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Progress in and Prospects of On-Board Communication Equipment Technologies for Communications Satellites in Japan

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SUMMARY Communications satellites have been the primary mission from the early period of Japanese space development and their on-board communication equipment are the core devices to realize satellite communications systems. The technologies for this equipment have been developed to meet the requirements of high capacity and high functionality under the severe satellite-imposed constraints. This paper summarizes progress in on-board communication equipment technologies developed and verified by using Engineering Test Satellites and commercial satellites in Japan and describes their prospects.

key words: *on-board communication equipment, communications satellites, multi-beam satellite communication system, transponder, antenna reflector, on board processor, beam forming*

1. Introduction

In initial Japanese space development activities, communications satellites and broadcasting satellites were always one of the most important missions. Satellite communications systems have a number of advantages over terrestrial systems, including flexibility, and rapidity and ease of network construction. To fully marry those advantages with the Japanese public network, Nippon Telegraph and Telephone Corporation (NTT) has been carrying out research and development work on domestic satellite communications systems since the 1960s. The on-board communications equipment for those satellites is core devices.

The experimental communications satellite (CS) [1], [2] launched in December 1977 offered medium circuit capacities via a Ka-band transponder, which was developed first in the world by NTT. An experiment on the satellite in-orbit was successfully performed.

Commercial Japanese interests launched two communications satellites (CS-2a and -2b) launched in 1983, which were succeeded by the CS-3a and -3b [3], [4] launched in February and September 1988. The on-board communication equipment on those satellites was developed using new technologies. The in-orbit performance of some technologies was confirmed by using Engineering Test Satellite (ETS) before actual utilization.

ETS-IV allowed the High Power Amplifier (HPA) using GaAs FET to be verified in orbit. ETS-VI [5], launched in August 1995, allowed various technologies for on-board communication equipment for multi beam domestic satellite communications systems to be evaluated and verified. Those technologies were carried over to N-STAR [6] and subsequent satellites.

After ETS-VI and N-STAR, further advanced technologies for on-board equipment were developed by using COMETS (Communications and Broadcasting Engineering Test Satellite) [7], ETS-VIII [8] and WINDS (Wide band Inter-Networking engineering test and Demonstration Satellite) [9]. COMETS, though its launch in February 1998 regrettably failed, was aimed at verifying a Ka-band advanced mobile satellite system, a 21 GHz band advanced satellite broadcasting system, and a large-capacity inter-satellite data relay communication system. ETS-VIII, which was launched in December 2006, aimed at verifying technologies for an S-band super multi-beam mobile communication system with handheld terminals for domestic services. WINDS, which was launched in 2008, aimed at offering broadband Internet to digital divided areas. To accommodate broadband Internet traffic as much as possible, the Ka-band was used and fundamental technologies such as Ka-band active phased array antenna, satellite onboard modem and high speed baseband switch were developed. Many useful challenging on-board communication equipment technologies have been developed in Japan.

This paper is organized as follows: Section 2 describes requirements for on-board communication equipment while summarizing launched Japanese communications satellites. They are derived from satellite communication systems as well as the mass and power allocated to the equipment. Section 3 describes representative technologies such as transponder, antenna reflector, beam forming, and on-board processor in details for commercial or engineering test satellites. Section 4 describes prospects of factors to affect the performances and functions of on-board communication equipment. Then this paper is concluded.

2. Requirements for On-Board Communication Equipment

Since the launch of the first Japanese communication satellite named "CS", about 40 Japanese communications satellites,

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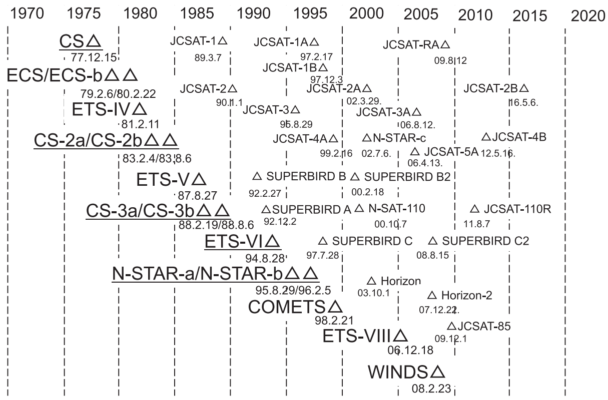

Fig. 1 Japanese communications satellites launched so far.

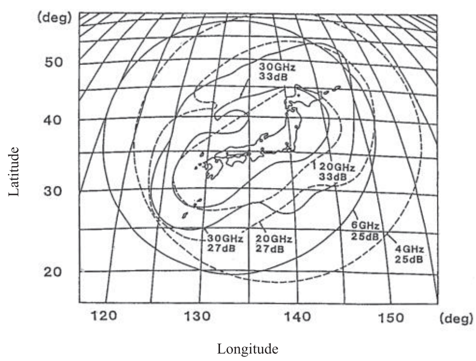

Fig. 2 Single beam coverage of CS-2.

such as CS series, N-STAR, JCSAT series, SUPERBIRD series, and ETS series have been developed and launched as shown in Fig. 1.

The technologies for on-board communication equipment were developed around two requirements packages. One was from the satellite communication system, the other from the severe limitations of total satellite weight, volume, and electrical power. The former mainly requires high capacity and advanced functionality. The latter focuses on light-weight, small-size, high efficiency in order to optimize the use of satellite resources such as payload and electrical power.

Early communications satellites such as CS, CS-2, and CS-3, are spin-stabilized and the service area for Japan is served by just a single beam as shown in Fig. 2. CS-2 and CS-3 are the successors to CS and the performance of their on-board communication equipment was greatly improved owing to the great increase in satellite mass. It is worth noting that the equipment was developed for and verified on commercial communications satellites.

Higher transmission capacity demands were satisfied by covering the service area with multi-beams as shown in Fig. 3. The service were offered by multi-beam satellite communication systems using the 3-axis stabilized communications satellites, which can accommodate much more communication equipment and generate much more electrical power. These multi-beam satellites are currently the main choice for high capacity. To cope with the traffic fluctuation among multi-beams, several on-board technologies such as Multi-Port Amplifier (MPA), On-board Processor (OBP) were developed. The technologies created in this development period were applied to commercial satellites after in experimental satellites such as ETS series, WINDS.

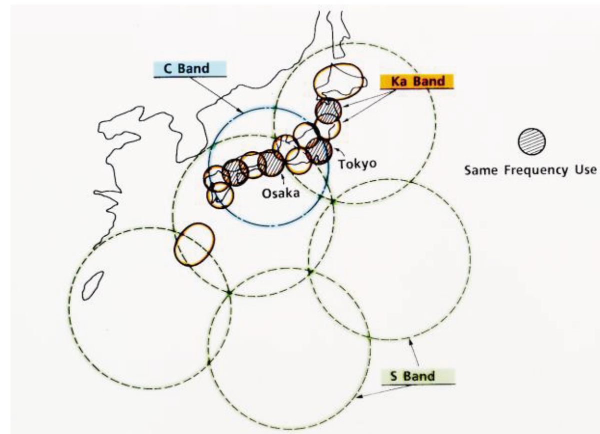

Fig. 3 Multi beam coverage of ETS-VI.

Table 1 On-board communication equipment technologies for Japanese communications satellites.

	Satellite communications system (Associated satellites)	
Technologies	Single beam (CS series)	Multi-beam (ETS series, N-STAR, WINDS)
System technologies	System architecture (C and Ka bands) - Transponder - Shaped antenna reflector	Multi-beam antenna -Large deployable reflector (S and Ka-bands) -Cluster feed, Phased array Resource allocation -S and Ka-bands-MPA -OBP (regenerative transponder, channelizer, DBF)
Hardware technologies	Ka Single conversion Ka High power TWTA C High power SSPA	Ka LNA (HEMT)

DBF: Digital Beam Forming TWTA: Traveling Wave Tube Amplifier SSPA: Solid State Power Amplifier HEMT: High Electron Mobility Transistor

Table 1 summarizes the technologies developed for Japanese communications satellites from CS to WINDS. In single beam systems, technologies are focused on light-weight and high power Ka-band transponders, which were realized as a world first. In the multi-beam system, technologies are focused on utilizing system resources such as frequency and electrical power efficiently with a great increase in total transmission capacity. These technologies are described in detail in subsequent sections.

3. On-Board Satellite Communication Technologies

Several technologies for on-board communication equipment were developed based on the requirements mentioned

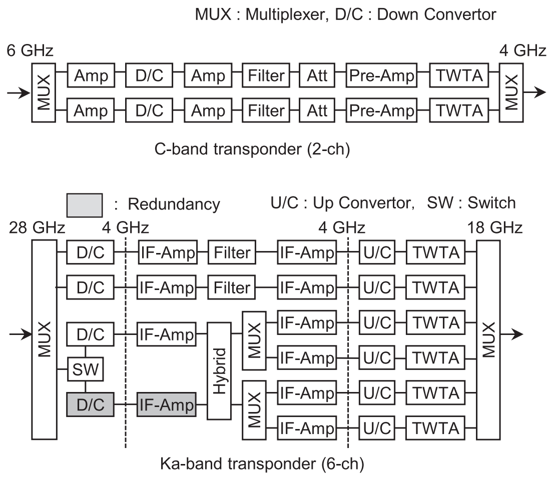

Fig. 4 Configuration of CS on-board communication equipment.

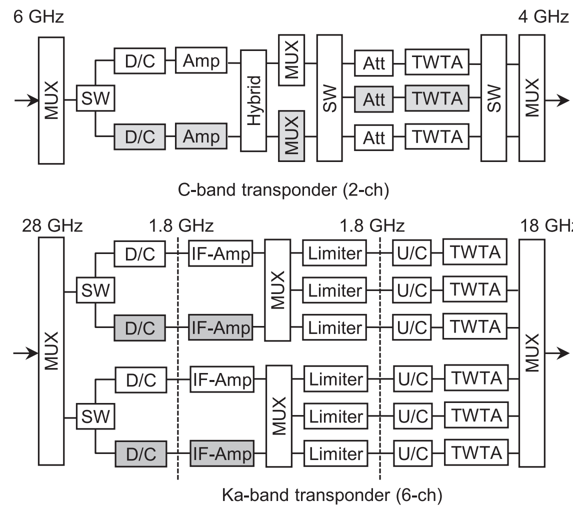

Fig. 5 Configuration of CS-2 on-board communication equipment.

above. Representative technologies are detailed in the following subsections, i.e., transponder, antenna reflector, beam forming, on-board processor, and specific features are clarified.

3.1 Transponder

This section describes satellite onboard transponder configurations and component technologies from CS to recent commercial and experimental satellites. The transponders described here are categorized as through repeaters, in contrast to regenerative transponders, because they just converts the frequency of the received signal to the frequency of the transmitting signal after amplification. A transponder fundamentally consists of amplifiers and a frequency converter, which composed of a local oscillator and a mixer. The development activities of transponder technologies have mainly targeted higher performance Low Noise Amplifiers (LNAs), frequency converters, High Power Amplifiers (HPAs) and the additional of new functions through advances in designs, materials, and circuits.

For the CS series, the goal was to develop a domestic onboard transponder for “Medium-Capacity Communications Satellite” [1]. CS, which was launched in 1977, had 6 transponders in the Ka-band (20/30 GHz) and 2 transponders in the C-band (4/6 GHz) as shown in Fig. 4. One transponder corresponding to Ka-band and C-band was domestically designed and manufactured. The domestically made Ka-band transponder amplifies and converts the 30 GHz received signals to 4 GHz IF (Intermediate Frequency) signals, which are then amplified and converted into 20 GHz transmitting signals. The intermediate frequency of 4 GHz was selected to match the transmission frequency band of the C-band transponder developed in parallel. CS satellites were equipped with a cross-link between Ka-band and C-band transponders. The IF band amplifier uses Si bi-polar-transistors. The Ka-band circuits use GaAs semiconductors. The C-band LNA is a reflect type amplifier using tunnel diodes [10].

CS-2, which was launched in 1983, had 6 transponders in the Ka-band and 2 transponders in the C-band as shown in Fig. 5, i.e. the same as CS. All CS-2 transponders were domestically produced. CS-2 transponders and their components had to be lighter and smaller than their CS equivalents, while offering lower power consumption, higher reliability, higher functionality, and higher performance.

Since the weight and power consumption budgets of the transponders were the same as those for CS, the savings in weight and power consumption achieved by these improvements were allocated to redundant transponders and the addition of new functions. Each band’s transponder receiver and transmitter used 1 : 1 and 1 : 2 redundant configurations, respectively. For higher functionality and performance, the Ka-band transponders were equipped with limiter amplifiers using GaAs Field Effect Transistors (FET) [11] so as to realize high efficiency TWTA operation against different input signal levels. In order to realize low noise and high gain, the IF frequency was changed to 1.8 GHz from the 4 GHz of CS. Variable attenuators using PIN diodes were used to support the Single Channel Per Carrier (SCPC) method. Moreover, to further reduce size and weight, many microwave integrated circuits [12] were adopted.

The satellite mass of CS-3, which was launched in 1988, was increased from the CS-2’s 350 kg to 550 kg. CS-3 has 10 transponders in the Ka-band and 2 transponders in the C-band as shown in Fig. 6 [13]. In the same way as CS-2, each band transponder’s receiver and transmitter used 1 : 1 and 1 : 2 redundant configurations, respectively.

To reduce size and weight, the Ka-band and C-band transponders adopted the single conversion method, a microwave integrated technology developed for ground radio communication systems that replaces waveguide based circuits with planer-line based integrated circuits. This contributed to a reduction in the Ka-band transponder weight of 20% compared to that of CS-2. The TWTA output power is double that of CS-2, and its electrical efficiency is approximately 8% higher by the use of technologies such as a

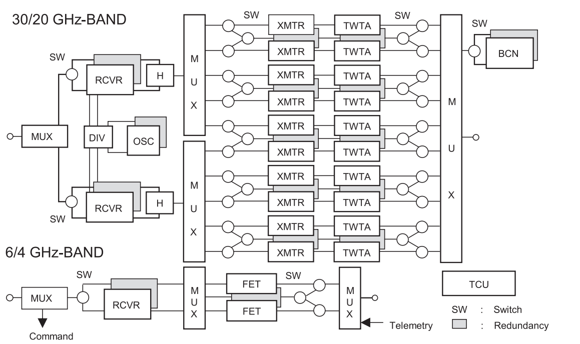

Fig. 6 Configuration of CS-3 on-board communication equipment.

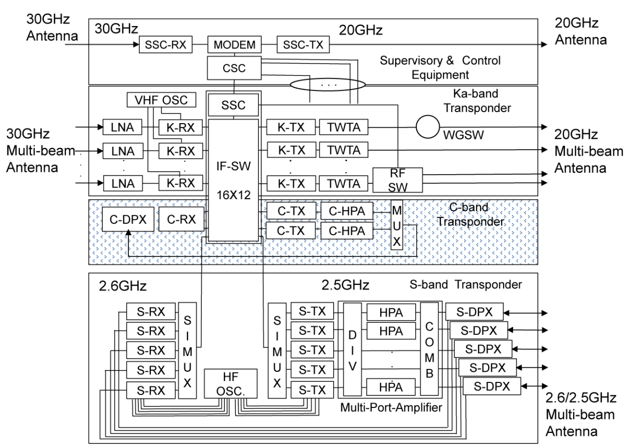

Fig. 7 Configuration of ETS-VI on-board communication equipment.

two-stage collector configuration and impregnated cathode [4]. For CS-3, a C-band total solid-state transponder was realized [13], [14] based on the space verification of the GaAs FET power amplifier in ETS-IV.

The purpose of the ETS-VI, which was launched in 1994, was to develop key technologies that could significantly increase the communication capacity by a multiple beam system. The Ka-band transponder for Fixed Satellite System (FSS) supports 4-beams. The S-band (2.5/2.6 GHz) transponder for Mobile Satellite System (MSS) covers all mainland Japan and Japanese EEZ (Exclusive Economic Zone) by 5-beams. C-band transponders were used for FSS and as a feeder link for the S-band. Each transponder and each beam can be interconnected using 1 GHz-band satellite switches [5].

Figure 7 shows the configuration of ETS-VI on-board communication equipment. The satellite switch interconnects 12-input ports to 16-output port, and was realized by using GaAs Monolithic Microwave IC (MMIC) [15] technology to reduce weight. It has a redundant configuration to improve reliability [15]. The Ka-band LNA uses HEMT to reduce noise (noise figure is 4.2 dB or less). Each Ka-band frequency convertor, of which weight is 1/6th that of the CS-3, uses GaAs MMICs [16].

As the traffic of each beam determines the transmitting power of the beam, allocating the power flexibly as required demands independent power amplifiers which low-

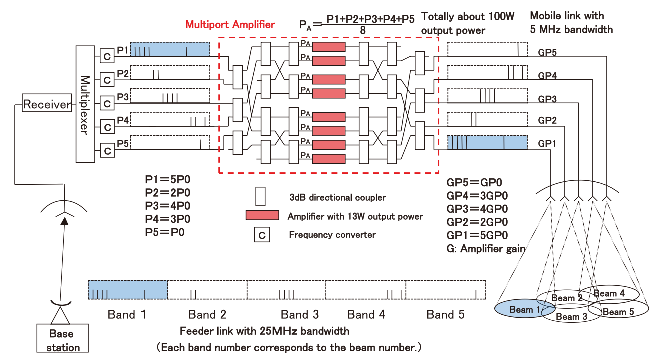

Fig. 8 ETS-VI Multi-Port Amplifier.

ers the power efficiency and raises the weight. The MPA system resolves this issue [17]. Figure 8 shows the functional block diagram of the ETS-VI onboard S-band MPA. The MPA consists of an input/output hybrid network, which divides/combines signals; the SSPA can finely adjust the phase and amplitude of the signals. The SSPA-equipped pre-distortion type linearizer increases efficiency and maximum output power. ETS-VI's MPA supports 5-beams with total and constant output power of 49.3 dBm.

The MPA technologies were adopted by many subsequent satellites. N-STAR a/b's MPA in the S-band MSS transponder consists of 5-stage hybrid networks and 32 SSPAs; it outputs 250 W [6]. In N-STAR c, launched in 2002, the S-band system has 4-beams and adopts 3-MPAs combined with a cluster feeder [18]. WINDS's Ka-band MPA consists of 3-stage hybrid networks and 10 TWTAs (includes two standby TWTAs); the output is 280 W [19].

The onboard transponder configurations of recent satellites have become much more complex to increase communication capacity by adopting digital signal processing technologies, see 3.4.

Figure 9 shows the payload configuration of N-STAR [6], which was launched first in 1995. It carries five communication payloads in four frequency bands: S-band multi-beam, Ka-band multi-beam, and C-band, Ku-band and Ka-band shaped beam payloads. Inter-channel connectivity between the shaped beam payloads is provided so that any frequency band can be used for any earth station. It also enables the integration of various communication systems, developed independent of each other using different frequency bands, into a unified system which yields far more flexible satellite communications.

The Ka-multi-beam payload consists of eight up-link beams and three down-link beams. Two frequencies are allocated to each beam and frequency re-use is employed in the up-link for different beams. Uplink signals from each earth station are received in Time Division Multiple Access (TDMA) burst form by the receiver corresponding to that beam. The received burst signals are converted into the same Intermediate Frequency (IF) and fed into a 16 x 6 on-board IF-switch matrix (IF-SW) that switches downlink beams. This function enables the realization of the Satellite Switched TDMA (SS-TDMA) scheme. Paths can be routed

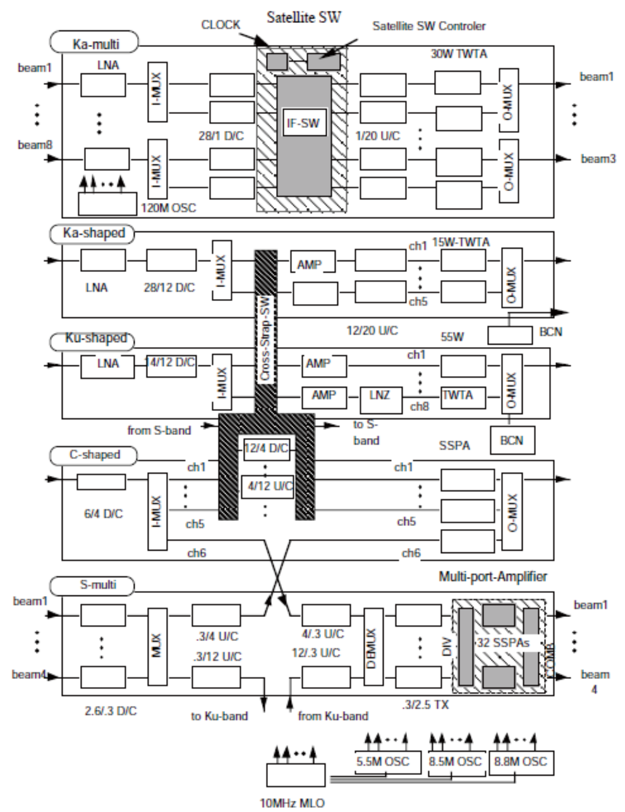

Fig. 9 Configuration of N-STAR on-board communication equipment.

at the same time to one, two or all three downlink beams by setting the switch pattern. This necessitated a high-speed, high-isolation, and highly reliable satellite switch which was small, even with its controller. Therefore, N-STAR adopts GaAs-FET MMIC technology originally developed by NTT for ETS-VI.

As one of special technologies in N-STAR, simultaneous multiple frequency band utilization with inter-frequency connectivity among three shaped beam payloads (C-band, Ku-band, and Ka-band) is realized by using cross strap switches so as to provide a flexible unified communication system with different frequency bands.

The S-band mobile communication payload adopts the MPA system the performance of which was also space-verified in ETS-VI. It is composed of 32 SSPAs, a divider and combiner, and provides an output power of about 200 watt. Four input signals corresponding to four beams are divided into 32 signals by the divider circuit. Each SSPA amplifies the signal and the outputs are combined by the combiner circuit; the divider circuit has the mirror image configuration. The final output signal for each of the four beams appears on the mirror image port of the corresponding input port. Normally, 28 SSPAs operate and four SSPAs are held as spares to enhance reliability.

3.2 Antenna Reflector

Satellite communication demands different types of antennas

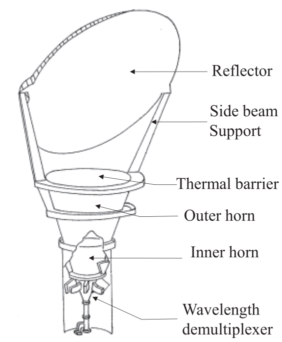

Fig. 10 Antenna reflector of CS-2.

systems in order to satisfy the various performance requirements. Communication satellites such as CS, CS-2, and CS-3, built during the 1970s and 1980s utilized horn antenna reflectors to provide adequate gain over the coverage region centered on the Japanese archipelago [20], [21]. The antennas were developed to suit contoured beam coverage applications at 6/4 GHz and 30/20 GHz. The CS reflectors had to be not only light-weight and strong, but also stiff enough to to resist vibration during launch with low thermal deformation in space [22]. In order to meet these requirements, Carbon-Fiber-Reinforced Plastic (CFRP) with high rigidity and low coefficient of thermal expansion was developed as the main structural material of the reflector. The reflectors consisted of a sandwich structure with high surface accuracy (below 0.2 mm RMS) and a horn. The dish's thickness varied continuously, and was composed of a sandwich of CFRP face-skins and aluminum flex-core. The horn structure consisted of an open shell support, a conical shell and a cylinder with stiffening rings and beams, all made of CFRP laminate. The dish was mounted on the horn structure with bolts which primarily sustained launch load, and the periphery was additionally bonded to increase stiffness and thermal conductivity [23]. The antenna reflector of CS-2 is shown in Fig. 10.

The single beam satellite communication systems put some restriction on the size of earth station antenna and capacity. To overcome the limitations of single beam systems, multi-beam satellite communication systems were developed. The signal power flux density at earth stations was effectively increased by narrowing the beam width through the use of a large onboard antenna. ETS-VI was developed for sophisticated multi-beam satellite communication systems [24], [25]. To form a small beam and to point the beam to a specified region, it is necessary to use a large deployable antenna reflector with precise surface and a highly accurate on-board pointing control subsystem. Thirteen beams in the 30 GHz and 20 GHz bands (Ka-band) covered the main island as shown in Fig. 3. Five beams in the 2.6/2.5 GHz bands (S-band) for mobile satellite communication covered an over 200 nautical mile area around Japan. In addition, a single beam in the 6/4 GHz bands (C-band) covered the main island of Japan. Fig. 11 shows the antenna system of ETS-VI.

A two-reflector Cassegrain arrangement with a 3.5 m

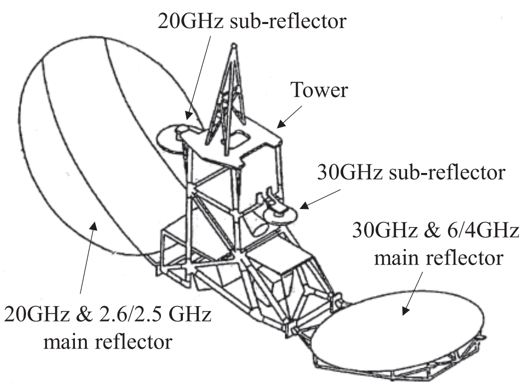

Fig. 11 Antenna system of ETS-VI.

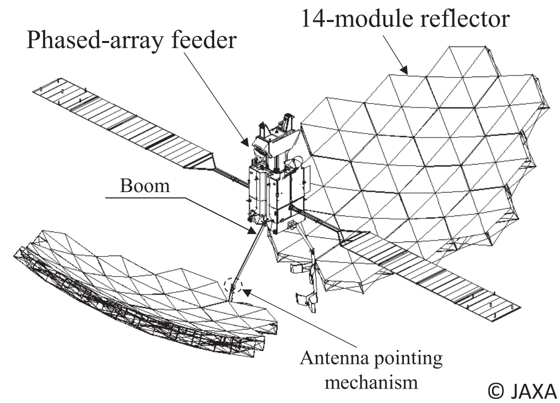

Fig. 12 ETS-VIII.

diameter reflector for the 20 GHz and S-bands, and a 2.5 meter reflector for the 30 GHz and the C-bands was designed based on the electrical characteristics. This achieved a compact layout of the reflectors and feeder assembly on a tower. The tower mounting provides more freedom in thermal and structural design as well as the convenience of conducting tests independent from the satellite body.

The reflector must be stowed in the launch vehicle fairing and withstand launch vibration. Moreover, it is necessary to reduce the weight of the reflectors to maximize the weight allowance of the communication equipment. The reflector consisted of a support truss structure fabricated by CFRP tubes, a surface painted white with sufficient surface accuracy, and studs connecting the surface to the support structure. The sandwich honeycomb panel structure had a skin surface made of CFRP sheet formed as a parabola and the aluminum flex core achieved the desired rigidity and strength. The 3.5 m diameter reflector was triple folded in the stowed configuration [26]. Consequently, the reflector weight per unit area was reduced to one third that of the CS-2 antenna.

Mesh deployable antennas are excellent and the latest design solution for space-borne antennas that require large aperture sizes operating at frequencies below the Ka-bands. Onboard mission systems and equipment for ETS-VIII were designed to realize mobile communications with handheld terminals in domestic service [8]. The onboard mission systems feature large diameter phased-array-fed reflector antennas and baseband switching by an onboard processor [27]. The phased-array-fed antenna consisted of a large deployable reflector and phased-array feed located at a defocused point to offer scanning over some range. The 13 m aperture cable-mesh antenna reflector was employed for transmitting and receiving. The reflector was designed as a modularized mesh deployable type, i.e., fourteen modules were used. Each module (4.8 m diameter) featured a metal mesh surface, a cable network, and a deployable truss as a supporting structure. The surface accuracy was designed to realize 2.4 mm RMS including thermal distortion in orbit. One of the major technical points of reflector structure design was estimating deployment forces [28]. The deployment forces are generated by coil springs on each module. The motion

Table 2 Trend in antenna reflector characteristics.

	CS-2/CS-3	ETS-VI	ETS-VIII
Launch date	1983/1988	1994	2006
Antenna reflector type	Horn	Solid / foldable	Mesh / foldable
Aperture diameter (m)	1	3.5	13
Surface accuracy (mm RMS)	0.26	0.18	2.4
Eigen frequency (Hz)	35	1.4	0.1
Weight per area (kg/m^2)	8.9	3.6	1.0

of the flexible multi-body, such as truss structure or form finding of the cable network, was simulated by an analysis program developed by NTT [29]. ETS-VIII and its reflector are shown in Fig. 12.

Large and high surface accurate as well as lightweight antenna reflectors have been developed in Japan as shown in Table 2. Surface forming with mesh is a very useful technique for large aperture reflectors as it can reduce the weight. The challenge for future mesh antennas is to extend the operating frequency above the Ka-band.

3.3 Multiple Beam Forming

In Japan, the ETS-VI project saw the first investigation of multiple beam systems and the target was to significantly increase satellite communication capacity. The typical onboard multiple beam antenna configuration is a reflector antenna with multiple beam feed [5]. Such multiple beam antenna systems are classified into two kinds by the feeder location.

One is a reflector antenna system in which the energy transmitted from a feed element on the focal plane forms a plane wave, the direction of which corresponds to the feed position [30]. This beam forming method uses multiple elements around the focal position. The ETS-VI's S-band system covered the specified area with five beams. Each beam used a single horn, the position of which corresponded to each beam. As for the Ka-band, its system had 5-spot beam, which were selected among 13 beams and whose side-lobe level had to be made low to permit frequency reuse. Fig. 13

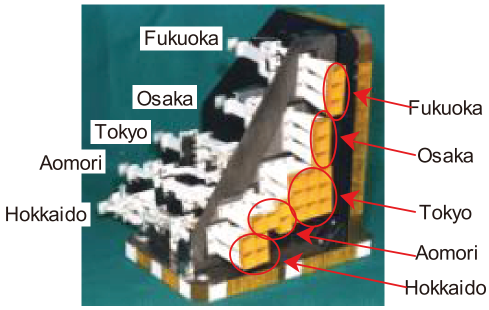

Fig. 13 ETS-VI Ka-band multiple beam feeder.

Fig. 14 ETS-VIII S-band multiple beam feeder.

shows the photograph of the ETS-VI's Ka-band multiple beam feeder. Each beam was formed by using several small horns, called cluster feeders; each horn is independently excited with appropriate amplitude and phase [31].

The other type is the off-focal fed type reflector antenna; the array feeder is located in front of the focal plane. The array feeder converts the wave-front at the array aperture to form the beam. Therefore, all elements are basically used for beam forming and must be controlled by setting the appropriate amplitude and phase weight by a Beam Forming Network (BFN).

ETS-VIII, launched in 2006, adopted this type of multiple beam antenna. The ETS-VIII feeder consists of 31 radiating elements directly connected to amplifiers and a 3-beam BFN that offers flexible beam direction control. As BFN circuit scale is proportion to the number of beams and elements, MMIC technologies were adopted to reduce size and weight. By using common amplitude weight for all beam forming, RF power could be allocated for each beam without making use of MPAs [32]. Figure 14 is a photograph of ETS-VIII's multiple-beam feeder.

For WINDS, different from the conventional reflector antenna combined with feeder, a Ka-band direct radiated type 2-beam antenna was developed consisting of 128 radiators with variable BFN [33]. Recent satellite beam forming schemes are based on digital signal processing techniques, which are described in the following subsection.

3.4 On-Board Processors

In the 1990s, digital signal processing techniques were drastically improved. The device capacity of LSI/FPGA as well as the processing speeds of A/D and D/A converters were greatly increased. With these great improvements, digital devices dedicated for space use also evolved, and it became possible to implement OBPs that could implement digital signal processing techniques in satellite transponders.

OBPs can perform various functions. Regenerative repeating, one of the major functions, demodulates the received signals and transmits the signals from the satellite after modulation. Since it can separate the uplink and downlink communication systems, it is possible to optimize the uplink access method and downlink multiplex method independently. In addition, by multiplexing the demodulated signals efficiently, it is also expected to improve frequency utilization efficiency by the statistical multiplexing effect.

COMETS is the first experimental communication satellite in Japan to offer regenerative repeating [7], [34]. Since the transmitted power and antenna size of user earth stations were limited, SCPC was adopted for the uplink access method. On the other hand, to enhance the power efficiency of the satellite transponder, it is desirable to operate the onboard amplifier around its saturated level. Thus, the OBP multiplexed the many demodulated SCPC signals in the time domain and re-modulate them as a higher bit rate single carrier TDM signal to improve power efficiency. The maximum communication speed in the regenerative repeating mode reached 24 kbit/s.

In the 2000s, OBP functionality further improved. It became possible to implement not only modulation/demodulation functions but also the switching function. Experiments on the advanced S-band Mobile Satellite Systems of ETS-VIII saw the first use of circuit switching and packet switching functions in Japan [35], [36]. Without onboard circuit switching, communications between user earth stations have to be mediated by the base station. The signals transmitted from a user earth station experienced the propagation delay equivalent to two round trips between station and satellite (=250 msec×2) to reach the other earth station. This delay was excessive and degraded the communication quality and throughput. To solve this problem, it was proposed to connect the uplink and the downlink directly on the satellite, the so called single-hop connection, see Fig. 15, by using onboard circuit switching. This new function halved the propagation delay. In the ETS-VIII project, the onboard circuit switching dealt with 855 channels. Multi-Carrier TDMA (MC-TDMA) was adopted as the satellite access method. Its communication speeds were 5.6 kbit/s (for voice) and 32 kbit/s (for data). Packet switching was also implemented on the satellite to flexibly connect the beams of service link and service/feeder link. The function of onboard packet switching adopted by ETS-VIII was quite simple as just a bridge function was realized. The satellite access method was slotted ALOHA and the communication speed was 1024 kbit/s.

In the 2000s, ATM switching was implemented in the WINDS satellite. ATM switching enabled downlink beam routing and QoS (Quality of Service) control by reading the overhead information of ATM packets carried in the uplink signals. It was expected to improve frequency utiliza-

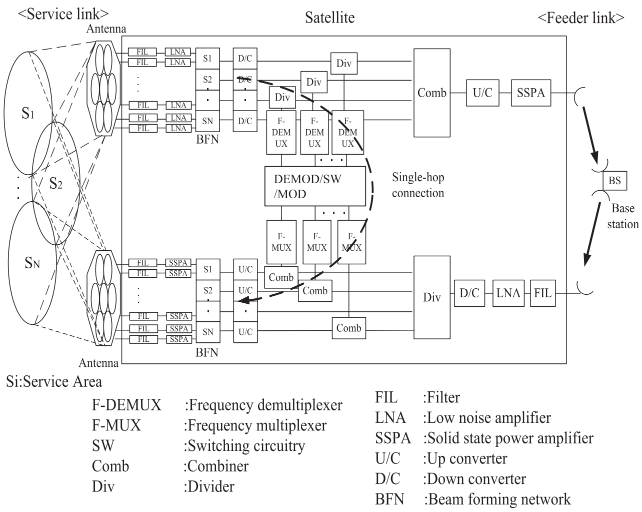

Fig. 15 Concept of single-hop connection by using OBP.

tion efficiency by the statistical multiplexing effect and/or removing invalid data in the satellite transponder. Multi-Frequency TDMA (MF-TDMA) was selected as the satellite access method, and the downlink signals (satellite to earth station) adopted TDM (Time Division Multiplexing). The maximum communication speed of the regenerative repeating mode was 155 Mbit/s. That of the non-regenerative mode was 1.2 Gbit/s.

4. Prospects

Satellite communication systems continue to play an important role in various applications such as emergency communications after natural disasters, nomadic communications such as satellite news gathering, and back-up links for higher network reliability. On-board communication technologies should still meet the requirement of higher communication capacity under severe conditions. After 2010, HTS (High Throughput Satellites) started to be commercialized globally by using the Ku or Ka-band with throughputs of several hundred Gbit/s [37]. Among the multi-beam on-board communication technologies described so far, OBP is a key technology to handle over 100 beams. Besides, the technologies for on-board communication equipment will be affected by the following two communications systems. One is satellite/terrestrial integrated mobile communications with Ancillary Terrestrial Component (ATC). The other is Unmanned Aircraft System (UAS).

The ATC-based satellite communications system has the potential to provide ubiquitous wireless service coverage using a handheld terminal with dual mode satellite and terrestrial communications functions. It is a 100 beam class mobile satellite communication system and shares frequencies with terrestrial communication systems. Conventional terrestrial and satellite systems each have their own dedicated terminals, and they use dedicated frequency bands. However, dual mode terminals can connect to both terrestrial and satellite communication networks, and moreover, have the same frequency bands. Therefore they can be used as a countermeasure against the digital divide in mobile communication dead zones, such as in mountain areas and coastal offshore areas, etc., and be used as an essential information and communications infrastructure during disasters, such as the transmission of accurate disaster information to residents and assisting in rescue activities, etc.

In order to realize the ATC system, inter-system interference between the satellite communication system and the terrestrial system should be mitigated by the real-time management of control information on frequency assignment, transmitting power, and beam forming in both the terrestrial system and the communications satellites. Technologies such as dynamic resource allocation/frequency sharing methods between terrestrial and satellite systems, formation of 100 beams, and a channelizer are very important. Reducing the side lobe level of 100 beam class phased array fed antenna reflectors is also very important.

In Japan, the project called STICS (Satellite/Terrestrial Integrated Mobile Communication System), which is intended to realize ATC-based satellite communications systems, was started in 2008, by NICT(National Institute of Information and Communications Technology) [38], [39]. In the 2000s, highly sophisticated OBPs capable of beam forming and switching over 100 beams were developed for commercial satellites globally. In Japan, an advanced OBP was developed for STICS as a new satellite system in which the frequency resources allocated to MSS were flexibly shared among terrestrial and satellite systems. Before this project, the trend was to implement a multi-beam beam former using analog techniques. However, this approach could not implement a multi-beam former with over 100 beams due to insufficient beam forming precision and excessive power feeding loss. Therefore, the digital multi-beam former is also needed. A reconfigurable/flexible DBF and channelizer were studied for an S-band multi-beam system with over 100 beams. Furthermore, assuming that the user traffic would concentrate on specified beams in the multi-beam system after natural disasters, onboard channelization that could allocate the limited system bandwidth flexibly among multi-beams is necessary. In addition, because of the limited bandwidth of the feeder link, it is also necessary to pack the service link signals in the feeder link after eliminating unused frequency resources and compressing the frequency interval as much as possible as shown in Fig. 16.

This requires an onboard bandwidth variable channelizer [40]. In the STICS project, a prototype OBP with variable bandwidth channelization and digital multi-beam forming was developed. The fundamental functions were verified by using a scale model that implemented 16 antenna elements assuming a 16 beam system.

UAS is expected to be utilized for many applications such as delivering commercial products, taking photographs from high altitudes to monitor disasters, and providing UAS as relay stations in case of disasters [41]. The economic impact of UAS is closely monitored by a number of industry groups and private consulting firms. Their forecasts con-

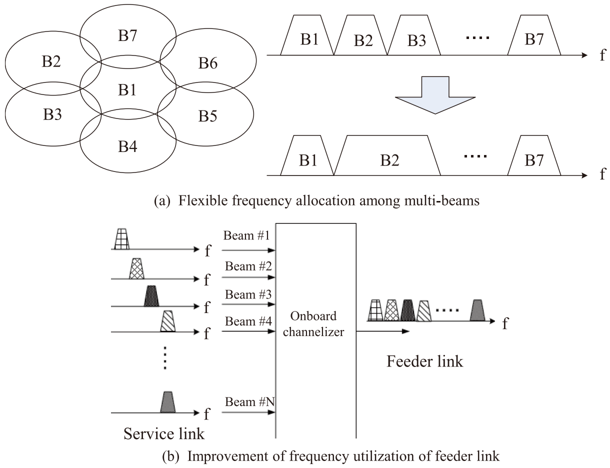

Fig. 16 Objectives of variable bandwidth channelization.

cerning the outlook for UAS manufacturing and sales vary widely. However, UAS have the potential to bring many changes in the way businesses and government agencies operate and regulations for UAS are under investigation or are being set [42]. However, according to one report [43], the annual UAS sales increase from present 35,000 units to 110,000 unit in 2017, 160,000 units in 2025. This means accumulated number reaches to 1.3 million units. In order to expand the utilization of UAS, it is necessary to ensure that Unmanned Aircraft (UA) can be operated in areas out of sight, at high altitude. To enable this, the frequencies used to monitor and control UAs and how to operate UAs are important issues. Satellite communication system is one of the promising system for monitoring and controlling so many UAS as the communications satellites have large service coverage compared to that of wireless communications system and fewer hand over is driven between coverages and relatively uninterrupted monitoring is realized.

The frequencies for UAS are under investigation in ITU-R and International Civil Aviation Organization (ICAO). In the World Radiocommunication Conference (WRC) held by ITU-R, the frequency bands of 5030–5091 Hz allocated to Aeronautical Mobile Satellite (Route) Service (AMS(R)S) were identified as adequate for UAS use in satellite links and the frequency allocated to Aeronautical Mobile (Route) Service (AM(R)S) was opened for UAS use in terrestrial links (WRC-12 Agenda Item 1.3). UAS is composed of satellite (FSS space station), UA with UA Earth Station (UA ES) and Unmanned Aircraft Control Station (UACS), the frequency for FSS satellite station use was also opened for the use of Control and Non-Payload Communications (CNPC) between UA ES and UACS with further issues to be resolved (WRC-15 Agenda Item 1.5). Including so many UAs, which exceed 1 million units in satellite communications systems will affect on-board communications equipment given the requirements of highly advanced resource allocation and strong interference mitigation in the same way as the satellite/terrestrial integrated mobile communications with ATC.

5. Conclusions

This paper has overviewed the 50 year history of on-board communication equipment technologies in Japan. Those technologies have been developed together with communications satellites like Engineering Test Satellite series and commercial communications satellites in order to increase the communication capacity under severe constraints. As Japanese R&D in satellite communication is evolving toward ubiquitous use in cooperation with terrestrial communications systems including UAS, R&D for on-board communication equipment in satellite communication is essential to resolve issues raised by ubiquitous use.

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