OVERVIEW OF SATELLITE ON-BOARD MULTIBEAM COMMUNICATIONS SYSTEM FOR ETS-VI

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Abstract

A multibeam system is one of the most promising next generation satellite communication systems. NTT is taking part in the Japanese national ETS-VI program in developing on-board equipment for fixed and mobile multibeam satellite communication systems and is preparing for the evaluation and verification of newly developed technologies. Ground verification tests of this equipment have successfully been completed and the assembly of the Proto-Flight-Model has started with the launch scheduled for 1993.

1. Introduction

Multibeam satellite communications systems are effective for increasing the signal power flux density at earth stations by narrowing the beam width with a large onboard antenna. The increased signal power flux density has significant advantages. One is increasing transmission capacity and the other is the use of smaller and more economical earth stations.

NTT (Nippon Telegraph and Telephone Corporation) has been studying various technologies to achieve a multibeam satellite communications system. It is desirable to actually validate the performance of onboard equipment by operating it before commercial use.

NTT is taking part in the ETS-VI program in developing on-board equipment for fixed and mobile multibeam satellite communication systems. Since the ETS-VI includes other mission equipment besides the fixed and mobile communications systems, the mass and power allocated to the system is limited.

The on-board equipment includes large aperture deployable multibeam antennas with precise surface tolerance, a highly accurate antenna pointing control system, a large scale satellite switch, compact, lightweight and high efficiency transponders, and a highly flexible and efficient mobile communications transponder. It is also important to know how to test the equipment on the ground before launching, and to predict the in-orbit performance.

This paper presents newly developed technologies for multibeam communications onboard system.

2. System Outline

The beam allocations of the ETS-VI satellite system for fixed and mobile communications experiments is shown in Fig. 1. This system employs three frequency bands, Ka-band (30/20GHz), C-band (6/4GHz) and S-band (2.6/2.5GHz). Thirteen RF beams in each of the 30 and 20 GHz bands cover the Japanese main islands. The C-band spot beam covers the center part of Japan. The S-band system uses five beams for mobile communications, covering a 200-nautical mile area around Japan. The features of the S-band mobile system are high satellite EIRP and the use of a very compact terminal with a small rod antenna that requires no satellite tracking as shown in Fig. 2.

Figure 3 shows the on-board communications system configuration. The transponders are not installed to all antenna beams, but a sufficient number of transponders are installed to confirm the multibeam transponder performance as well as system performance.

Frequency reuse is another advantage of multibeam systems enabling capacity increase with limited frequency bandwidth. Frequency reuse between Tokyo and Osaka areas is carried out in addition to cross-polarization use in the same beam.

An on-board switch matrix is employed in the IF-band to connect traffic between different beams. All of the signals in every band (S-band, C-band and Ka-band) are connected to the IF switch so that the maximum system flexibility can be achieved.

3. Antenna System

3.1 Configuration

The antenna design parameters are shown in Table 1. Among the many combinations of frequency bands sharing each reflector, the two-reflector arrangement was selected with a 3.5 m reflector for the 20 GHz and S bands, and a 2.5 m reflector for the 30 GHz and C bands.

To fulfill the required electrical characteristics, the stowability in the rocket fairing and the mountability on the satellite bus, an offset dual reflector Cassegrain antenna system is most preferable. Sub-reflectors are used for antenna pointing control.

Large antennas used in space require a deployment capability that can meet the volume limitations of the launch vehicle and can also withstand the severe vibration environment during launch. The reflector and a highly reliable deployment mechanism enable the 3.5 m and 2.5 m reflectors of the ETS-VI to be stowed in the H-II class rocket fairing (Inner Diameter: 3.7 m) and reliably deployed.

The deployed and stowed configuration of the antenna system is shown in Fig. 4.
3.2 Feeders & FSS

In order to establish effective frequency reuse in alternate beams, a cluster type horn, which is composed of multiple horns for each beam, is developed. Figure 5 shows the fabricated cluster horns for the 30 GHz band.

On the other hand, a patch type feeder, as shown in Fig. 6, is used for the S-band antenna.

Frequency selective surface (FSS) technology is adopted to separate and combine the 20 GHz and S bands as well as the 30 GHz and C bands and to allow the shared use of the reflectors by these frequencies.

3.3 Reflector

The structural requirements for the main reflectors are precise surface tolerance, light weight, high stiffness, and high durability. To achieve these requirements, a truss structure allowing post-fabrication adjustment is developed for the main reflector. As a result, the 2.5 m and 3.5 m reflectors have a surface tolerance due to fabrication errors of 0.17 mm and 0.18 mm rms, respectively. Their masses are 19 kg and 44 kg, respectively, including the deployment mechanisms and the thermal control materials.

3.4 Antenna Pointing Control System

The narrower the beam, the more accuracy is required in pointing. To keep the beam direction within one 20th of the beam width of the beam diameter, an antenna pointing control system is necessary in addition to the satellite attitude control system. In order to achieve a high pointing accuracy of 0.015 degrees, it is necessary to control an antenna reflector independently of the satellite attitude control system. Therefore, a highly accurate antenna pointing control system (APS) has been developed by incorporating both the antenna drive control system (ADCS) and the conventional satellite attitude control system (SACS) as shown in Fig. 7. The ADCS consists of an RF sensor, a tracking receiver (TRX), an antenna pointing control electronics (APE), and an antenna pointing mechanism (APM) to drive the sub-reflector.

A lubrication-free direct drive mechanism has also been developed to improve system reliability. Figure 8 shows the APM structure consisting of four flexible pivots and linear motors.

4. Transponder

4.1 Satellite Switch

The complexity of the switch matrix is proportional to the product of the input and output port numbers. The IF switch (IF-SW) for the ETS-VI has 16 input and 12 output ports. A monolithic GaAs switch module with switching speeds of 20 nanoseconds or faster, has been developed to reduce the switch matrix mass and size. The module contains two switch ICs and two driver ICs. Figure 9 shows the configurations of the IF-SW and the switch module. The developed 16x12 IF-SW size, which is composed of 48 modules, is 195x323x130mm³ and the mass is 6.8 kg with cross point redundancy and one-out-of-two redundant DC/DC converters.

The Satellite Switch Controller (SSC) changes switching patterns every 8 microseconds according to the switching patterns stored in the memory. The developed SSC uses a CMOS microprocessor, an 8-kgate CMOS Gate Array and a 64 kb SRAM to satisfy mass and power requirements.

Figure 10 shows the satellite switch subsystem that is composed of the IF-SW, the SSC and a highly stable oscillator.

4.2 Transponders

In a multibeam system, the size, mass and power efficiency of the transponder become more and more important as the number of transponders increases. For the Ku-band transponder, a 30-GHz band MIC low noise amplifier (LNA) using a HEMT (High Electron Mobility Transistor) device, up/down frequency converters using MIC and MMIC technology, a 10W small-size TWTA and a 20GHz-band all solid state transmitter, have been developed. For the C-band, 7W GaAsFET SSPAs are employed.

To reduce the transponder mass, magnesium was used for the housing material. Also, several miniaturized Hybrid IC modules have been developed for the circuits that are used in many components (such as the power supply and the local oscillator) to reduce mass and cost. Furthermore, to reduce equipment cost, many parts that are widely used in terrestrial radio communication systems and verified to be highly reliable are employed instead of specially tailored space-use-parts. Figure 11 shows the improvement in the newly developed technologies compared with those of the CS-3. Figure 12 shows an external view of the Ka-band MMIC receiver (§).

4.3 Multi-Port-Amplifier

The application of a multibeam satellite enables small and economical mobile terminals to be used in a mobile satellite communications system. In a multibeam mobile communications system, traffic distribution fluctuates among the multiple beams. In an ordinary transponder configuration, the total transmission capacity decreases when the traffic concentrates in a specific beam because there is only one specific high power amplifier on-board for each beam. A new type of transponder configuration has been developed, which is called the Multi-Port-Amplifier (MPA). Figure 13 shows the mobile communications transponder configuration implementing the MPA. One of the advantages of the MPA is that full transmission capacity is secured independent of traffic distribution among the multiple beams. Furthermore, the MPA has high reliability because communications to all beams will be maintained even if individual amplifiers fail with a small decrease in total transmission capacity.

The MPA is composed of 8 GaAs high power amplifiers, a power divider and a power combiner. The output power is 100 W in the 2.5 GHz band. Figure 14 shows an external view of the MPA.
5. Ground Verification Tests and Estimation

All the components for the on-board equipment were manufactured in early 1989. Since then, performance evaluations of the antenna and transponders have been carried out through ground verification tests and estimation.

5.1 Antenna Electrical Tests

When testing on the ground, the antenna deformation caused by gravity is on the order of centimeters and the electrical performance deviates from that in-orbit due to this deformation. First, the electrical performance was independently measured on the ground for the 2.5 m and 3.5 m antennas. Each antenna component was integrated using test fixtures with high stiffness. Figure 15 shows the antenna electrical testing.

Next, the antenna performance was calculated using the performance estimation data obtained from our antenna CAD system. That is, the fabrication error in manufacturing, the alignment error in integration with the test fixture, and the gravity cancellation error estimated by an antenna structural mathematical model. Surface error data of the main reflectors were measured by photogrammetry with a high accuracy of 20 μm.

The calculated performances were compared with the measured ones. On the basis of the comparison, evaluation error data and permissible alignment error data were obtained.

In-orbit performance was calculated using the in-orbit thermal deformation data, tower alignment error data, and fabrication error data. The performance estimation error is on about the same order as the error obtained from on-ground tests because the calculation procedures are similar. In-orbit performance was estimated taking this evaluation error into account.

Table II shows the peak gain comparison of the whole antenna system. The results of the comparison show that the evaluation errors are less than 0.5 dB in peak gain. The evaluated performances agree well with design values.

5.2 Antenna Structural Tests

One of the main requirements for on-board antenna design is to survive dynamic loads during the launch phase.

Natural frequencies and their modes are studied by low level sinusoidal excitations. For the 2.5 m and 3.5 m reflectors, the lowest natural frequencies are 36 Hz and 32 Hz, respectively, when each reflector is fixed on a shaker base. The results agree with the analysis both in the frequency and vibration mode. Next, qualification level sinusoidal vibration tests were conducted and the strength requirements were verified with a positive margin of safety.

Another critical environment for the large reflectors is an acoustic one. The antenna was exposed to an overall sound pressure level of 145 dB (36 kg/m²) for 60 seconds. The acoustic test was completed without any damage and the structural safety of the antenna was verified.

5.3 Antenna Deployment Test

Ground deployment tests are indispensable in verifying deployment capability. However, in ground deployment tests, gravity force and air drag have a great influence on the deployment dynamics of the antenna. Therefore, each antenna was suspended by wires to minimize the gravity effects, and the wires were controlled to keep vertical during antenna deployment. Figure 16 shows the antenna deployment testing. Measured deployment time of the 2.5 m reflector was 18.7 seconds with the air drag effects, while the calculated one was 18.2 seconds using air drag obtained through separate experiment.

5.4 Antenna Thermal Vacuum Test

The solar simulation thermal balance test was performed, and temperature distributions were measured in three typical cases with different solar incident angles. Figure 17 shows the thermal vacuum test setup.

Since there was good agreement between the test results and the analytical model predictions, it was concluded that the antenna temperatures can be maintained within acceptable limits throughout all the phases of the mission. Also, it was confirmed that the temperature distributions and gradients are small enough to satisfy the sidelobe requirements of -30 dB.

5.5 Antenna Pointing Control System Tests

It is difficult to evaluate the APS in a fully assembled configuration. The major difficulties are far field antenna operation in a simulated space environment, residual reflector deformation even after compensating for gravity, and dynamic compensation in the APM. To overcome these difficulties, the following three tests were conducted: (1) the RF sensor electrical test, (2) the ADCS simulation test, and (3) the APS simulation test.

Overall control performances were verified, including the interaction between the ADCS and the SACS. This was done by using actual on-board components with two motion tables to simulate satellite and reflector dynamics, respectively.

The antenna pointing error analysis of the ETS-VI multibeam antenna was conducted based on component characteristics and the above tests results. It is confirmed that the total pointing accuracy in orbit will be 0.015 degrees.
5.6 Transponder Tests

A vibration test, thermal vacuum test and EMC test were conducted for each component and it was verified that all of the components have the adaptiveness to a space environment. After the component test, all components were assembled to the satellite panel to check the interface compatibility between the components and to evaluate the overall electrical performance. One of the problems in testing the overall performance is the large number of signal paths. As every receiving and transmitting signal is connected to the IF-SW, the possible signal paths are in the order of thousands. Thus, it is time consuming to check every possible electrical characteristic. Using each component characteristic, overall characteristics were calculated by software and the critical combinations were selected. The overall performance of the transponder was measured for the selected configurations by using the automatic check-out system newly developed for this transponder system. Figure 18 shows the transponder system testing. It was confirmed that required performance such as the input-output characteristics, amplitude-frequency characteristics, and switching function were satisfactory.

5.7 Overall System Tests and Proto-Flight -Model

The satellite system Engineering-Model was assembled and the EMC, electrical power source interface and telemetry/command interface were checked under the full operation mode as shown in Fig.19. All of the tests were completed successfully and the electrical design validity of the system was confirmed through those tests.

After the tests, the Engineering-Model was disassembled. Almost all components used in the Engineering-Model of the multibeam system are installed to the Proto-Flight -Model. The assembly of the transponder Proto-Flight-Model has already completed. Figure 20 shows the Proto-Flight-Model of the multibeam transponder system for ETS-VI.

6. Conclusion

The on-board equipment was developed for fixed and mobile multibeam satellite communications systems. On-ground verification tests were successfully conducted under simulated launch and space conditions, and in-orbit performance was estimated. As a result, all the design requirements were fully satisfied. These results are applicable to an envisioned Japanese economical domestic satellite communication system.

REFERENCES


Fig. 1 ETS-VI beam allocation for fixed and mobile communications
Fig. 2  S-band mobile multibeam communications terminal

Fig. 3  On-board communications system configuration in ETS-VI program

Fig. 4  Deployed and stowed configuration of the antenna system

Fig. 5  30GHz-band cluster horns
Fig. 6 S-band patch type feeder

Fig. 7 Antenna pointing control system

Fig. 8 Structure of APM

Fig. 9 Configuration of satellite switch

Fig. 10 Satellite switch subsystem

Fig. 11 Improvement in transponder technologies
Fig. 12 External view of the Ka-band MMIC receiver

Fig. 15 Antenna electrical testing

Fig. 13 Mobile communications transponder configuration

Fig. 16 Antenna deployment testing

Fig. 14 External view of MPA

Fig. 17 Antenna thermal vacuum test
Table 1: Antenna System Design Parameter

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<tr>
<th>Parameter</th>
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<td>Antenna diameter</td>
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Table 2: Antenna Peak Directivity Gain Comparison (dB)

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Fig. 18 Tranponder electrical testing

Fig. 19 Overall system test (NASA Space Center)

Fig. 20 Proto-Flight-Model of multibeam transponder system