
MIC7 Lecture 5
Ultra-Small Deep Space Mission
Telecommunication Systems Design
March 19,2021
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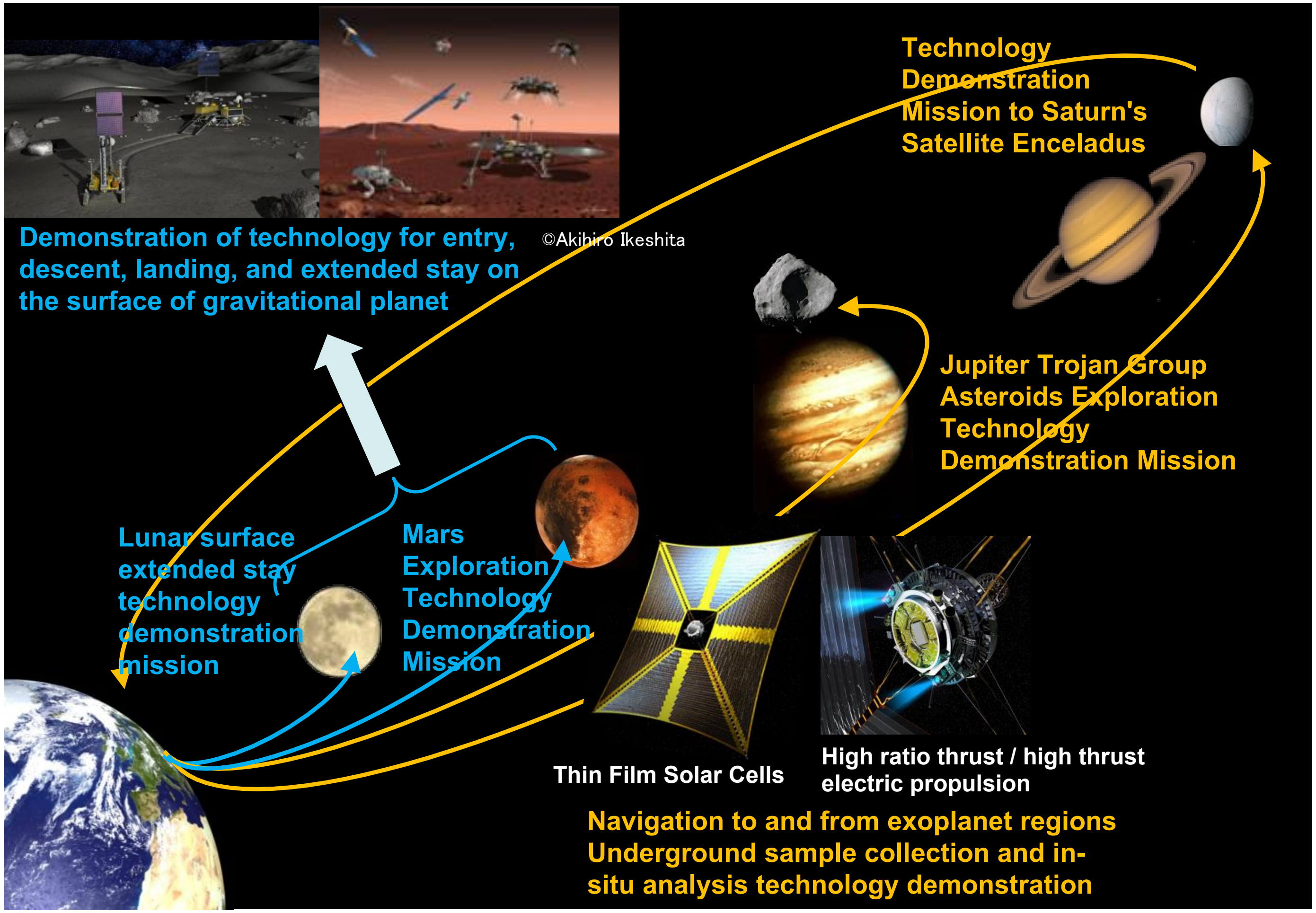
Biography

- 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.

1. Introduction and Background

Plan of ISAS Deep Spacecraft Fleet

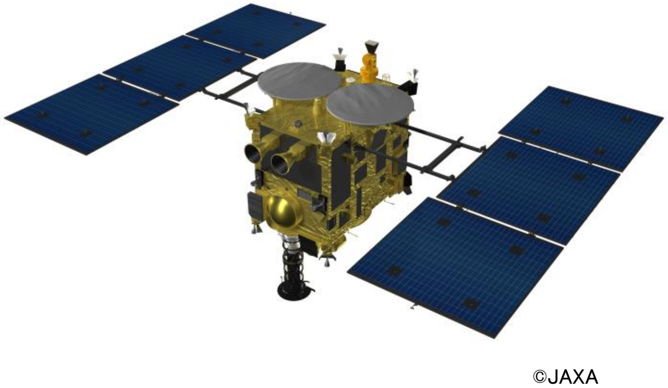
1. Introduction and Background



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

2. Overview of Deep Space Telecommunication System

(a)



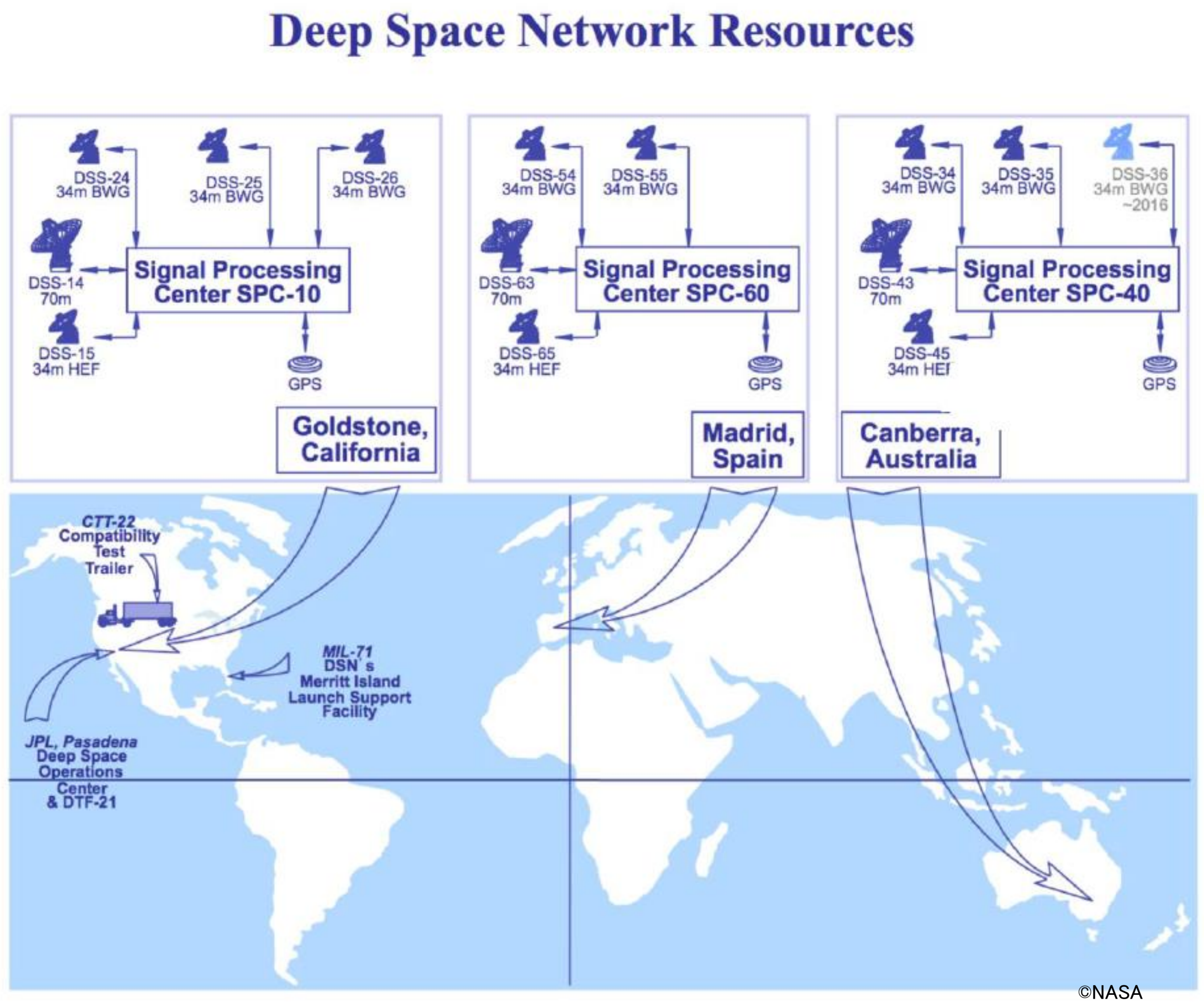
(b)

(c)

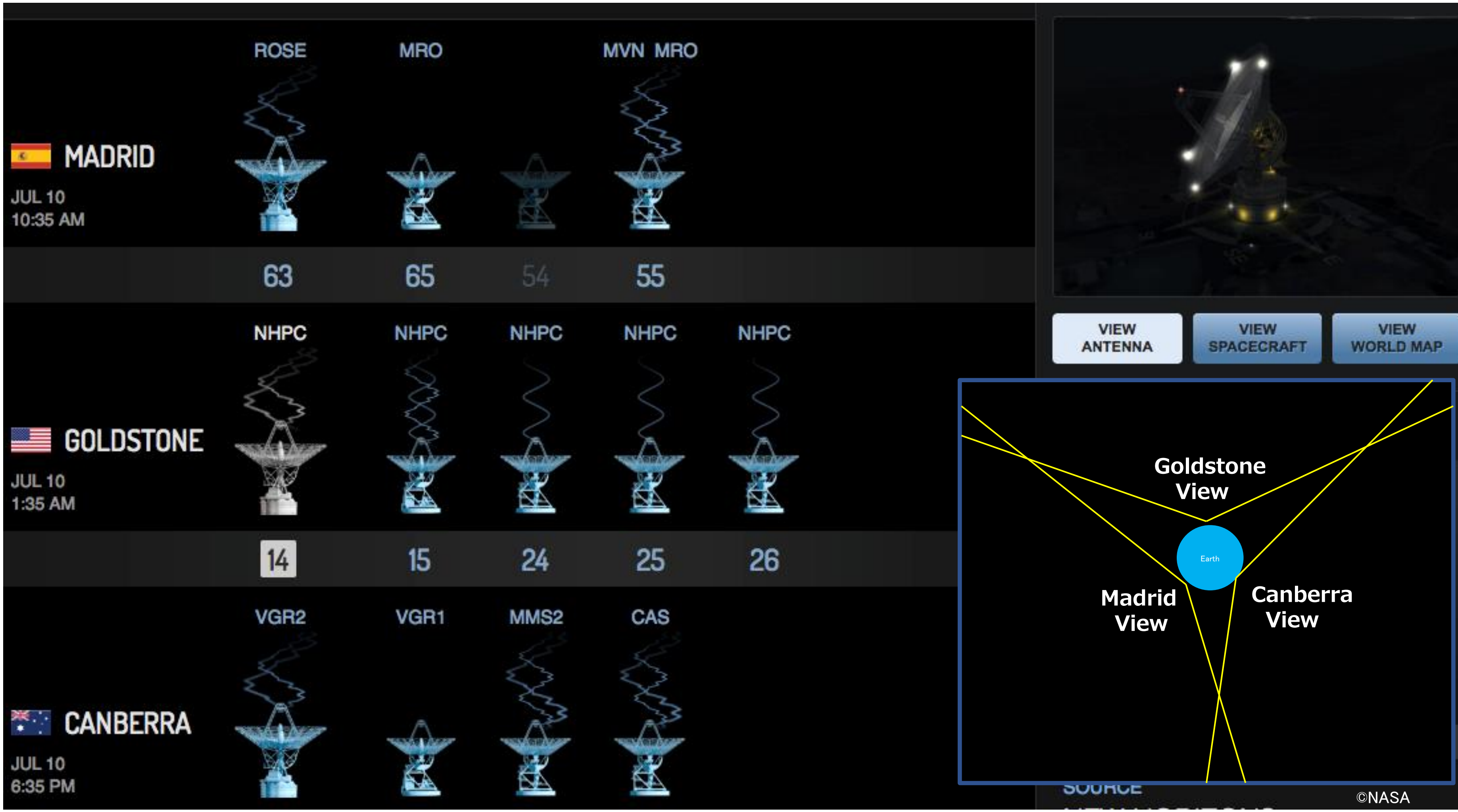
Telecommunication System of (a) 64m antenna of Usuda Deep Space Center, (b) Hayabusa2 spacecraft, and (c) 54m antenna of Misasa for Ka-band reception, which is currently under construction.

Deep Space Network Between Agencies

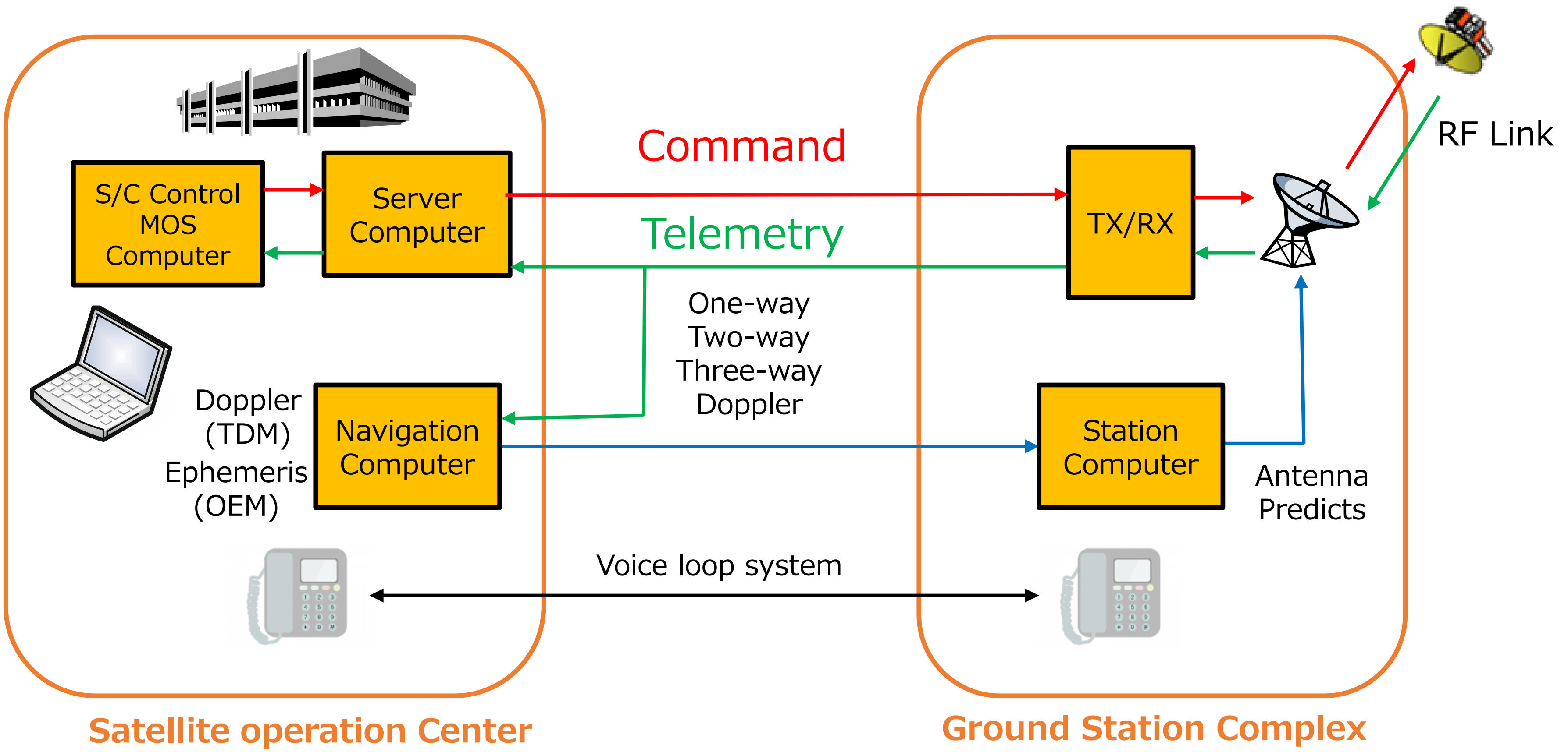
NASA/JPL Deep Space Network Capabilities



NASA/JPL DSN Now!



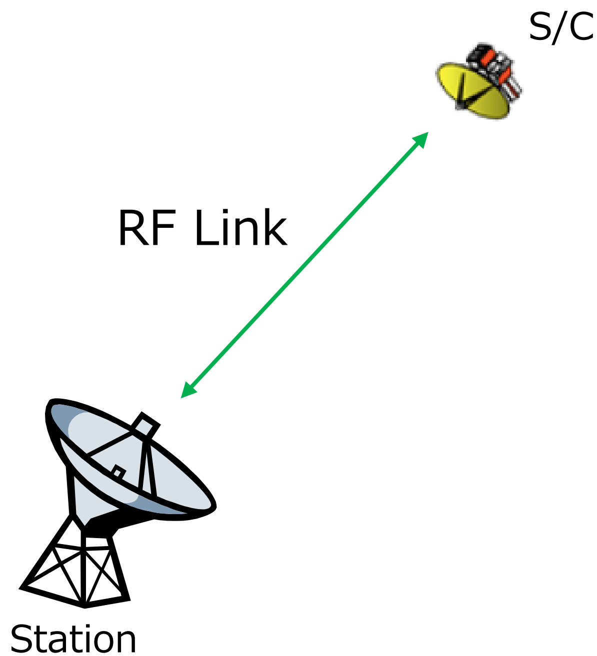
Command and Telemetry Modulation and Codling



Link Equation on Physical layer

$$\frac{S}{N} = \frac{P_t A_t A_R f^2}{T_s L_t L_a L_r R^2} \propto data\, rate$$

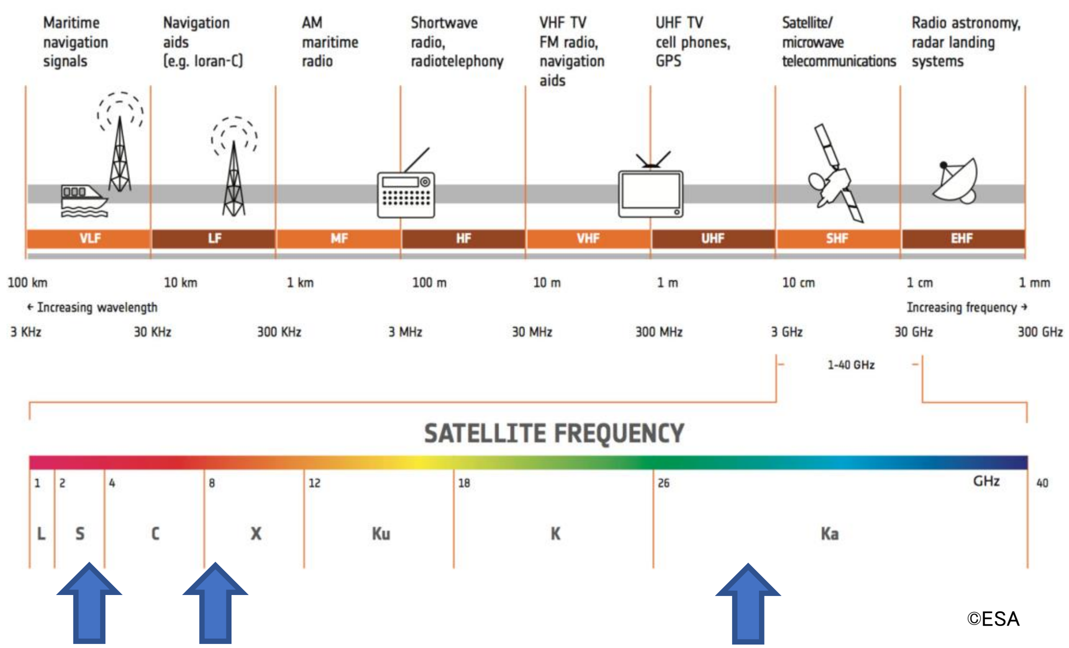
Reference 2, No.2



- f = Communication Frequency
- P_t = Transmitter Power
- L_{TP}&L_{RP} = Pointing Loss
- L_A = Loss through the Atmospheres (Rec. ITU-R P.676, Ref2, No.6)
- A_T&A_R = Effective Apertures (areas) of Transmit & Receive Antenna
- R = Range between S/C and Ground Station Antenna
- T_s = System Noise Temperature

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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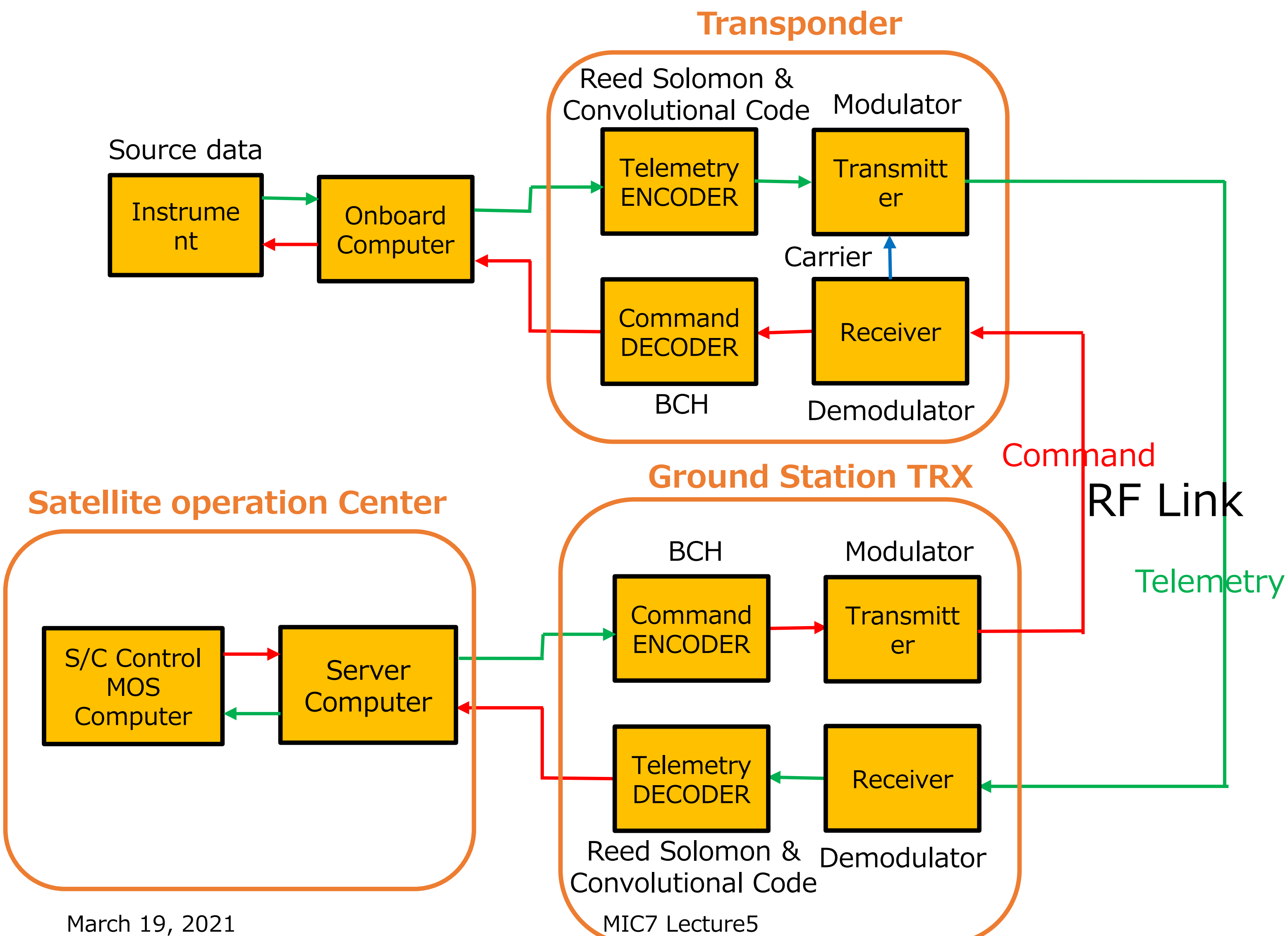
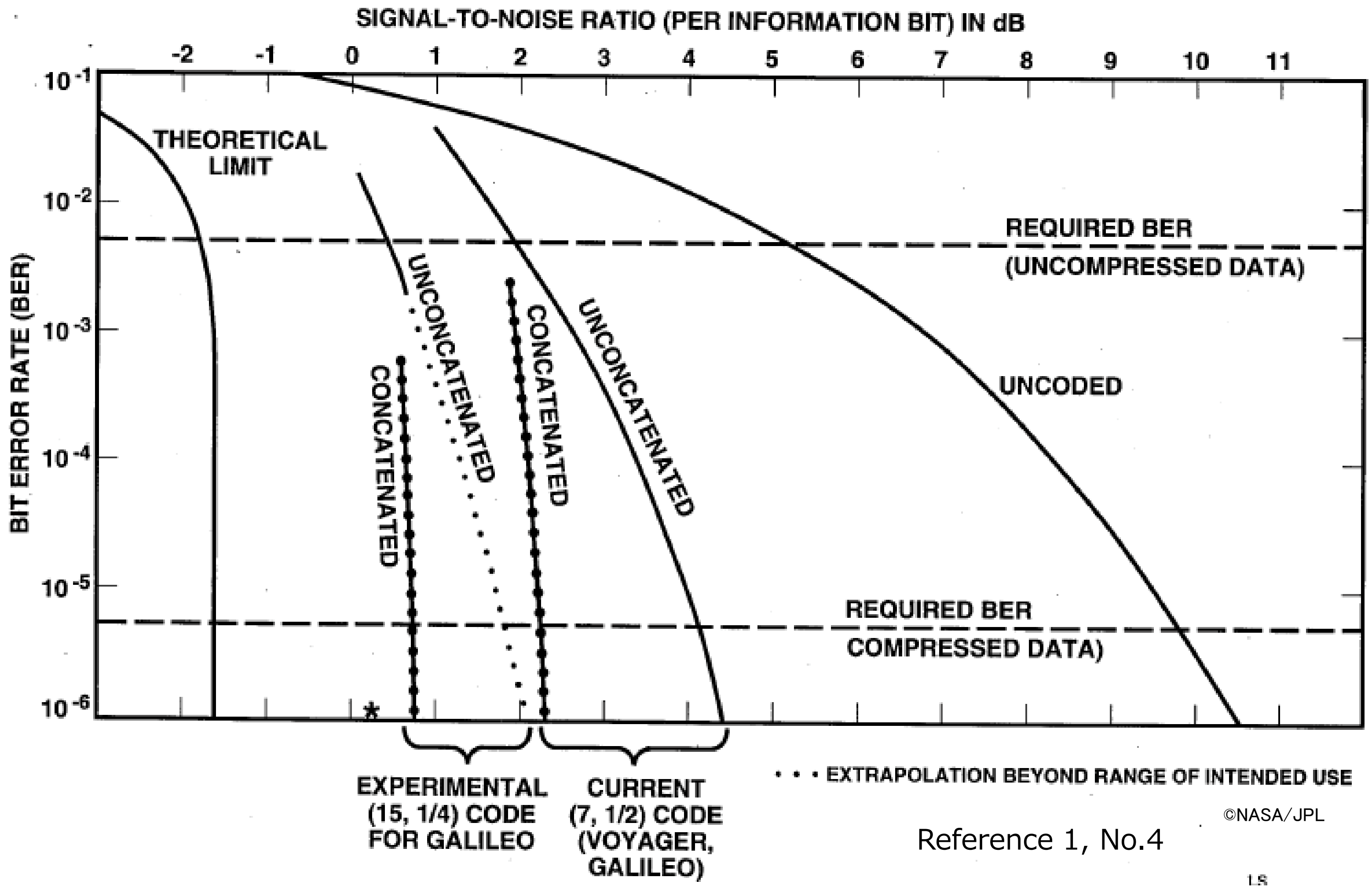
Satellite frequency band

- 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.

Typical Command and Telemetry Modulation and Coding

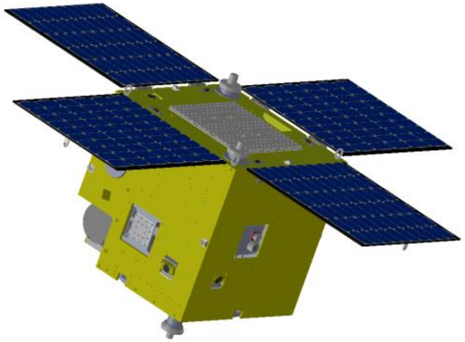


Typical telemetry channel encoding improve the Bit Error Rate

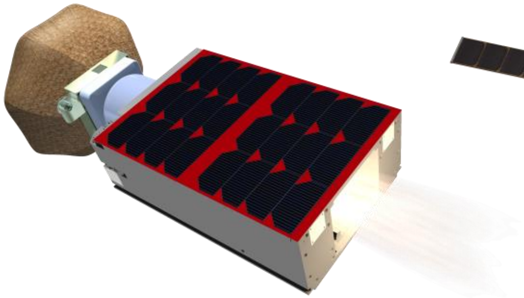


Reference 1, No.4

2. Overview of Deep Space Telecommunication System



(a) ©University of Tokyo/JAXA



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(b)

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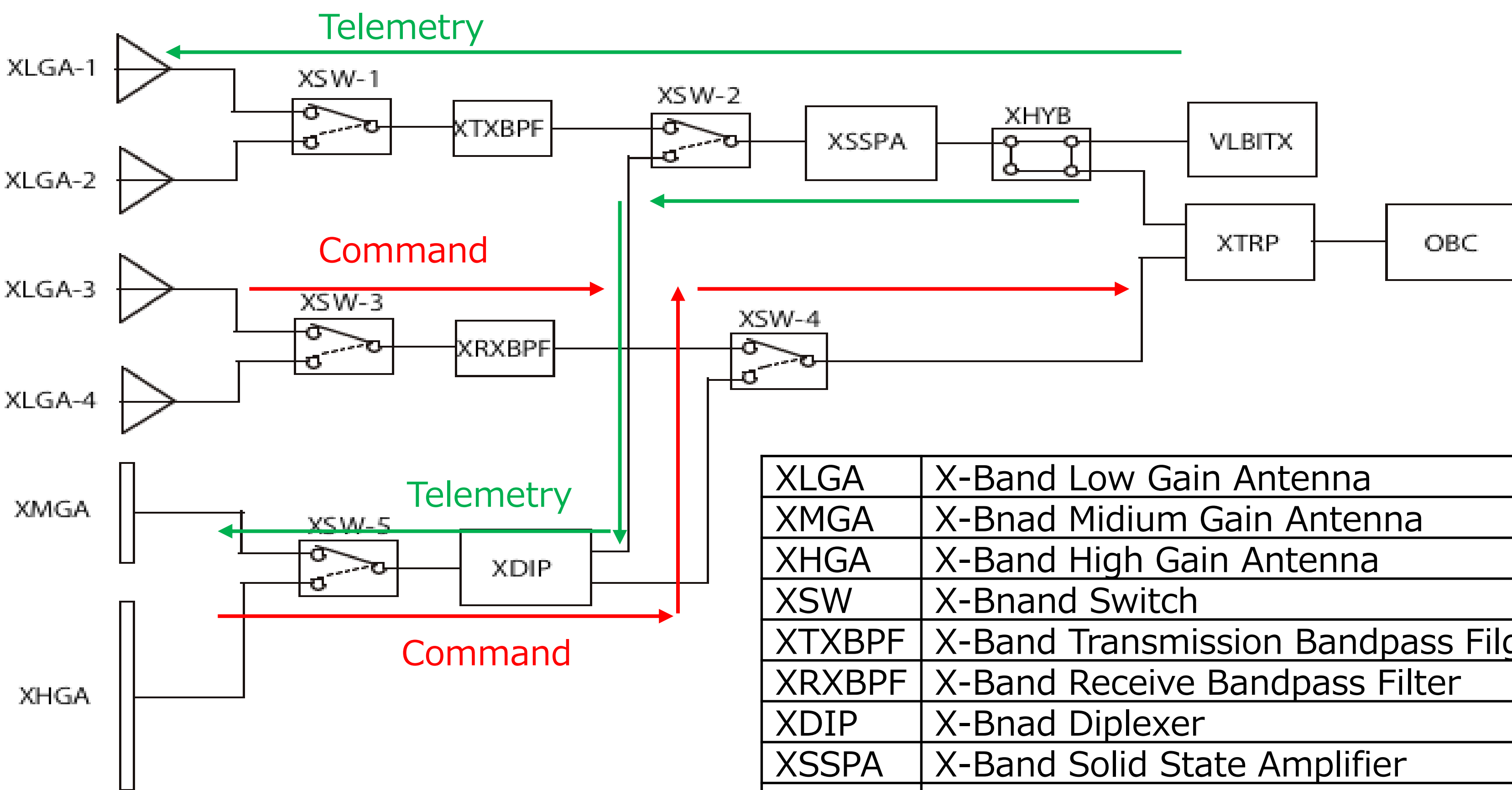
(c)

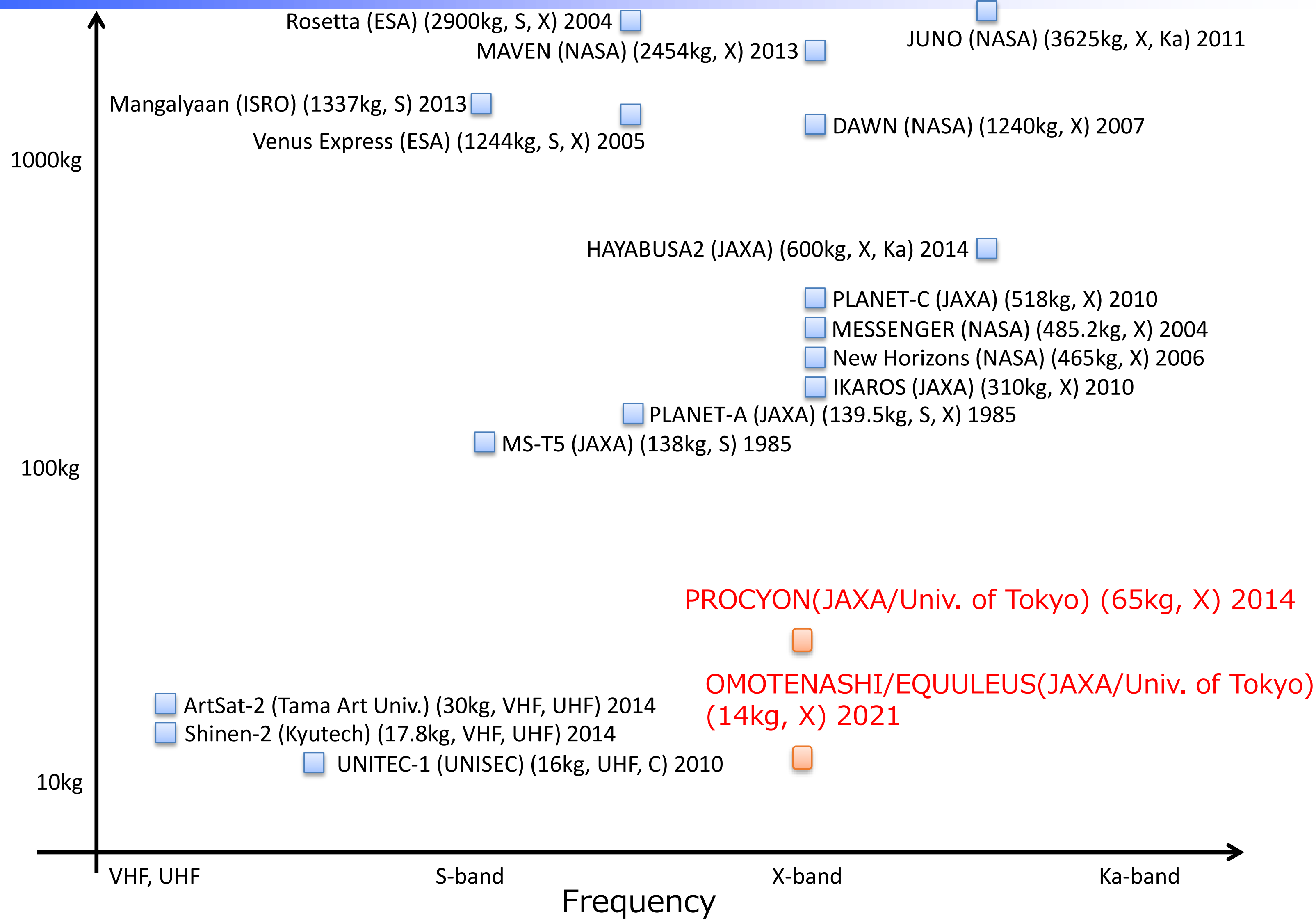
Micro-satellite missions for deep space exploration: (a) PROCYON, a 50 kg-class micro-spacecraft, (b) OMOTENASHI, a 6U-Cubesat, and (c) EQUULEUS

Block Diagram of PROCYON Telecommunication Systems



XLGA	X-Band Low Gain Antenna
XMGA	X-Bnad Midium Gain Antenna
XHGA	X-Band High Gain Antenna
XSW	X-Bnand Switch
XTXBPF	X-Band Transmission Bandpass Filgter
XRXBPF	X-Band Receive Bandpass Filter
XDIP	X-Bnad Diplexer
XSSPA	X-Band Solid State Amplifier
XHYB	X-Band Hybrit
XTRP	X-Band Transponder
VLBITX	VLBI Transmitter
OBC	Onboard Computer

Comparison of spacecraft frequency band and total mass



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

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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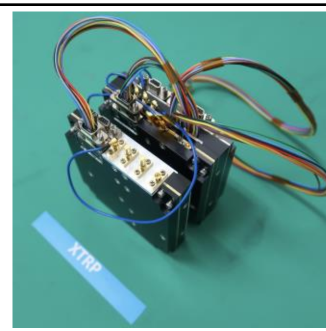

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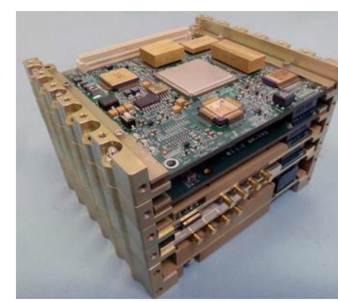
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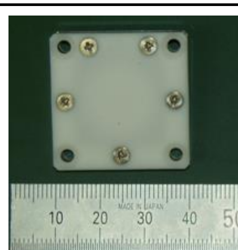
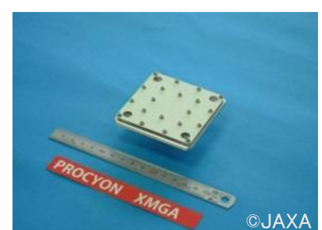
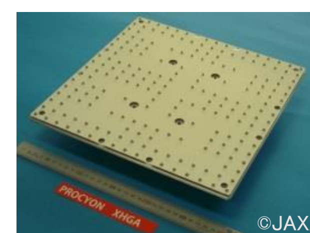
Applicable Ultra-Small Spacecraft Antennas

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		

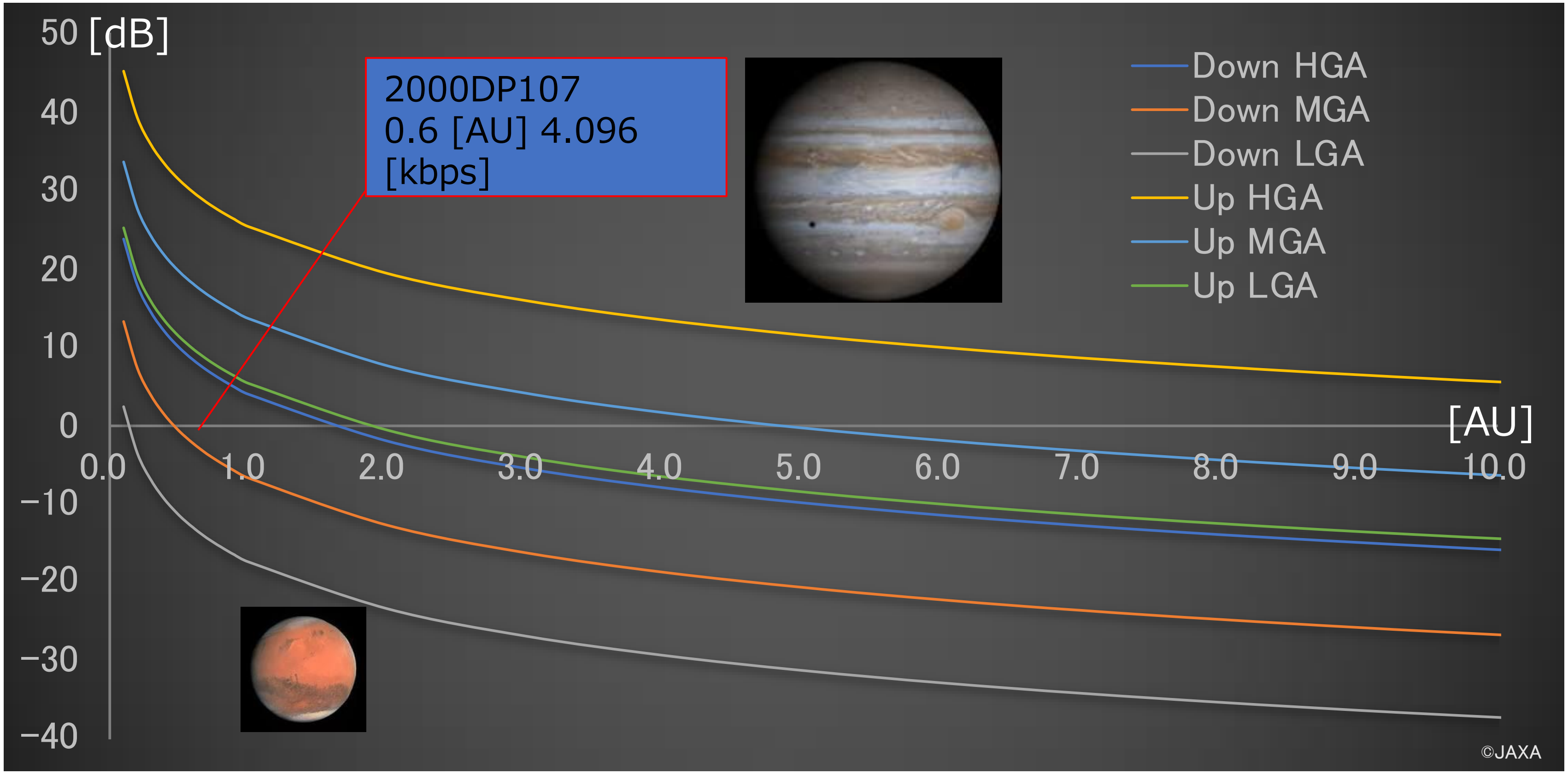
PROCYON Components specifications

	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

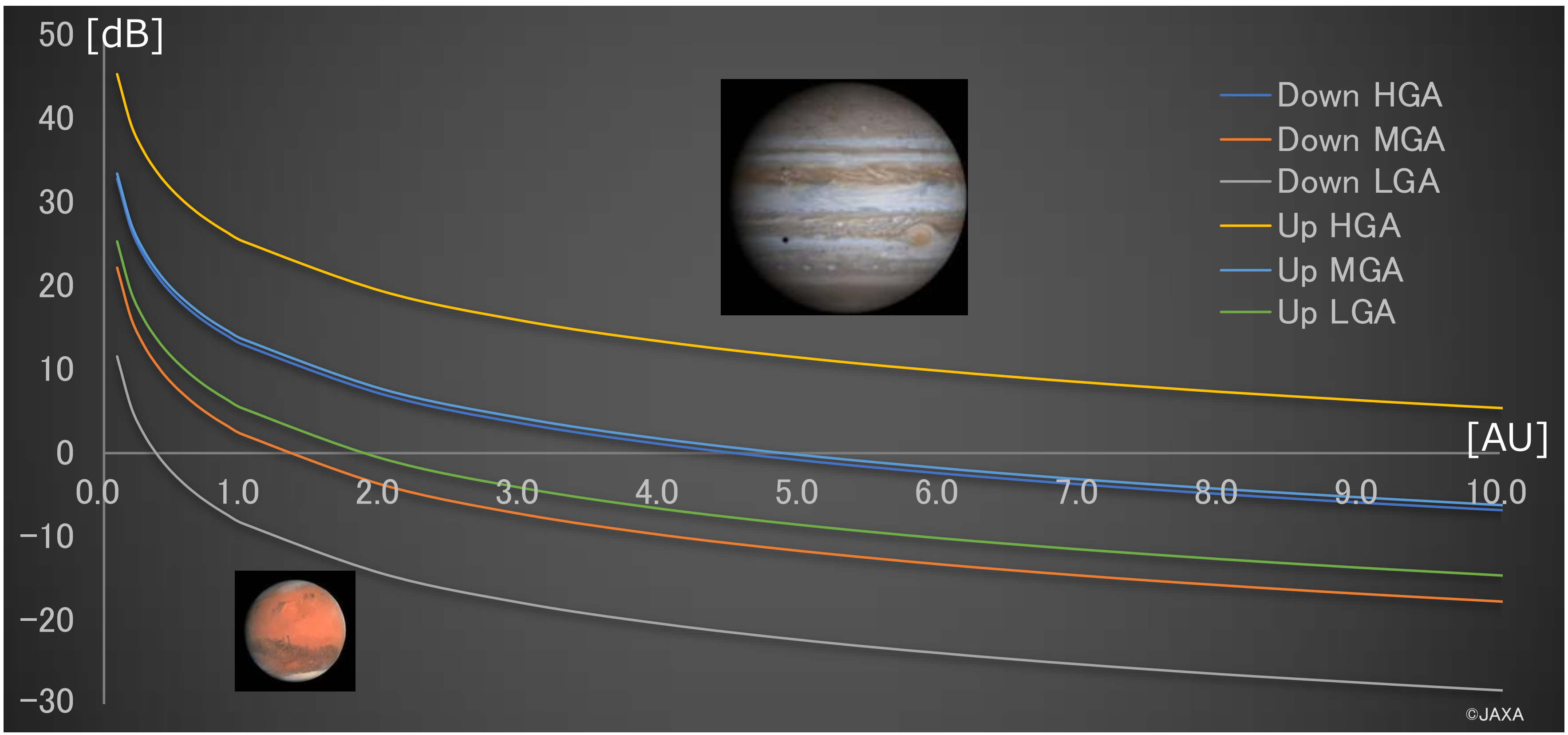
Command and Telemetry performance assuming the PROCYON onboard telecommunication system

- 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.



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.



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

Conclusion 2

- Since the resources of the bus section will be reduced, it is also essential to make the communication device smaller and lighter. Miniaturization cannot be achieved without the use of consumer components. Even with the use of recent high-performance semiconductors and ultra-small components, as typified by cell phones and smartphones, miniaturization has already reached its limit in terms of mounting. The size of 0.5 to 1.0 [U] is the limit, and to reduce the size below this, integration of communication devices and system-on-a-chip are essential.

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