
Omni directional	0–4	-27 to -23	Quadrifilar,	Low speed data (message)
			Drooping-	Ship (Inmarsat-C)
			dipole	Aircraft
			Patch	Land mobile

Table 3. Typical gain for L band satellite communications (Ohmori et al., 1998 & Ilcev, 2005)

The beams of mobile antennas are required to cover the upper hemisphere independent of mobile motions. Low gain antennas have advantages in terms of establishing communication channel without tracking the satellite because of their omnidirectional beam patterns. In contrary, high gain antennas have to track satellites owing to their narrow directional beam patterns. We design a medium gain antenna owing to the use of large dimension and high gain satellite antenna in this application.

3.1.2.4 Satellite Tracking

Unlike omnidirectional antennas, medium and high gain antennas need a tracking function. Tracking capabilities depend on the beamwidth of the antennas and the speed of mobile motions, where the directional antennas with narrow beams have to track the satellite both in elevation and azimuth directions. In general, the required accuracy of tracking is considered to be within 1 dB (Ohmori et al., 1998), which is an angular accuracy within about a half of half power beam width (HPBW). However, directional antennas with relatively narrow beams

should track the satellite only in the azimuth directions because the elevation angles to the satellite are almost constant, especially in land mobile satellite communications.

Figure 4 classifies satellite-tracking functions. Tracking function divide into two function groups, namely beam steering and tracking control method. There are two types of satellite tracking systems: mechanical and electrical. A mechanical tracking system uses mechanical structures to keep the antenna in the satellite direction by utilizing a motor or mechanical drive system. An electrical tracking system tracks the satellite by electrical beam scanning.

There are two tracking algorithm, namely an opened-loop method and closed-loop method. The difference between them is whether the satellite signal is considered or not. The opened-loop uses information of mobile position and its bearing from one or several sensors regardless the satellite signal. In contrary, the closed-loop method utilizes the satellite signal to track it. To use this method, received signals from the satellite must be stable without severe fading. It is adopted in aeronautical and maritime mobile communications but quite difficult to apply in land mobile satellite communication due to its stability is predominantly affected by shadowing and fading.
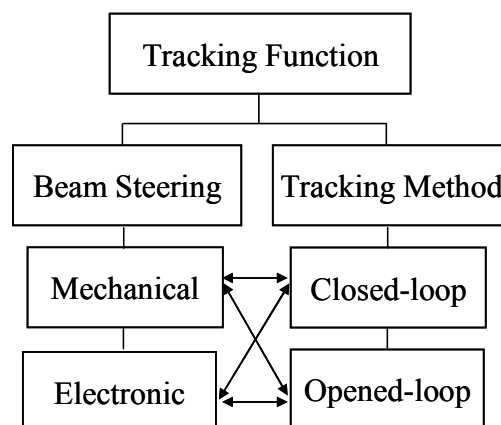
Fig. 4. Classification of satellite tracking function

3.2 Design of Vehicle-Mounted Antenna System

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 (Kilgus, 1975, Terada & Kagoshima, 1991, Nakano et al., 1991, Yamaguchi & Ebine, 1997), drooping dipole (Gatti & Nybakken, 1990) or even patch antenna in higher mode operation (Nakano et al., 1990, & Ohmine et al., 1996) and the satellite-tracking antennas (Ito et al., 1988). As described in the previous subsections, an attractive feature of the former antenna design is that, as the radiation is omnidirectional in the conical-cut direction and also their beam is broad in the elevation plane, satellite-tracking is not necessary. However, such antennas offer typical gain about 0 - 4 dBi (Ohmori et al., 1998, Ilcev, 2005, Fujimoto & James, 2008) because of their isotropic energy in the conical-cut direction. Further, owing to our application target for ETS-VIII, which is described by a link budget calculation in Table 2, the gain is designed by more than 5 dBi in the overall azimuth

coverage area at specified elevation angles (Table 4). Therefore, in case of omnidirectional antenna, their typical gain will not satisfy the specification. Therefore, a beam-tracking antenna is selected to suit the target. By utilizing a beam-tracking antenna, owing to its directional beam property, the beam can be deflected towards the satellite direction when the vehicle moves. Although such antenna type needs a tracking function, owing to the generation of directional beam and smaller fading effects from surrounding terrain, higher transmission rate are possible.

Most recent decades of the developed antenna system for vehicle-based applications are impractical since their design, based on mechanical steering that makes them extremely bulky. This type of antenna system is heavyweight and high power consumption as well as low tracking-speed owing to the use of electric motors responsible for mechanical steering (Kuramoto et al., 1988, Huang & Densmore, 1991, Jongejans et al., 1993, Strickland, 1995). An alternative solution is a planar phased array antenna which performs beam steering by electronic means (Nishikawa et al., 1989, Ohmori et al., 1990, Alonso et al., 1996, Konishi, 2003). However, the use of phase shifters for beam forming is quite expensive owing to their large quantities requirement. Such phase shifters, need to be properly designed in order to avoid the beam squinting in which the beam direction may considerably differ at receive and transmit frequencies. Moreover, nonlinear effects from electronic phase shifter and switches generate the noise problem in phased array antenna (Ohmori, 1999). Design of antenna system requires as compact and lightweight as possible to minimize the space and easy installation. In the following subsection, we describe specifications, targets and structure of our vehicle antenna system.

3.2.1 Specifications and Targets

The specifications and targets of the antenna are shown in Table 4. The ETS-VIII is 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 is left-handed circular (LHCP) for both transmission and reception units. As this antenna is assumed to be used in Tokyo and its vicinity, the targeted elevation angle is set to 48°. In the system, the antenna beam is 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.

Specifications		
Frequency bands	Transmission (T_x)	2655.5–2658.0 MHz
	Reception (R_x)	2500.5–2503.0 MHz
Polarization	Left-handed circular polarization for both T_x and R_x	
Targets		
Angular ranges	Elevation angle *(El)*	48° (Tokyo) ±10°
	Azimuth angle *(Az)*	0° to 360°
Minimum gain	5 dBic	
Maximum axial ratio	3 dB	

Table 4. Specifications and targets for ETS-VIII applications

3.2.2 Antenna System Architecture

Figure 5 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.
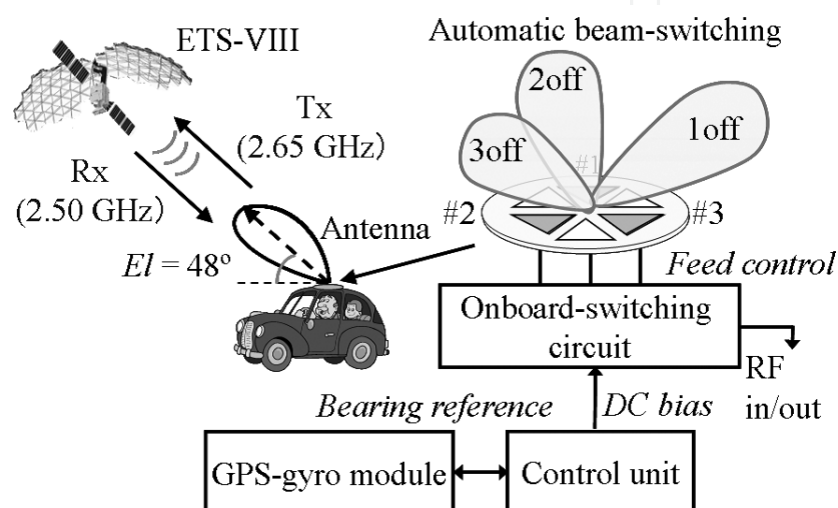
Fig. 5. Antenna system architecture

The array antenna configuration has a beam switching capability, where in principle, *n* circularly polarized elements are (360°/*n*) sequentially rotated (Teshirogi et al., 1983 & Hall et al., 1989) and set with an equal distance between each elements following a circular path. Our antenna is a 120º sequentially physical rotated and set with an equal distance between each element following a circular path. With such alignment, each element is fed in-phase allowing their relative phase is physically shifted. The feeding of each antenna element is successively turned off by controlling the onboard-switching circuit and thus the whole azimuth range can be scanned by step of 120º. Three beams can be generated to cover all of the azimuth angles. The beam is generated in the azimuth plane at -90º from the element that is turned off. As a result, if each element i.e. element no. 1, 2 and 3 is turned off, the beam is generated in the direction Az = 0, 120º and 240º (Sri Sumantyo et al., 2005), respectively as shown in Fig. 1. In addition, the satellite-tracking is conducted in the azimuth plane regardless considering the elevation direction owing to the antenna gain is predicted quite enough to communicate with the geostationary satellite as earlier listed in Table 2, Section 2.2.

The antenna system is operated by a control unit allowing the antenna beam is automatically steered. The beam-forming of array antenna is generated by providing bias voltages to switch on and off the P-I-N diodes on the onboard-switching circuit and thus two elements of the array can be correctly fed and afterwards a desired beam is created

among three selectable-beams. As the ETS VIII satellite lies at southern from the Japanese archipelago, by considering position of array antenna installation on car's roof, the antenna beam can be invariably controlled in south direction. By such a way, antenna tracks the satellite in good reliability and high-speed beam scanning.
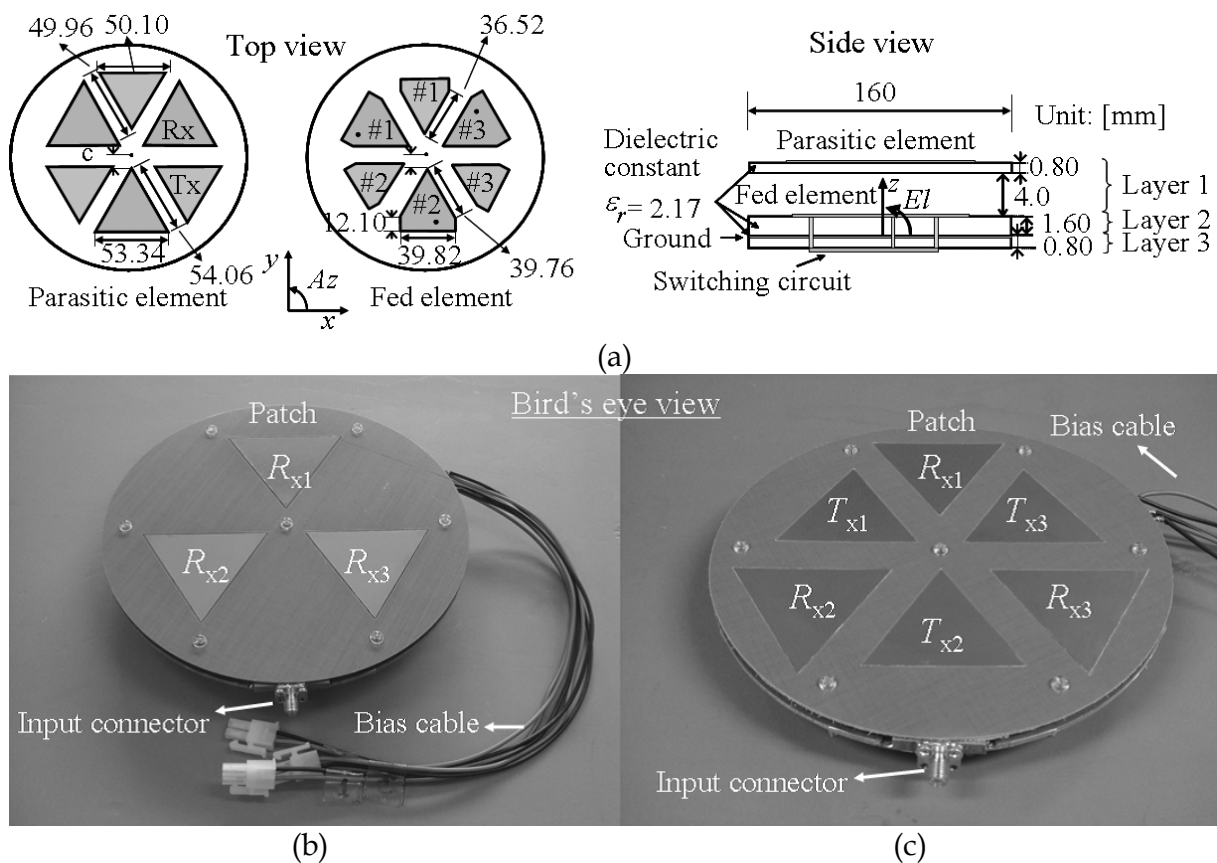

(a)

(b)   (c)

Fig. 6. Structure and fabricated antenna: (a) proposed construction, (b) receive-use antenna, (c) receive and transmit-use antenna

3.2.3 Array Antenna Structure

We basically design an antenna for both of transmit and receive use by arranging them on the same layer for achieving a compactness. We develop the antenna started from a single element, a receive-use antenna up to a final structure namely a receive–transmit-use antenna. Examples of antenna structures and their developed antenna are depicted in Fig. 6. The antenna is composed of three layers, i.e. parasitic elements with air gap (layer 1), fed elements (layer 2) and switching circuit (layer 3). The fed elements are three pentagonal patch antennas that directly excited from the feeding line on layer 3. In the top of the construction is put three isosceles triangular patches as parasitic elements to enhance bandwidth and gain of the antenna. In order to match on 50-ohm feeding, air gap is inserted in the layer between fed and parasitic elements. This design excites 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 feeding point, air gap height, and parasitic patch size.

The antenna structure is integrated with a power divider and a switching circuit, which mounted on the backside of the structure. The circuit is functioned as a feeding control of the antenna. The mounted circuit composed of a simple power divider and a Double Pole Triple Throw (DP3T) switching circuit developed by (Kaneko et al., 2006). This integrated antenna allows its compactness and low loss because no additional cable required.

4. Laboratory Test Performance

In earlier section, configuration of array antenna structure is proposed for receive-use and receive–transmit-use as well. Nevertheless, due to satellite problem (NICT, 2007), we utilize the antenna for receive-use only in our measurements. Basically, the transmit-use antenna performance and its characteristics are similar to the receive-use one. Once we fabricate the antenna, we test in laboratory for some basic antenna measurements. Following is the measurement results such as S_{11}, axial ratio, and radiation pattern characteristics.

4.1 Input Characteristics
Owing to the stacked-parasitic patch structure, two generated-resonant modes enhance impedance bandwidth as described in Fig. 7(a). Impedance bandwidth of the antenna i.e. ($|S_{11}|$ < -10 dB) is about 8.50%, quite enough for ETS-VIII applications. Moreover, the measured antenna gives a good input matching at the target frequency 2.5025 GHz by (50.28 – j24.86) ohm.

4.2 Axial Ratio Characteristics
The array antenna gives good performance at El = 48° in the target frequency. Good axial ratio is required to eliminate polarization tracking because of circular polarization. The measured result shows the axial ratio is 1.0 dB at center frequency 2.5025 GHz for each of three generated-beams. In addition, the 3 dB axial ratio bandwidth gives about 1.8% as shown in Fig. 7(b).

4.3 Radiation Characteristics

4.3.1 Radiation Pattern in Elevation-Cut Plane
Figure 7(c) shows the radiation characteristics of the array antenna in the elevation-cut plane when element no. 1 is switched off. The antenna main beam is generated at Az = 0 which is shown at the right side of the figure. Same manner is obtained in case of no. 2 is off and no.3 is off where each beam occurs at Az = 120° and Az = 240°, respectively. Noted that the gain more than 5.2 dBic and the axial ratio less than 1.7 dB meets the requirements for elevation angle El = 38°–58° where this is an approximation of elevation range of the satellite by considering the Japanese archipelago from northern to southern. We confirmed that the gain is 6.6 dBic and the axial ratio 1.2 dB at El = 48°. The measurement is taken at center frequency 2.5025 GHz. These results surely allow us to track the satellite regardless its elevation with regard to vehicle.
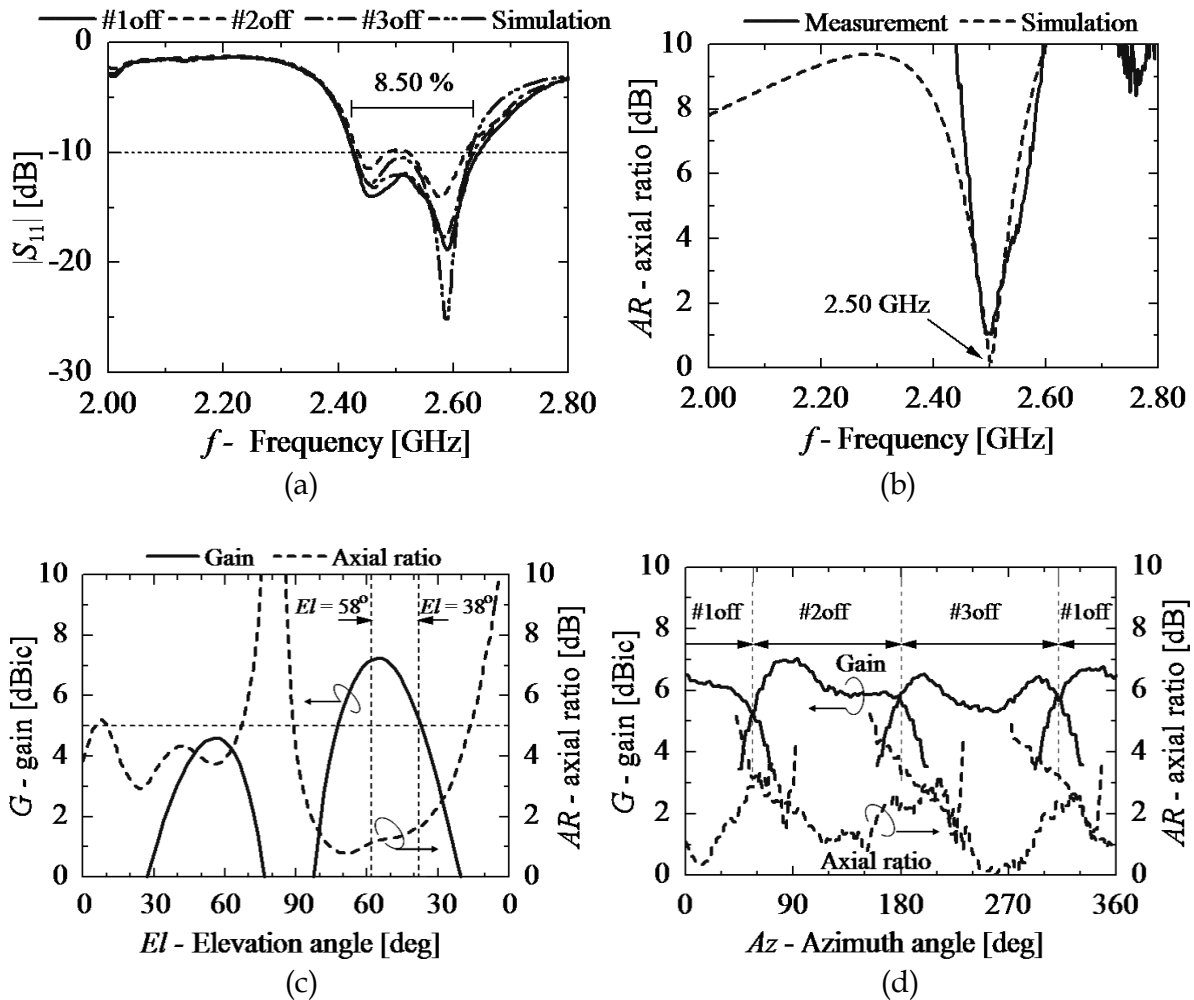
Fig. 7. Antenna performance in laboratory test measurement: (a) S_{11} (b) axial ratio characteristics, (c) radiation pattern in *El*-plane and (d) radiation pattern in *Az*-plane

4.3.2 Radiation Pattern for Beam-Switching

Figure 7(d) 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 is satisfied enough. In addition, 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 satellite-tracking.

5. Verification of Antenna System

Following all the required components of the system are developed and individually examined, testing of the completed array antenna is performed in anechoic chamber. Here, we test the tracking system performance of the antenna with regard to the conical-cut radiation pattern at specified elevation angle. Figure 8(a) illustrates an antenna system measurement set up where a transmitting (*Tx*) antenna is employed as though a satellite and

the array antenna as a receiving antenna. The antenna is covered by a radome and put on a ground plane because in mobile measurement campaign the antenna will be located on car roof as well as to avoid mechanical restriction or weather hindrance like snow, wind, and rainfall. The antenna is put 8 mm upper from the ground plate to avoid the switching circuit of the antenna on the rear-side touches the ground plane which may cause a shorted-circuit due to the bias cables connections. This measurement evaluates capability of the array antenna allowing the beam automatically switched pursuing the transmitting antenna.

In order to realize such a measurement we developed a simple control program on PC to control the antenna beam by use of a gyro sensor inside of GPS module. The measurement is performed without and with ground plane–radome. Such measurement is carried out to grasp the influence of ground plane and radome on the antenna performance specifically the gain and the axial ratio in azimuth scanning. In fact, we confirmed that a hemisphere radome is less effect on gain and axial ratio performance as well.

The beam of the antenna is generated by a mechanism that consists of switching off one of the radiating elements as earlier mentioned in Section 3.2.2 where the tested results is depicted in Fig. 7(d). Fig. 7(d) represents the beam-switching characteristics in manual operation that each beam is separately measured. Having performed a manual beam measurement in Fig. 7(d), we decide at which point we should to switch the beam automatically with regard to the gain value at the coincide point of each beam. Since the beam is possibly to be switched at minimum gain more than 5 dBic, then the antenna beam is switched at specific azimuth angle (this measurement is at $Az = 56^{\circ}$, 180° and 312°). With such decision, we confirmed that the gain can be switched automatically at the given azimuth angles and the axial ratio for each beam satisfies below 3 dB to cover 360° conical-plane. This tracking result is shown in Fig. 8(b). In this case, the beam is switched by itself as the azimuth angle changes to track the transmitting antenna.

In order to figure out the differences of the antenna characteristics caused by ground plane and radome installed, Fig. 8(c) depicts the automatic tracking when ground plane and radome installed. It is shown that the characteristics of each beam does not change drastically when the radome and ground plate are employed (Fig. 8(c)) compared with the only antenna structure (Fig. 8(b)), except the axial ratio owing to the scattering from the ground plane affects the incident phase onto the antenna. The effect of radome is considerably neglected since its hemisphere shape gives minimum scattering and its thin material provided less loss. In general, our antenna system is able to automatically control and correctly select the beam in the azimuth direction whose gain more than 5 dBic and axial ratio less than 3 dB, although when the ground plane is mounted, its axial ratio rises by 0.5 dB at the coincide point.
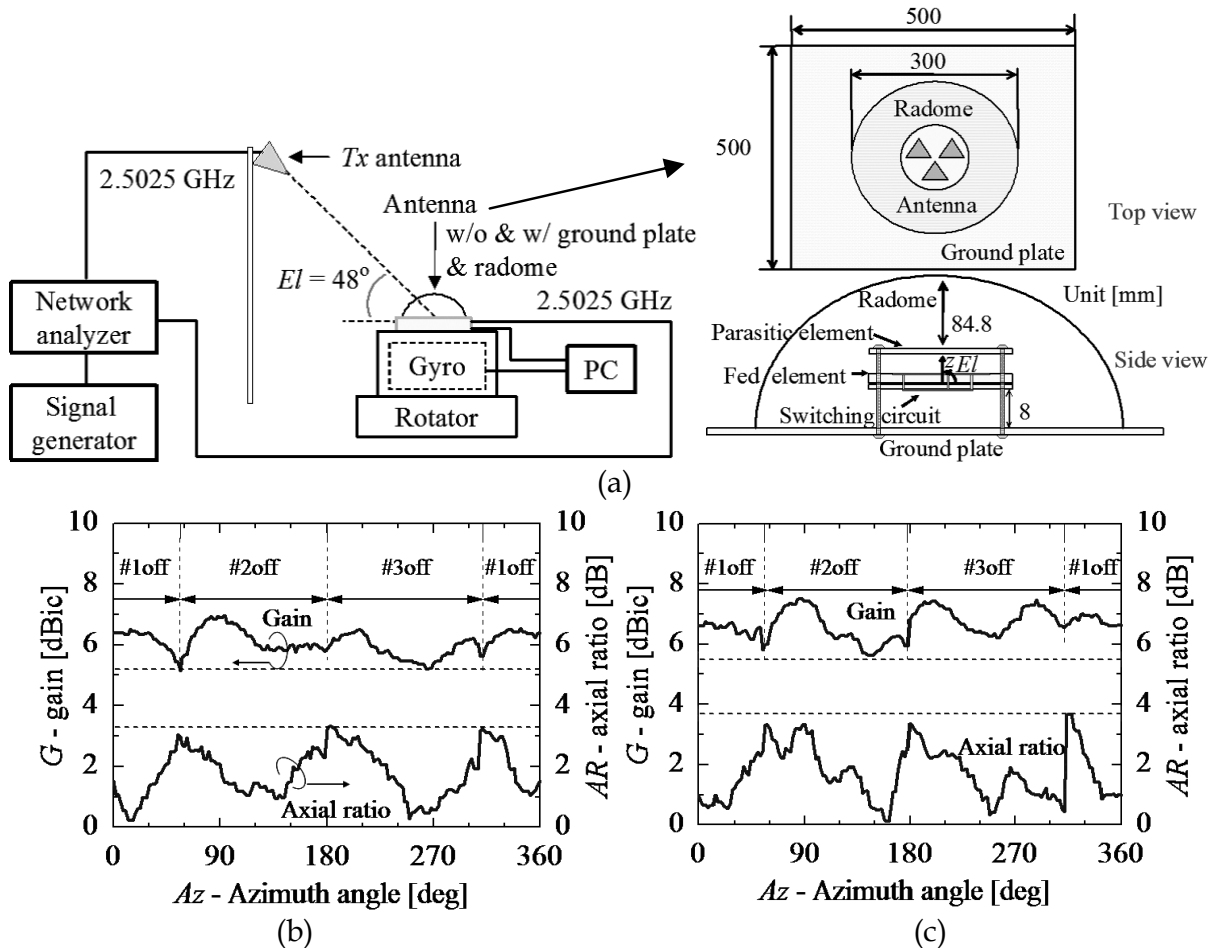
Fig. 8. Verification of antenna system in laboratory anechoic chamber: (a) Measurement set up (b) antenna performance without radome and ground, (c) antenna performance with radome and ground

Additionally, before we perform a measurement campaign, we also confirm the validity of the overall antenna system by carrying out an outdoor measurement using signal from the ETS-VIII satellite. The antenna system is tested by a fixed-state testing rig in Chiba Prefecture area ($El = 48°$) without obstacle present (direct signal) as illustrated in Fig. 9(a). This measurement utilizes a spectrum analyzer (Agilent E4403B) to measure the received signal power from the satellite. In order to compensate the weak satellite signal, an amplifier (Agilent 83017A) is associated with the antenna and thus the signal level has enough C/N_0. Measured result showed that C/N_0 is about 47.30 dBHz with link margin 1.45 dB, sufficiently to make a satellite-tracking measurement.

The measurement of satellite-tracking for array antenna is performed as same as the antenna system test in the anechoic chamber. For this purpose, we take the received signal power while the antenna is rotating. A gyro sensor inside of GPS module is put on the beneath of the antenna and connected to PC for automatic satellite-tracking. As a result, the satellite-tracking is well operated with good level as depicted in Fig. 9(b). Moreover, three selectable beams are smoothly switched to cover all the azimuth direction.
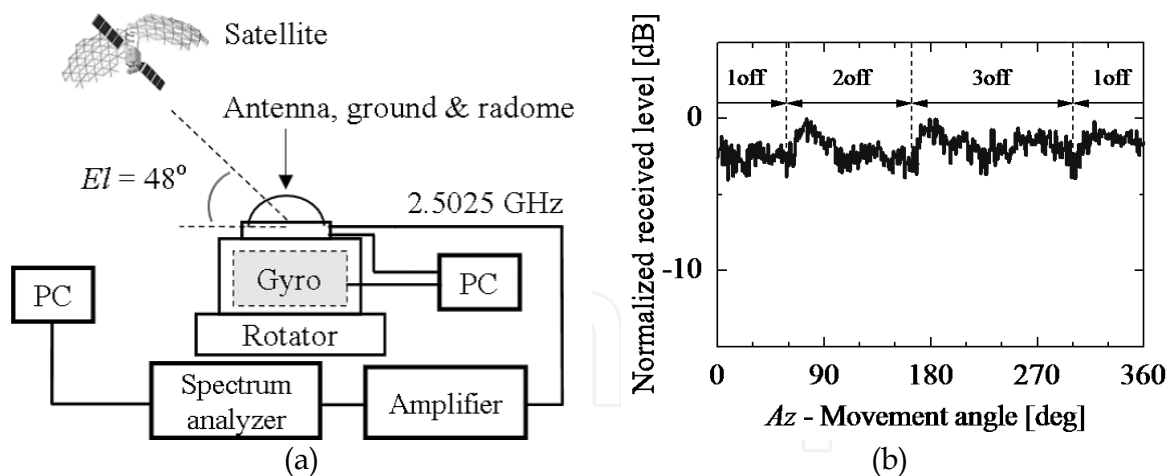
Fig. 9. Verification of antenna system in outdoor test: (a) Measurement set up (b) satellite tracking performance

6. Measurement Campaign using Geostationary Satellite

We have validated the antenna system performance by immobile-state measurements in Section 5. Afterwards, we carry out a measurement campaign to verify possibility for application in real environment. Reported by (NICT, 2007), however, large deployable reflector (LDR) antenna that installed on ETS-VIII satellite cannot be used because of improper situation at power supply of low noise amplifier (PS-LNA), thus the measurement campaign is conducted by using high accuracy clock (HAC) receiving antenna with lower gain 25 dBi instead of 43.80 dBi of the LDR antenna. Because of such circumstance, the measurement is also assigned only for forward link namely from ground fixed-station (transmitter) to vehicle (receiver) through the ETS-VIII satellite (Basari et al., 2009). In this case, we modify the calculated-link budget instead of listed-parameters in Table 2, to deal with the situation, for 8 kbps of transmission rate and BER = 1.0×10^{-4} . We use a parabolic antenna (gain 22.4 dBi) at the transmitter to boost a transmitted signal. Afterwards, we measure received signal power and average bit error rate (BER) at the receiver. The received signal power is retrieved from intermediate frequency (IF) signal of handset terminal. Configuration of measurement is represented by a block diagram in Fig. 10(a) and an example of measurement is viewed in Fig. 10(b).

6.1 Verification of Satellite-Tracking
At first, verifying a single antenna beam is performed in line of sight area without obstacles present. We utilize a spectrum analyzer (Agilent E4403B) to retrieve the IF signal amplitude. By setting it at zero-span in specified frequency, received signal power can be recorded. One of three selectable beams of the antenna is viewed in Fig. 11(a). The experiment result tends to agree with the calculation even though small difference is observed. We employ an aluminium ground plane on the antenna under which is mounted (Fig. 10(b)). Such plate affects the antenna performance especially its beam. Small difference exists, particularly the beam-shape and the beam-width. However, such differences do not significantly worsen the received signal of the antenna.
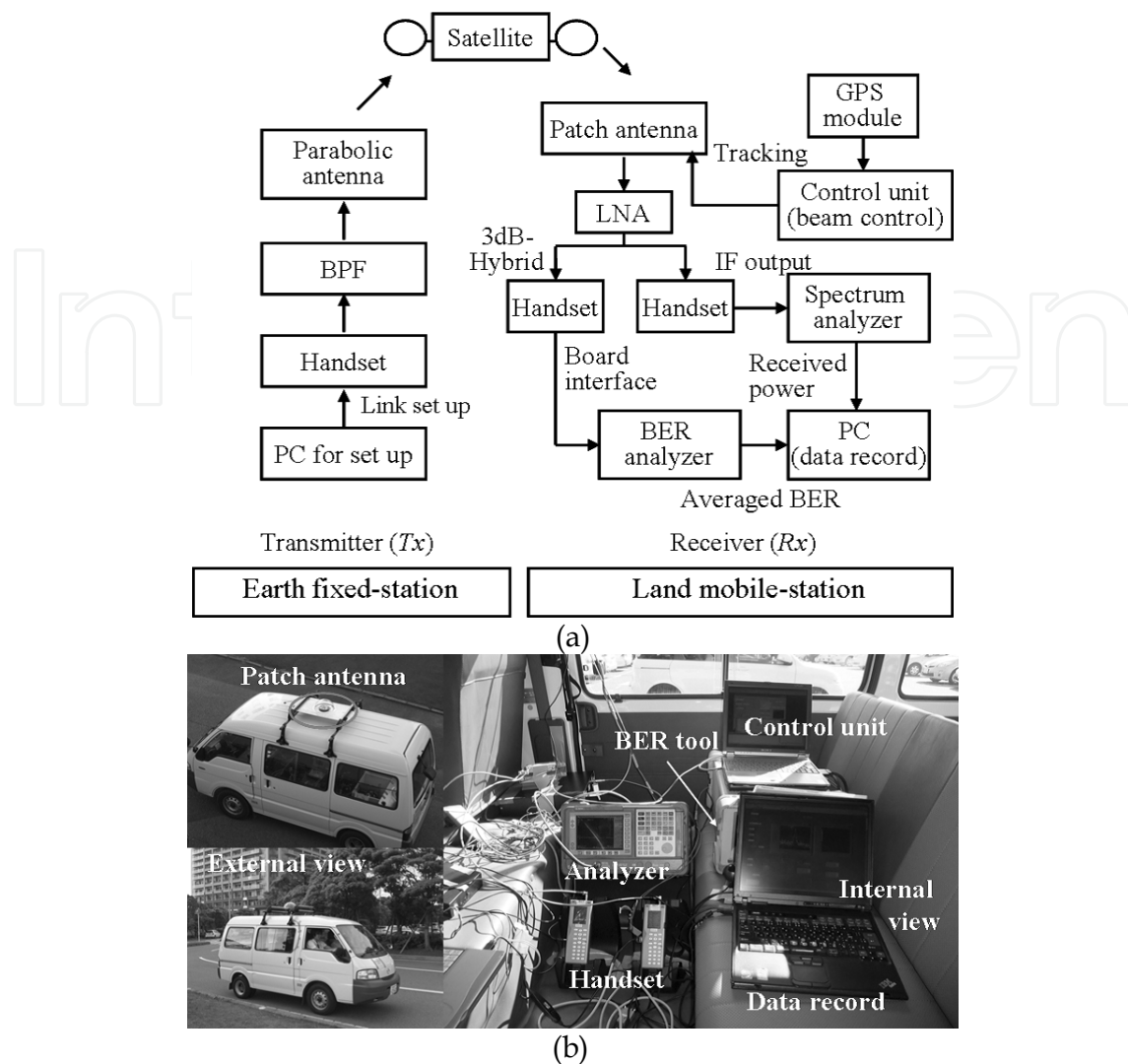
(a)

(b)

Fig. 10. Experimental set-up for measurement campaign: (a) block diagram of configuration (b) measurement view

The measurement also verifies the satellite-tracking of antenna system. While vehicle moves around at the rotary, the antenna beam is electronically steered pursuing the satellite associated with vehicle's orientation. Three selectable beams are smoothly switched towards the satellite in azimuth direction as described in Fig. 11(b). In addition, due to we use spectrum analyzer for measuring signal power, the C/N_0 can be calculated by the following formula (Hranac & Currivan, 2006 and Agilent, 2003):

$$C/N_0 = (\text{signal power}) - (\text{noise floor}) + (10 \log \text{RBW}) \tag{7}$$

where, RBW is resolution bandwidth of measurement. By considering the received signal power is averaged by -60 dBm and noise floor -83 dBm, the C/N_0 is approximately 47.77 dBHz and link margin 1.94 dB is obtained.
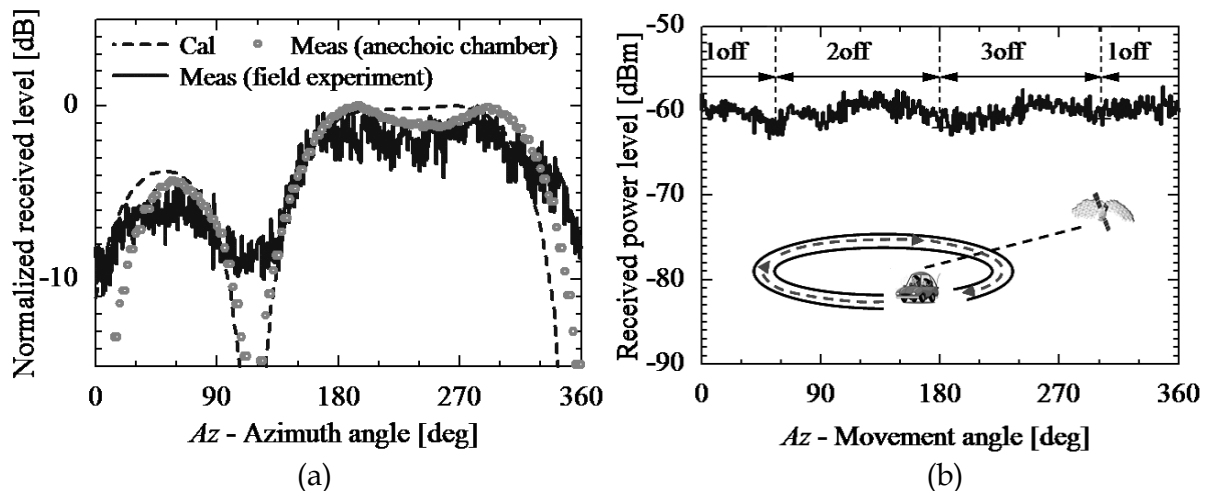
Fig. 11. Verification of antenna system measurement using satellite in line of sight places: (a) Single-beam verification (b) automatic satellite tracking verification

6.2 Evaluation in Blockage Areas

In this measurement, we thoroughly evaluate 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 signal qualities of the antenna. Fig. 12(a) shows an experiment at buildings area. There are two high buildings on the test field which expected to block the signal from the satellite. While vehicle moves on straight path, the signal from the satellite is blocked becoming same level with the noise floor and thus it cannot be detected well as a received signal. If it happens for too long period, communication link will be disconnected.

We also examine the blockage due to roadside-trees. The measurement is carried out in summer season since dense foliages exist and will affect the performance of the received signal power. As shown in Fig. 12(b), the measurement is performed on straight path where the satellite is situated at the left side of the measurement path. Unlike the blockage due to buildings, roadside-trees are less effect to the received signal even though they barred by an average 3–5 dB, decreasing well-received signal. It is obvious shown in Fig. 12(b) in comparison with the direct wave signal. In addition, almost 75% of the satellite signal is approximately attenuated by 2–6 dB at this dense foliages area.

In order to confirm the antenna system usability in common land mobile applications, we test the system in expressway and common road. The field experiment of expressway is carried out in Chiba prefecture area (El = 48°) between Kisarazu-kita and Soga interchange by speed 70–80 km/h. With almost no obstacles present, well received signals are obtained and yet the beam-switch happens at the beginning and the last measurement path. We confirmed that the signal drastically dropped in very short time (0.2–0.4 s) when the vehicle passes through overpasses or bridges. This result is shown in Fig. 13(a).

Our antenna has radiation characteristics in the elevation direction, so thus it is required to confirm with real environment for vehicle application. For that purpose, we test the antenna system at inclined-road. The vehicle passes on the 5° inclined-road with speed of motion is constantly kept by 40 km/h without any beam-switch happens. Fig. 13(b) shows an example

of the measured satellite signal for downward-motion. The received signal tends to increase in 0.5 dB. In this case, downward-motion means increasing elevation allowing increasing the antenna gain.
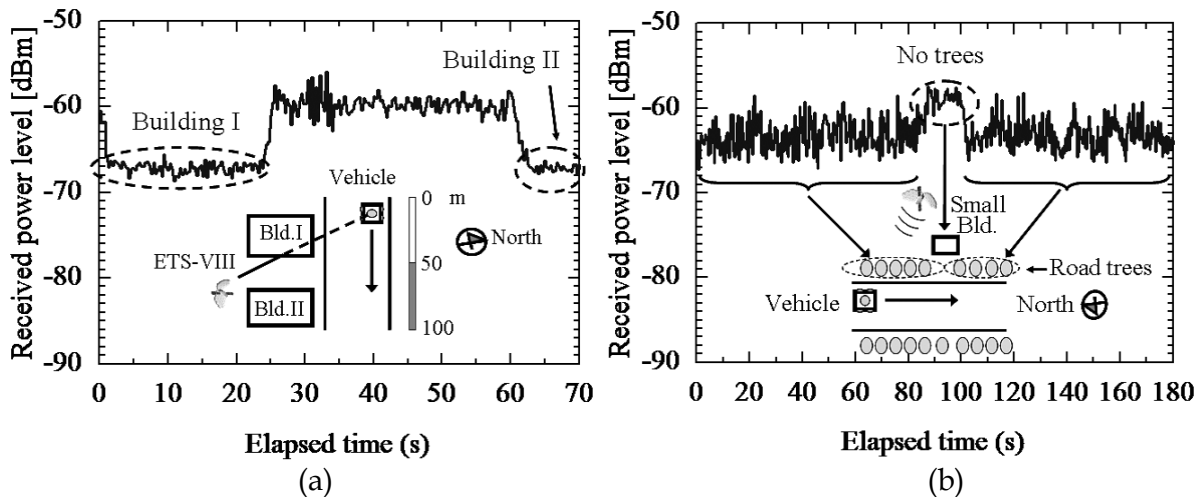

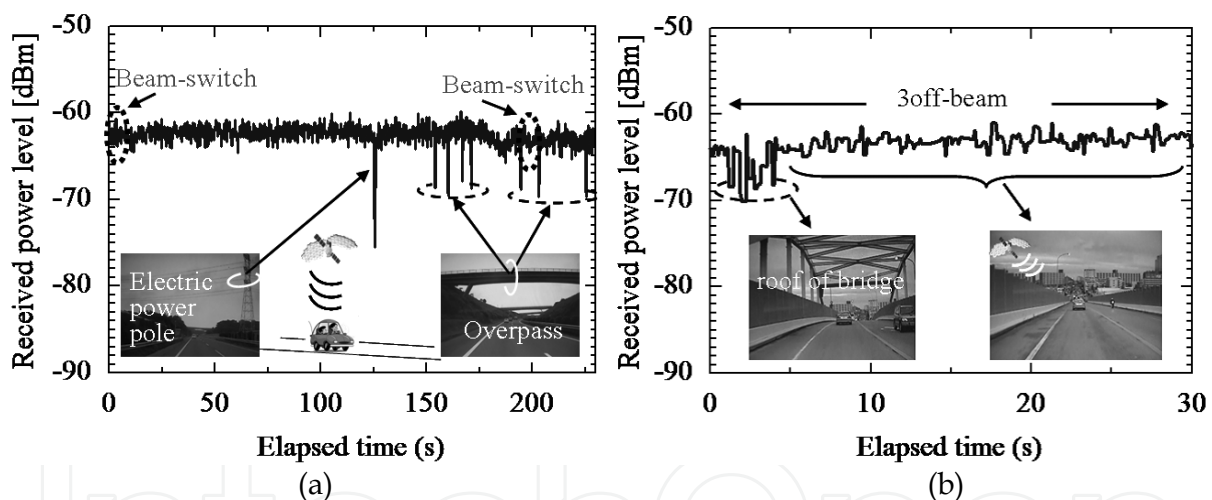Fig. 12. Evaluation on blockage signal measurements: (a) due to buildings (b) due to roadside trees

Fig. 13. Evaluation on blockage signal measurements: (a) due to overpasses and pole (b) due to roof of bridge and inclined-road constraint

6.3 Bit Error Rate Verification

As we earlier designed the antenna system, BER is set by 1.0×10^{-4}. Therefore, we confirm it by performing a measurement on BER characteristics besides the propagation measurements. Here, the measurement is carried out at rotary in line of sight area to verify the satellite-tracking. As previously reported, binary-phase shift keying (BPSK)-modulated pseudo-noise sequences (PN-code) is transmitted from the ground-station through the satellite and received at our vehicle-station. We use a BER analyzer (Anritsu MD6420A) to retrieve the BER value that measured from interface board to which connected with the analyzer from handset terminal. The modulation rate is set to be 8 kbps. The measurement circumstance is similar to measurement path in Subsection 6.1 for satellite-tracking. As

shown in Fig. 14, the BER performance is kept stable in range 5–7×10⁻⁴ while beam-switching occurs. Thus, validity of our antenna system design in the beginning Section is confirmed.
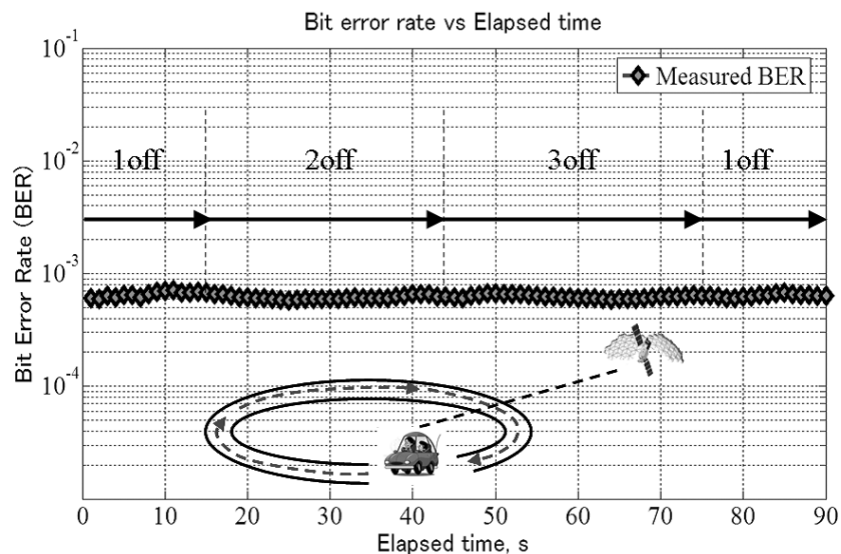

Fig. 14. Bit error rate characteristics on satellite-tracking

7. Conclusion

Simple selectable-beam antenna system for vehicle-mounted mobile satellite communication applications was presented. We have discussed it from design, laboratory test as well as outdoor test and verification in measurement campaign. System components discussed include array antenna includes its switching system to activate the array, and satellite-tracking function as well. The measurement in anechoic chamber was thoroughly examined with satisfactory performances, well suited with the calculations. The basic measurement included S_{11}, axial ratio, and radiation pattern characteristics. Overall antenna system performances in anechoic chamber test gave satisfactory results. Further, the antenna system was also confirmed by using signal from satellite for immobile-state outdoor measurement on the testing-rig. Without any obstacles present, the system was able to correctly select the beam for tracking the satellite with regard to the rotation of the antenna.

Following the satisfactory performances in anechoic chamber measurement and fixed-state outdoor measurement, the antenna system was also examined in measurement campaign using the satellite signal to verify the validity of the developed system for possibility use in land mobile satellite applications. We built a connection with the satellite and tested the antenna system in particular its tracking capability. As a result, the system was correctly track the satellite while vehicle was moving by considering its position and bearing information that retrieved from GPS module.

In addition, we also considered and tested the antenna system under environment constraints that affecting its received signal power, such as buildings, roadside-trees, utility poles, highway overpasses and inclined-road present. The results showed us the blockage and shadowing happened and significantly attenuated the received signal owing to its

dependence on direct wave signal. Moreover, the BER performance of the system has been verified with satisfactory result by about 10^{-4}.

In addition, this vehicle-mounted antenna system design and its measurement results will help engineers and practitioners to design a costly-effective land-mobile satellite communication system. Ultimately, our developed antenna system is simple, compact and promising in low cost, for contribution in the future mobile satellite communication applications.

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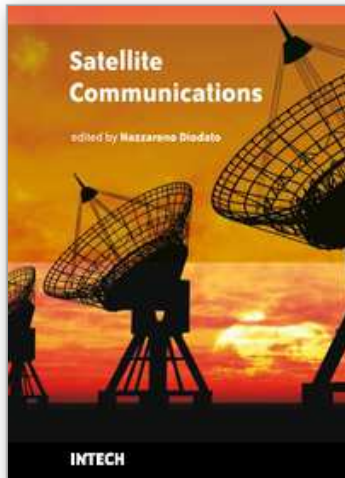
Satellite Communications

Edited by Nazzareno Diodato

This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.

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