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COMMUNICATIONS SYSTEM FOR THE JAPANESE INTERPLANETARY SPACECRAFT MS-T5/PLANET-A

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ABSTRACT

Institute of Space and Astronautical Science (ISAS), Japan, launched the first Japanese interplanetary spacecraft "Sakigake" (the former name is MS-T5) on January 8, 1985, as an engineering test spacecraft for ISAS's Planet-A mission, Halley's comet exploration. The main spacecraft, Planet-A, will be launched around August 17, 1985. Both spacecraft will encounter Halley's comet in early March, 1986, at the distance of about 1.1 AU from the earth. The communications system have operated quite satisfactory since the launching of Sakigake, including the on-board units and the earth stations, and no major problems are expected on the forthcoming Planet-A mission as well as the remaining period of Sakigake. In this paper we present the design and the features of the communications system for Sakigake and Planet-A, and the on-orbit performance of the communications system of Sakigake.

INTRODUCTION

MS-T5 and Planet-A are spacecraft in Japan's first interplanetary flight project. MS-T5 was successfully launched on January 8, 1985, and was named "Sakigake"; Planet-A will be launched around August 17, 1985. The aim of these spacecraft is to investigate Halley's comet together with Russian "VEGA 1/VEGA 2", ESA's "GIOTTO" and American "ICE".

Planet-A will encounter Halley's comet at a distance of 200,000 km in March, 1986. It will take close-up UV images of the coma and the tail of the comet and observe the interaction between the solar wind and the comet. The spacecraft Sakigake is for engineering test purposes, though it carries some scientific insturments. Such techniques as trajectory estimation and correction are being verified by Sakigake as the precursor to Planet-A. Sakigake will be at a distance of about 0.05 AU from Halley's comet when Planet-A encounters the comet.

In this paper we present the design and the features of the communications system for Sakigake and Planet-A missions and the on-orbit performance of the communications system of Sakigake. Details of the earth station, the Usuda Deep Space Center, that ISAS constructed in 1984 and has become the major earth station for Sakigake and Planet-A tracking, is described in a companion paper (Nomura and others, 1985).

THE SPACECRAFT MS-T5 AND PLANET-A

The spacecraft systems of Sakigake (MS-T5) and Planet-A are identical in the design except the scientific instruments. Figure 1 shows Sakigake, and Fig. 2 shows Planet-A.

Figure 3 shows the trajectories of two spacecraft relative to a fixed Sun-earth line. As seen in Fig. 3, the slant range between two spacecraft and the earth will be about 1.1 AU, when two spacecraft encounter Halley's comet.

The scientific instruments on-board Sakigake are a plasma wave probe, a Faraday cup and a magnetometer. Those on-board Planet-A are a Lyman-α imaging camera and a solar wind particle analyzer. The positions of these instruments can be seen in Fig. 1 and 2.

COMMUNICATIONS SYSTEM PERFORMANCE REQUIREMENTS

The communications system for Sakigake and Planet-A is designed so that it satisfies the following requirements:

1. Communications should be maintained up to a distance of 1.5 AU, where missions will be completed.

2. PCM data of 64 bps should be transmitted as real time or stored data with a bit-error-rate of less than 1×10^{-5}.

3. A real time command or a programmed command data should be transmitted and decoded through a PCM signal of 16 bps with a bit-error-rate of less than 1×10^{-5}.

4. Accurate range and range-rate measurements should be performed by coherent two-way doppler and turn-around ranging tones.

5. Weight of the on-board system should be minimized, while reliability should be maximized.

COMMUNICATIONS SYSTEM DESIGN

On-board Communications System

The communications system on-board the two spacecraft is identical, consisting of S-band antennas, a S-band transponder, a command decoder and a data-processing unit. Figure 4 shows the block diagram of the on-board communications system. The S-band antennas consist of three antennas: a high gain one (HGA) on the despun section, and medium and low gain ones (MGA and LGA) on the spinning section. The S-band receiver is duplicated.

In the launching phase, when the lower portion of the spacecraft is directed towards the earth, the communications are maintained through LGA having a wide gain pattern. Soon after the spacecraft is injected into the interplanetary orbit, the spacecraft automatically controls its attitude so that its spin axis and the sun forms an angle of 90° (See Fig. 5) and the angle between the spin axis and the earth direction (θ_E in Fig. 5) becomes 90°; then the communications using MGA, with a gain in the direction perpendicular to the spin axis, become possible. Finally the spacecraft is controlled so that its spin axis is normal to the ecliptic plane, and the communication linkage using HGA is established.

Earth Station and Communications Network

ISAS established the Usuda Deep Space Center (UDSC) at Usuda-cho, Nagano-Prefecture, in 1984 as a tracking station for interplanetary spacecraft. The station is equipped with a 64-meter-diameter antenna, a S-band high-power transmitter and S-band low-noise amplifiers for carrying out deep space communications. Table 1 gives the major performance of the communication systems of the UDSC.

The communications network of Sakigake and Planet-A is shown in Fig. 6. During the initial tracking phase, we ask tracking support of NASA Deep Space Network, mainly for the purpose of initial orbit determinations, and of the Katsuura Station of NASDA, which provides antenna angle information to the 64-meter antenna of UDSC. Kagoshima Space Center (KSC) is ISAS's launching and tracking station for scientific satellites. It works as the major control center in the launch phase of the Sakigake and Planet-A missions as well as a back-up earth station for UDSC in the initial phase of tracking. Mission controls of Sakigake and Planet-A are carried out at Komaba Deep Space Operation Center (KDSC) in ISAS, Tokyo.

Telemetry, Command and Ranging Systems

Table 2, 3 and 4 show the performance of the telemetry, command and ranging systems, respectively, that we have designed for the Sakigake and Planet-A missions. Features of these systems are as follows:

- The telemetry system has two modes: one is a low-bit-rate mode with a bit-rate of 64 bps and the other is a high-bit-rate mode with a bit-rate of 2048 bps. The low-bit-rate mode is for long distance communications and employs an error correcting code to improve the transmission efficiency. The high-bit-rate mode is for short range communications. To simplify the on-board system, the high-bit-rate mode does not employ error correcting codes.

- The bit rate of 16 bps is adopted for the command signal so that communications (commands) over the distance of 1.5 AU is possible even when the low-gain antenna or the medium-gain antenna is used.

- A discrete spectrum ranging system with a chopper frequency of about 500 kHz is used. This is compatible with the NASA DSN system. The minimum frequency of the code components is about 1 Hz, which resolves the one-way ambiguity up to about 150,000 km.

Link Design

Table 5 shows the main parameters of the communications system that we have designed on the basis of the communications system performance requirements already mentioned and are provided from the performances of the earth stations. Using the parameters given in Table 5, we can calculate the link margin of the communications system as a function of the distance between spacecraft and the earth station. Figure 7 shows the typical results for the communications between UDSC and the spacecraft: Link margins for telemetry and ranging when the HGA is used, and the link margin for command when the LGA is used. We see that there are enough margins at the slant range of 1.5 AU.

On-board Units

Antennas. The high-gain antenna (HGA) is a mechanical despun control one with an offset parabolic reflector of 80 cm in diameter (Fig. 8). The medium-gain antenna (MGA) is a 3-element colinear array. It has a pancake pattern, with a directivity perpendicular to the spin axis of the spacecraft. The low-gain antenna (LGA) is a cross dipole with a reflector. The performance of these three antennas are outlined in Table 6 and are described in detail by Nomura and others (1984).

S-band transponder. The transponder consists of two S-band receivers (Fig. 9), a S-band transmitter (Fig. 10), an elimination filter, two diplexers and a coaxial switch. The main functions of the transponder are:

- To receive the carrier of 2.11 GHz, phase-modulated by a command base-band signal, and provide the command decoder (CMD) with the demodulated signal.

- To phase-modulate the 2.29 GHz carrier by a telemetry signal generated in the data processing unit (DPU) and transmit the phase-modulated carrier to earth stations.

- To receive the carrier of 2.11 GHz, phase-modulated by a ranging signal, and phase-modulate the carrier of 2.29 GHz by the demodulated ranging signal; and then transmit the modulated carrier to earth stations. The ratio of receiving frequency to transmitting frequency is set to 221/240 in order to maintain phase coherency.

The performance of the SBR and the TMS are described in Table 7 and 8, respectively. The stability of the transponder delay for the ranging signal is less than 27 nsec.

Command decoder. By applying a digital phase-lock loop in the PSK demodulator, we have designed the command decoder (CMD) so that its whole circuit is digitalized (Hayashi and others, 1982). The functions of the command decoder are:

- To select one from two command signals (PSK modulated subcarriers) provided by the two SBR's (See Fig. 4).

- To demodulate the command signal from the subcarrier.

- To provide the data processing unit with the demodulated command signal.

Figure 11 shows the command decoder and Table 9 gives its performance.

Data processing unit. The functions of the data processing unit (DPU) are:

- To edit the telemetry data from each on-board unit according to a predetermined format and transmit the formatted data to the TMS.

- To decode the command signal from the CMD, generate a discrete or block command, and transmit them to each on-board unit.

- To provide a program command, programmed in advance by a command from the earth station, to each unit in accordance with a predetermined time sequence.

The main performance of the DPU is shown in Table 10. The feature of the DPU is that it employs the convolutional coding for a coding of telemetry and the Hamming code, capable of correcting a 1-bit error, for the coding of program command. Figure 12 shows the DPU.

ON-ORBIT PERFORMANCE

The communications system for Sakigake has operated quite satisfactory since the launching of Sakigake on Jan. 8, 1985. The on-orbit operations on Sakigake and the performance of the communication linkages will be briefly reviewed in the following.

Operations and controls. Sakigake was tracked from KSC, the launching place, for about ten minutes. Twenty minutes after the launch, NASA Goldstone Station established communication linkage with the spacecraft. 28 minutes after the launch, the control to make θ_S ninety degrees was carried out and the on-board transmission antenna was switched from the LGA to the MGA. At 4 hours and 33 minutes after launch, just before the spacecraft became visible again from Japan, the transmitting power of the TMS was changed from 70 mW to 5 W. The control to make the spin-axis of the spacecraft normal to the ecliptic plane started at the Pass 18. The HGA was despun at the Pass 21 and the communication linkage using the HGA was established.

Uplink performance. Figure 13 shows the on-board S-band receiver (SBR) receiving level determined from the AGC telemetry data on the SBR from the Pass 2 (Jan. 9, 1985) to the Pass 79 (March 27), together with their estimations. The estimations are obtained using the uplink parameters shown in Table 5 except that the transmitting power of UDSC is 20 kW, the gain of the on-board MGA is 5.0 dBi and the polarization loss of the on-board HGA is 0.1 dB. The agreements between the received level and the estimations are good.

Downlink performance. Figure 14 shows the receiving level at UDSC determined from the AGC data of the receiver from the Pass 2 to the Pass 79. The estimated values, also shown in the figure, are derived using the downlink parameters shown in Table 5 except that the output power of the on-board transmitter is 37 dBm, the gain of the MGA is 5.0 dBi and the polarization loss of the MGA is 0.1 dB. Again the agreements are good; thus we confirm, from Fig. 14 together with Fig. 13, that the communication linkages between Sakigake and UDSC are being established.

CONCLUSIONS

We have described the communications system for MS-T5 (Sakigake) and Planet-A, the ISAS's interplanetary spacecraft for Halley's comet exploration. Sakigake was launched on January 8, 1985, and the communications with Sakigake have been carried out successfully since its launching.

The key on-board components or technologies that realized the successful communications are:

- The high-gain antenna having an antenna gain of 23.1 dBi.

- The highly sensitive receivers with a threshold level of -145 dBm.

- The command demodulator using digital PLL.

- The high power transmitter with an output power of 5 W.

- The data processing unit using a convolutional encoding with Vitterbi decoding algorithm.

The UDSC, including the 64-meter-diameter antenna, has operated quite safisfactory in the tracking of Sakigake as well. We expect no major problems in communications in the Planet-A mission as well as in the remaining period of the Sakigake mission.

ACKNOWLEDGMENT

The authors would like to express their thanks and gratitude to many people from the Institute of Space and Astronautical Science and the Space Development Division of NEC Corporation for their contributions and supports during the design and fabrication of the communications system.

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Nomura, T., T. Hayashi, T. Nishimura, H. Hirosawa and M. Ichikawa (1985). Usuda deep space station with 64-meter-diameter antenna. 36th I.A.F. Congress, Stockholm, IAF-85-381.

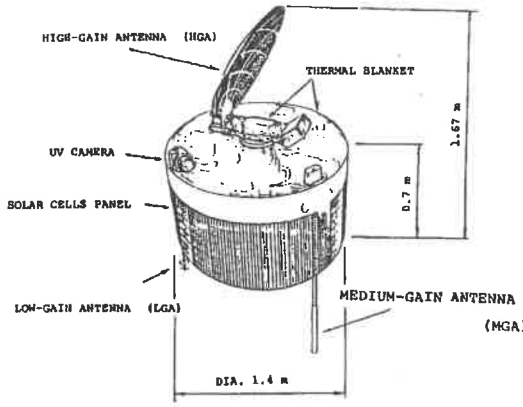

Fig. 2 PLANET-A

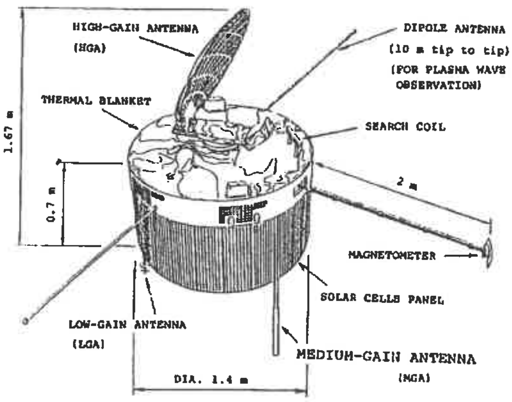

Fig. 1 SAKIGAKE

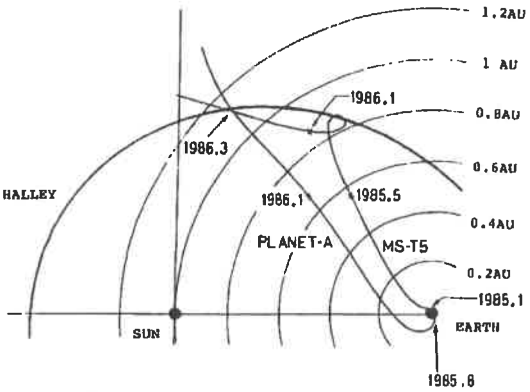

Fig. 3 Trajectories

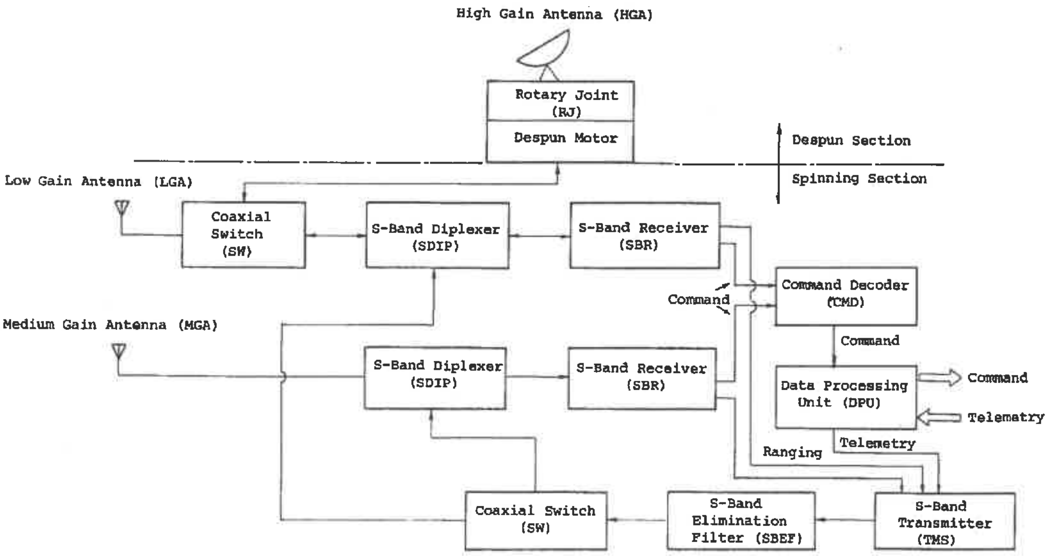

Fig. 4 SAKIGAKE/PLANET-A Communications System Block Diagram

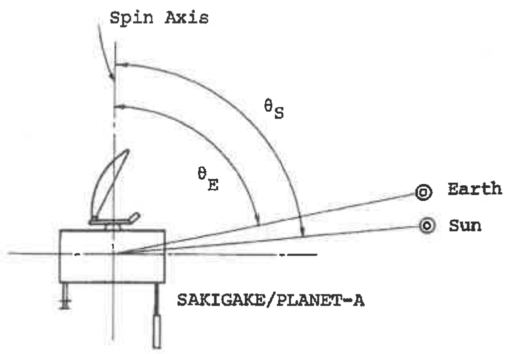

Fig. 5 Definitions of Angles

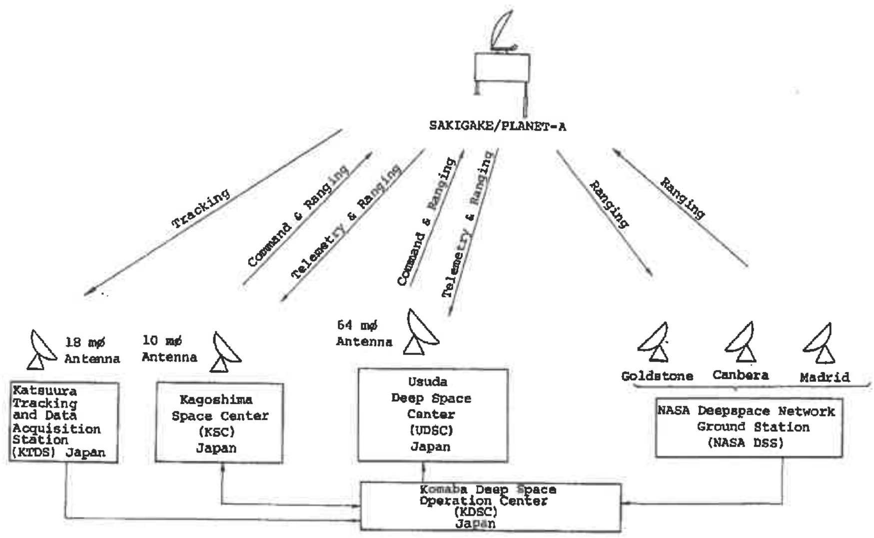

Fig. 6 SAKIGAKE/PLANET-A Communications Network

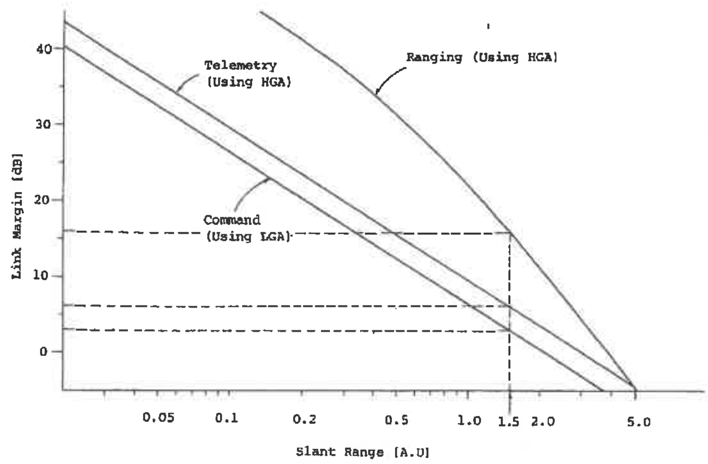

Fig. 7 Link Margin (UDSC-Spacecraft)

Fig. 8 HGA

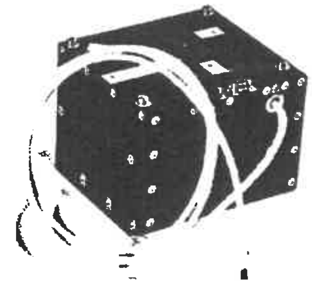

Fig. 11 CMD

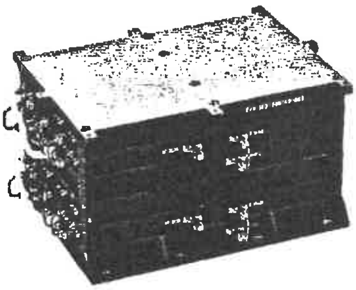

Fig. 9 SBR's

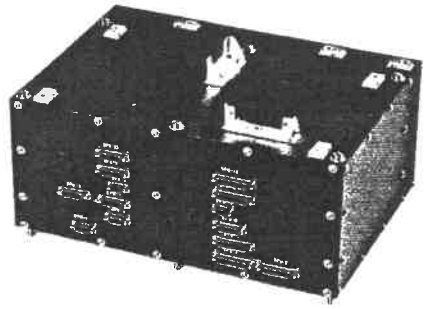

Fig. 12 DPU

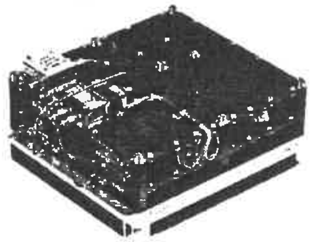

Fig. 10 TMS

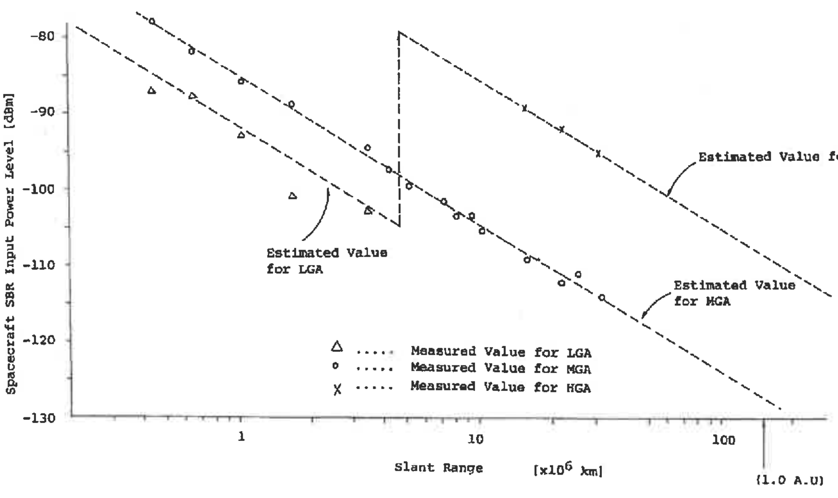

Fig. 13 Uplink Receiving Power Level (SAKIGAKE)

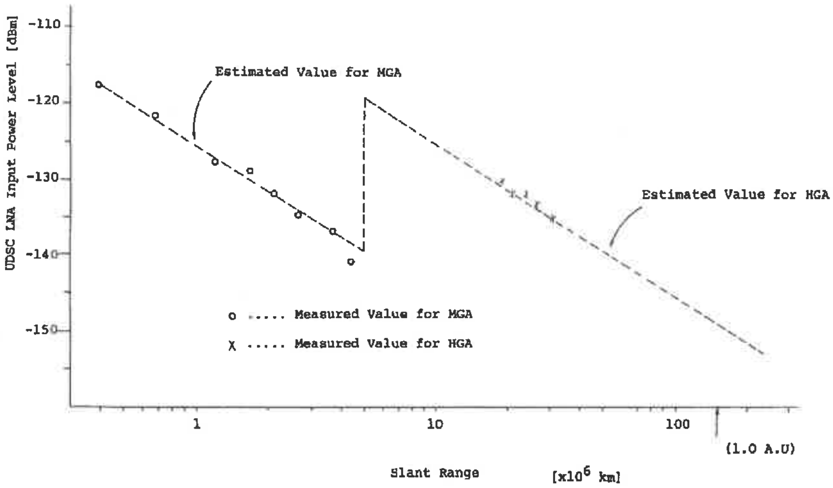

Fig. 14 Downlink Receiving Power Level (SAKIGAKE)

Table 1 Performance of UDSC

Parameter	Performance
Transmitting Parameter	
. Frequency	2105 ∿ 2120 MHz
. RF Output Power	40 kW/20 kW/2 kW/200W
. Antenna Gain	61.8 dB
. Feeder Loss	0.5 dB
Receiving Parameter	
. Frequency	2280 ∿ 2290 MHz
. Antenna Gain	62.5 dB
. Dynamic Range (LNA Input)	-165 ∿ -85 dBm ($2B_L$=3Hz)
	-160 ∿ -85 dBm ($2B_L$=10Hz)
. System Noise Temperature	30K (toward the zenith)
. Feeder Loss	0.3 dB

Table 2 Telemetry System

Design Parameter	Performance
Modulation Type	PCM-PSK-PM
PCM Signal Type	NRZ-L / NRZ-S
Error Correcting Code	Convolutional Encoding Rate = 1/2 Constraint Length = 7 (K)
PCM Bit Rate	2048 bps without Coding 64 bps with Coding (128 sps)
Subcarrier Frequency	8192 Hz
Subcarrier Waveform	Square-Wave
Carrier Frequency	SAKIGAKE 2293.14815 MHz PLANET-A 2293.88889 MHz

Table 3 Command System

Design Parameter	Performance
Modulation Type	PCM-PSK-PM
PCM Signal Type	NRZ-L (PN)
PCM Bit Rate	16 bps
Subcarrier Frequency	512 Hz
Subcarrier Waveform	Square-Wave
Carrier Frequency	SAKIGAKE 2111.60725 MHz PLANET-A 2112.28935 MHz

Table 4 Ranging System

Design Parameter	Performance
Modulation Type	Tone - PM
Baseband Signal Type	Schop ⊕ Scode Schop: Chopper Signal Scode: Code Component Signal
Chopper Frequency (fchop)	fup / 4096
Code Component Frequency (fcode)	fchop / 2^n (n = 1, 2, -----)
Baseband Signal Waveform	Square-Wave
Carrier Frequency	
Uplink (f up)	SAKIGAKE 2111.60725 MHz PLANET-A 2112.28935 MHz
Downlink (f down)	SAKIGAKE 2293.14815 MHz PLANET-A 2293.88889 MHz
Carrier Coherency	
Uplink/Downlink Ratio	221 / 240

Table 5 SAKIGAKE/PLANET-A Communications System Parameters

Parameter	Uplink	Downlink
Frequency SAKIGAKE	2111.61 MHz	2293.15 MHz
PLANET-A	2112.29 MHz	2293.89 MHz
Spacecraft Parameter		
· HGA Antenna Gain	21.5 dB	23.1 dB
· MGA Antenna Gain	-1.5 dB	-0.5 dB
· LGA Antenna Gain	-4.5 dB	-3.0 dB
· TX Power		5W ±1 dB
· Feeder Losses	2.1 dB	3.2 dB
· RX Noise Figure	3.0 dB	
· RX PLL Bandwidth	40 Hz	
· Transponder Loss (Limitter Supression)		
HGA	———	8.7 dB
MGA	———	33.7 dB
LGA	———	33.9 dB
UDSC Parameter		
· Antenna Gain	61.8 dB	62.5 dB
· TX Power	40 kW ±1 dB	
· Feeder Loss	0.5 dB	0.3 dB
· RX Noise Temperature		9K
· RX PLL Bandwidth		10 Hz
KSC Parameter		
· Antenna Gain	42.4 dB	43.2 dB
· TX Power	10 kW ±1 dB	
· Feeder Loss	1.7 dB	1.4 dB
· RX Noise Temperature		125K
· RX PLL Bandwidth		100 Hz
Modem Parameter		
· Radio Loss	0.5 dB	1.2 dB
· Telemetry Demod. Loss		0.4 dB
· Command Demod. Loss	1.3 dB	
· Data Bit Error Rate	10^{-5}	10^{-5}
· Required S/N (Eb/No)		
Telemetery (coded)		4.5 dB
Telemetry (uncoded)		9.6 dB
Command	9.6 dB	
Ranging (UDSC)		6.0 dB
(KSC)		-105 dBm
Propagation Parameter		
· Slant Range (UDSC)	1.5 AU	1.5 AU
(KSC)	2×10^5 km	2×10^5 km
· Axial Ratio (Polarization Loss)	2.0 dB	2.0 dB
	0.2 dB	0.2 dB
· Rain Loss	0.2 dB	0.2 dB
System Loss		
· Antenna Pointing Loss		
Spacecraft	0.2 dB	0.2 dB
UDSC and KSC	0.2 dB	0.2 dB
· Antenna Noise Temperature		
Spacecraft	300K	
UDSC		13K
KSC		50K

Table 6 Performance of Antennas

	Design Parameter	Transmission	Reception
HGA	Frequency	2.3GHz Band	2.1GHz Band
HGA	Bandwidth	More than 6MHz	More than 6MHz
HGA	Gain	23.1dBi	21.5dBi
HGA	Axial Ratio	1.3dB	1.3dB
HGA	3dB Beamwidth	11.0°	11.5°
HGA	Polarization	Right-Hand Circular	Right-Hand Circular
MGA	Frequency	2.3GHz Band	2.1GHz Band
MGA	Bandwidth	More than 6MHz	More than 6MHz
MGA	Gain for perpendicular plane of spin axis	+5.5dBi	+5.0dBi
MGA	Pattern	PANCAKE	PANCAKE
MGA	Polarization	LINEAR	LINEAR
LGA	Frequency	2.3GHz Band	2.1GHz Band
LGA	Bandwidth	More than 6MHz	More than 6MHz
LGA	Gain within ±68° towards the aft side of spin axis	More than -3dBi	More than -3dBi
LGA	Pattern	Cardioid	Cardioid
LGA	Polarization	Right-Hand Circular	Right-Hand Circular

Table 7 Performance of SBR

Design Parameter	Performance
Receiving Frequency	2111.60725 MHz (SAKIGAKE) 2112.28935 MHz (PLANET-A)
Tracking Threshold Level	-145 dBm
Dynamic Range	
. Command	-142 ∿ -60 dBm
. Ranging	-135 ∿ -60 dBm
Uplink Modulation Index	0.6 rad
Noise Figure	≤ 3 dB
Tracking Range	-90 ∿ -60 dBm (fR ±90 kHz)
	-140 ∿ -90 dBm (fR ±50 kHz)
Weight	3.99 kg (2 units)
Sizes	182 x 234 x 134 mm (2 units)

Table 8 Performance of TMS

Design Parameter	Performance
Transmitting Frequency	2293.14815 MHz (SAKIGAKE) 2293.88889 MHz (PLANET-A)
Carrier Frequency Stability (Non-Coherent)	
. Long Term	$\pm 1 \times 10^{-6}$/year
. Short Term	$\leq 1 \times 10^{-9}$ rms/sec
Output Power	
. High Power	37 dBm
. Low Power	18.5 dBm
Downlink Modulation Index	
. Telemetry	0.9 rad
. Ranging	0.9 rad (strong signal)
Weight	1.18 kg
Sizes	159 x 170 x 64 mm

Table 9 Performance of CMD

Design Parameter	Performance
Modulation format	PCM-PSK (PN CODE)
Subcarrier frequency	512 Hz
Subcarrier waveform	Squarewave
Data rate	16 bps
Bit error rate	1×10^{-5} (at Eb/No=10.6 dB)
Weight	1.36 kg
Sizes	149 x 196 x 119 mm

Table 10 Performance of DPU

Design Parameter	Performance
PCM Data Format	
. 1 word	8 Bits
. 1 Minor Frame	128 Words
. 1 Major Frame	256 Minor Frames
. Bit Rate	2048 bps (1 Frame/0.5 sec) * 64 bps (1 Frame/16 sec) * Symbol Rate: 128 bps
. Frame Sync.	3 words
Modulation Format	
. 2048 bps	NRZ-L/NRZ-S/BPSK
. 64 bps	NRZ-L/NRZ-S/Conv. Code/ BPSK
Error Correcting Code	Convolutional Code (Viterbi Decording) K = 7 R = 1/2
Number of Command	
. Discrete Command	224
. Block Command	8 Bits Serial Data
. Programmable Command	224
Weight	3.53 kg
Sizes	292 x 201 x 116 mm