

# Antennas for Terrestrial Microwave Relay Links

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**SUMMARY** Antennas for Japanese terrestrial microwave relay links have been developed since the 1950's and put into commercial use up to now in Japan. In particular, the path-length lens antennas developed in 1953 represents a monumental achievement for terrestrial microwave relay links, and the offset antenna for 256 QAM radio relay links developed in 1989 has the best electrical performance in the world. This paper reviews the antennas for Japanese terrestrial microwave relay links that have historical significance and describes the antenna design technologies developed in Japan.

**keywords:** terrestrial microwave relay links, path-length lens antenna, reflector antenna, reflector shaping, frequency sharing, space diversity

## 1. Introduction

The first Japanese terrestrial microwave relay link system was put into service between Tokyo and Osaka in 1953. Since then, many terrestrial relay link systems using microwave bands have been developed and put into service. For these systems, many types of antennas have been studied and developed [1]-[7]. In particular, the path-length lens antenna developed in 1953 represents a monumental achievement for terrestrial microwave relay links [8], and the offset antenna for 256 QAM radio relay links developed in 1989 has the best electrical performance in the world [9].

This paper describes a historical overview of antennas for Japanese terrestrial microwave relay links. First, the advances in major antennas for Japanese terrestrial microwave relay link systems are presented with respect to antenna types and frequency bands. Example of the types of antennas described are the path-length lens antenna, parabolic antenna, horn reflector antenna, offset antennas without and with reflector shaping, Cassegrain antenna, backnet antenna, and diffractor grating. The frequency bands considered for these antennas are the microwave and millimeter-wave bands. Cassegrain antennas were applied to many microwave relay links, but this paper does not describe Cassegrain antennas for microwave relay links except 20-GHz band relay links. Here, this paper narrows down to flow from path-length lens antennas to offset antennas.

Next, Japanese antenna design technologies are summarized. The reflector shaping techniques for realizing the best electrical performances, frequency sharing techniques

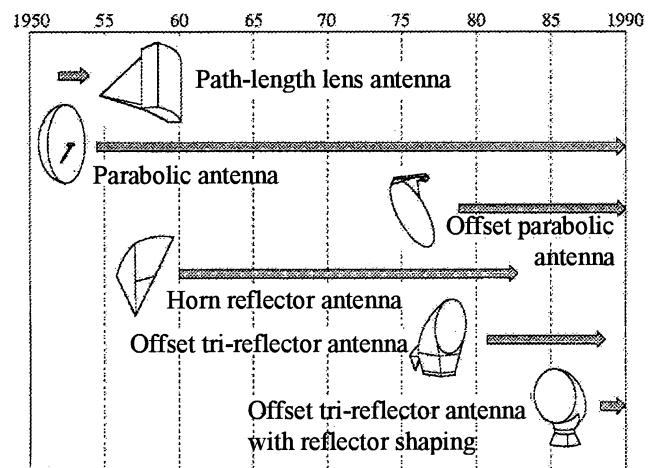
for increasing channels, and space diversity techniques for reducing fading are presented.

## 2. Historical Overview

Figure 1 shows the advances in major antennas for Japanese terrestrial microwave relay link systems. As shown in the figure, the antenna types are the path-length lens antenna, parabolic antenna, offset parabolic antenna, horn reflector antenna, and offset reflector antenna without and with reflector shaping. The frequency bands for these systems are the microwave bands, that is, 2-GHz band, 4, 5, 6-GHz bands and 11, 15-GHz bands. In addition, Cassegrain antennas have been also used for the microwave and 20-GHz band relay links. For other microwave relay links, a backnet antenna, a diffractor grating and a planar reflector have been also used.

In order to install on a telephone tower and to increase the channel capacity and the number of links, the Japanese terrestrial microwave relay link systems require the best electrical performance, lower weight and lower cost. The required electrical performances are high antenna efficiency, low mutual coupling level between antennas, low wide-angle radiation patterns, a low VSWR and frequency sharing capability.

First, the research objectives of the antennas for these systems were increasing the antenna efficiency and reducing the VSWR and coupling level between neighboring anten-



**Fig. 1** Advances of major antennas for terrestrial microwave relay links.

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Fig. 2 Path-length lens antenna installed on a telephone building.

nas in order to increase the channel capacity. After that, improvement in wide-angle radiation patterns, sharing polarization, and sharing frequencies were studied in order to avoid increasing the number of links.

The performance of these antennas were improved by Japanese original techniques as shown in the following chapters. The characteristics of the offset reflector antenna are superior to those of the other antennas. The offset reflector antennas utilizing reflector shaping have the best electrical performance in the world [9].

### 3. Typical Antennas for Terrestrial Microwave Relay Links

#### 3.1 Path-Length Lens Antennas [8]

The path-length lens antenna shown in Figs. 2 and 3 is the first antenna developed for terrestrial microwave relay links. Research on this antenna started in 1951 at Nippon Telegraph and Telephone Public Corporation (now, NTT: Nippon Telegraph and Telephone Corporation), and was put into service in a 4-GHz band radio relay system between Tokyo and Osaka in 1954.

At that time, this type of lens antennas was the best solution because parabolic antennas performances did not yet exhibit sufficient performances (ex. VSWR). Many kinds of lens antennas were studied in other countries, but in Japan, Takeuchi et. al. started research on the path-length lens in 1951. The principle of the path-length lens antenna is that the spherical wave front is converted into a planar wave front. This antenna is not dependent on the frequency of the radio waves, the wavelengths of which are more than two times the spacing of metal plates of the antenna. By developing this path-length lens antenna, the first terrestrial microwave relay links could be realized. The major performance characteristics are given in Table 1.

Table 1 Major Antenna Performances of Path-Length lens Antenna and Parabolic Antenna.

	Path-Length Lens Antenna	Parabolic Antenna
Frequency Band	3.7 - 4.2 GHz	3.6 - 4.2 GHz
Aperture Size	3.3 m * 2.7 m	3.3 m $\phi$
Gain	37.7 - 38.7 dB	39.8 - 40.2 dB
Front/Back Ratio	more than 65 - 75 dB	more than 65 dB
Side to Side Coupling	85 - 90 dB	more than 85 dB
VSWR	less than 1.15	less than 1.07



Fig. 3 Path-length lens antenna.



Fig. 4 Parabolic antenna.



Fig. 5 Snow-stuck microwave antennas on the telephone tower.

### 3.2 Parabolic Antennas [10]-[14]

In order to improve the electrical performance of the path-length lens antennas, the parabolic antennas were developed. Although these antennas employed a revolutionary parabolic design, the performance was not sufficient for broadband communication systems. To improve the VSWR characteristics further, the focus of research became impedance matching of the primary horn. By developing impedance matching techniques for a wide frequency band using the vertex matching plate, and by improving the measuring techniques, the performance of parabolic antenna became superior to that of the path-length lens antenna. Therefore, these antennas were the first to be put into service between Tokyo and Sapporo in 1955. Consequently, they were used in microwave systems. Figure 4 shows the parabolic antenna using linear polarization, and major performance characteristics are given in Table 1.

Another important research subject was the degradation of electrical performance due to snow and rain as shown in Fig. 5, especially the effect of a mist type of rain on the aperture of the primary horn. In order to improve the electrical performance, circularly polarized waves were applied. By using circular polarization, reflected waves were canceled, and the vertex matching plate was not needed. Therefore, the characteristics of the gain and the wide-angle radiation patterns were improved.

After that, circularly polarized parabolic antennas were used in the Hokkaido and Hokuriku regions where we had much snow, and linearly polarized parabolic antennas were used in other regions.

VSWR characteristics of the improved antennas developed in 1958 were lower than 1.035 in the 3.6 to 4.2-GHz frequency bands. At that time, these characteristics were superior to those of the parabolic antennas developed in other

countries. Moreover, the parabolic antennas for 6-GHz systems were put into service in 1960. The 4-m diameter of the antennas had a 44.5-dB gain, a lower VSWR of 1.025, 1.1-dB axial ratio, and wide-angle radiation patterns that were lower by -60 dB compared to that of the peak (at the angle of more than 60 degrees).

### 3.3 Horn Reflector Antenna [15], [16]

Horn reflector antennas had the advantages of high antenna efficiency, low mutual coupling level between antennas, low wide-angle radiation patterns, a low VSWR and frequency sharing capability, therefore, it was considered a good candidate for application to terrestrial microwave relay links. However, it was never realized because of its heavy weight and high cost.

Horn reflector antennas have been developed since



Fig. 6 Horn reflector antennas on the tower.



Fig. 7 Horn reflector antennas on the tower.

1960's and put into service of mainstay terrestrial microwave relay links in order to increase the channel capacity. The research target was frequency sharing in the 4, 5, 6-GHz bands. These antennas were superior to parabolic antennas with respect to broadband characteristics, low wide-angle radiation patterns and high antenna efficiency. Especially, for sharing in multi-frequency bands, high performance branching filters and low loss feeding waveguides have been studied to realize practical systems. The outside appearance on the tower is shown in Figs. 6 and 7.

### 3.4 Offset Parabolic Antennas [17]-[20]

In order to reduce the interference level from other links caused by the increasing number of relay links, an antenna with lower wide-angle radiation patterns was needed, especially for 11 and 15-GHz band relay links in urban areas.

To realize lower wide-angle radiation patterns, an offset parabolic antenna was studied. This type of antenna was first developed for satellite communication system. Though satellite system did not use dual polarization, the important research subject of this antenna was to share the dual polarization. In 1979, this antenna was developed for the 11 and 15-GHz band relay links in urban areas as shown in Fig. 8. This antenna shares the 11 and 15-GHz bands by replacing the primary horns for the 11 and 15-GHz bands. The diameter of this antenna was 4 m and a corrugated horn was used as a primary horn.

To realize low wide-angle radiation patterns, an absorber was applied to an offset parabolic antenna [21]. This antenna was used for 2 and 6-GHz band relay systems.

### 3.5 Tri-Reflector Offset Antennas

The demerit of the horn reflector antenna shown in Figs. 6



Fig. 8 Offset parabolic antenna.

and 7 is its high antenna height. In order to reduce the height, a folded horn reflector antenna shown in Fig. 9 was developed in 1976 [22]. This is an offset Cassegrain antenna that employs a plane reflector. The electrical performance characteristics are almost the same as those of the horn reflector antenna described above.

In order to realize superior electrical performance, especially lower wide-angle radiation patterns to increase number of relay links and better Cross Polarization Discrimination (XPD) characteristics for digital communication links, tri-reflector offset antennas were studied and put into commercial services in 1982 [23]-[25]. This offset antenna comprised quadratic curved surfaces which were a parabolic surface for the main reflector, a plane reflector for a sub-reflec-

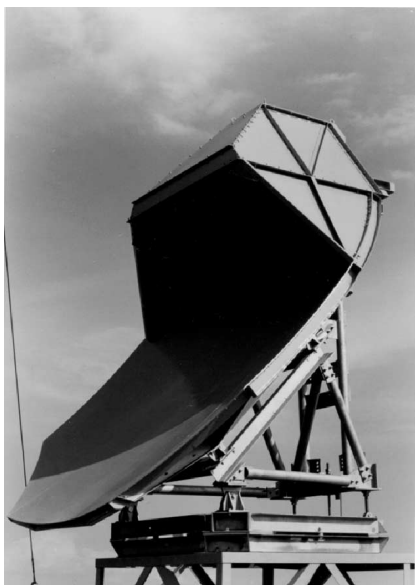


Fig. 9 Folded horn reflector antenna.



Fig. 10 Offset tri-reflector antenna.

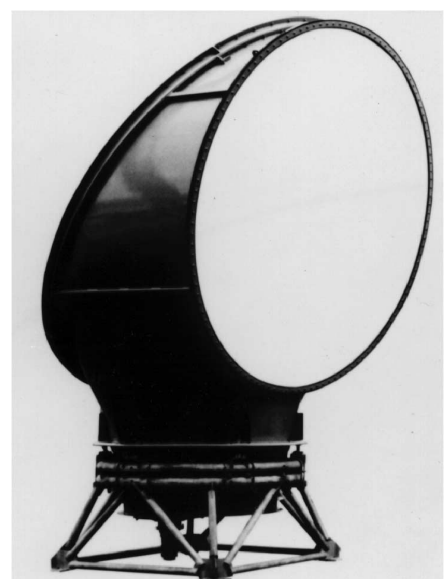
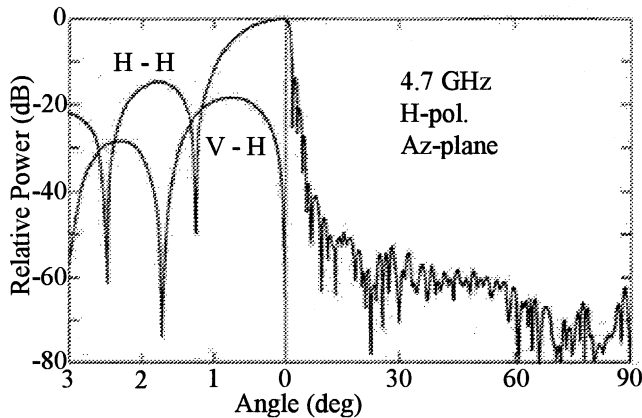


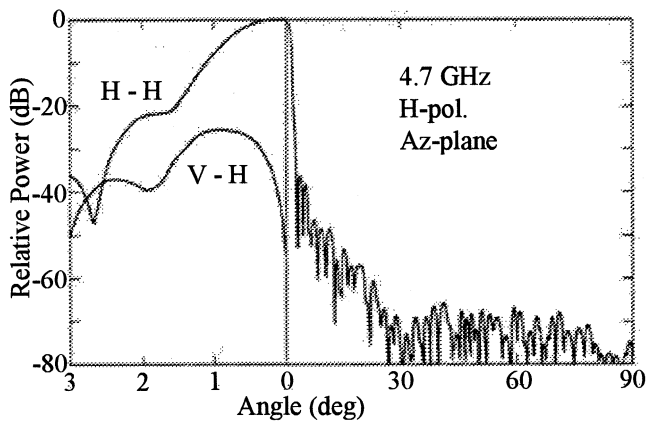
Fig. 11 Offset tri-reflector antenna with reflector shaping.

tor and an elliptical surface for the #1 focusing reflector. The diameter of the antenna was 3.6 m. By developing this antenna as shown in Fig. 10, the wide-angle radiation patterns were improved and the height of this antenna was lowered to below that of the horn reflector antennas.

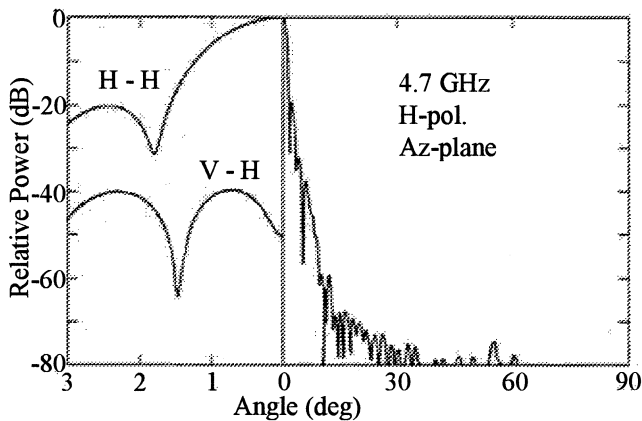
After that, development began on the 256 QAM microwave relay system with high channel capacity. This system required an antenna with improved cross polarization characteristics and wide-angle radiation patterns reduced noise from itself and other route interferences. Toward these re-



(a) Horn reflector antenna.



(b) Offset tri-reflector antenna.



(c) Offset tri-reflector antenna with reflector shaping.

Fig. 12 Horn reflector antenna and offset tri-reflector antennas.

quirements, research on the tri-reflector offset antenna using reflector-shaping techniques was initiated in 1984 [26]-[28]. The development of this shaped reflector antenna was enabled by advanced production techniques that provided high accuracy of shaping surfaces for the offset reflectors and by the evolution of computers for both designing reflector surfaces and calculating the electrical performance. Using these shaping techniques, the tri-reflector offset antenna with shaped reflectors was developed for the 256 QAM microwave relay system in 1989 [9]. The outside appearance is shown in Fig. 11. The 3.6-m diameter of the antennas had a 39.9 to 45.0-dB gain in the 3.6 to 6.175-GHz frequency bands, a higher aperture efficiency of 53 to 64 %, a lower VSWR of 1.03, 38-dB XPD, and wide-angle radiation patterns that were improved by 10 dB compared to other antennas. This antenna has the best electrical performance in the world as indicated in Fig. 12.

#### 4. Antennas for Other Microwave Relay Links

##### 4.1 Backnet Antennas for Over-the-Horizon Microwave Relay Links [29]-[31]

Since the above-mentioned parabolic antennas were realized, these antennas were considered for service in over-the-horizon microwave communication systems. At that time, large aperture parabolic antenna with an 18-m diameter was realized for over-the-horizon radio relay links in the 1.3-GHz band in Japan [32].

The challenges to this antenna were both realizing a larger aperture of 400 square meters and the sharing of 700-MHz band horizontally polarized waves, 800-MHz band vertically polarized waves, and 2-GHz band dual-polarized waves.

In a wind-tunnel test, the backnet antenna, which had a parabolic surface measuring 16-m high and 25-m wide, was developed as shown in Fig. 13, and was put into service of over-the-horizon microwave communication systems between Kagoshima and Naze in Okinawa in 1961. The focal length of this antenna was 15 m, and the primary radiators were dipole arrays for the 700-MHz band, a horn array for the 800-MHz band, and four divided horns for 2-GHz band.



Fig. 13 Backnet antenna.

The gain of this antenna was 39.4-39.8 dBi in the 700-MHz band, 42.0-42.8 dBi in the 800 MHz band, and 50.2-51.0 dBi in the 2-GHz band.

#### 4.2 Diffractor Grating for Passive Repeater Microwave Relay Links [33]-[36]

In order to improve the transmission quality of microwave radio links utilizing mountain diffraction, a diffractor grating was first proposed by Ugai and Aoyagi [33], [34]. The diffractor grating had advantages due to its simple structure and low construction cost. Therefore, it was considered for application to 11-GHz band passive repeater microwave systems.

The principle behind the diffractor grating is the use of a Fresnel lens in the optical region. In 1962, experimental tests were performed on two kinds of diffractors, a screen type and a dielectric type to investigate the propagation characteristics, mechanical structure, and design problems for practical use.

In 1967, the diffractor grating using dielectric plates was put into service in 11-GHz band passive repeater microwave systems between Matsuzaka and Ise in the Tokai region as shown in Fig. 14. The size of the diffractor grating was 3.1-m long and 1.2-m wide.

#### 4.3 Cassegrain Antennas for 20-GHz Band Radio Relay Links [37], [38]

The development of Cassegrain antenna for 20-GHz band radio relay links started in 1970. This type of antenna for 20-GHz band radio relay links was realized by applying the antenna design techniques developed for satellite communication system. The topics of research were reflector shaping techniques, wide band characteristics, low wide angle radiation patterns, snow accretion and its effect described in Chapter 3.2.

The main-reflector and sub-reflector of this antenna were shaped by dual-reflector shaping technique for eliminating XPD component described in the following chapter. By the experimental tests in Hokuriku region, propagation characteristics was made clear [38], and the new 20-GHz band radio relay link was realized. 1.8 and 3.3-m diameter Cassegrain antennas were developed for 20-GHz band radio relay links. This antenna was not installed on a telephone tower but also a telephone pole as shown in Fig. 15.

### 5. Technologies for Microwave Antenna Design

#### 5.1 Conditions of Non-Shaped Reflector Design for Eliminating XPD Component

In order to eliminate the XPD component, the main reflector and a sub-reflector of the dual-reflector antenna must be set under the proper conditions. This zero cross polarization condition was first derived in Japan [39], [40]. This condition is well known as Mizugutch's condition. This technique was

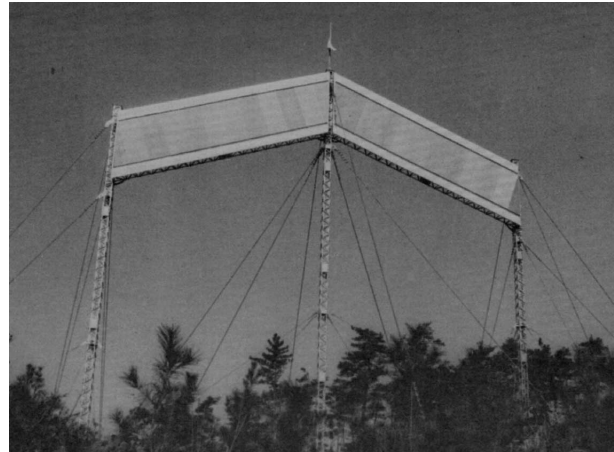


Fig. 14 Diffractor grating.



Fig. 15 Cassegrain antennas for 20-GHz band relay link.

applied to the offset Gregorian antenna and was put into service for 2-GHz link [41], [42]. However, the reflector design method based on this condition has a restricted inclination angle of the primary horn axis due to the shaping of only two reflectors.

The condition for a non-shaped tri-reflector offset antenna was derived by Urasaki et. al. [43]. The tri-reflector antenna designed by using these conditions had no restrictions and exhibited good cross polarization performance as 27 dB XPD in the 4, 5, and 6-GHz bands. However, this condition is based on the ray theory, therefore, the antenna designed using this method is not the best solution for improved XPD performance.

Non-shaped tri-reflector offset antenna design using the wave theory has been studied and has achieved good performances [25], [44], [45]. The 3 m and 3.6-m diameter antennas designed using these methods have been used in terrestrial microwave relay links up to now.

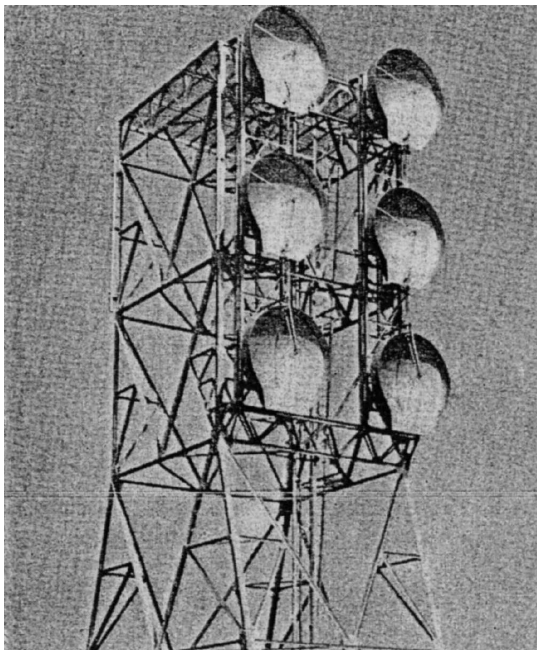
## 5.2 Reflector Shaping Techniques for Eliminating XPD Component

In order to satisfy the requirements of high capacity microwave relay link systems, the design method of shaped offset reflector antennas has been studied. However, offset dual-reflector antennas with reflector shaping do not have any aperture distribution [40]. So, the optimum solution has been derived by the approximation method. Karikomi et. al. derived that offset dual-reflector antennas with reflector shaping have an optimum inclination angle for the primary feed [26]. The inclination angle is determined based on the radiation pattern of the primary horn, aperture distribution, and offset angle of the main reflector. When the inclination angle is selected, any reflector surface can be formed.

Moreover, the design method for offset tri-reflector antennas using reflector-shaping techniques were studied [27], [28], [46]. Presently, the offset tri-reflector antenna with reflector shaping has the best electrical performance for microwave relay links as described in Sect. 3.5.

## 5.3 Frequency Sharing Techniques

Sharing of the 4 GHz, 5 GHz and 6-GHz bands, high performance branching filters and low-loss feeding waveguides have been studied [47], in order to develop the horn reflector antenna as described in Sect. 3.3. Furthermore, sharing the 11 GHz and 15-GHz bands, replacing the primary horns for the 11 and 15-GHz bands were studied [20], in order to develop the 11/15-GHz band parabolic reflector antenna as described in Section 3.4. Sharing of the 2 GHz and 11-GHz



**Fig. 16** Space diversity for reducing K-type fading in the propagation link over the sea.

bands, and the parabolic reflector antenna with horn and printed radiators as primary feeds were proposed [48], [49]. This sharing technique is effective in frequency bands where the frequency ratio nearly equals 5, but it has never been put into service.

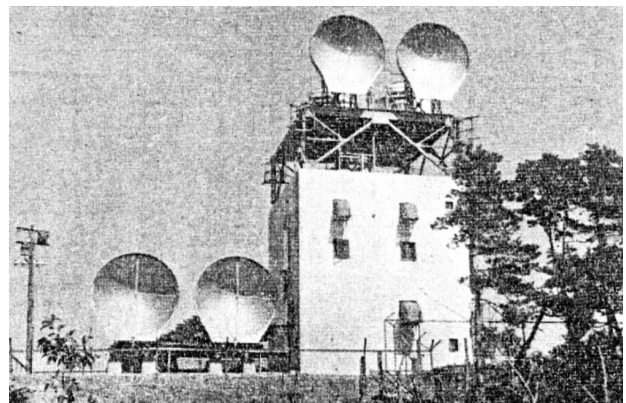
## 5.4 Space Diversity Techniques for Reducing Fading

To reduce K-type fading in the propagation link over the sea, the space diversity system has been studied since 1954, and was put into service in 4-GHz relay systems in 1959 [50]. The distance is 45 to 100 km. The number of antennas for reducing reflected waves from the sea was more than three. As shown in Fig. 16, six antennas were used for reducing the reflected waves from the sea surface in the experimental test.

After that, in order to reduce duct fading in the line of sight microwave links, another space diversity system has been studied since 1958, and was put into service in 4-GHz relay systems in 1963 as shown in Fig. 17 [51]. Since 1960's, such a space diversity system has been used for the Japanese terrestrial relay links up to now.

## 6. Concluding Remarks

This paper reviewed the antennas for Japanese terrestrial microwave relay links that have historical significance, and described the antenna design technologies developed in Japan since the 1950's. Many types of antennas such as the path-length lens antenna, parabolic antenna, horn reflector antenna, and offset antennas have been studied and put into service in commercial terrestrial microwave relay links. The last offset tri-reflector antenna has the best electrical performance in the world for terrestrial microwave relay links up to now. In addition, reflector design techniques have been studied and applied to develop these antennas. Unfortunately, since the 1990's, new types of antennas for terrestrial microwave relay links have not been developed in Japan. The author hopes that new antennas will be studied for the next generation systems.



**Fig. 17** Space diversity for reducing duct fading in the line of sight microwave link.

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