

Reflector Antennas for Earth Stations and Radio Telescopes

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SUMMARY The paper overviews and surveys Japan's reflector antennas for earth stations and radio telescopes since the 1960's. Some interferometers for radio astronomy are included. Japanese original technologies regarding reflector antenna design and measurement are also described. There are 35 figures and 3 tables.

key words: antennas, reflector antennas, earth stations, radio telescopes, satellite communications.

1. Introduction

This paper overviews and surveys Japan's reflector antennas for earth stations, including radio telescopes, for, especially non-Japanese, engineers in the antenna and wireless communications arena. Japanese reflector antenna technologies have tremendously contributed to the popularization and advancement of satellite communications systems. This is most evidenced by a shaped Cassegrain antenna fed by a four-reflector beam waveguide, which is symbolized as a standard reflector antenna for large earth stations all over the world. An offset dual-reflector system with no cross polarization was also invented in Japan and has been used for international and domestic satellite communications. Many studies and developments have been conducted regarding beam-steerable and/or multiple-beam antennas, which involved various technologies in terms of reflector configurations and reflector shaping approaches. This paper also introduces a number of telescopes for radio astronomy in Japan, which include not only a reflector antenna but also radio interferometers (an array of reflector antennas). The intention is not to exhaustively cover the related activities in Japan but to provide representatives.

The paper is organized as follows. Section 2 presents a historical review of reflector antennas in Japan in a chronological manner from the viewpoints of systems, services and applications. Section 3 summarizes technologies for earth station antennas and radio telescopes. Technologies concerning reflector antenna measurements are reviewed in Sect. 4. Finally, concluding remarks are given in Sect. 5.

2. Historical Review

2.1 Overview

A chronological table is presented in Table 1 showing

Manuscript received October 18, 2002.

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Japan's distinguished antennas for satellite communications and radio astronomy since the 1960's. In Fig. 1, the locations of major sites are shown. The large reflector antennas mostly evolved during the 1960's to the 1970's when satellite communications emerged and were rapidly growing. First, towards higher efficiency, then, towards lower sidelobes and higher polarization purity. Since the 1980's, thanks to the improved performances of satellites, smaller earth station antennas of offset configuration with much lower sidelobes were introduced for implementation in or near metropolitan areas. Antennas for VSAT (Very Small Aperture Terminal), USAT (Ultra Small Aperture Terminal) and mobile earth stations were also in demand. For other popular applications of satellites, namely TVRO (Television Receive Only) and DBS (Direct Broadcasting Satellite), small antennas on customer premises as well as transportable antennas for SNG (Satellite News Gathering) were

Table 1 Japan's distinguished reflector antennas for earth stations and radio telescopes.

Year	Size	Location/ID	Frequency Bands	Antenna Type	Appl.(*)
1962	8x1.2m+ 2x3m	Toyokawa	9.4GHz	Compound-Interferometer	RA
1963	20m	Ibaraki	6.4/4.2, 1.7GHz	Cassegrain	ES(IS)
1964	30m	Kashima	7.36/1.812GHz	Cassegrain	ES
	18m	Kagoshima	400MHz	Cassegrain	ES
1965	24m	Tokyo (Mitaka)	1.42GHz	Spherical	RA
1967	22m	Ibaraki No.1	6/4GHz	Cassegrain	IS
1968	27.5m	Ibaraki No.2	6/4GHz	Cassegrain	ES(RA)
	26m	Kashima	6/4GHz	Near-Field Cassegrain	IS
1969	27.5m	Yamaguchi No.1	6/4GHz	Near-Field Cassegrain	IS
1970	6m	Tokyo (Mitaka)	37.5, 75, 90GHz	Cassegrain	RA
1971	29.6m	Ibaraki No.3	6/4GHz	Cassegrain	IS
1972	12.8m	Yokosuka	4, 6, 12, 18, 26GHz	Cassegrain	ES
1977	13m	Kashima	30/20GHz	Cassegrain	DS
	30m	Okinawa	136MHz (2GHz)	Parabola (Gregorian)	ES
1978	13m	Yamaguchi Inmarsat	1.6/1.5, 6/4GHz	Cassegrain	MS
	11.5m	Sendai	30/20GHz	Offset Cassegrain	DS
1980	32m	Yamaguchi TTC&M/IOT	6/4GHz	Cassegrain	IS(RA)
	34m	Yamaguchi No.2	6/4GHz	Cassegrain	IS
1981	45m	Nobeyama	1.4, ..., 86GHz	Gregorian/Cassegrain	RA
1982	5x10m	Nobeyama	22, 115GHz	Supersynthesis	RA
	13m	Ibaraki Inmarsat	1.6/1.5, 6/4GHz	Cassegrain	MS
1984	32m	Ibaraki No.4	6/4GHz	Cassegrain	IS
	64m	Usuda	2, 8GHz	Cassegrain	ES(RA)
1985	34m	Yamaguchi No.3	6/4GHz	Cassegrain	IS
1986	5.5m	Tokyo No.1	14/11GHz	Offset Gregorian	IS
1987	4.2m	DYANET	30/20GHz	Offset Dual-Torus	DS
1988	34m	Kashima	1.5, ..., 43GHz	Cassegrain	RA
	5.5m	Tokyo No.2	14/11GHz	Offset Gregorian	IS
1989	5.5m	Osaka	14/11GHz	Offset Gregorian	IS
1991	6.5m	Osaka	14/11GHz	Offset Spherical	DS
	18m	Yamaguchi Inmarsat-2	1.6/1.5, 6/4GHz	Cassegrain	MS
1992	84x0.8m	Nobeyama	17GHz	Tee-shaped array	RA
	32m	Ibaraki No.5	6/4GHz	Cassegrain	MS
	4.2m	DYANET-II	14/12GHz	Offset Dual-Torus	DS
1997	18m	Yamaguchi No.5	6/4GHz	Cassegrain	IS
1998	32m	Tsukuba	2, 8, 22GHz	Cassegrain	RA

(*) RA: Radio Astronomy. ES: Experimental Satcom. IS: INTELSAT. MS: INMARSAT. DS: Domestic Satcom.



Fig. 1 Location of historical/major sites for satellite communications and radio astronomy in Japan.



Fig. 2 Ibaraki Space Communications Laboratory.

developed. As far as radio astronomy is concerned, Japanese large reflector antenna technology demonstrated its capability in the construction of a 45-m Cassegrain antenna (capable of mill-meter wave operations) at Nobeyama in 1981 followed by a 64-m Cassegrain antenna (S/X-bands) at Usuda in 1984.

2.2 Dawn of Space Communication in Japan [1]–[14]

Japan’s first earth station was constructed assuming that the trans-Pacific space communication experiments would be carried out with ATT’s Telstar-II satellite. The transmitting and receiving frequencies with respect to the earth station antenna were 6.39 GHz and 4.17 GHz, respectively, and the bandwidth was 25 MHz for both. At KDD (now KDDI) Ibaraki Space Communications Laboratory, a Cassegrain reflector antenna of 20 m in diameter (2-m sub-reflector) was developed which had an advantage over the horn reflector antenna, used at Andover Earth Station, USA, in terms of weight and cost. Since the early communication satellites were in a low earth orbit, the antenna was required to con-

Table 2 Performances of experimental antennas for space communications [5].

	Ibaraki 20m		Kashima 30m	
	Tx	Rx	Tx	Rx
"Telstar" Satellite				
Frequency	6.39GHz	4.17GHz	X	
Gain	58.1dBi	55.9dBi		
Efficiency	36%	51%		
"Relay" Satellite				
Frequency	1.725GHz	4.17GHz	1.725GHz	4.17GHz
Gain	47.6dBi	55.5dBi	49.4dBi	58.1dBi
Efficiency	44%	46%	30%	38%

tinuously track the satellite in a wide angular range with high precision. To achieve this, another small parabolic antenna of 6 m in diameter was installed to which the 20-m Cassegrain one was slaved. Figure 2 is the aerial view of Ibaraki Space Communication Laboratory showing two radomes, 260 m apart, which sheltered a communication antenna and a tracking antenna, respectively. After the initial experiments between Ibaraki and Andover (ATT) via Telstar-II in July 1963, TV relay experiments were carried out in November 1963. This time, NASA’s Relay-I satellite relayed the first trans-Pacific TV images from Mojave Earth Station to Ibaraki Earth Station, which incidentally reported the assassination of the 35th U.S. President J. F. Kennedy occurred on that day in Dallas. Although the receiving frequency was the same as Telstar-II, the transmitting frequency from the earth station to Relay-I was 1.725 GHz so that the primary horn needed to be replaced. The antenna performances are summarized in Table 2.

The next tests were scheduled in January 1964. Just prior to the successful launch of Relay-II satellite [6], the radome was blown off course due to heavy winds of 26 m/s on 22nd January, revealing the naked Cassegrain antenna, as shown in Fig. 3. The accident, however, persuaded the engineers, after the second experiments and heated discussions among them, that no radome would have been required if proper modifications had been given. The antenna was also utilized for the first Japan-Europe TV relay via Telstar-II satellite in April 1964 [7].

Japan’s second earth station antenna shown in Fig. 4 was installed at RRL (now CRL) Kashima Laboratory in May 1964 [10]. The Cassegrain antenna had a main reflector of 30 m in diameter (1.5-m sub-reflector). The performances are listed in Table 2. Apart from the large size, the key feature of the antenna was its auto tracking system so that it needed no separate antenna. Coarse tracking was carried out by receiving 136-MHz telemetry signal through a 1.2-m parabola reflector piggybacked behind the sub-reflector. Fine tracking was carried out by a higher mode auto tracking system at 4.08 GHz. However, a smaller Cassegrain antenna of 10 m in diameter was later developed at Kashima for the first international TV relay of Tokyo Olympic Games through SYNCOM-III satellite in October 1964 [12]. Because SYNCOM-III was transmitting a linear polarized wave in the geostationary orbit, the smaller

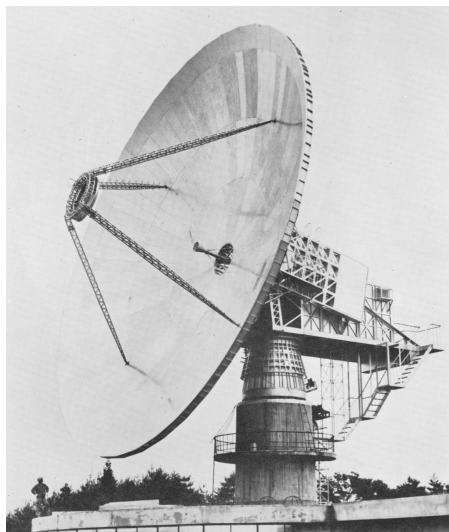


Fig. 3 20-m Cassegrain antenna for Japan’s first earth station [4].

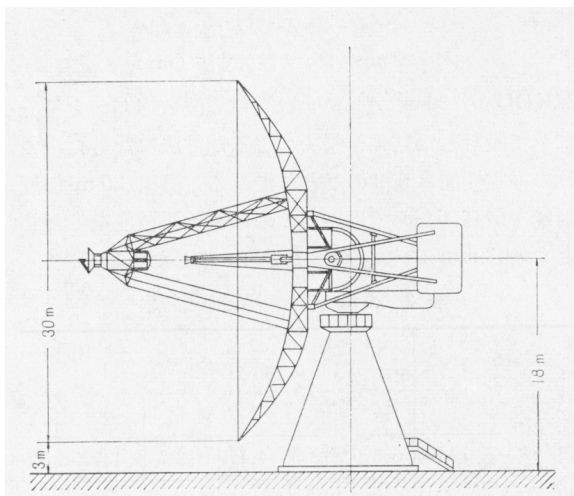


Fig. 4 30-m Cassegrain antenna with a small parabola piggybacked behind the sub-reflector [5].

antenna with manual tracking was appropriate to transmit a high power of 7 kW, whereas the 30-m antenna was used for reception only at 1.812 GHz [13]. The transmit gain of the 10-m antenna was 55.5 dBi at 7.36 GHz, which corresponds to an aperture efficiency of about 60% [14].

2.3 INTELSAT Earth Stations [15]–[40]

After the successful experiments using Relay geostationary satellites, INTELSAT (International Telecommunications Satellite Organization) was established on 20th August, 1964. Early-Bird (INTELSAT-I) satellite began commercial services over the Atlantic Ocean Region (AOR) in June 1965, then expanded the area to the Pacific Ocean Region (POR) and the Indian Ocean Region (IOR) in 1967 and 1969, respectively. Since then, KDDI, as one of the oldest signatories of the organization, have been actively

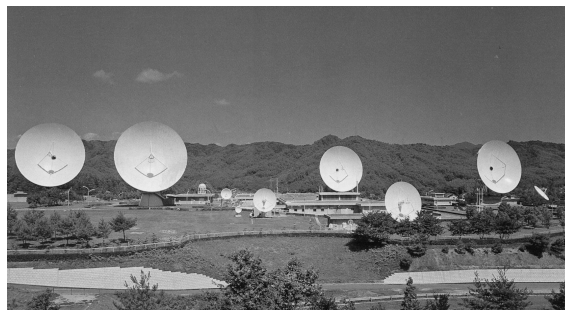


Fig. 5 Bristling dishes at Yamaguchi satellite communications center in the mid 1980’s.

participating in the system. For the INTELSAT system, many earth stations were developed; most of them were installed at Ibaraki (for satellites above POR) and at Yamaguchi (for satellites above IOR) Satellite Communications Centers. As listed in Table 3, new earth stations were developed to fulfill growing international telecommunications demand (including TV relay) by introducing a new antenna with higher efficiency, lower sidelobes, wider bandwidths, and higher polarization purity in accordance with a new series of INTELSAT satellites. Until trans-ocean optical fibers were commercialized, the number of antennas at the border earth stations were increased as shown in Fig. 5. In the 1990’s, the powered-up satellites and the advancement of digital communications technologies made it possible to utilize smaller earth stations which could be installed in suburban or urban areas. Metropolitan earth stations in Tokyo and Osaka and even VSAT/USAT, which can be installed on customer premises, have emerged requiring an antenna with much better sidelobe characteristics. Moreover, satellite communications service portfolios expanded to include transportable (including fly-away type) and vehicle mountable earth stations. As far as fly-away earth stations are concerned, it was memorable that an earth station with a 10-m Cassegrain antenna which weighed 30 t was carried over to China by DC-8 airplane for TV relay through INTELSAT-IV of Prime Minister K. Tanaka’s historical visit in September 1972 [15].

The 22-m Cassegrain antenna of the Ibaraki No.1 Earth Station was based on the 20-m experimental one, described in Sect. 2.1, by increasing the diameter of the reflectors by 10% and improving the surface accuracy to 1.2 mm (rms). Because the reflector system was improved by adopting a near-field feed type, the aperture efficiency at the 6 GHz band increased by about 10 points, although it remained still below 50%. The antenna needs to adjust the polarization by rotating the feed horn, since INTELSAT-I and INTELSAT-II satellites used a linearly polarized wave. The dedicated 6-m tracking antenna was used as a master because the higher mode mono-pulse tracking system was difficult to realize for linearly polarized wave. Commercial services began through INTELSAT-II (F2) on 27th January in 1967 [16], [17].

Ibaraki No.2 Earth Station was developed for

Table 3 Representative earth station antennas for INTELSAT system in Japan.

Year	Earth Station ID	Aperture Diam.	Frequency Range	Gain	Aperture Efficiency	Weight	Key Features	Standard (**)	Satellite Series
1967	Ibaraki No.1 Earth Station	22m (2.2m)	Tx: 6.274-6.4GHz Rx: 4.058-4.184GHz	Tx: 60.0dBi (6.39GHz) Rx: 56.9dBi (4.17GHz)	Tx: 46% Rx: 53%	110t	Near-field feed Cassegrain	-	I, II
1968	Ibaraki No.2 Earth Station	27.5m (2.8m)	Tx: 5.925-6.425GHz Rx: 3.7-4.2GHz	Tx: 62.7dBi (6GHz) Rx: 58.9dBi (4GHz)	Tx: 62% Rx: 58%	350t	Cassegrain fed by conical horn reflector	A (1st)	II, III
1969	Yamaguchi No.1 Earth Station	27.5m (2.6m)	Tx: 5.925-6.425GHz Rx: 3.7-4.2GHz	Tx: 63.2dBi (6GHz) Rx: 59.8dBi (4GHz)	Tx: 70% Rx: 72%	300t	Shaped Cassegrain fed by conical horn reflector	A	II, III
1971	Ibaraki No.3 Earth Station	29.6m (2.8m)	Tx: 5.925-6.425GHz Rx: 3.7-4.2GHz	Tx: 63.4dBi (6.2GHz) Rx: 60.0dBi (4.0GHz)	Tx: 59% Rx: 65%	250t	Shaped Cassegrain on wheel-and-track structure fed by four-reflector beam-waveguide with corrugated	A	III, IV
1980 (1993)	Yamaguchi TTC&M/IOT Station (No. 4 after modification)	32m (2.9m)	Tx: 5.925-6.425GHz Rx: 3.7-4.2GHz	Tx: 64.96dBi (5.925GHz)	Tx: 79% Rx: 82%	280t	Ring-loaded corrugated conical horn	A	IV, V
1980	Yamaguchi No.2 Earth Station	34m (2.9m)	Tx: 5.925-6.425GHz Rx: 3.7-4.2GHz	Tx: 65.6dBi (6.0GHz) Rx: 61.9dBi (4.0GHz)	Tx: 79% Rx: 76%	430t	Cross-polarization compensation system and shaped struts	A	IV, V, VI, IX
1984	Ibaraki No.4 Earth Station	32m (2.9m)	Tx: 5.85-6.725GHz Rx: 3.4-4.2GHz	Tx: 64.4dBi (5.85GHz) Rx: 61.35dBi (4.0GHz)	Tx: 72% Rx: 76%	380t	Similar to Yamaguchi No.2 but without cross-polarization	A	V, VI, VII, VIII
1985	Yamaguchi No.3 Earth Station	34m (2.9m)	Tx: 5.85-6.725GHz Rx: 3.4-4.2GHz	Tx: 64.9dBi (5.85GHz) Rx: 61.7dBi (4.0GHz)	Tx: 71% Rx: 73%	430t	Similar to Yamaguchi No. 2.	A	V, VI, IX
1986	Tokyo No.1 Earth Station	5.5m	Tx: 14.0-14.5GHz	Tx: 56.7dBi (14.25GHz)	Tx: 69%	-	Offset Gregorian on screw-jack mount with step-tracking.	E2	V, VIII (Ku: IBS, IDR)
1988	Tokyo No.2 Earth Station		Rx: 10.95-11.7GHz	Rx: 54.7dBi (11.2GHz)	Rx: 71%				
1989	Osaka Earth Station								
1992	Ibaraki No.5 Earth Station	32m (2.9m)	Tx: 5.85-6.425GHz Rx: 3.625-4.2GHz	Tx: 64.5dBi (5.85GHz) Rx: 61.0dBi (3.95GHz)	Tx: 73% Rx: 72%	-	Similar to Ibaraki No. 4 but with step tracking.	A	VI, VII
1997	Yamaguchi No. 5 Earth Station	18m	Tx: 5.85-6.425GHz Rx: 3.625-4.2GHz	Tx: 59.3dBi (6GHz) Rx: 56.1dBi (4GHz)	Tx: 66% Rx: 72%	-	Shaped Cassegrain on screw-jack mount with step-tracking.	Revised A	VII, VIII

(**) INTELSAT Earth Station Standard is defined by required "Figure of Merit" in terms of G/T. Std-A: G/T>=40.7dBK. Std-E2: G/T>=29.0dBK. Revised Std-A: G/T>=35.0dBK.

INTELSAT-III series satellites that had a wider bandwidth of 500 MHz than INTELSAT-II's 126 MHz. The earth station, for which the antenna was designed to maximize the figure of merit, G/T, was approved as the first Standard-A in the world to be specified by ICSC (Interim Communications Satellite Commission). Although the main reflector was a parabola, the sub-reflector was so shaped that the aperture efficiency reached about 60%. Since the sub-reflector was fed by a conical horn-reflector feed with a rotary joint on the elevation axis, the transmitter and the receiver were free from the elevation rotation. The antenna was equipped with a higher mode auto-tracking system [18]–[21].

Yamaguchi No.1 had almost the same antenna design as Ibaraki No.2, however both the main reflector and sub-reflector were shaped in Yamaguchi No.1. The surface accuracy of the main reflectors was less than 1 mm (rms) [22], [23].

Ibaraki No.3 Earth Station was developed to access INTELSAT-IV series satellites. A four-reflector beam waveguide feed system enabled it to de-couple the transmitter and the receiver with the antenna, making the earth station maintenance and operation much easier. The antenna mount was of wheel-and-track type, rather than the conventional yoke-and-tower type, and driven by electric motors. A corrugated conical horn was used to feed the main reflector through the sub-reflector, both of which were shaped the same as Yamaguchi No.1 antenna [24], [25].

Yamaguchi TTC&M/IOT (Tracking, Telemetry, Command and Communications System Monitoring/In-Orbit Test) station was designed for operation and maintenance of INTELSAT satellites, including INTELSAT-V series which operated orthogonal dual polarizations, in POR and IOR under contract between INTELSAT and KDD. The 32-m dual polarization Cassegrain antenna proved to have high per-

formance characteristics, especially in high polarization purity and accurate tracking capability. The polarization axial ratio of less than 0.2 dB over the 500-MHz bandwidth in both transmit and receive bands was the highest in purity among large antennas in the world. The reflector shaping was applied to obtain the high gain by illuminating the aperture almost uniformly. The achieved gain corresponded to aperture efficiencies of about 80% and 85% at receive and transmit bands, respectively. The four-reflector beam waveguide was so designed to reduce cross polarization and a ring-loaded corrugated conical horn was developed for the primary feed. The antenna mechanical structure was also improved by adopting cylindrical pipes instead of H-shape steel [26].

Within a year after the construction of the TTC&M/IOT facilities, another antenna with a slightly larger dish of 34-m was developed for Yamaguchi No.2 Earth Station for communications services to work with the INTELSAT-V series satellite. A special network was provided in the feed system to compensate for the degradation of polarization purity due to precipitation on the Earth-to-satellite and satellite-to-Earth paths. Moreover, particular attention was paid to reduce the sidelobe levels in cross polarization components using shaped struts for the sub-reflector. The antenna, shown in Fig. 6, is considered a perfection of the large reflector antenna for earth stations [27]. The following INTELSAT earth stations in Japan had a similar type of antenna with some modifications. For example, they had wider bandwidths of 800 MHz or 875 MHz [28]–[30].

Thanks to the advancement of satellite technologies, including a higher precision of satellite station keeping, the requirements for border earth station antennas could be relaxed and less expensive implementation became possible. Although the aperture size was very large, Ibaraki No.5

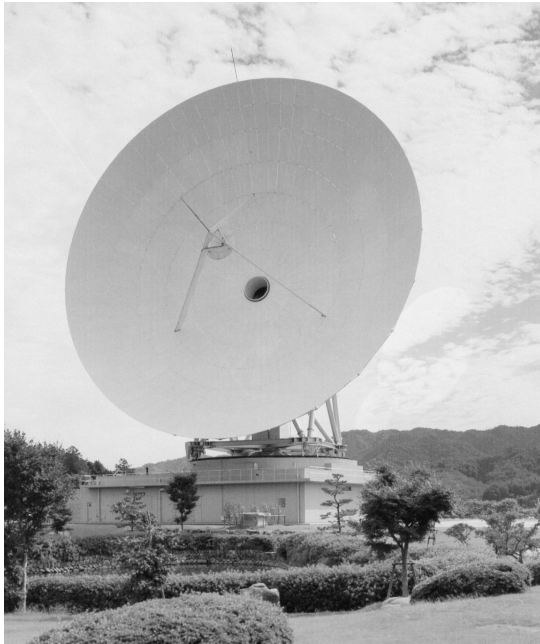


Fig. 6 34-m Cassegrain antenna for Yamaguchi No.2 Earth Station.

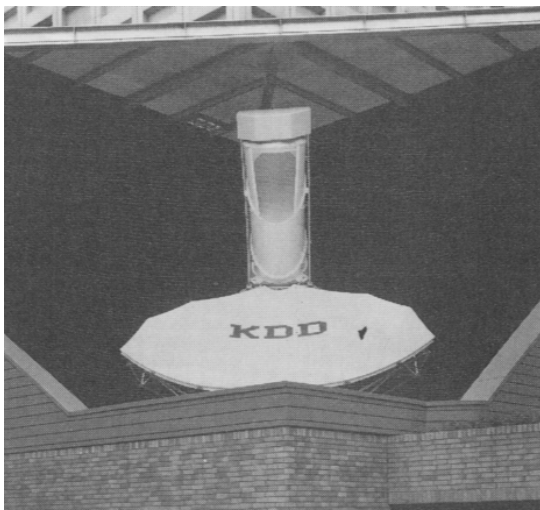


Fig. 7 5.5-m Offset Gregorian antenna for Tokyo No.2 Earth Station.

Earth Station antenna adopted a step-track method for the auto-tracking system making the feed system much simpler. The aperture size of Yamaguchi No.5 antenna was 18 m in diameter since the specifications of INTELSAT Standard-A earth station was revised to allow the smaller size [31], [32].

From 1983, INTELSAT system commenced IBS (INTELSAT Business Service) using Ku-band to fulfill emerging demand for economical, multimedia communications services, especially in urban areas where the criteria of radio interferences were very strict. To meet the requirements, an offset dual-reflector antenna was developed that had much better sidelobe characteristics. Figure 7 shows Tokyo No.2 Earth Station, which was of an offset Gregorian type. An offset Gregorian type has an advantage over



Fig. 8 1.2-m Ku-band Shaped offset Gregorian antenna for VSAT.

an offset Cassegrain type because a primary feed and a sub-reflector can be installed and enveloped in a single structure reducing both position errors and spillover unwanted radiation. Moreover, the aperture distribution of the antenna was optimized by reflector shaping of sub- and auxiliary reflectors. Eventually, a direct satellite access to/from a customer was enabled by VSAT/USAT systems. Figure 8 shows a 1.2-m shaped offset Gregorian antenna for Ku-band VSAT [33]–[40].

2.4 INMARSAT Earth Stations [40]–[52]

In 1976, MARISAT satellites were launched and maritime satellite communications services commenced in AOR first, then in POR. For global services, a land earth station was required in IOR and Yamaguchi Land Earth Station was developed for the mission, which introduced the service in July 1977. The first IOR land earth station equipped a dual band (C/L-band) 13-m Cassegrain antenna, shown in Fig. 9, since the feeder link was C-band (6/4 GHz) while the service link was L-band (1.6/1.5 GHz). A special feed system was developed to illuminate a shaped sub-reflector, the outer part of which was a frequency selective reflector (FSR). The aperture efficiency was about 72–82% in C-band and about 26–32% in L-band [41].

INMARSAT (International Maritime Satellite Organization) was established in 1982 to succeed the MARISAT system and was reinforced by MARECS satellites and MCS (Maritime Communications Subsystem) piggybacked on-board INTELSAT-V satellites. This year, another land earth station for AOR communications [42], [43] and a TT&C station for MARECS satellites [44], [45], under contract with ESA (European Space Agency), were developed at Ibaraki Satellite Communications Center. Both earth stations had a shaped Cassegrain antenna of 13 m in diameter similar to the Yamaguchi one except for the feed systems. Particularly,

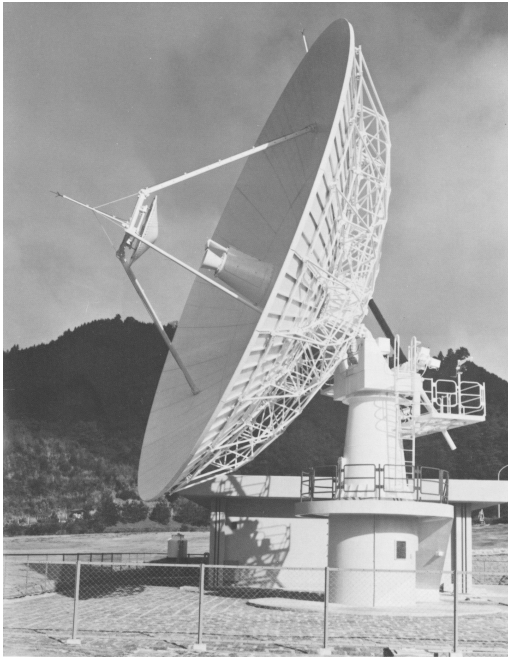


Fig. 9 13-m L/C dual band Cassegrain antenna for Yamaguchi Land Earth Station [41].

the TT&C station was required to operate for orthogonal circular polarizations in both C and L bands. INMARSAT system continued to grow steadily and included aeronautical services in 1985 (1990 in Japan) and land mobile services in 1989 (1991 in Japan). After INMARSAT-2 satellites were introduced in 1990, second generation land earth stations for POR and IOR were developed in Yamaguchi Satellite Communications Center in 1991 [46]. The stations equipped a dual band 18-m Cassegrain antenna. The aperture efficiency was about 65% in C-band and about 30% in L-band. The older Ibaraki TT&C station was modified to become an INTELSAT earth station in 1992.

Regarding ship-borne antennas, a representative ship earth station had a parabola antenna of about 1.2 m in diameter at an early stage of INMARSAT services. Later, smaller and less heavy antennas, such as those shown in Fig. 10, were developed. Although the 0.4-m improved short back fire antenna fed by cross dipoles had a gain of only 15.0 dBi at 1.54 GHz, 5–6 dB less than a 0.85-m parabola, it was operationally sufficient since it utilized a fading reduction technique by polarization shaping. Because the technique was based on the phenomena that the reflected signal from a sea surface has an elliptical polarization depending on the elevation angle, the cross dipoles were fed by a variable phase shifter to produce an arbitrary elliptical polarization and were also mechanically rotatable to be adjusted with the sea surface regardless of antenna orientation at the sea. For aeronautical antennas and land mobile antennas, an array of planar antenna (e.g. microstrip) was used instead of reflector antennas because of the system requirements and customer demand [47]–[52].

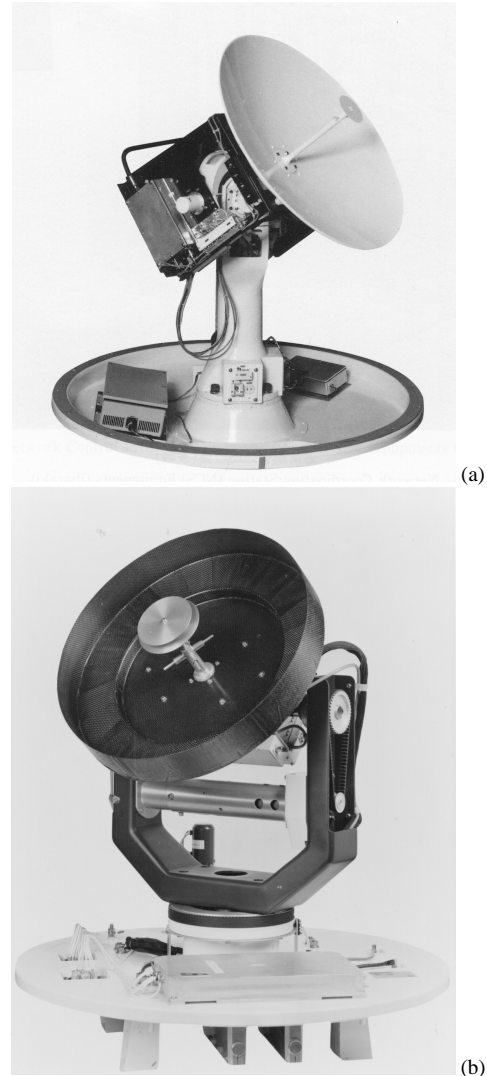


Fig. 10 INMARSAT ship-borne antennas. (a) 0.85-m parabola [47]. (b) 0.4-m short back fire.

2.5 Earth Stations for Domestic Satellite Communications [53]–[75]

After the successful TV transmission of the Tokyo Olympic Games, RRL continued space communications experiments with ATS (Applications Technology Satellite) developed by NASA, USA. In 1968, a 26-m shaped Cassegrain antenna with a 2.2-m sub-reflector fed by a horn reflector was developed at Kashima Laboratory, since the initial 30-m Cassegrain antenna had relatively poor surface accuracy. The gain was 62.06 dBi (56% efficiency) and 59.10 dBi (65% efficiency) at 6.2 GHz and 4.1 GHz, respectively [53]–[55]. The antenna was used not only for space communications experiments but also for radio astronomy especially for VLBI experiments as explained later. The public corporation for Japan's domestic telecommunications services, NTT, also contributed to various satellite communications experiments.

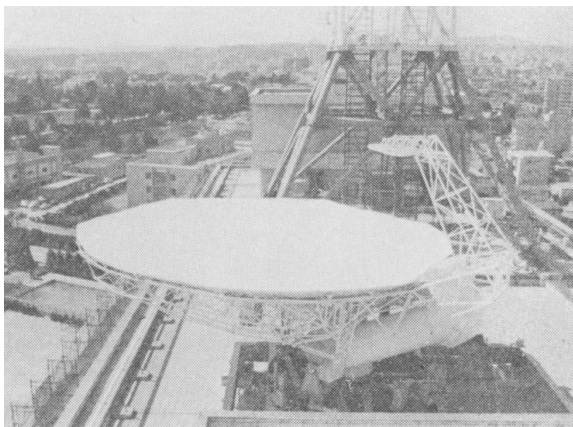


Fig. 11 Ka-band offset Cassegrain antenna at Sendai station [60].

Japan's first communications satellite, CS (Sakura), and Japan's first broadcast satellites, BS (Yuri) were launched by USA rockets, Delta, in 1977 and 1978, respectively, and the domestic satellite communications experiments were boosted by RRL and NTT. The key feature of the CS was that it had not only a C-band (6/4 GHz) transponder but also a Ka-band (30/20 GHz) transponder. At the RRL Kashima main ground station, a couple of 13-m Cassegrain antennas, one for CS (Ka-band) and the other for BS (Ku-band: 14/12 GHz), and a 10-m Cassegrain antenna for CS (C-band) were implemented. The 13-m Cassegrain antenna was fed by a four-reflector beam waveguide system. At NTT Yokosuka Electric Communications Laboratory, a 12.8-m Cassegrain antenna was developed in 1972 that was capable of operating in both Ka-band and C-band. The 1.5-m sub-reflector was fed by a two-reflector beam waveguide system [56], [57].

For the CS experiments, various types of antennas were developed. The offset Cassegrain antenna with an 11.5-m aperture diameter was representative and innovative. The aperture distribution was optimized by reflector shaping of sub- and auxiliary reflectors. The gain was 68.7 dBi (29.25 GHz) and 65.8 dBi (19.45 GHz) corresponding to an aperture efficiency of 60% and 69%, respectively. The sidelobe characteristics were roughly 10 dB better than conventional symmetric reflector antennas. Since the main dish was installed almost horizontally, as shown in Fig. 11, it had an advantage in terms of the mechanical design (i.e. anti-wind) [58]–[61].

An 11-m Cassegrain antenna for transportable C-band earth station and two types of vehicle mounted earth stations with 3-m Cassegrain (C-band) and 2.7-m Cassegrain (Ka-band) were developed, too. Another idea to make a small earth station attractive was to utilize an elliptical beam to simplify the tracking system, since the CS movement viewed at earth stations was almost along the north-south plane. A highly efficient elliptical offset Cassegrain antenna was developed utilizing a reflector shaping method. The aperture was an ellipse of 4.7 m by 2.3 m achieving a gain of 58.6 dBi (27.65 GHz) and 55.0 dBi (17.85 GHz). An ellipti-

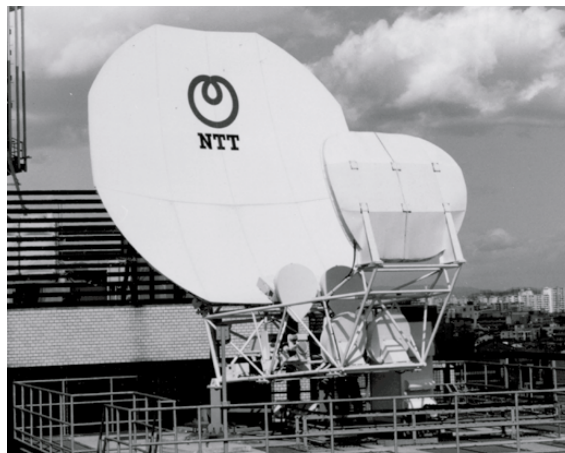


Fig. 12 Dual beam antenna for CS-3a/CS-3b.

cal aperture was also applied to C-band small earth stations using an offset parabola antenna of 2.4 m by 1.35 m (1.8-m effective diameter), or 3.2 m by 1.8 m (2.4-m effective diameter). The gain of 1.8-m effective aperture was 39.5 dBi (6.345 GHz) and 35.8 dBi (4.015 GHz) while that of 2.4-m was 41.8 dBi (6.345 GHz) and 38.5 dBi (4.015 GHz) [62]–[67].

In 1983, the second-generation CS series, CS-2a and CS-2b, were launched by the Japanese rocket, N-II, and commercial services were introduced. CS-2 was the first satellite in the world by which Ka-band spectrum was utilized commercially in satellite communications. Also, the second generation of the BS series, BS-2a and BS-2b, were launched by the Japanese H-I rocket in 1984 and 1986, respectively. Thus, in the mid 1980's, a large number of earth stations were implemented all over Japan.

When the follow-on CS series, CS-3a and CS-3b, were launched by H-I rockets in 1988, NTT devised a new telecommunication network called DYANET (Dynamic Channel Assigning and Routing Satellite Aided Digital Networks) that had a harmonized architecture of terrestrial and satellite networks with a common alternative routing system. For the DYANET, since full-mesh topology was preferred, a dual-beam antenna was developed. The 30/20 GHz-band dual-torus reflector antenna shown in Fig. 12 could access simultaneously to CS-3a and CS-3b, which were separated from each other by 4° in orbit. The main and sub-reflectors were of torus type and fixed on the ground and the sub-reflectors were fed by a primary system consisting a conical horn and two specially shaped auxiliary reflectors [68]–[70].

In 1988, two business corporations, JCSAT and SCC, were established to provide commercial satellite communications services using new satellites of their own. Thus, a variety of satellite networks and services were introduced. The need for multiple beam earth stations antennas were increased and a modified version of dual-torus antenna for DYANET-II earth stations was developed to access Ku-band (14/11 GHz) JCSAT-1 and JCSAT-2, simultaneously [71].



Fig. 13 Offset spherical reflector antenna at Osaka Teleport.

Another type of multiple beam antenna was developed in 1991, which utilized a spherical reflector of 6.5 m in diameter fed by a set of specially designed primary feed systems, as shown in Fig. 13. Up to four beams were simultaneously and independently steerable [72].

Smaller antennas for Ku-band VSAT were also developed. Various types of the antennas were installed on vehicles for SNG systems, which included Ku-band offset Gregorian antennas with an elliptical beam [73], [74], as shown in Fig. 14.

2.6 Radio Telescopes [76]–[92]

Reflector antennas have been in longer use for radio telescopes than for satellite communications. Radio emissions from a galaxy were first observed at 20 MHz by K. G. Jansky, USA, in 1932. It is a little known fact that the first observation of solar radio emission was made by Japanese engineers, M. Nakagami and K. Miya, in 1938. In Japan, radio astronomy became active in the late 1940's after World War II. Initially, an array of half-wavelength dipoles was utilized since the observation frequency was low. In 1951, a 2.5-m parabola antenna at 3.75 GHz was installed at Atmospheric Laboratory, Nagoya University, in Toyokawa. Since then, the laboratory tried to make arrays of parabola antennas for an interferometer at 4 GHz, 2 GHz and 9.4 GHz bands and, in 1962, a compound-interferometer at 9.4 GHz was developed as shown in Fig. 15, which was composed of eight 1.2-m parabola antennas with two 3-m parabola antennas. On the other hand, NRO (National Radio Observatory) in Mitaka, Tokyo, built a 10-m parabola antenna operating at 200 MHz with an equatorial mount system in 1953. In 1965, a 24-m spherical reflector was constructed, partly embedded in the ground as shown in Fig. 16. By using a 1.42 GHz line feed, which compensated spherical aberration, the antenna achieved an aperture efficiency of about 22–28% depending on the direction of the beam. Hiraiso branch of RRL was also equipped with several types of antennas for their observation [76]–[78].

Since the mid 1960's, large reflector antenna technologies developed for satellite communications systems have



(a)



(b)



(c)

Fig. 14 Vehicle mounted earth station antennas. (a) 2.4-m offset Gregorian, (b) 1.2-m offset shaped Gregorian, and (c) offset elliptical shaped Gregorian antennas.

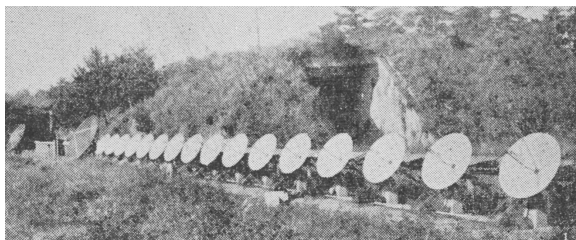


Fig. 15 Compound-interferometer at Toyokawa [77].

been directly applicable to radio telescopes. Actually some of the earth station antennas were modified to become radio telescopes. For example, the Kashima 26-m Cassegrain antenna was used for radio astronomy and opened Japan's history of VLBI (Very Large Baseline Interferometer) ob-

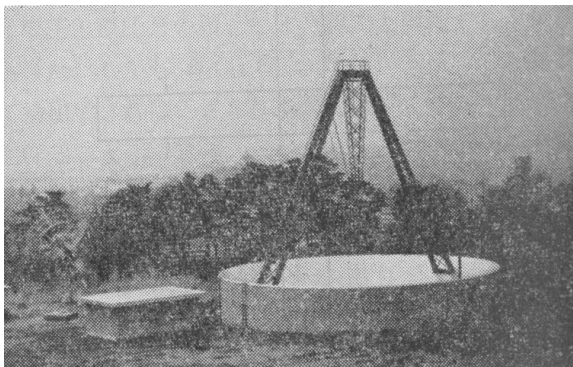


Fig. 16 24-m spherical reflector antenna at Tokyo (Mitaka) [77].



Fig. 17 34-m Cassegrain antenna at Kashima.

servation from the late 1970's. It successfully measured the distance between Japan and USA at an accuracy of 2 cm in 1984 and proved the relative movement of the North American and Pacific plates in 1985. The VLBI activities were enhanced when a 34-m Cassegrain antenna shown in Fig. 17, was constructed at Kashima in 1988. The antenna was designed to operate at six frequency bands from 1.5 GHz to 43 GHz. In 1992, the older Kashima 26-m antenna was transferred to GSI (Geographical Survey Institute) from RRL for a VLBI station. For a newer VLBI station, GSI constructed a 32-m Cassegrain antenna at Tsukuba in 1998. Transportable 5-m and 3.8-m antennas for a VLBI station were also developed. Incidentally, in 2001, the Yamaguchi (No.4) 32-m Cassegrain antenna was also transferred to NRO, which will also be used for a VLBI project.

Japanese large reflector antenna technology climaxed when a 45-m radio telescope, shown in Fig. 18, was constructed at Nobeyama Radio Observatory, NRO, in 1981, which was located at 1350 m in altitude, appropriately chosen for a radio observatory. The huge telescope, which weighs 700 t, was designed to operate at 1.4 GHz, 1.6 GHz, 2.7 GHz, 5 GHz, 10 GHz, 15 GHz, 22 GHz, 30 GHz, 40 GHz, and 86 GHz bands. For lower bands, up to 5 GHz, the large reflector was front-fed at the focus of the reflector like a parabola antenna. On the other hand, for 10–86 GHz bands, a sub-reflector of 4 m in diameter was initially

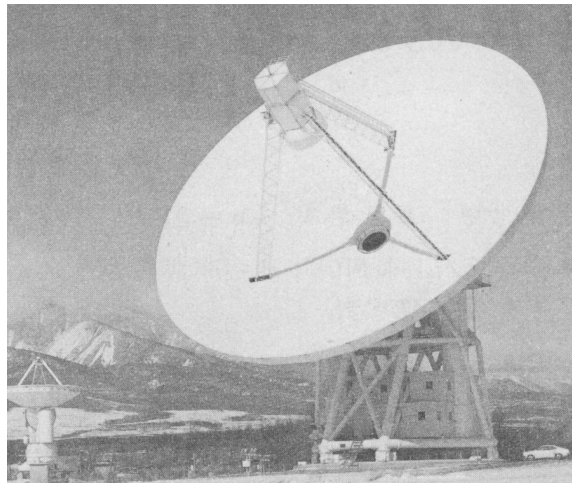


Fig. 18 45-m Cassegrain telescope at Nobeyama [84].

utilized to be a Gregorian antenna fed by a four-reflector beam waveguide with a Coude-type beam combining system. The main reflector had a homologous structure design to minimize the reflector deformation due to the gravity depending on the elevation angle. Homologous design copes with the deformation by adopting a flexible structure to suppress the higher deformation modes while enabling the adjustment of the position and angle of the sub-reflector according to the best-fit paraboloid of the deformed main reflector. Moreover, the 600 reflector panels were individually adjustable by an electric motor. Thus, a very high precision of 0.2 mm (rms) was achieved. The typical aperture efficiency was about 65% (5 GHz), 59% (22 GHz), and 20% (86 GHz) [79]. Later, the Gregorian sub-reflector was replaced by a Cassegrain sub-reflector of 3.8 m in diameter to reinforce the structure for higher pointing accuracy. The implication was that observation below 10 GHz at the prime focus would not be available. In 1990, the surface accuracy of the main reflector was improved from 0.2 mm (rms) to 65 μm (rms) by radio holography to enable observation of even higher frequency, up to 150 GHz. The aperture efficiency at 147 GHz measured in 1992 was $34 \pm 4\%$, corresponding to about 92 dBi. One of the well-known research achievements of the telescope was the discovery of huge black-holes in 1995 (together with a USA group) and in 2001 [80].

Large-scale aperture synthesis antennas for interferometers were also developed at Nobeyama, including a 12-element grating array of 17-GHz 1.2-m parabolas for a solar radio interferometer [81]. In 1982, 10-m Cassegrain antennas were developed for the 5-element super-synthesis telescope shown in Fig. 19. The operating frequencies were 22 GHz and 115 GHz bands selectable by replacing the feeder. The main reflector surface accuracy was below 0.15 mm (rms) and the 1-m sub-reflector was fed by a Coude-type four-reflector focused beam waveguide. The antennas were movable on rails along the north-south and east-west baselines [82]–[85]. In 1996, the antennas were upgraded to achieve higher efficiency by applying the reflector shaping

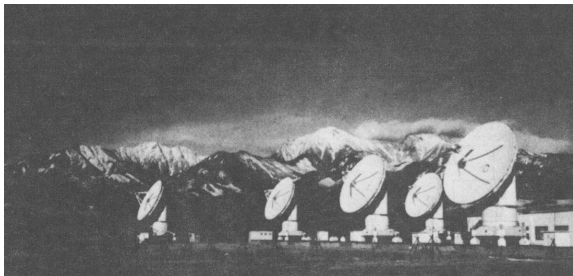


Fig. 19 10-m radio interferometer at Nobeyama [84].

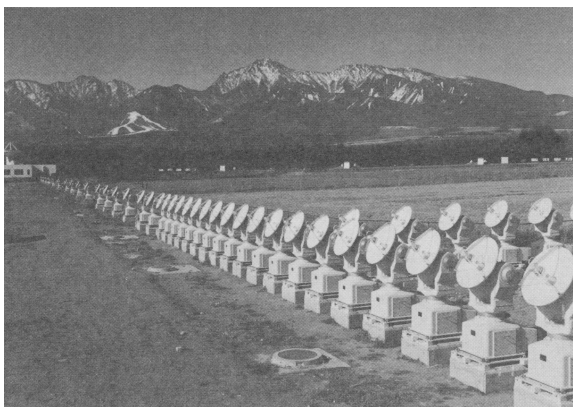


Fig. 20 Radioheliograph of 84 parabolae at Nobeyama [89].

to the pair of reflectors in the beam waveguide system [86], [87].

Another example of aperture synthesis antennas was a radioheliograph developed in 1992 at Nobeyama. It was dedicated for solar radio observation and consisted of eighty-four 80-cm-diameter antennas arranged in Tee-shaped array extending 490 m east-west and 220 m north-south as shown in Fig. 20 [88]. The operating frequency was first at 17 GHz only then the antenna was enhanced to be compatible with dual-frequency of 17/34 GHz by introducing a frequency selective sub-reflector in 1995 [89]. There were also a 2-element 80-GHz radiometer and a 35-GHz polarimeter on a common equatorial mount in Nobeyama [90].

As far as the physical size of the reflector is concerned, the largest antenna ever constructed in Japan is the Usuda 64-m Cassegrain antenna shown in Fig. 21 constructed in 1984. It was with the earth station for deep space communications at S-bands or X-bands, e.g. Halley's comet explorers Sakigake and Suisei, Mars explore Nozomi, and Earth's magnetotail observation satellite Geotail. The main reflector, which was designed based on a homologous structure, consisted of 1152 panels and the 6-m sub-reflector was fed by a four-reflector beam waveguide. The surface accuracy was 1.5 mm (rms) and the gain at 2.293 GHz was 62.6 dBi (77%). Later, the antenna was so modified that it could receive 1.6-GHz, 4.9-GHz, and 22-GHz signals simultaneously and be used as a radio telescope, too. The gain was 57.5 dBi (49%), 68.9 dBi (72%), and 76.6 dBi (21%), respectively [91], [92].

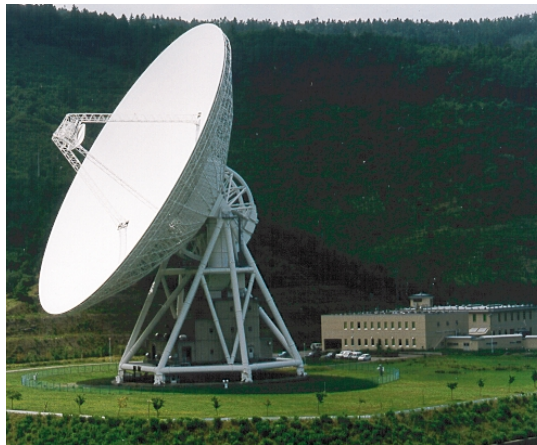


Fig. 21 64-m Cassegrain antenna at Usuda.

3. Earth Station Antenna Design Technologies

3.1 Auto-tracking Systems [93], [94]

A fundamental difference of antenna requirements for earth station antennas from those for terrestrial fixed microwave relay stations is the necessity for tracking. A mono-pulse tracking system was developed from the very early stage of space communications. The first experimental antenna at Ibaraki Laboratory had a dedicated tracking antenna with a cluster of four square horns, which outputs were mixed by four hybrids to produce a reference signal and a couple of orthogonal error signals as shown in Fig. 22 [93]. Although the method was reliable, another antenna for communications was required. The 30-m Kashima Cassegrain was equipped with different type of mono-pulse tracking system allowing a shared antenna, which was a higher mode auto-tracking system. The Yamaguchi TTC&M/IOT antenna used a combination of not only TM_{01}^o mode but also TE_{01}^o mode as higher modes, as shown in Fig. 23, since it was required to operate with an arbitrarily polarized, elliptical in general, electromagnetic wave [94].

For a small earth station antenna with a wide beam width with respect to the station keeping accuracy of a geostationary satellite, a less expensive step-track system became applicable. A beam is continuously steered, within

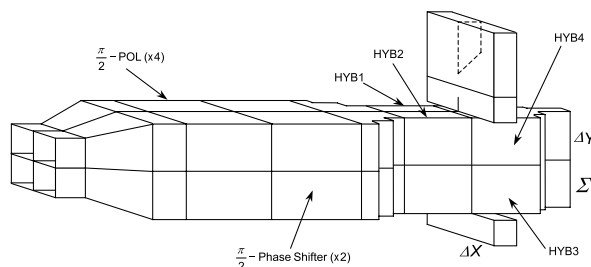


Fig. 22 Four-element array horn for simultaneous lobing (circular polarization).

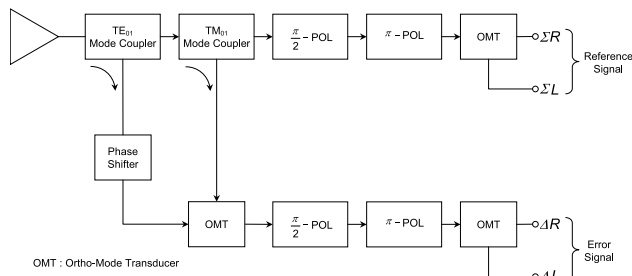


Fig. 23 Higher mode mono-pulse feeder for arbitrarily polarized wave.

Multi-Mode				Hybrid-Mode	
Step	Dielectric Loaded	Multi-Flare	Continuous Flare	Corrugate	Ring-Loaded Corrugate

Fig. 24 Various types of conical horns.

the main lobe beam width, to search for the right direction by maximizing the beacon signal level.

3.2 Primary Horns [95]–[104]

To broaden the frequency bandwidth of a primary feed horn was a big challenge for realizing wideband and dual-band earth stations. Also, pattern symmetry and polarization purity were important for sidelobe reduction and frequency reuse by orthogonal polarizations. Various types of conical horns have been studied as shown in Fig. 24.

Obviously, a simple conical horn was not adequate because of its asymmetrical characteristics of the aperture field distribution. A step horn, sometimes called a Potter horn [95], is of dual-mode type, i.e. TE_{11}^o plus TM_{11}^o , but has a narrow bandwidth. Another type of dual-mode horn was a dielectric loaded horn, which was used as an INTELSAT-VI satellite-borne global beam antenna because it could shape a beam pattern [96], [97].

A corrugated horn of hybrid-mode type exhibited a wide bandwidth [98] and well-designed corrugated horns were widely adopted for INTELSAT earth stations. Further broadening of bandwidth was achieved by a ring-loaded corrugated waveguide [99], [100]. Although the characteristics of corrugated horns were satisfactory, the disadvantage of structural complexity remained. For a lighter and less expensive horn, multi-mode horns were studied [101], including a triple-mode horn of double flare type developed for Ku-band VSAT [102]. Recently, a compact dual-band horn was proposed which had an optimized, continuous cross-section [103], [104].

3.3 Beam Waveguide Feeds [105]–[113]

A beam waveguide feed system allowed a receiver and trans-

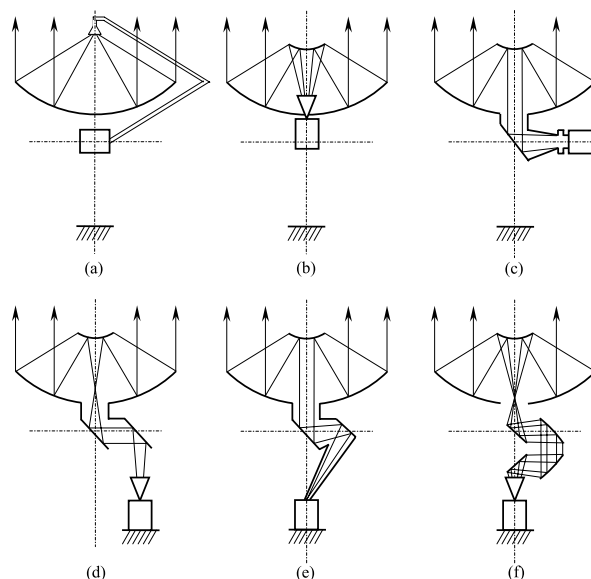


Fig. 25 Cassegrain reflector systems and beam waveguide feeds. (a) Front fed parabola. (b) Cassegrain. (c) Near-field Cassegrain fed by a horn-reflector. (d) 2-reflector beam waveguide. (e) Folded horn-reflector feed. (f) 4-reflector beam waveguide.

mitter to be located fixed on the ground regardless of the antenna orientation. The evolution of large antenna feed systems are depicted in Fig. 25.

A front fed parabola antenna has the disadvantage of a large loss of feeder, whereas a Cassegrain antenna makes it possible to be fed by a primary horn located behind the main reflector. The early stage of Cassegrain antennas for space communications had low aperture efficiency as shown in Table 2. The reason was two-fold. First, the reflector surface accuracy was poor. Second, since the phase center of the primary horn observed by the sub-reflector (at the near-field of the horn) was not on the horn aperture, a phase error was added [105]. After the phase characteristics of the horn were investigated, a near-field Cassegrain antenna was adopted, which was fed by a horn-reflector [106]. It had an advantage in terms of bandwidth and, moreover, an elevation axis rotary joint allowed the orientation of receiver and transmitter free from elevation angle.

The concept of a beam waveguide was originated by Goubau and Schwering [107]. In Japan, a beam waveguide feed system with two reflectors [108] was applied to the Yokosuka 12.8-m Cassegrain antenna, the mechanical azimuth axis was offset with respect to the feed. To eliminate the offset configuration, a folded horn-reflector was proposed and applied to an earth station in Europe. Instead, a four-reflector waveguide feed system [109], [110] was developed in Japan, which became the de facto standard of large earth station antennas, allowing a wheel-and-track mount instead of a conventional yoke-and-tower mount. A beam mode expansion is appropriate in the analysis and design of beam waveguide [111]–[113].

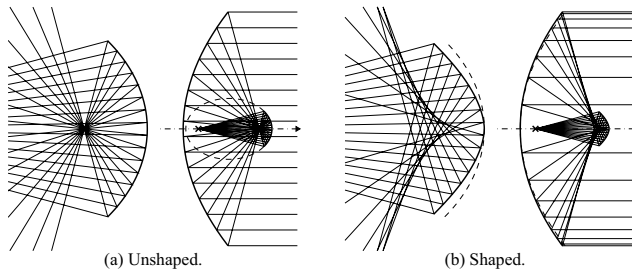


Fig. 26 Shaped dual-reflector antenna. The left half of the diagrams shows an enlarged picture around the sub-reflector.

3.4 Reflector Shaping [114]–[120]

Apart from the feeding configuration, another important advantage of Cassegrain antennas over parabola antennas is the applicability of reflector shaping [114], [115] because of the additional degree of freedom using a dual-reflector system. By reflector shaping, i.e. slight modification of reflector surface from a quadratic surface of revolution, the aperture field distribution can be so controlled that trade-off between the efficiency and the sidelobe characteristics becomes possible. For axially symmetric dual-reflector system, shaped reflector synthesis based on geometrical optics can be carried out by solving a set of ordinary differential equations. Example cross-sections of a dual-reflector system of Gregorian type are shown in Fig. 26.

When the electrical size of the sub-reflector, i.e. the size with respect to wavelength, is small, the diffraction effect needs to be taken into account. Considerations were given and incorporated for the INTELSAT earth station antenna design [116], [117]. Also, the optimum aperture distribution which maximizes the aperture efficiency under the sidelobe level constraints was given taking account of the sub-reflector blocking effect [118].

The shaping technique was also studied to apply to sub-reflector struts. The cross-section of struts was investigated to reduce the wide-angle sidelobes [119] and saw-shaped fins were added to the struts of the 34-m Yamaguchi No.2 INTELSAT earth station antenna, as shown in Fig. 27, so that the superior side lobe characteristics were achieved for not only the reference polarization but also cross-polarization [120].

Frequency selective surfaces (FSS) were also applied to earth station reflector antennas and radio telescopes. One example shown in Fig. 28 is the sub-reflector of the Nobeyama radioheliograph for selectivity of 17 GHz from 34 GHz bands, which was achieved by a Jerusalem cross pattern of the convex FSS reflector [89]. Many other FSS examples could be given that are used to select a certain band in a multiple-band beam waveguide.

3.5 Cross-polarization Compensation [121], [122]

Because the elevation angle of INTERSAT IOR satellites viewed at the Yamaguchi satellite communications center is

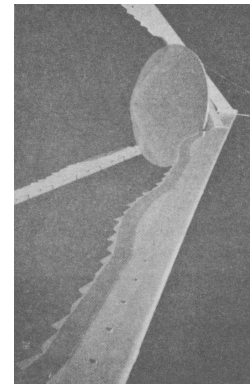


Fig. 27 Shaped sub-reflector struts for wide angle sidelobe reduction [120].

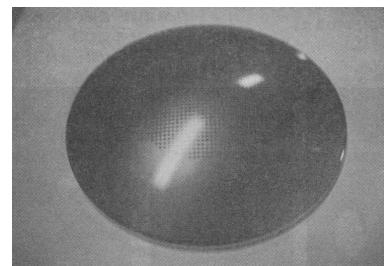


Fig. 28 Frequency selective reflector [89].

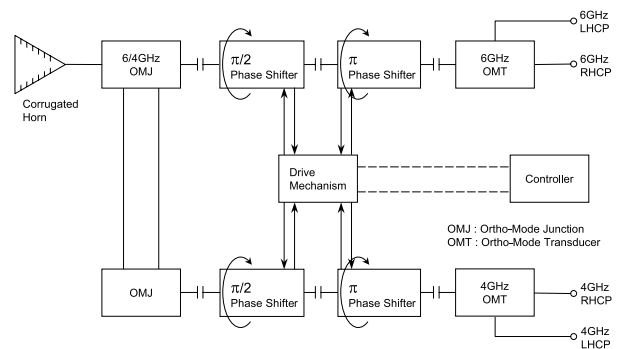


Fig. 29 Block diagram of cross polarization compensation equipment.

low (about 6°), the cross polarization discrimination (XPD) is deteriorated by differential attenuation and differential phase shift due to rain. This was a problem to be solved for communications with INTELSAT-V series satellites since dual-polarization was utilized in order to double the capacity [121], [122]. Therefore, a cross-polarization compensation network, as shown in Fig. 29, was developed. The compensation for the degradation of polarization purity is automatically achieved by controlling the position angles of two independently rotatable 90° and 180° phase shifters incorporated in the feed system [27].

3.6 Offset Dual Reflector Antennas [123]–[129]

In principle, an offset reflector configuration free from the

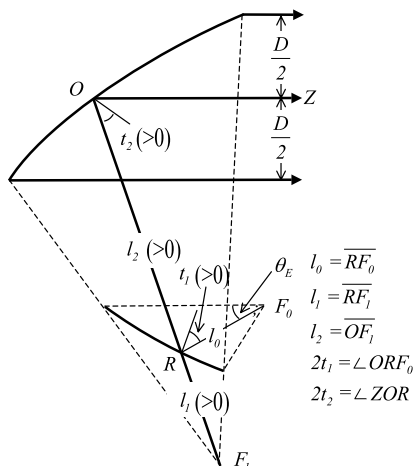


Fig. 30 Cross polarization cancellation condition.

blockage of primary horn, sub-reflector, and struts has a great advantage in achieving low sidelobe characteristics. Although a large aperture greater than about 15 m is difficult to construct due to the asymmetrical structure, it is appropriate to apply an offset configuration for small earth stations for urban areas requiring very low sidelobe levels. Because of the asymmetrical nature of an offset system, the radiation characteristics, especially polarization purity, could suffer. However, a proper combination of asymmetry of a main reflector and that of a sub-reflector can eliminate mutually the asymmetrical nature and achieve high performance in terms of both sidelobes and polarization purity. The condition was first derived by Japanese engineers [123]–[126] and commonly called Mizugutch’s condition in the USA and Europe. The zero cross-polarization condition, using the parameters in Fig. 30, is given by

$$l_0 = -Ml_1$$

$$M = \frac{\tan t_1}{\tan t_1 + \tan t_2}$$

where the sub-reflector shape and parameters are related as follows.

i) Gregorian:

$$l_0 > 0, l_1 > 0, t_2 > -t_1 > 0, M < 0$$

ii) Cassegrain (convex):

$$l_0 > -l_1 > 0, -t_1 > t_2 > 0, M \geq 1$$

iii) Cassegrain (concave):

$$-l_1 > l_0 > 0, t_2 > 0, t_1 > 0, 0 < M \leq 1$$

The condition has been generalized to include multiple-reflector systems with three or more reflectors, since a series of mirrors of quadric surface of revolution is equivalent to an offset parabola in terms of geometrical optics [127].

Another problem with an offset dual-reflector system

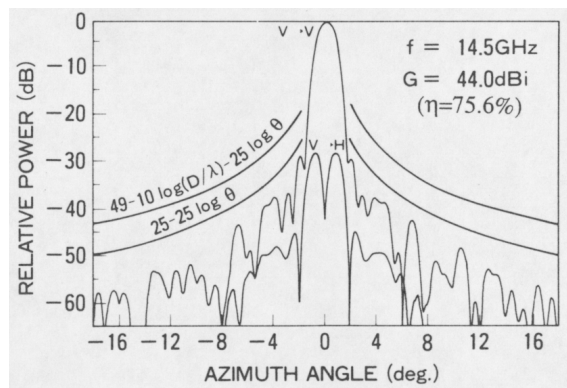


Fig. 31 Near axis sidelobe characteristics of shaped offset Gregorian antenna [128].

was that the reflector shaping method had not been established because of confusion in solving the partial differential equations; a total differentiation condition needed to be taken into account. Moreover, when the electrical size of the sub-reflector becomes less than about 10 wavelengths, a reflector synthesis based on geometrical optics begins to fail. The optimization technique was developed to synthesize a shaped reflector system using physical optics and was applied to a 1.2-m Ku-band offset shaped Gregorian antenna for a VSAT, which achieved ultra-low sidelobe characteristics as shown in Fig. 31 [128].

If a main reflector size is relatively large (e.g. 5 m or larger), it is practical and convenient to utilize an offset parabola for the main reflector fed by shaped sub- and auxiliary reflectors controlling the aperture distribution [129] in a tri-reflector system. The design method was applied not only to the Ka-band offset Cassegrain earth station for domestic CS but also to the Ku-band offset Gregorian earth station for INTELSAT IBS.

3.7 Steerable and Multiple Beam Antennas [69]–[72], [130]–[142]

As far as geostationary satellites are concerned, since the relative movement of a satellite is limited, it was natural to study a reflector antenna configuration that allowed the use of a fixed large reflector with an independently movable feed system. Along the line, COMSAT, USA, lead an initial experiment based on a parabolic torus antenna [130], [131].

3.7.1 Multiple Torus Reflector

A torus antenna uses a reflector surface of revolution, of which the cross-section curve is arbitrary but usually a parabola. Since the configuration unavoidably causes aberration, the aperture efficiency cannot be increased, especially when the electrical size of the aperture is large, except by introducing a phase correcting feed system. The DYANET offset antenna was of dual-torus type (offset Gregorian cross-section) and had a two-reflector phase correcting feed system as shown in Fig. 32 [69]–[71].

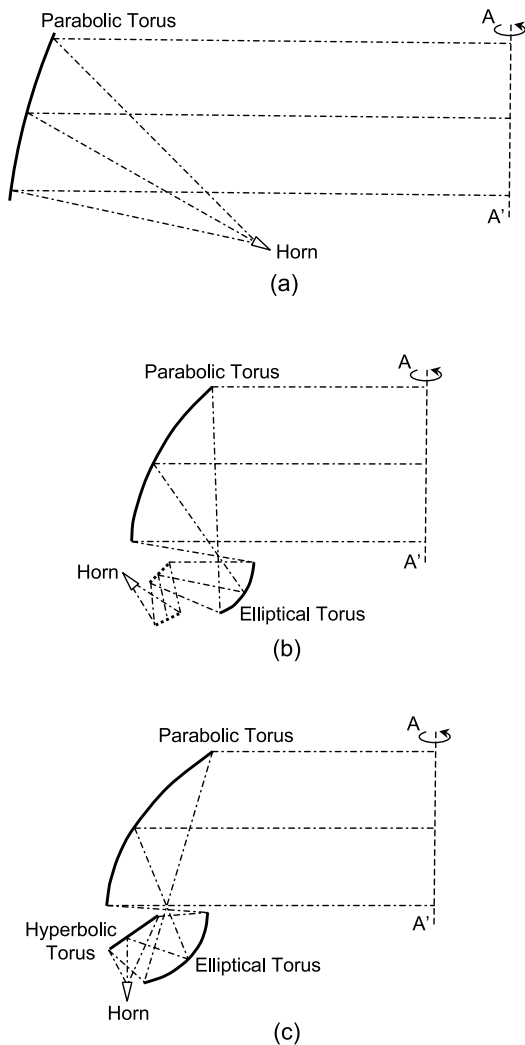


Fig. 32 Torus antennas. (a) Parabolic torus. (b) Dual-torus. (c) Triple-torus.

Another offset torus reflector system with three toroidal reflectors was studied, though it was not specifically designed for earth stations. The cross-section curve of the main, second, and third reflector was a parabola, ellipse, and hyperbola, respectively. The key feature of this reflector system was that all of the three reflectors were toroidal with the same rotational axis A-A'. The parameters of those cross-section curves as well as the distance between the main reflector and the principal axis were optimized to minimize the aberration over the aperture without a phase correcting auxiliary reflector. The experimental antenna achieved a gain of about 42.2 dBi with an effective aperture diameter of 50 wavelengths [132].

3.7.2 Spherical Reflector

The most famous spherical reflector in the world is the 300-m spherical telescope at Arecibo Observatory, Puerto Rico [133]–[135]. The 24-m spherical telescope at Mitaka, To-

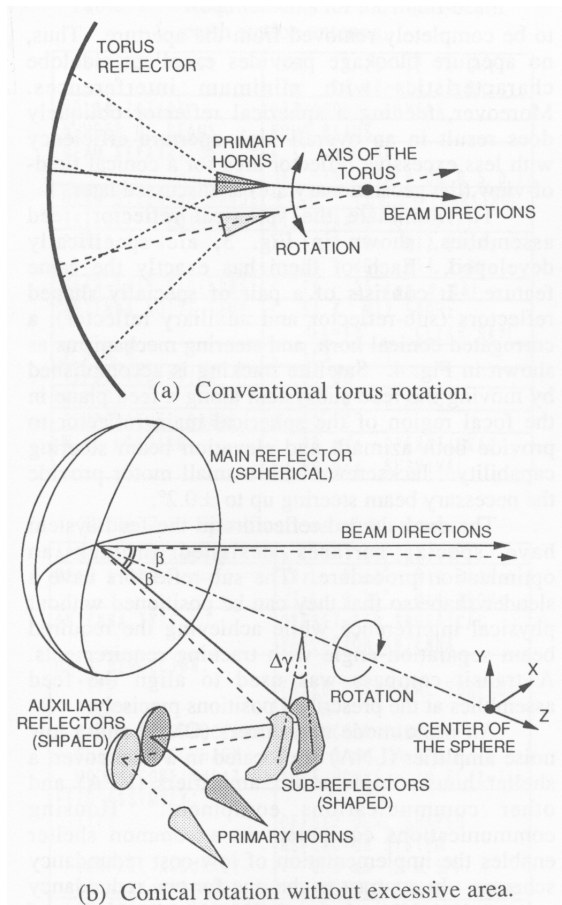


Fig. 33 Spherical antenna compared with conventional torus reflector.

kyo, is of the same category. The technology exploited by the 6.5-m offset spherical reflector antenna described in Sec. 2.1 was, however, much more advanced. The advantages of the spherical reflector over the torus reflector are two-fold. First, the former possesses fully symmetrical features with respect to its center enabling two-dimensional steering and the tilted feed arrangement is possible which requires less reflector area. Second, a high-precision reflector surface is easy to manufacture, evaluate, install and adjust because of the uniform curvature and simple structural configuration. The scheme of the tilted feed arrangement is shown in Fig. 33. The spherical aberrations were compensated for by the two specially shaped auxiliary reflectors [72], [136], [137].

3.7.3 Other Reflector System

Other reflector antennas studied for multiple beam applications included a multi-focus system and a composite reflector system. An offset bifocal dual-reflector system with no aberration in two directions was invented that had a satisfactory beam scanning characteristics along a plane including the foci [138]. An offset multi-focal dual-reflector had more than 2 quasi-foci, 6 in the experimental antenna, by optimally synthesize the two reflectors [139]. For a composite



Fig. 34 Single reflector dual beam antenna with 60° beam spacing angle.

reflector, a composite of two paraboloids were first investigated and, then, a composite of a torus and two paraboloids on both ends of the torus was proposed [140],[141]. As a less complex, inexpensive antenna for TV reception only (TVRO), a single reflector antenna capable of producing a wide beam-spacing multiple beams (60° separation) was developed based on detailed investigation of aberrations of an offset parabola [142].

4. Antenna Measurement Technologies

4.1 Gain Measurement Using Radio Stars [143]–[145]

The gain of a large antenna was difficult to measure precisely, since the distance between the signal source and the antenna under the test needed to be quite large to meet a far-field condition (or in a Fraunhofer region). A conventional method using a collimation system, which was installed at several kilometers away from the earth station, was often not appropriate even with calibration by defocusing and so forth.

A gain measurement method of large antennas using an artificial satellite was appropriate if the flux density of a satellite signal was exactly known. If this was not the case, a method using celestial radio sources such as Cassiopeia A (Cas A), Taurus A (Tau A), and Cygnus A (Cyg A) was applicable. The astronomical method was considered universal, since the radio sources were internationally available. The parameters, such as power flux density, source polarization, and brightness temperature distribution, were given in CCIR (now ITU-R) documentation, which were actually the study results of Japanese engineers back in the 1960–1970's [143]–[145]. It is noted that the Sun and planets, e.g. Mars, could also be used for gain measurement.

4.2 Radio Holographic Metrology [146]–[148]

For a large reflector antenna, the problem arises how not only to achieve surface accuracy but also to measure it. In

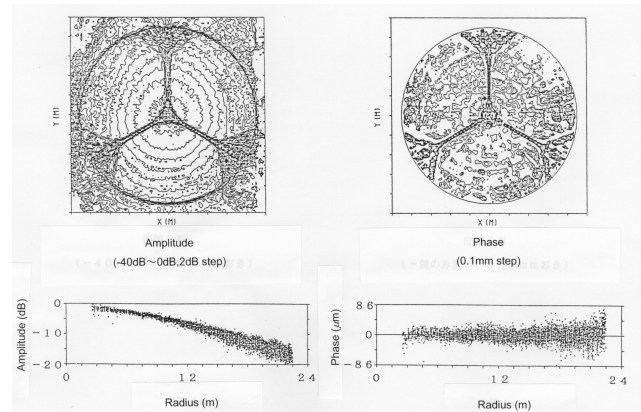


Fig. 35 Example results of holographic metrology of the Nobeyama 45-m Cassegrain antenna[146].

early days, only a mechanical method was available and an optical system, theodolite, was later introduced for a large reflector antenna. However, the method was time consuming and forced the antenna in a certain orientation. Radio holography opened a new solution to the problem. The principle is first to measure the far-field radiation pattern and then to convert it to the near field pattern, whose phase distribution over the aperture represents the surface error relative to the constant phase of a plane wave. The conversion from the far-field to the near-field can be done by FFT. The measurement method was applied to the Nobeyama 45-m antenna, where a phase coherent holograph was obtained using a small (0.45-m) reference antenna piggybacked behind the main feed system at the primary focus of the 45-m main reflector, since a reference signal was required for phase coherent detection of the far-field pattern measurements. It was reported that the surface accuracy of 0.15 mm (rms) was achieved based on the measurement using CS-2a and CS-2b satellites' beacon signal at 19.45 GHz . One of the results is shown in Fig. 34 [146],[147]. As described in Sect. 2.6, much higher surface accuracy of $65\text{ }\mu\text{m}$ (rms) was reported for the Nobeyama 45-m antenna [80].

Another type of radio holograph, the phase retrieval holograph, was applied to the Usuda 64-m antenna. Phase retrieval holography requires amplitude information only and no complex receiving system for phase coherent detection is required. In case of Usuda measurement, order, Misell's algorithm was utilized to retrieve the phase by measuring defocused far-field patterns as well as the original focused pattern. It was reported that by using ETS-V satellite signal at 1.545 GHz , the surface accuracy of 1.57 mm (rms) was achieved [148].

5. Concluding Remarks

This paper surveys Japan's numerous reflector antennas for earth stations and telescopes since the 1960's. The author hopes that the readers have gained a good understanding of how and to what extent Japanese antenna engineers and radio scientists have contributed to this field. It is noted that

the antennas included in the paper are not exhaustive but representative.

Acknowledgement

The author wish to thank Prof. T. Takano of The Institute of Space and Astronautical Science, Prof. Y. Karasawa of University of Electro-Communications, Prof. T. Hori of Fukui University, and Dr. S. Makino of Mitsubishi Electric Corp. for their providing me with the photographs and materials.

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