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30/20-GHz Band Earth Stations

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High-performance hardware for K-band (30/20-GHz) Earth stations, e.g., 300-W output power and 200-MHz bandwidth, 30-GHz high-power amplifiers, 80-K noise temperature, and 2.5-GHz bandwidth low-noise amplifiers, etc., have been developed recently. Two K-band Earth stations were constructed for experiments using a Medium-Capacity Communications Satellite for Experimental Purpose "CS." Presented here are K-band fixed-Earth-station design methods, basic subsystem performance, and experimental results using CS.

Introduction

A MEDIUM-Capacity Domestic Satellite Communications System[1] is being developed to provide circuit relief after failure of Japanese terrestrial transmission systems. This is accomplished by using K-band fixed Earth stations installed on the roof tops of telephone offices which correspond to regional centers in the overall Japanese telephony hierarchy.

Selection of the K-band was made after taking into consideration that 1) radio interference between terrestrial radio relay systems and satellite communication systems are slight, and 2) wide bandwidths are alloted for satellite communications. In the K-band, radio-wave attenuation due to rainfall is so severe that it is important to raise margins of the EIRP and G/T of the Earth station.

Research on K-band Earth-station equipment has been conducted since 1967. In 1972, a water-cooled 26-GHz high-power amplifier[2] and 18-GHz band low-noise amplifier[3] cooled by liquid helium were developed. An experimental K-band Earth station[4] was constructed in 1972 by integrating the above mentioned technologies. This Earth station is the first K-band Earth station for communication purposes in the world. Since 1972, improvement of Earth-station hardware performance such as output power, noise temperature, gain flatness, group delay, VSWR, weight, size, and reliability, has been continuing. To evaluate the total system performance through CS,[5] launched in 1977, two new experimental Earth stations were constructed using the technologies established by the research conducted since 1967.

This paper describes the novel design considerations and main characteristics of the newly developed K-band fixed Earth stations, including the main communication subsystems that obtained satisfactory results.

Medium-Capacity Domestic Satellite Communications System Outline

Medium-Capacity Domestic Satellite Communications System plans have been developed to be put into commercial use by 1983. In this system, two spin-stabilized satellites, i.e., prime and orbital redundant satellites similar to CS, will be used. Each satellite with a shaped-beam antenna, will have six K-band and two C-band transponders. The system outline is shown in Table 1. The K-band fixed Earth stations are used for two missions—communication between fixed Earth stations and communication between small transportable Earth stations and a fixed Earth station (type A). Both communication systems are to provide network relief after failure of transmission lines due to natural disasters such as earthquakes and storms.

The TDMA-60M[1] system was adopted for communication between fixed Earth stations. This system can transmit 960 one-way voice channels per transponder. In the communication between small transportable Earth stations and a fixed Earth station, the K-band fixed Earth station is used as a base station. A small transportable Earth station is composed of an antenna system and two containers which can be easily transported by truck or helicopter.

Experimental K-band Fixed-Earth-Station Configurations

Two experimental fixed Earth stations were constructed for CS experimental use. One was constructed in Yokosuka Electrical Communication Laboratory, NTT, located about 60 km south of Tokyo (the Yokosuka Earth Station). Another ws installed in a NTT telephone office in Sendai about 300 km north of Tokyo (the Sendai Earth Station). The fundamental configurations of two Earth stations are the same as commercial Earth stations. An example of the Sendai Earth Station configuration is shown in Fig. 1.

The RF transmitting system is composed of transmitting-frequency converters, 30-GHz high-power amplifiers (HPA), and a transmitting channel multiplexer. The IF signals are transmitted to a transmitting-frequency converter through a low-loss coaxial cable.

The RF receiving system is composed of two low-noise amplifiers (LNA)—prime and stand-by amplifiers—and receiving frequency converters. Receiving signals (six channels) are commonly amplified by a LNA. Each amplified signal frequency is converted to IF (1.7 GHz) and transmitted to the TDMA equipment and fm MODEMS through IF switching equipment and the coaxial cable.

The antenna tracking system is composed of a tracking receiver and an antenna controller.

Design Objectives of the K-band Fixed Earth Stations

The following design goals are considered: 1) stations should be as simple as possible in order to facilitate installation in telephone offices; 2) stations should be of high mechanical strength to withstand Earthquakes, storms, etc.; 3) system availability, including Earth-station equipment, should be larger than 99.5% in communications between every Earth station. System availability is limited by rain attenuation, ground-segment, and space-segment availability. Availability objectives for rain attenuation were set at 99.6%. Thus, Earth station EIRP and G/T had to be larger than 91 dB-W and 44 dB/K, respectively.

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Table 1 Medium-capacity domestic satellite communications system outline

	Communication between fixed Earth stations	Communication between remote island and mainland Earth stations	Communication between small transportable Earth station and fixed Earth station Type A	Type B	Type C
Frequency	30/20 GHz	6/4 GHz	30/20 GHz	6/4 GHz	6/4 GHz
Transmission mode	TDMA	TDMA	FM	FM	FM
Transmitting capacity	1920 two-way TP	192 two-way TP 2 color TV	132 two-way TP	60 two-way TP	1 color TV
Transponder number	4	1	1	1	1
Earth station	11.5-m antenna small Earth station	10-m antenna small Earth station	2.7-m antenna vehicle-mounted Earth station	3-m antenna vehicle-mounted Earth station	3-m antenna vehicle-mounted Earth station

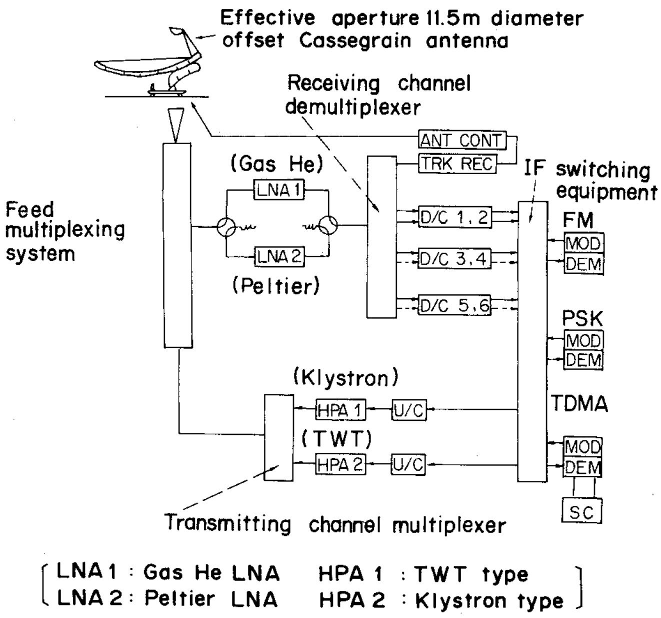

Fig. 1 Experimental K-band fixed Earth station configuration (Sendai Earth Station).

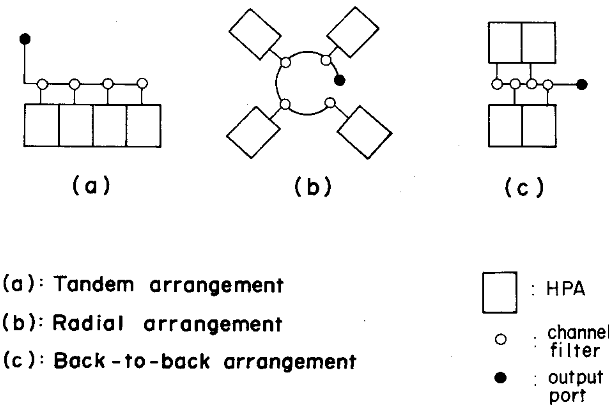

Fig. 2 High-power amplifier arrangements.

Antenna Subsystem Design

Communication system requirements for an Earth station are as follows:

1) Gain. In K-band, a radio wave suffers rain attenuation, therefore, antenna gain is required to be as high as possible. Antenna-gain objectives were 69 and 66 dB, in the 30- and 20-GHz band, respectively.

2) Sidelobe levels. In Japan, satellite downpath and terrestrial radio relay frequency commonly use the 20-GHz band. To avoid interference between systems, low sidelobe directivity is required over a wide angle range.

3) Installation on a building. The Earth station antenna is installed on the roof top of a telephone office building. Therefore, the antenna structure should be light, compact, wind resistant, and amenable to various installation requirements.

4) Mechanical requirements. High mechanical accuracy for mounting main reflector panels and for reflector axis alignment is required in K-band. This requirement is also necessary to ensure electrical performance without use of a collimation tower, which can not be constructed in large cities.

5) Tracking accuracy. A precise satellite tracking system is required due to the sharp beamwidth.

In order for Earth station antennas to satisfy the above-mentioned requirements, the axisymmetrical Cassegrain antenna[6] and the offset Cassegrain antenna[7] have been developed. The axisymmetrical Cassegrain antenna was installed at the Yokosuka Earth Station while the offset Cassegrain antenna was installed at the Sendai Earth Station.

The vernier autotrack system (VAT) was adopted to antenna tracking because of high tracking accuracy and low transmission loss. A phase-locked narrow-bandwidth beacon receiver (5-Hz bandwidth) has been developed to keep the rainfall attenuation margin above 40 dB. Antenna tracking subsystem performances are shown in Table 2.

RF Subsystem Arrangement

To obtain the higher EIRP and G/T, it is necessary to reduce waveguide loss between HPA and LNA and the antenna feeding system. Several possible HPA arrangements (tandem arrangement, radial arrangement, and back-to-back arrangement) are shown in Fig. 2. In Fig. 2c, HPAs can be more closely connected than with the other two arrangements. Consequently, the back-to-back arrangement was adopted. The HPAs and LNAs are directly connected to the feeding system as shown in Fig. 3.

High-Power Amplifier Design

Three hundred watts output power transmitters were necessary to achieve a 91.0 dBW EIRP. Two types of high power amplifiers were developed, i.e. TWT and Klystron types. Research on HPAs put emphasis on realizing high effective output power, a side bandwidth, simplification, and high stability performance.

HPA Output Circuit

To reduce waveguide loss, rational methods of arc detection (arc detector position and numbers), and reduction of high-power circulator loss, etc. were investigated. Before designing an RF output circuit, experiments on arc discharge in a waveguide were carried out for tube protection circuit

Table 2 Antenna tracking subsystem performance

Tracking method	VAT
Antenna mount method	Az-El
Antenna driving method	Limited steerable driving by two jackscrews
Tracking accuracy	0.01 deg rms and less
Tracking receiver receiving frequency	19.45 GHz ± 2 MHz
Threshold level	− 132 dBm (LNA input)

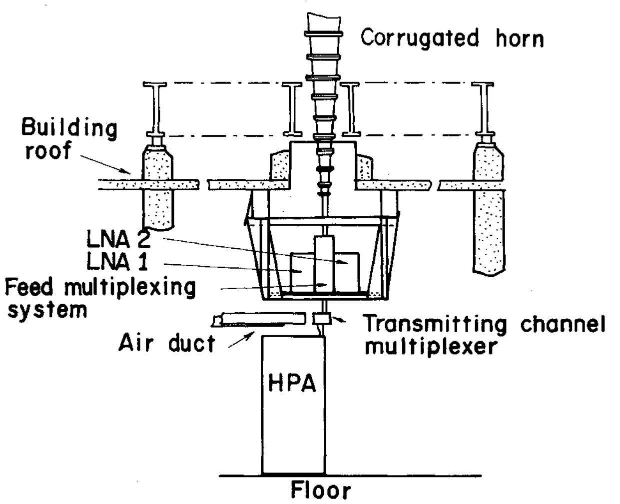

Fig. 3 RF equipment arrangement of experimental K-band fixed Earth station.

design. Through these experiments, arc photodetector numbers and optimum position were determined. The arc that is produced in the antenna feeding system can be detected by monitoring reflected RF power at HPA output port. Therefore, the tube protection circuit could be simplified and output circuit loss was reduced by 1.5 dB, compared with the water-cooled HPA[2] developed in 1972. A simplified RF circuit block diagram is shown in Fig. 4. Output RF circuit loss is about 1.0 dB.

Forced Air Cooling

The most effective air-cooling system for realizing a simplified and compact HPA was sought. A 750-W blower was selected under the condition that collector temperature was to be maintained below 160°C. Moreover, to suppress noise below 65 phone 1 m apart from the HPA, a hermetically sealed air-cooling system was employed.

TWT HPA Configuration

The RF circuit of TWT[8] is the coupled cavity type with three sections severed by carbonized bereyllia. High gain and stable characteristics are obtained. Beam focusing is done by a solenoid-type electromagnet.

The TWT HPA is composed of an amplifier and a power-supply bay. In the amplifier bay, a TWT, a blower, a low-loss RF circuit, and a low-voltage power supply are mounted; in the power-supply bay, high-voltage power supplies (collector and body voltage) are mounted. To realize a simplified and compact HPA, simple power-supply configurations are sought. Body voltage is given by a DC/DC converter. The DC/DC converter chopping frequency is raised to 10 kHz and input voltage—three-phase 200 V—is stabilized by a SCR. In this power supply, the high-voltage supply is shielded with Teflon and resin order to the utilization efficiency. As a result, a small-sized power supply is obtained. The amplifier frequency of TWT HPA can be electronically shifted over 3.5 GHz by changing the body voltage. The whole CS frequency range can be covered by one kind of TWT.

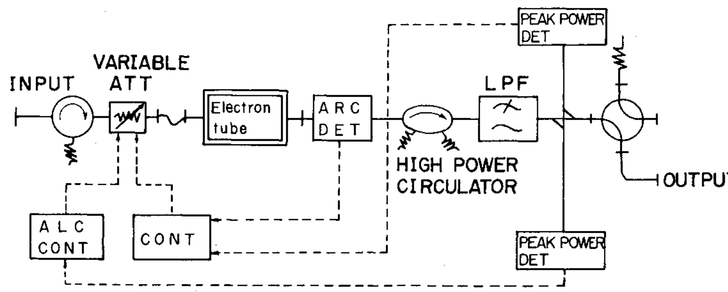

Fig. 4 High-power amplifier RF circuit configuration.

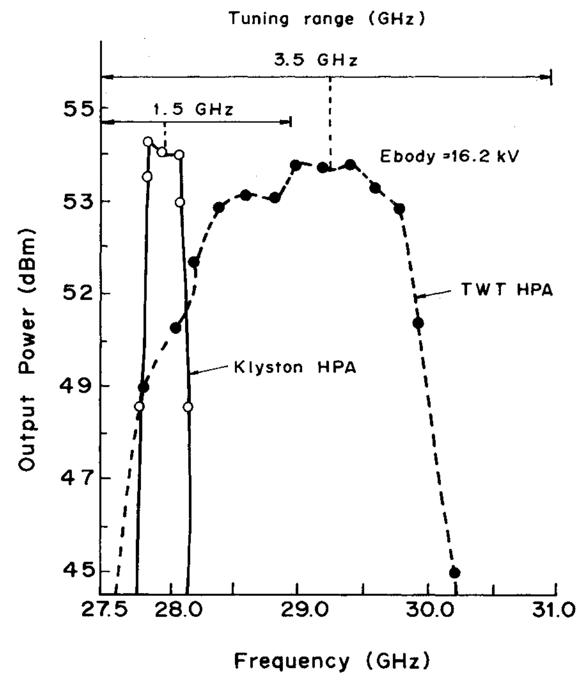

Fig. 5 Typical HPA frequency responses.

Klystron HPA Configuration

Six-cavity klystron has been developed recently. Beam focusing is done by permanent magnet. The resonant frequency of each cavity is controllable by adjusting the short plunger in the cavity. This mechanism offers rapid and precise changes in channel selection over 1.5 GHz by using the microprocessor control. Therefore, the whole CS frequency range of 2.5 GHz can be covered by two kinds of klystrons. An automatic power control was adopted because it responds to high-speed level changing like the burst signal used in the TDMA system.

Measured power frequency response of TWT and klystron HPAs are shown in Fig. 5 while output power and AM/PM conversion characteristics are shown in Fig. 6. Communication bandwidth are more than 200 MHz for both HPAs. A summary of the HPA electrical performance is given in Table 3.

Low-Noise Amplifier (LNA) Design

A low-noise temperature (100 K), wide bandwidth (2.5 GHz for CS), wide linearity range, and easy maintenance are required for a LNA. Two LNA types have been developed. One is a helium-gas-cooled parametric amplifier and the other is a Peltier-effect-cooled parametric amplifier. In this experimental Earth station, the helium-gas-cooled parametric amplifier is employed as the prime LNA and the Peltier-effect-cooled parametric amplifier as the standby LNA. In the helium-gas-cooling system, maintenance is required about once a year. The Peltier-effect-cooled parametric amplifier was adopted as a standby LNA because maintenance is very easy.

Table 3 HPA performance summary

	TWT HPA	Klystron HPA
1-dB bandwidth	200 MHz	200 MHz
Center frequency tuning range	3.5 GHz	1.5 GHz
Output power	200 W/200 MHz	200 W/200 MHz 300 W/150 MHz
AM/PM conversion coefficient	4 deg/dB max	2.2 deg/dB max
Noise figure	28.5 dB	44.3 dB
Cooling method	Forced-air cooling	Forced-air cooling
Consumed power	8.2 kW	6.4 kW

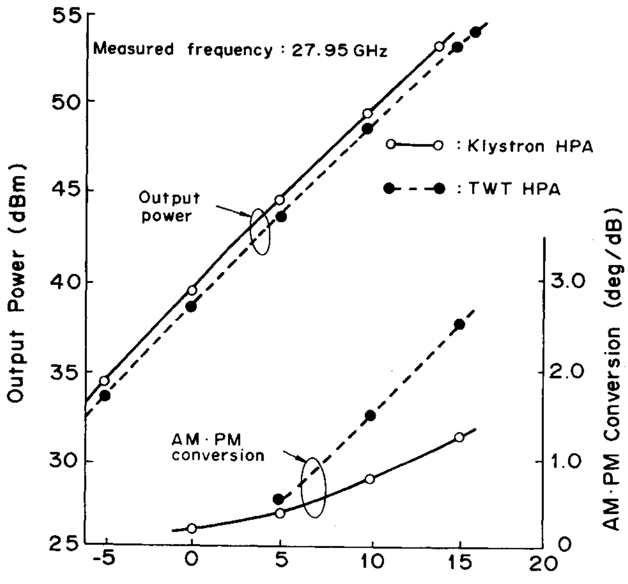

Fig. 6 Typical HPA characteristics.

The receiving G/T, when using the standby LNA, decreases by 1.5 dB during rainy periods with a 10-dB downpath loss. However, it is felt that the overall periods over which standby LNAs are used is very short in comparison with prime LNAs, and that such periods seldom coincide with periods of heavy rainfall. Therefore, total system availability degradation is negligible.

The parametric amplifier was designed considering the following points: a) low-noise operation, b) wideband operation, and c) realization of small-size equipment and high reliability.

Low-Noise Operation

Optimum diode parameters and packaging methods were investigated to obtain low-noise performance. The parametric amplifier noise temperature is given by Eq. (1). The higher dynamic Q is, the lower T_{e0} becomes. A high dynamic Q GaAs Schottky barrier varactor diode in a minidot package have been developed recently with dynamic Q of the varactor being about 4 at 20 GHz. Thus, Eq. (1) gives the optimum pumping frequency as 80 GHz:

$$\frac{T_{e0}}{T_s} = \left(1 - \frac{1}{G}\right) \frac{Q^2 (f_1/f_2)^2 + 1}{Q^2 (f_1/f_2) - 1} \quad (1)$$

where, T_{e0} is noise temperature; T_s is junction temperature, Q is dynamic Q at f_1, f_1 is input signal frequency, f_2 is idler frequency, and G is the gain.

Table 4 Low-noise amplifier performance

Bandwidth	2.5 GHz (17.75-20.25 GHz)
Noise temperature	80 K and less (helium-gas-cooled) 220 K and less (Peltier-effect cooled)
Gain	30 dB and more
Gain deviation	± 1 dB and less
Group delay deviation	± 1 ns and less
Input and output VSWR	1.2 and less

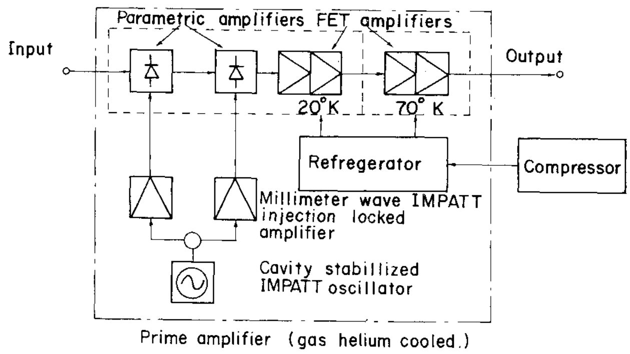

Fig. 7 Low-noise amplifier configuration.

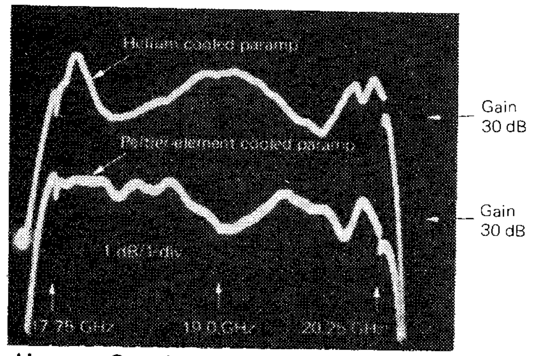

Fig. 8 Frequency responses of LNAs.

The parallel resonant frequency of the minidot-type package used in this amplifier is about 57.6 GHz. By using this frequency as the idler frequency, the pumping frequency is about 76.5 GHz. This is nearly equal to optimum pumping frequency giving the lowest noise temperature. Furthermore, the parametric amplifiers are cooled by helium-gas or Peltier-effect devices.

Wideband Operation

Two methods were tried to obtain the wideband characteristics. One was the employment of double-tuned characteristics using the new half-wavelength resonant-type input signal circuit between the input port and varactor mount. By this method, a one-stage parametric amplifier[9] with a 2-GHz bandwidth was developed. Another method was to spread the bandwidth by connecting two or more of the above wideband parametric amplifiers in cascade. Noise characteristics depend almost entirely upon the first- and second-stage amplifier noise characteristics. The higher the frequency the higher the noise temperature becomes. Therefore, the second-stage center frequency was set to the lowest frequency to get the inverse characteristic to the first stage. Consequently, the frequency response of both noise temperature and gain became almost flat.

Table 5 EIRP and G/T measured results of Sendai Earth Station (F3/f3 channel)

	Transmitting system (28.55 GHz)	Receiving system (18.75 GHz)
Antenna gain (dB)	62.9	65.9
Feed multiplexing system loss (dB)	0.29	0.54
Channel multi- and demultiplexer loss (dB)	1.3	1.9
Output power (dB-W)	24.8	...
System noise temperature (K)	...	125
EIRP (dB-W)	92.5	...
G/T (dB/K)	...	44.4

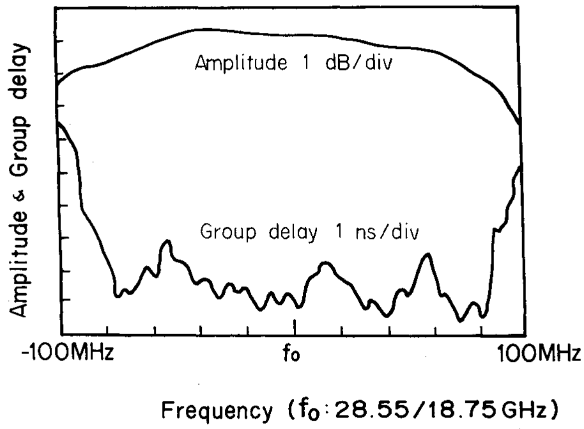

Fig. 9 Frequency response through CS (Yokosuka Earth Station).

Table 6 Comparisons of measured C/No with calculated C/No

			F1/f1 channel C/N_0^a	F5/f5 channel C/N_0^a
Sendai	Yokosuka	Measured	99.5	100.9
		Calculated	100.3	101.2
Yokosuka	Sendai	Measured	100.2	101.2
		Calculated	101.2	101.6

[a]Output power—100 W; weather—fine. Yokosuka LNA—Pelfier-effect cooled. SEndai LNA—helium-gas cooled.

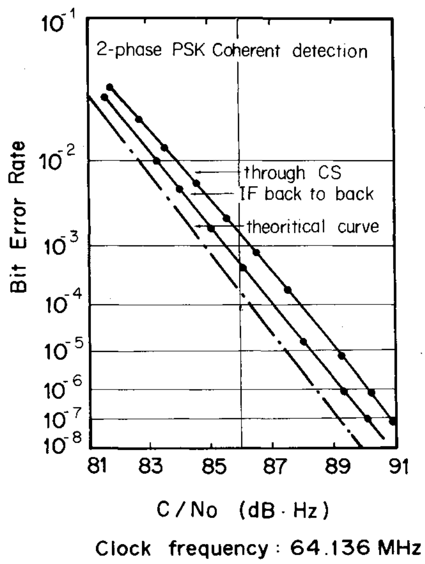

Fig. 10 Bit error performance vs C/N_0.

Realization of Small-Sized Equipment and High-Reliability Performance

GaAs MES FET amplifiers were used as post amplifiers to accomplish a reduction of amplifier stages. The pumping source is composed of a high-reliability solid-state circuit. The LNA configuration is shown in Fig. 7. The prime LNA consists of two-stage parametric amplifiers and four-stage GaAs FET amplifiers. The parametric amplifiers and the former two-stage FET amplifiers were cooled to about 20 K by adiabatic expansion of helium gas. The standby LNA is the same configuration as the prime LNA except that the parametric amplifiers are cooled to about $-50°C$ by Peltier-effect devices and that the FET amplifiers operate at room temperature. The pumping power source of both the prime and standby amplifiers is composed of an 80-GHz IMPATT diode oscillator stabilized by a high-Q cavity and IMPATT injection locked amplifiers.

Amplitude frequency response of the helium-cooled and Peltier-effect cooled LNAs are shown in Fig. 8. Performance characteristics of the LNAs are outlined in Table 4. All characteristics satisfied the design objectives.

Other Communication Subsystems

Transmitting Frequency Converters

This equipment is used to convert IF to a 30-GHz band frequency signal that has high enough power to drive HPA. Amplitude and delay equalizers for the transponder are used in IF stages. Three-stage IMPATT stable amplifiers are used in the final stage.

Receiving Frequency Converters

This equipment is used to convert the 20-GHz receiving signal to IF signals. Signal peak detected automatic gain control suitable for TDMA signals are used.

EIRP and G/T Measured Results of Experimental K-Band Fixed Earth Stations

Performances of the experimental K-band fixed Earth stations were measured. Measured EIRP, G/T, and circuit loss of the Sendai Earth Station F3/f3 channel are shown in Table 5. Experimental results satisfied the design objectives.

Experimental Results through CS

C/N_0 Characteristics

The carrier power to noise power density ratio, C/N_0, through CS was measured using the Sendai and Yokosuka Earth stations. Measured C/N_0 and calculated C/N_0 are shown in Table 6. Differences between measured and calculated C/N_0 values were less than 1 dB.

The required C/N_0 of TDMA-60M system is 86.7 dB-Hz ($BER = 1 \times 10^{-4}$ with error correction). Therefore, margins of the uppath and downpath, taking C/N_0 degradation due to spin into account, are 17.0 and 12.3 dB, respectively (including increasing the sky noise temperature). These margins correspond to availability of 99.9% and 99.95% in Sendai, respectively.

Transmission Characteristics

Frequency responses through CS using the Yokosuka Earth Station is shown in Fig. 9 under the condition when an equalizer is used. Deviation of amplitude and group delay are 1 dB and 2.4 ns in the $f_0 \pm 70$ MHz range, respectively.

Bit error rate performance through CS using the Sendai Earth Station and the Yokosuka Earth Station is shown in Fig. 10. The C/N degradation at an average bit error rate of 10^{-4} is about 2 dB from the theoretical value, and about 1 dB from TDMA IF loop back measured results.

Conclusion

Newly developed K-band fixed Earth stations and their RF subsystems showed satisfactory measured performance. The feasibility of 30/20-GHz satellite communication systems were proved. The developed Earth stations are the first ones in the world of their kind for communication purposes.

It is felt that the newly developed technologies in this paper contribute to the growth of 30/20-GHz band satellite communication systems in the world.

Acknowledgments

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