
MIC7 Lecture 5
Ultra-Small Deep Space Mission
Telecommunication Systems Design
March 19,2021
ISAS/JAXA ©

Biography

- Dr. Atsushi Tomiki received B.E., M.E., and Ph.D. degrees from Tokyo Denki University in 2002, 2004, and 2007, respectively. He joined the Japan Aerospace Exploration Agency (JAXA), Tokyo, Japan in 2007 and was engaged in development on deep space telecommunication systems.
- He is currently an associate professor at the Department of Spacecraft Engineering, the Institute of Space and Astronautical Science in the Sagamihara Campus. His research interests include wireless telecommunication systems in low-cost planetary and lunar exploration, ultra wideband systems for fly-by-wireless spacecraft, and electromagnetic compatibility in scientific spacecrafts.

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1. Introduction and Background

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Plan of ISAS Deep Spacecraft Fleet

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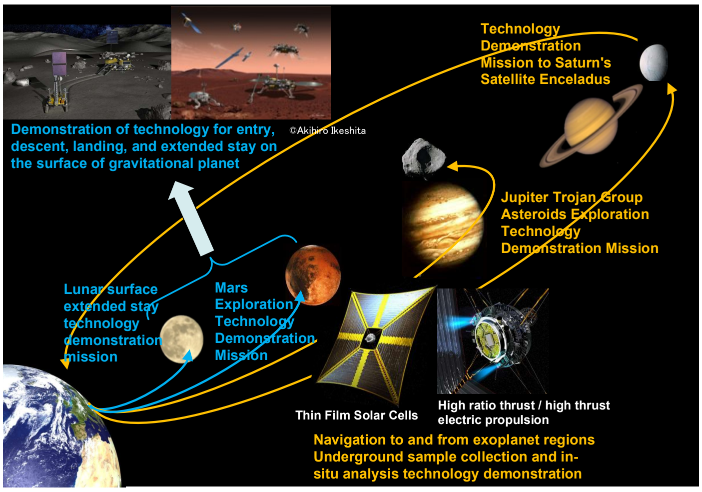
I would like to introduce some of the research and development work, missions and departments, that I have been involved with, in order to help aspiring space communication engineers understand the technology that may be required in the work that they are interested in, and to help them understand the essence of it when they consider their future career path.

In recent years, the trend of international space exploration has been shifting from the International Space Station to Moon and Mars exploration, and then to the deep space area (beyond 2 million km from the Earth) The era of competition and cooperation among the world has arrived. In particular, unmanned robotic missions, such as spacecraft and rovers, are being planned not only by space agencies in China and India, but also by private venture companies using inexpensive heavy rockets from emerging countries, and this is one of the fields where technological development is remarkable.

Japan's space science and exploration will be carried out under a strategic plan to acquire key technologies for the period from 2020 to 2040, with the aim of maintaining and strengthening the industrial, scientific, and technological foundations for the expansion of space development and utilization, as well as the scientific exploration of the beginning of the universe, the formation of structures from galaxies to planets, and the origin of the solar system and life. At the same time, to maintain and strengthen the industrial, scientific, and technological infrastructure for the expansion of space utilization, we declared the research, development, and demonstration for the acquisition of strategic key technologies for the period from 2020 to 2040 in the Space Science and Technology Roadmap (1). From the mission roadmap presented here, the concept of the ISAS Deep Spacecraft Mission is summarized mainly for space exploration as shown in this slide.

1. Introduction and Background



Sample return mission in the outer region of the solar system adopted in the Master Plan 2017.

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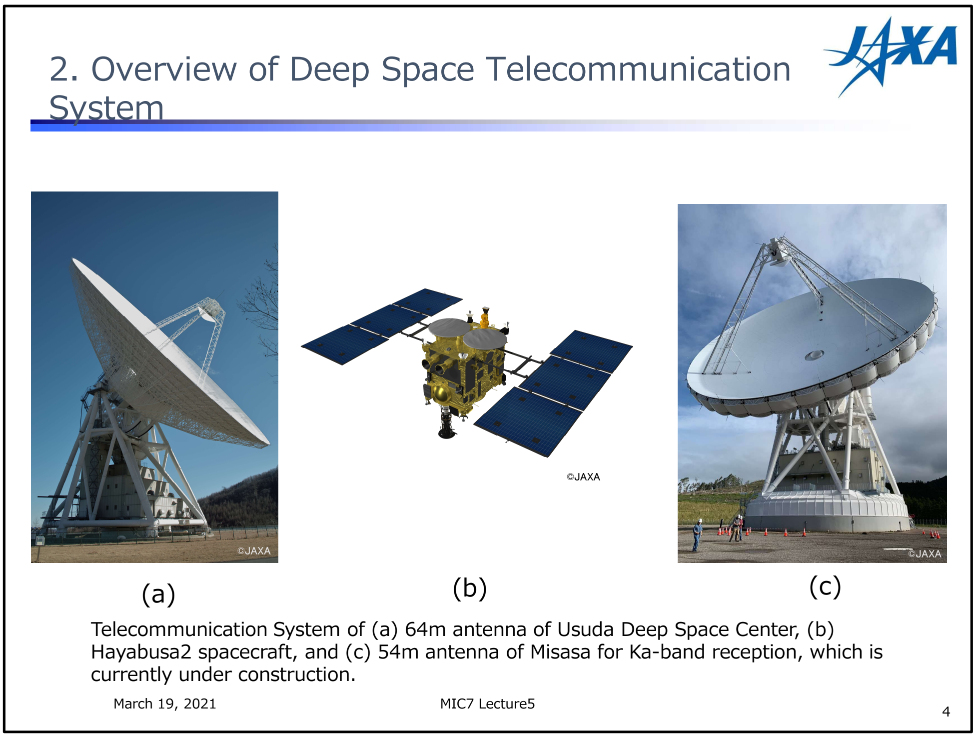
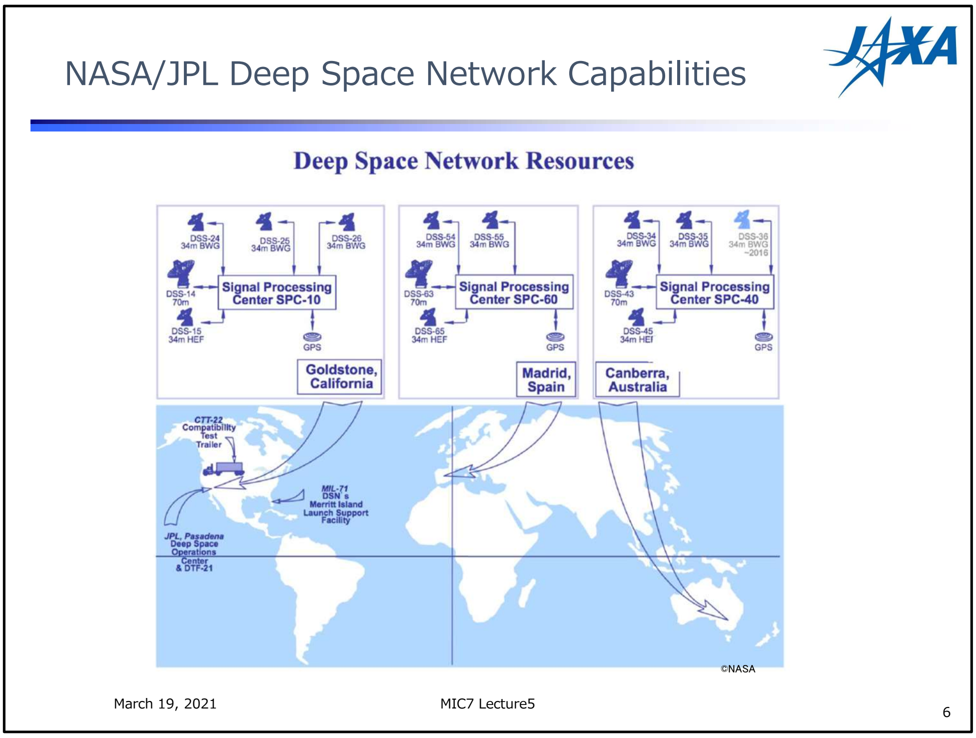
The outer region of the solar system, which is one of the frontiers to be pursued here, is included as a sample return mission in the Master Plan for Large-scale Research Projects of the Science Council of Japan, and the technology development and demonstration plans have been proposed, shown in this slide. One of the essential technologies for satellite operation in such space exploration missions is wireless communication and orbit determination technology.



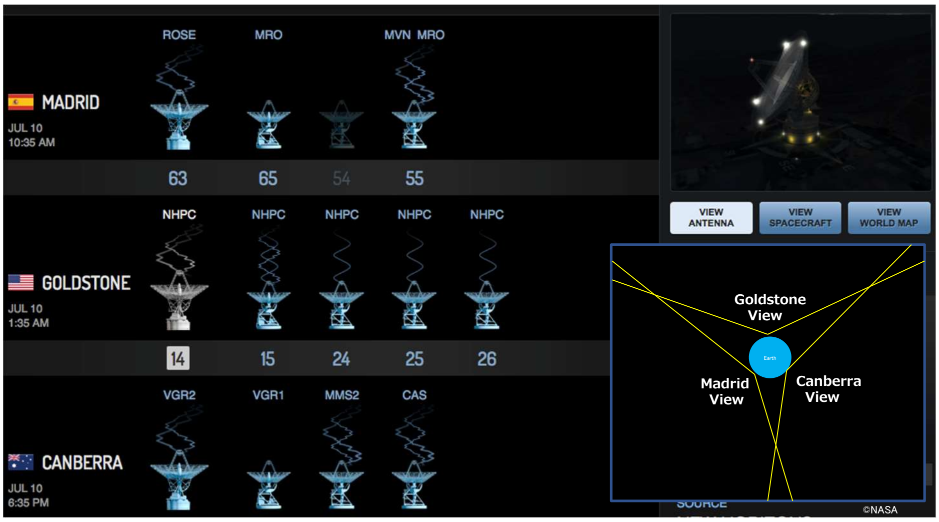
Hayabusa2 (b), launched in 2014, arrived at the asteroid "Ryugu" in June 2018, and succeeded in observing the asteroid from a very close distance, which had never been seen by humans before. In September 2018, two MINERVA-II-1 rovers were separated from the asteroid, and in October 2018, MASCOT of DLR (German Aerospace Center) was separated from the asteroid, with rovers successfully landing on the asteroid. The clear images of the asteroid surface taken by the MINERVA-II-1 rover during the world-first leap were quickly broadcasted to the world via the Internet and became a fresh memory. The wireless system used to transmit such observation data to the Earth and to command the rover, is the deep-space communication system shown in this slide.

There are many antennas for deep space communications in operation all over the world, and NASA, ESA, and JAXA not only conduct their own missions, but also share their antennas with each other to enable various missions. Currently, JAXA has one 64-meter and one 54-meter antenna in Saku City, Nagano Prefecture, and 34-meter and 20-meter antennas in Kagoshima Prefecture.



This slide shows the resources of the DSN worldwide: one 70-m antenna and four 34-m antennas in one complex, capable of operating more than 100 space exploration missions simultaneously.

NASA/JPL DSN Now!



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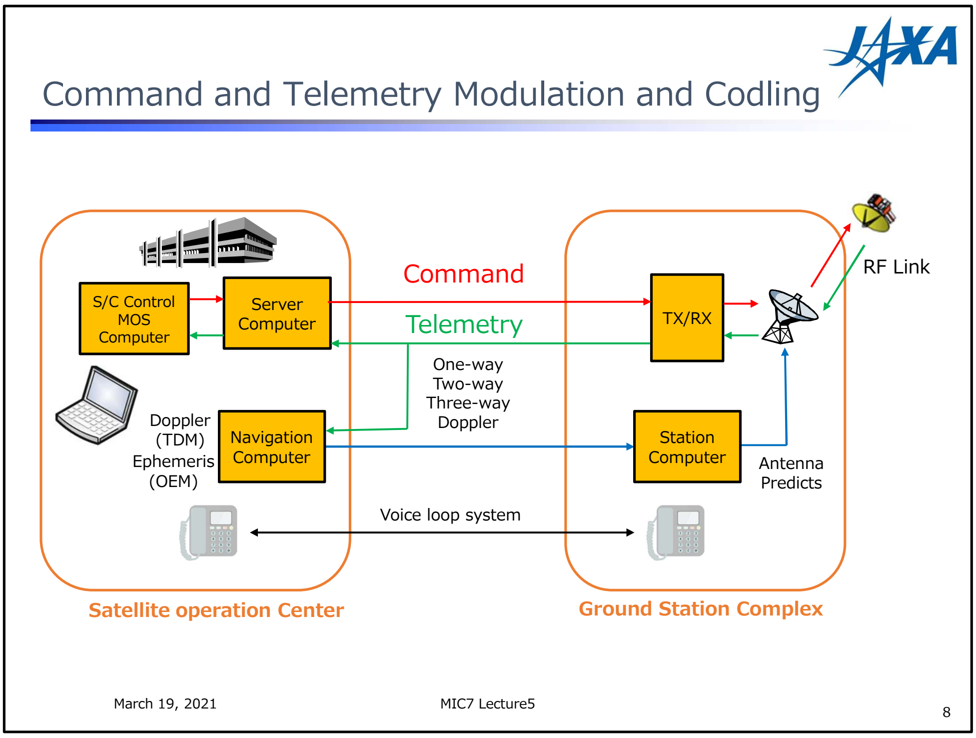
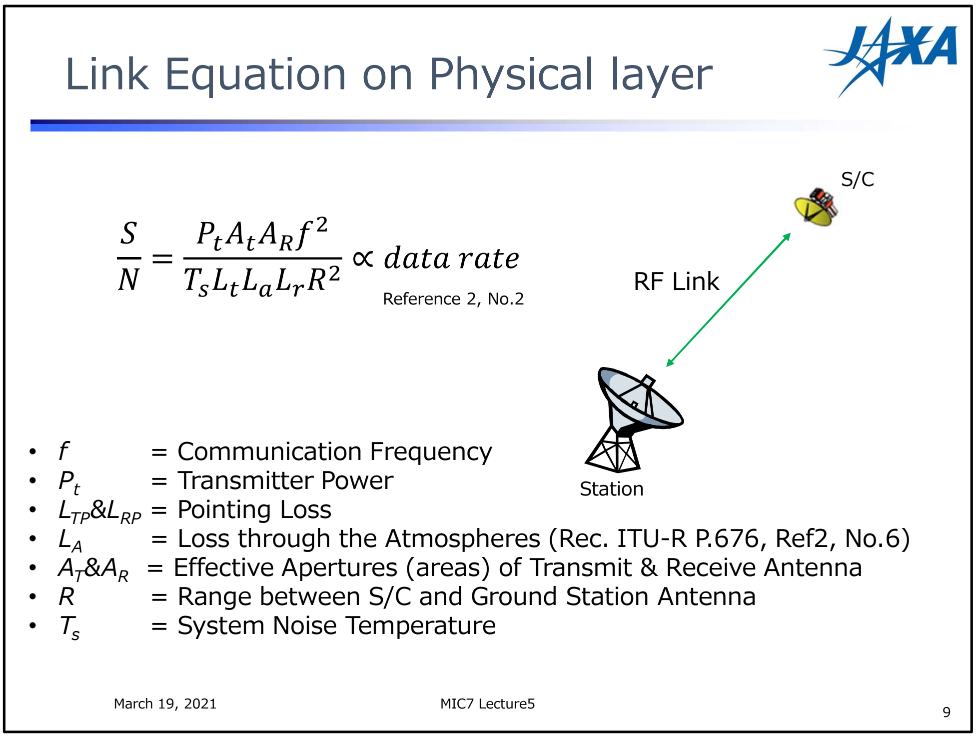
You can check the operation status at any time on the DSN NOW Web site. In this way, DSN can communicate with the spacecraft continuously by placing earth stations every 120 degrees.
Goldstone's ground station receives signals from the Pluto probe. By combining the signal outputs of a total of five antennas into an array, the signal-to-noise ratio of weak signals can be increased to improve the communication speed. The visible range of each antenna overlaps in order to take the spacecraft over to the next station. The 70m antenna is mainly used for missions beyond Jupiter-Saturn, such as Voyager, Pluto and Jupiter-Saturn missions.



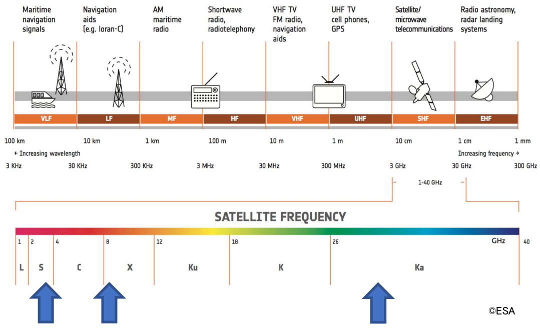
The spacecraft receives radio waves transmitted from the Earth station, demodulates and decodes the command data, and passes it to the onboard computer (OBC) to control the spacecraft for mission execution. At the same time, engineering data collected by the OBC and science data observed by the OBC are encoded and modulated as telemetry, and transmitted to Earth via radio waves. In addition, the spacecraft needs to know exactly where it is in space, so it measures the distance and the rate of change of distance from the earth station by sending back carrier signals and ranging signals at the same time as data communication. Since the X-band frequency is mainly used in deep space exploration, we call it a transponder. The antenna forecast value obtained from the trajectory calculation allows the antenna with high gain to be accurately pointed at the spacecraft.   The voice loop allows the satellite operator and the station operator to communicate as needed for the operation.



Downlink frequency selection for telemetry is generally driven by two operating modes: emergency telemetry and high rate telemetry. These modes use, typically, a spacecraft Low Gain Antenna (LGA) or High Gain Antenna (HGA), respectively. LGAs are generally used for command and for engineering telemetry when relatively near earth, as well as in emergency conditions. HGAs are used for high rate telemetry and commanding when far from earth.
To a first approximation, data rate depends on antenna apertures, frequency, transmit power and range as follows:
where Pt is transmitter Power,
At and AR are transmit and receive antenna aperture, respectively,
f Is frequency, and
R is the range between the transmitter and receiver.
The Link Equation demonstrates that the data rate that a communications system can support between two aperture-limited antennas is, to a first approximation, proportional to the frequency (f).
The ground antenna can be considered a fixed-aperture resource, while the aperture of a spacecraft High Gain Antenna (HGA) is normally limited by configuration considerations independent - to a first approximation of frequency. Thus communications through the spacecraft HGA improve with the square of frequency once again, to a first approximation.

Satellite frequency band

- Common Frequencies for space exploration
  - S band UPLINK 2.0, DOWNLINK 2.2 GHz on category-A region
  - X band UPLINK 7.1, DOWNLINK 8.45 GHz on category-A and –B(Deep Space) region
  - Ka band DOWNLINK 32 GHz



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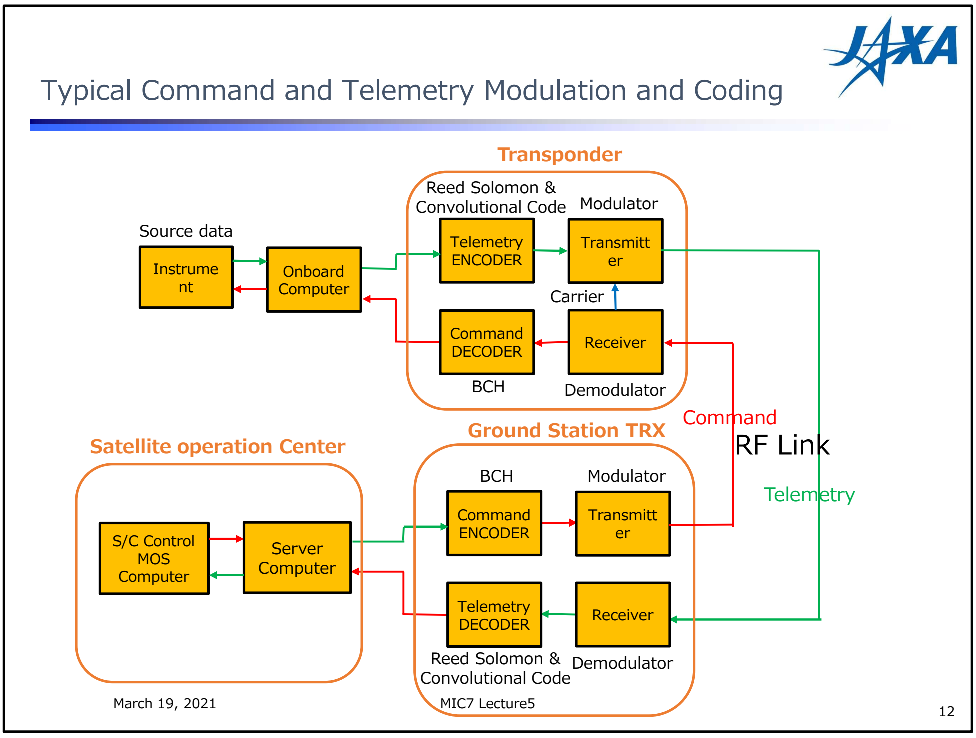
For the reasons in the previous slide, it is recommended that deep space communications use frequencies above the X band. The wavelength of the Ka band is very short, approximately 1 cm.

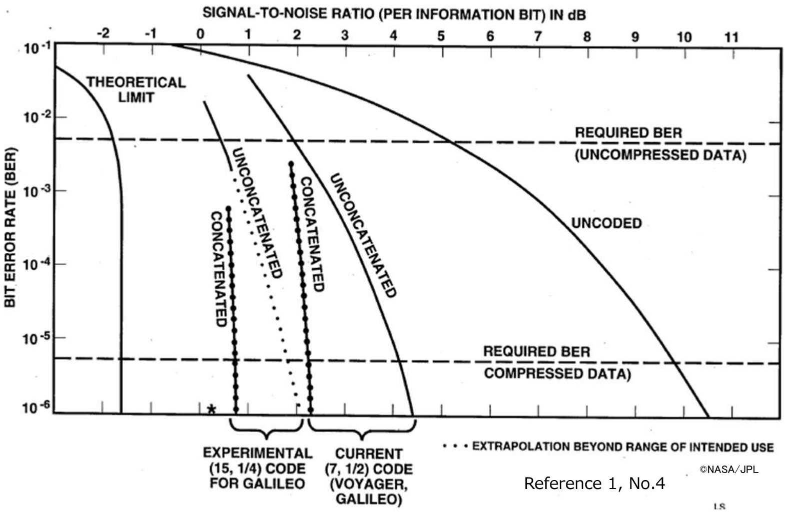
Satellite frequency band

- Frequency allocations are defined by international organizations such as ITU-R, SFCG, and CCSDS. Command commands (uplink) and telemetry (downlink) are divided into their own frequencies and also used by channel allocation.
- Each spacecraft is assigned a frequency after international coordination, including the presence or absence of interference to other communication systems, and a radio station license is granted by the regulatory authority of each country.
- In recent years, advances in semiconductor technology such as MMICs have led to the increased use of the X and Ka bands, which allow for wider bandwidths.



The transponder is responsible for receiving radio signals coming from the earth station, extracting commands and passing them to the onboard computer, while receiving telemetry from the satellite from the OBC and transmitting it to the earth station. The XTRP is called a transponder because it receives signals transmitted from the Earth and transmits them back to the Earth side in order to accurately determine the location of the satellite in space.

Typical telemetry channel encoding improve the Bit Error Rate



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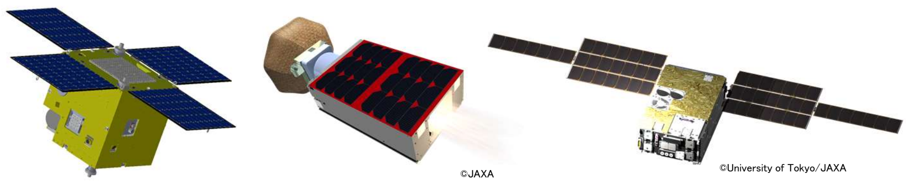
2. Overview of Deep Space Telecommunication System



(a) (b) (c)

Micro-satellite missions for deep space exploration: (a) PROCYON, a 50 kg-class micro-spacecraft, (b) OMOTENASHI, a 6U-Cubesat, and (c) EQUULEUS

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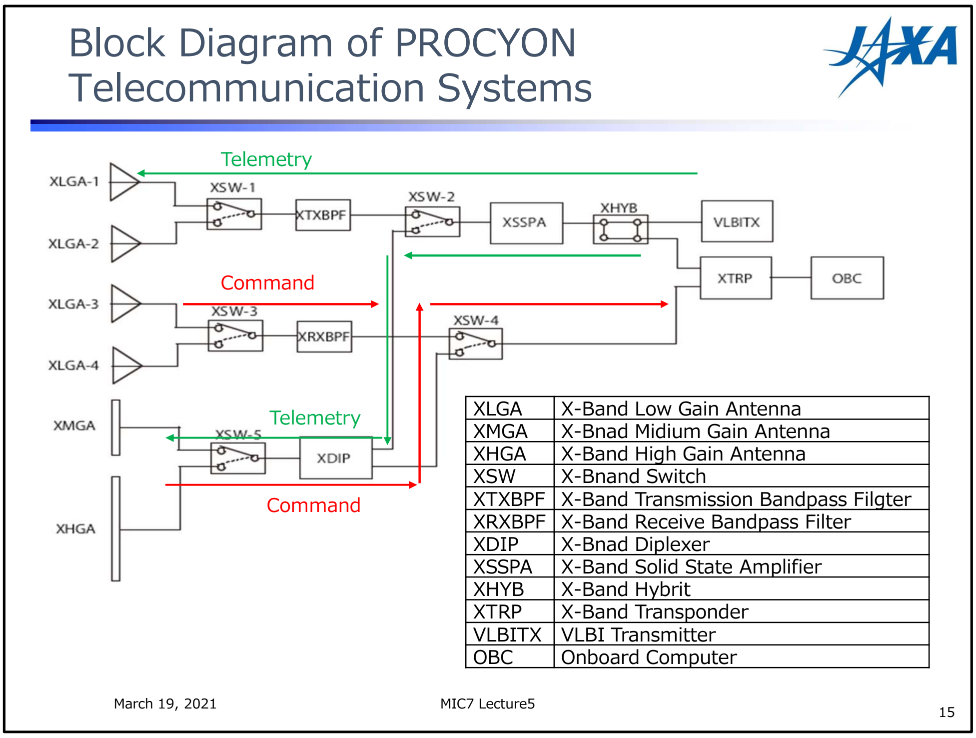
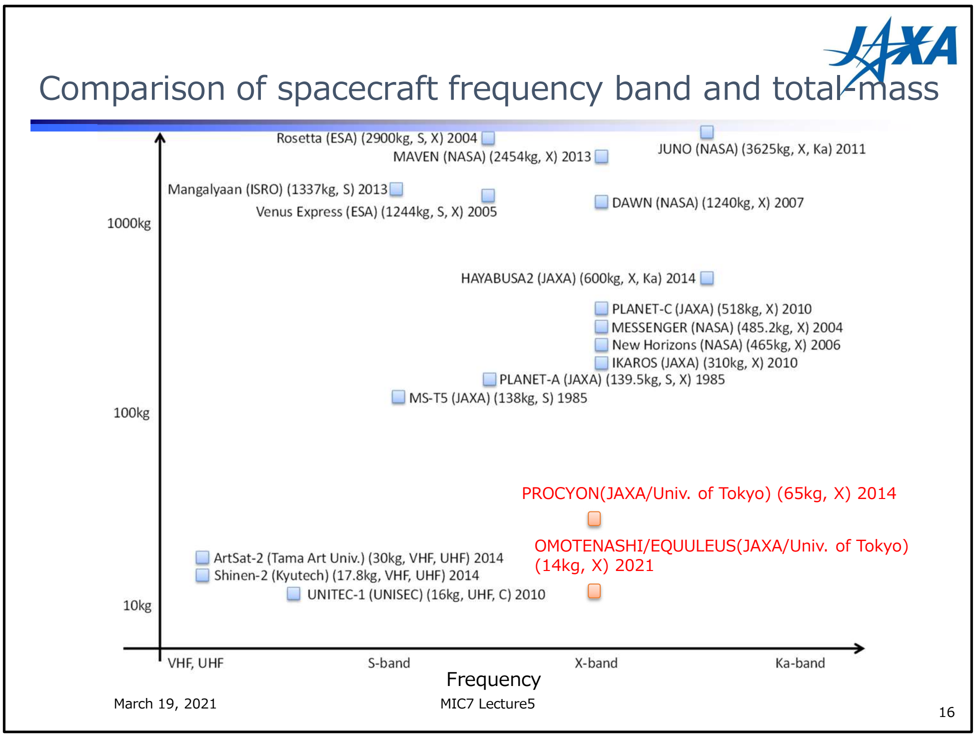
Deep space communication systems have long been developed with the use of high-gain directional antennas such as; parabolic antennas, narrowing of frequency bandwidths, pursuit of transmission power efficiency by combining vacuum tube amplifiers and phase modulation methods, and low noise communication systems such as low noise amplifiers and ultra-low phase noise oscillators. In addition, we have pursued the limits of the individual technology level. On the other hand, in recent years, with the remarkable development of terrestrial information and communication technology, advanced signal processing techniques such as highly efficient modulation and coding have become available due to the emergence of new semiconductor processes and highly integrated circuits. As a common technical issue, this paper discusses how to improve the communication performance of the ultra-small spacecraft as shown as shown in this slide, which are expected to be used more and more in the future.



This slide shows is a system diagram of the communication system installed in PROCYON. Looking at this diagram, we can see that the communication system consists of many components and is a collection of elemental technologies.



In their respective years, PROCYON and EQUULEUS have achieved the world's smallest deep-space communication systems compared to the conventional ones.

Onboard Resources comparison Between Micro-satellite and Small Satellite missions

	JAXA / Univ. of Tokyo	JAXA / Univ. of Tokyo	NASA/JPL	JAXA	JAXA
Name	PROCYON	EQUULEUS	MarCo	MUSES-C	PLANET-C
Size	0.55*0.55*0.63 m	0.20*0.30*0.10m (6U)	0.20 * 0.30 * 0.10 m(6U)	1.0*1.6*1.1m	1.04*1.45*1.4m
Weight	68kg	14kg	13.5kg	502kg	518kg
Power	240W (Earth)	36W (Earth)	35W (Earth)	2.57kW (Earth)	500W (Earth)
Comm.	7.3kg 54.3W SSPA15W	0.65kg 13.3 W SSPA 1W	1kg 35W SSPA 4W	21.1kg 130W SSPA20W	26.6kg 77.3W SSPA10W 88.1W TWTA20W
Output power/ weight	0.221 W/kg	0.0714 W/kg	0.1143 W/kg	0.0398 W/kg	0.0386 W/kg

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This slide shows a comparison of the resources of JAXA's spacecraft and the University of Tokyo's micro spacecraft. 6UCubesat's resources are extremely small. 6U Cubesat has only desktop PC-sized power resources.

Deep Space Transponder

Space craft	PROCYON (JAXA/Univ. of Tokyo)	EQUULEUS(JAXA/Univ. of Tokyo)	PLANET-C, IKAROS, MMO, HAYABUSA2 (JAXA)	MarCo (NASA/JPL)
Freq. (Up/Down)	X/X	X/X	X/X	X/X
Carrier threshold level [dBm]	-150	-150	-150	-130
Size [mm]	120×120×100	80×80×54	180×160×159	100×101×56
Weight [kg]	1.17	0.467	2.4	1.2
Power consumption [W]	8 (TX off) 12 (TX on)	5.9 (TX off) 13.3 (TX on)	17.4 (TX off) 19.6 (TX on)	12.6 (TX off) 36 (TX on)


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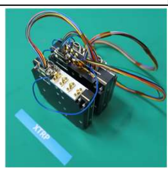
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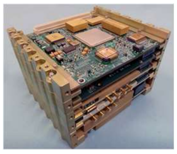
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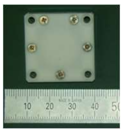
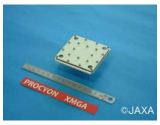
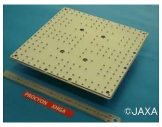
PROCYONS XTRP has physical dimensions of 120 × 120 ×100 mm and mass of 1.17 kg. Power consumption is less than 12 W when transmitting and no more than 8 W when receiving.
EQUULEUS XTRP has physical dimensions of 80 × 80 ×40 mm and mass of 0.468 kg. Power consumption is less than 13.3 W with 1W RF power output when transmitting and no more than 5.9 W when receiving.
The fact that it is small, yet multifunctional with low power consumption, is due to the use of consumer FPGAs, but there is always a concern about malfunctions due to the effects of radiation in the space environment.
In order to investigate the effects of heavy particles, a type of cosmic radiation, on FPGAs, we brought a prototype breadboard model (BBM) of the XTRP to the Takasaki Advanced Radiation Research Institute of the Japan Atomic Energy Agency (JAEA Takasaki), and conducted irradiation tests to confirm what phenomena occur when the transponder is operating.

Applicable Ultra-Small Spacecraft Antennas

Antenna	MGA(EQUULEUS)	XLGA	XMGA	XHGA
Frequency	8.4 GHz	7.1/8.4 GHz	7.1GHz and 8.4GHz	7.1GHz and 8.4GHz
Gain	8.9 dBi	5.0/3.6 dBi	13.3 dBi（7.1GHz） 13.9 dBi（8.4GHz）	24.7 dBi（7.1GHz） 25.5 dBi（8.4GHz）
Beam width	+8[dBi]（±12[deg]）	160 deg (±80 deg)	30 deg (±15 deg)	8 deg (±4 deg)
Physical Dimension	30×30×7.6[mm]	φ68 mm, h 43 mm /φ68 mm, h 37.5mm	75×75×12 mm	295×295×12 mm
重量	14.3 [g]	145 g/130 g	82 g	1.22 kg
構成	Circular Patch Antenna using Parasitic Element	4-Elemet Helical antenna	4-Element Circular Patch Array Antenna using Parasitic Element	64-Element Circular Patch Array Antenna using Parasitic Element
外観	 ©JAXA	 ©JAXA	 ©JAXA	 ©JAXA

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For example, the PROCYON antenna is designed to be light with a total weight of 1.22 kg and low in height. Small secondary payloads are limited in size and weight so as not to affect the launch of the main satellite. In order to make full use of the limited size of the satellite, the antenna must be as small and low in height as possible. In addition, if the HGA is placed directly on the same top surface as the solar cells, the heat input from the sun to the satellite will be large. Therefore, germanium-deposited Kapton sheets are placed on the top surface of the antenna to change the thermo-optical properties while maintaining the radio wave transmission characteristics, and an air gap is created between the antenna and the satellite to insulate it.

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PROCYON Components specifications

	Physical diimension [mm]	Weight [kg]	RF characteristics	Power consumption
XTRP	120×120×100	1.17	Max. output power: +17 dBm (tunable), Receiving level: -150 to -50 dBm, Coherent ratio: 749/880, Modulation: PCM/PSK/PM, two-way Range & two-way Doppler, DDOR (±0.5F_0, ±2F_0)	<8 W（Tx off) <12 W（Tx on)
XSSPA	150×120×62	1.5	Amplification device: GaN HEMT, Output power: 41.85±0.15 dBm, Band width: Fc±50 MHz, Efficiency > 32.7% (Max. 35.1%)(-20 to +60 °C)	< 47.7 W (42.5 W at +20 °C)
VLBITX	150×125×40	1.07	Max. output power: +9 dBm (each tone), Max. tone width: 86 MHz, Max. sweep width: 7.9 MHz, Sweep time: 2 to 40 min, Alan variance < 1E-10 (1-100 s), < 1E-9 (1000 s) (-20 to +60°C)	<23.4 W（3 tones on)
XHGA	295×295×12	1.22	Tx gain: 25.5 dBi, Rx gain: 24.7 dBi, 3dB Beam width: ±4 deg	
XMGA	75×75×12	0.082	Tx gain: 13.9 dBi, Rx gain: 13.3 dBi, 3dB Beam width: ±15 deg	
XLGA	Tx : φ68×37.5 Rx : φ68×43	0.13 0.145	Tx gain: 3.6 dBi, Rx gain: 5.0 dBi (-1.0 dBi at ±85 deg, 1.5 dBi at ±70 deg)	
XSW	38×59×13	0.05	Transmission loss: -0.2 dB, Isolation: 80 dB, VSWR: 1.1	<1.82 W
XHYB	25.4×34×9.6	0.02	Transmission loss: -3.3 dB, Isolation: 20 dB, VSWR: 1.3	
XDIP	273×200×118 (outer shape)	0.93	Tx transmission loss: -0.9 dB, Rx transmission loss: -1.1 dB, Isolation: 100 dB, Tx/Rx VSWR: 1.3	
XTXBPF XRXBPF	152×47.6×51	0.27	Tx transmission loss: -0.55 dB, Rx transmission loss: -0.75 dB, Isolation: 100 dB, Tx/Rx VSWR: 1.3	

Total weight : 7.3 kg (excluding RF harness), Total power consumption: 54.3W

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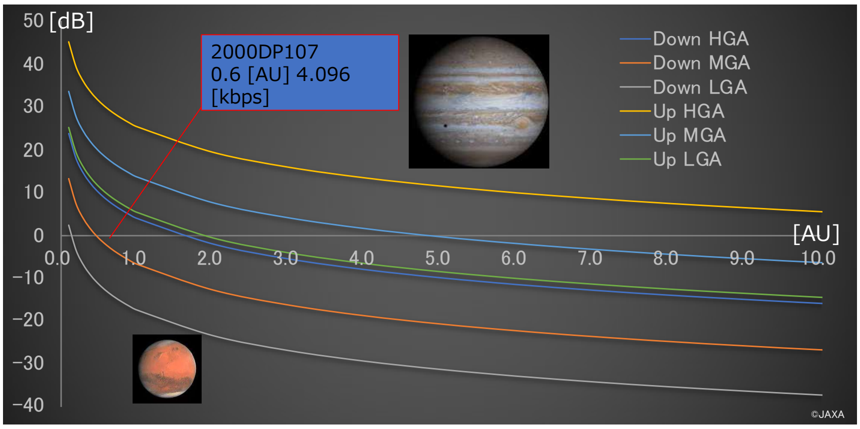
This slide shows the summary of the onboard telecommunication components' specifications such as physical dimension, weight, RF characteristics and power consumption. The signal output from the repeater is weak and needs to be amplified to reach the earth; the power consumption of the PROCYON communication system is about 54.3W, of which about 70% is consumed by the XSSPA. Therefore, we newly developed a combination of semiconductor devices using the latest GaN process and our own circuit configuration to achieve high power efficiency.

Command and Telemetry performance assuming the PROCYON onboard telecommunication system

- Distance at which a Micro-satellite with a communication system equivalent to PROCYON can communicate with the Usuda 64m antenna
  - Downlink bit-rate 1.024 [kbps]
  - Uplink bit-rate 125 [bps]
- It is directed to the HGA and just barely reaches Mars. Because of asymmetric communication, there is much more room for uplink.



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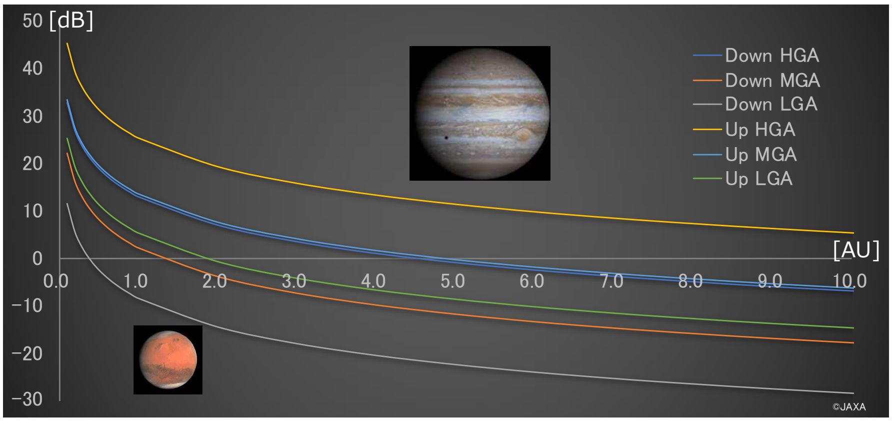
Command and Telemetry performance assuming the PROCYON onboard telecommunication system

- Distance at which a Micro-satellite with a communication system equivalent to PROCYON can communicate with the Usuda 64m antenna
  - Downlink bit-rate 128 [bps]
  - Uplink bit-rate 125 [bps]
- The telemetry is just barely reachable from Jupiter even if the HGA is oriented. Direct communication with Jupiter is possible by improving the antenna, SSPA, and coding by about 10[dB], but relay communication with the mother ship is essential for high bit rate.



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Conclusion 1

- As satellites become smaller, the power generated by SAPs becomes smaller, and the equivalent isotropic radiated power (EIRP), which radiates radio waves into space, decreases significantly. For nano-satellites to communicate in deep space, a decrease in EIRP means a decrease in communication data rate. In order to communicate with the earth at a practical communication speed, it is essential to improve the EIRP. In addition, free antenna directional control is required to ease the attitude constraint.
  - Reduction of instrumentation loss (using the waveguide possible)
  - Planar patch array antenna, or such as deployable high-gain antenna
  - Improvement of power efficiency by New Semiconductor Devices
  - Coding gain reduces the transmit power

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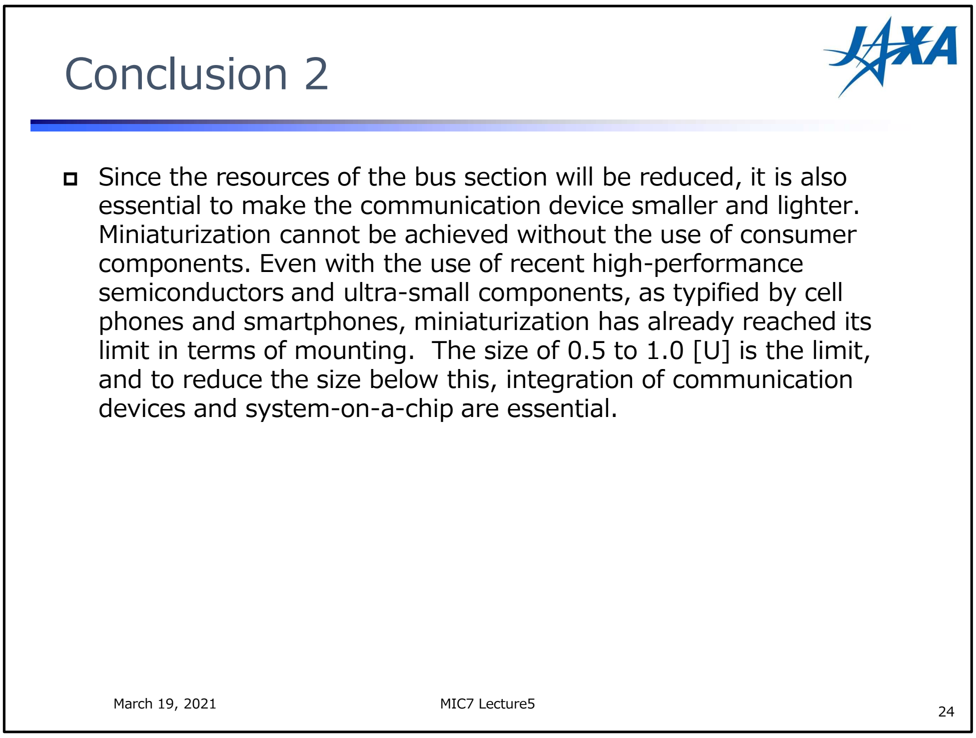

Deep space exploration has entered a new era in which satellites are designed and developed by universities, and operated by faculty and students. The deep-space communication system on board the nano-satellite we developed this time was able to operate perfectly in space as originally envisioned, thanks to the use of consumer components and the sparing application of feasible technologies under severe weight, power consumption, and time constraints.

Nano-satellites, which are increasingly used as an inexpensive means of mission accomplishment, are now mass-produced in manufacturing plants with the same quality as general electric products. Such a revolution is also coming to space communications, and new private space companies such as SpaceX and Oneweb are already planning formation flights of several thousand or ten thousand satellites. With the development of the space communication system introduced in this paper, we expect to realize more familiar use of space.

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No.1 book is used as a textbook in universities.

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