KiboCUBE Academy

Live Session #2-2

Radio Link Margin Assessment

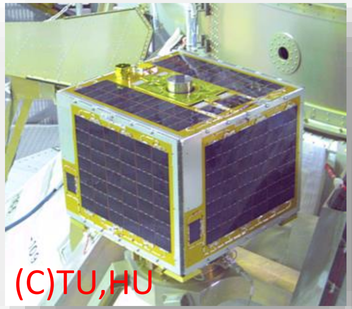
Hokkaido University

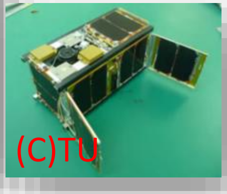
Division of Mechanical and Aerospace Engineering

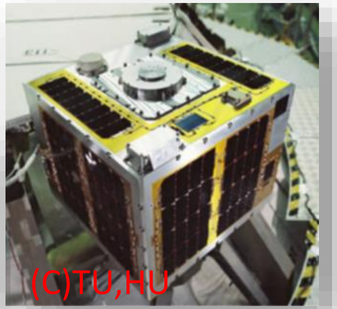
Associate Professor Dr. Yuji Sakamoto

This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction







TU = Tohoku University
HU = Hokkaido University
DOST = Department of Science and Technology, Philippines
UPD = University of the Philippines Diliman

Yuji Sakamoto, Dr.

Position:

2006 - Assistant Professor (-2015), Associate Professor (2015-)
Department of Aerospace Engineering, Tohoku University

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Research Topics:

Design, Assembly, and Evaluation of Micro and Nano Satellites
Satellite Operation and Ground Station Management

Contents

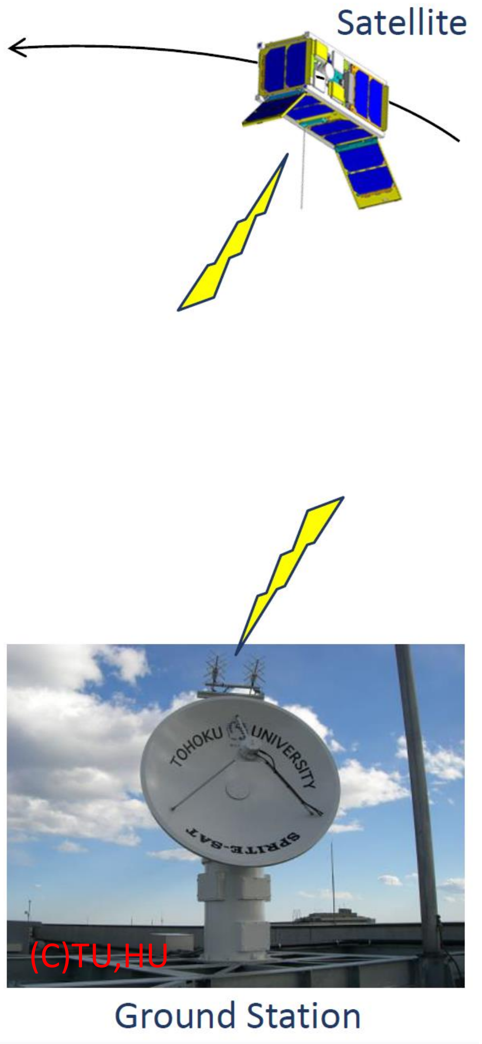
** = digest of previous seminar "Live Session #1-2: CubeSat Launch and Operation"*

1. Introduction to Satellite Operations

1. Introduction to Satellite Operations

- Satellites rotate around the Earth, about **14 to 16 times** per day in Low Earth Orbit (LEO)
- About **10 to 12 minutes** per contact from a single ground station, and about **4 passes per day**

  => data communication time will be **total of 40 to 48 minutes** per day
- Satellite operations **send commands** to satellite from ground stations and **receive telemetries** from satellites



1. Introduction to Satellite Operations

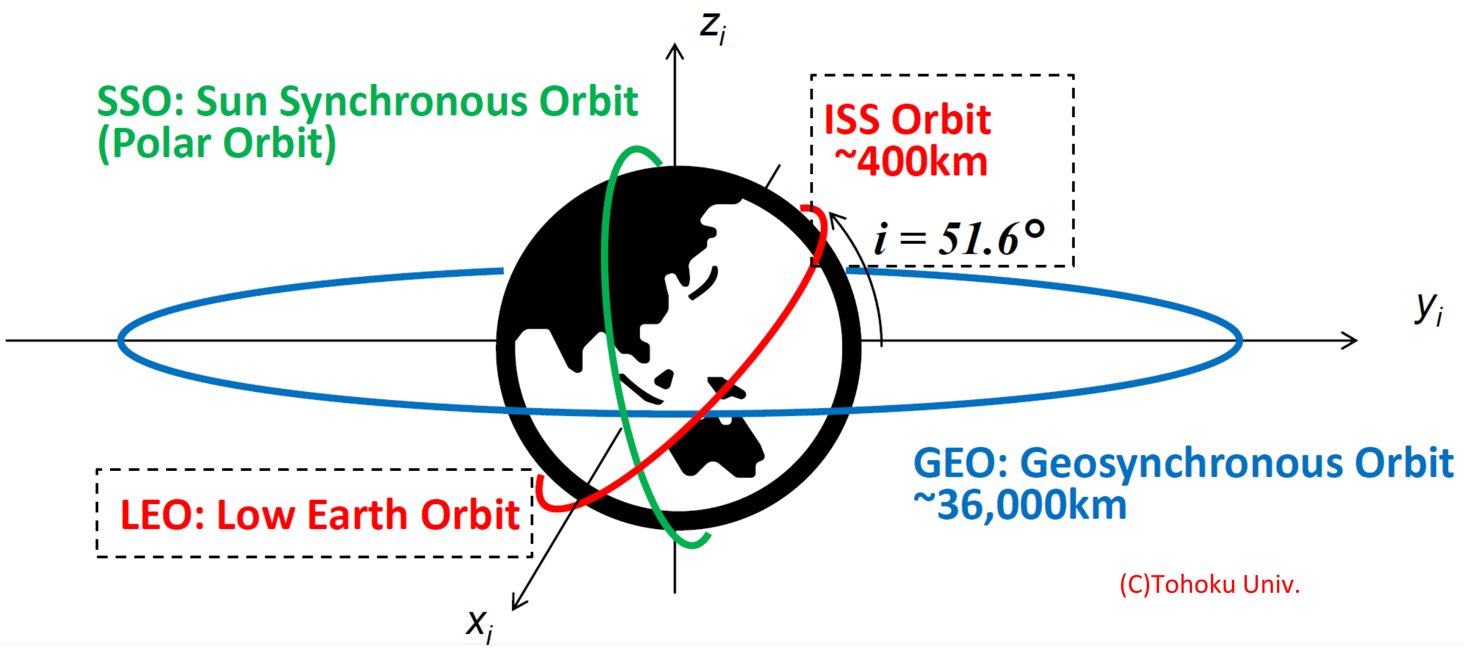
Low Earth Orbit has

1. **Many launch** opportunities

2. **Short distance** to Earth

=> communication **transmitting power** can be **decreased**

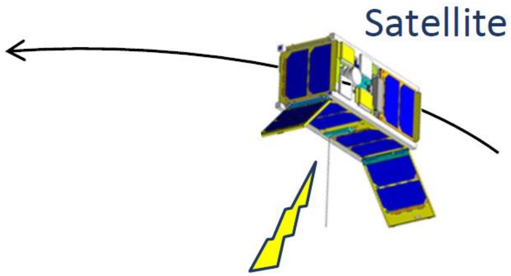
=> **high resolution images** can be obtained

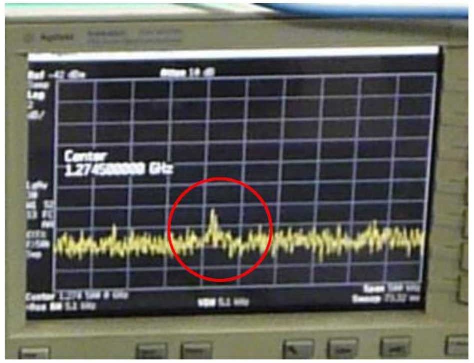


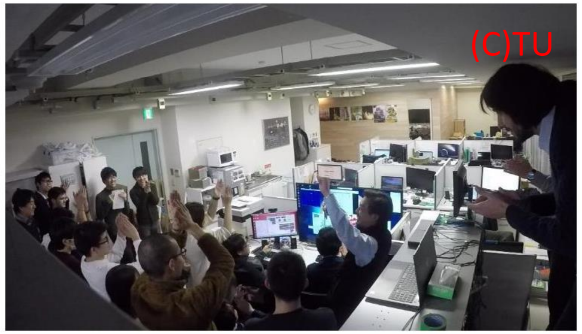
1. Introduction to Satellite Operations

First Contacts

1. CubeSats **automatically start** the functions in space, including **RF transmission**
2. We observe **1st signals** from a satellite at the ground station, **most exciting moment**
3. **Satellite health** is checked including normal **power generation, battery charge, temperature** of components, etc.







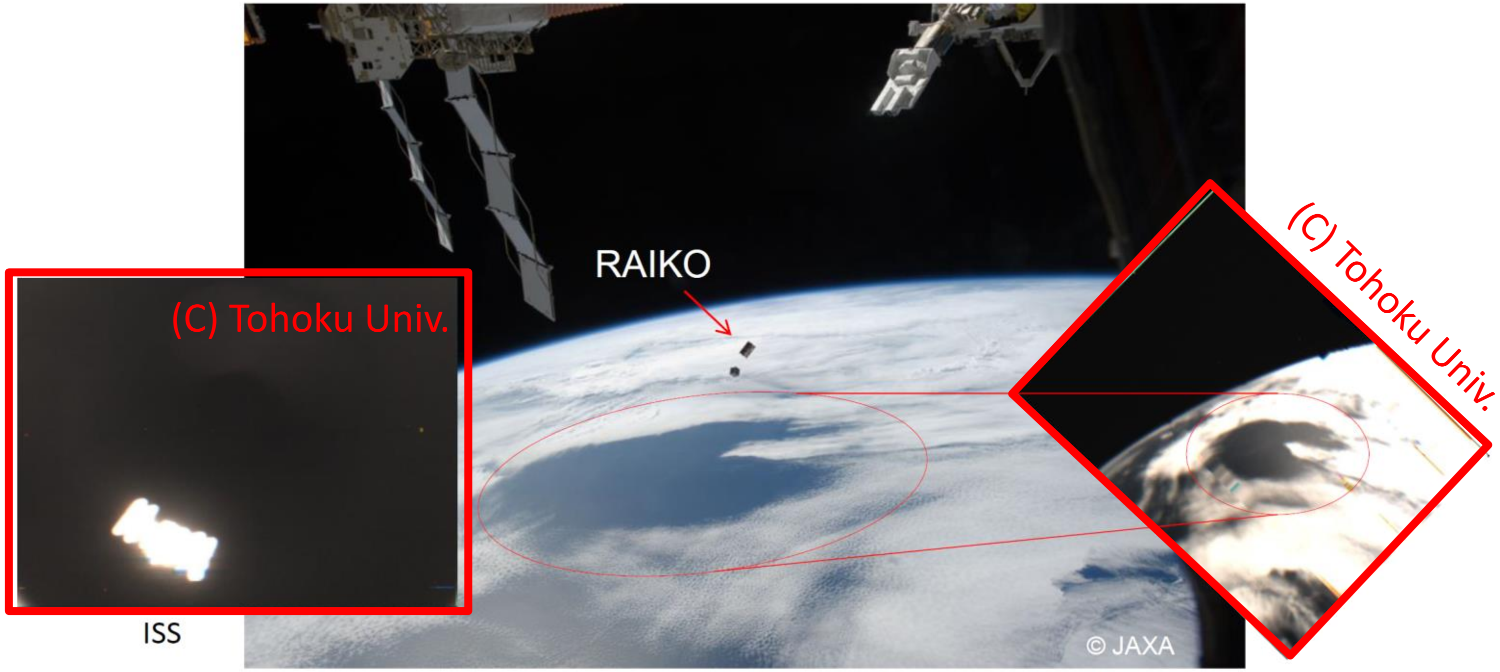
First Light

4. We need to **confirm the successful of command uplink** as well as telemetry receiving.

- **a lot of CubeSats had defects** in command function

- [!] **be careful of the electrical noise** environment **inside** of satellite

5. We send commands of **camera trigger** and **data download,** and check the **1st light images**

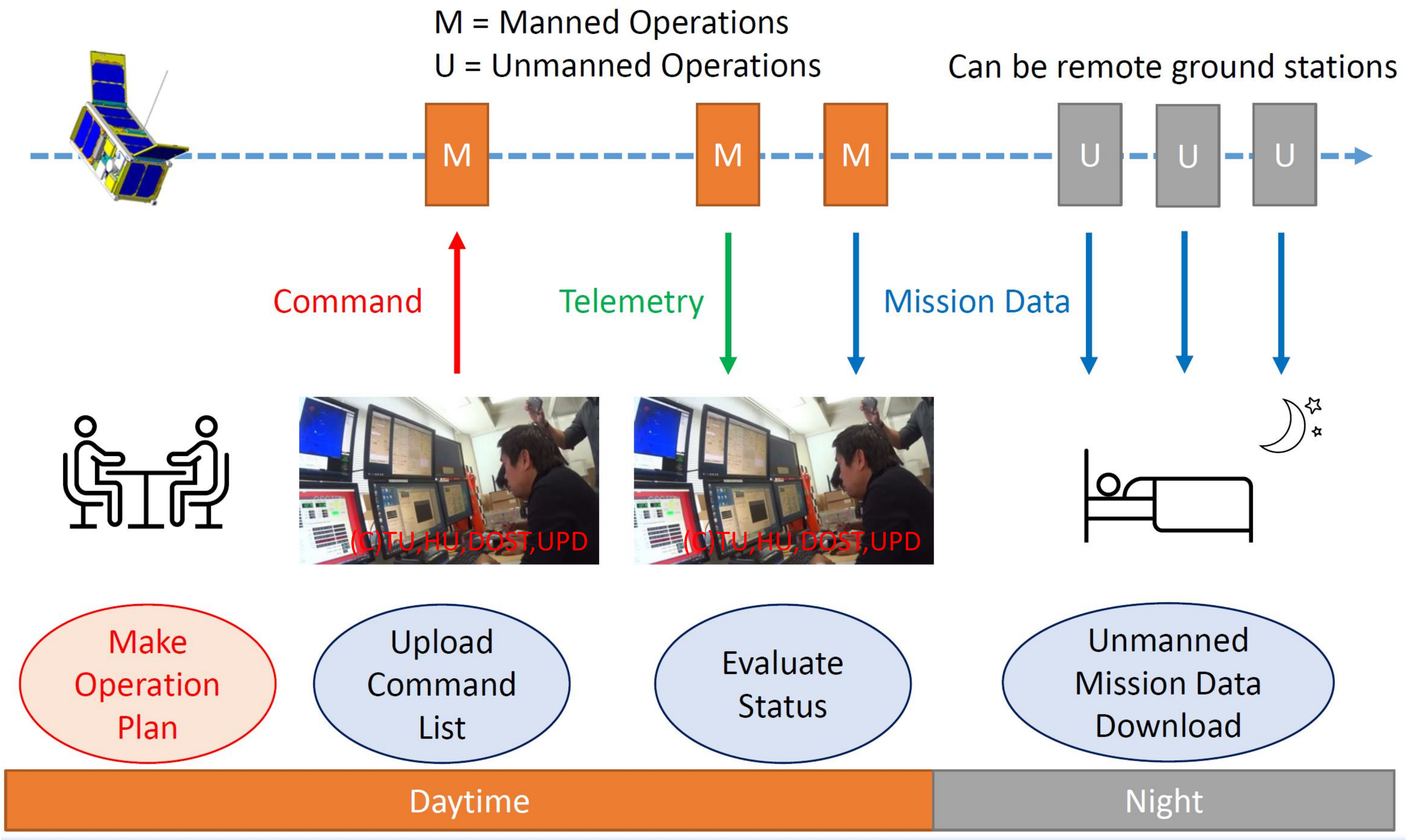


Images obtained by CubeSat RAIKO just after the deployment from the ISS

1st light images by RAIKO

1. Introduction to Satellite Operations

Operation Routine



2. Communication System

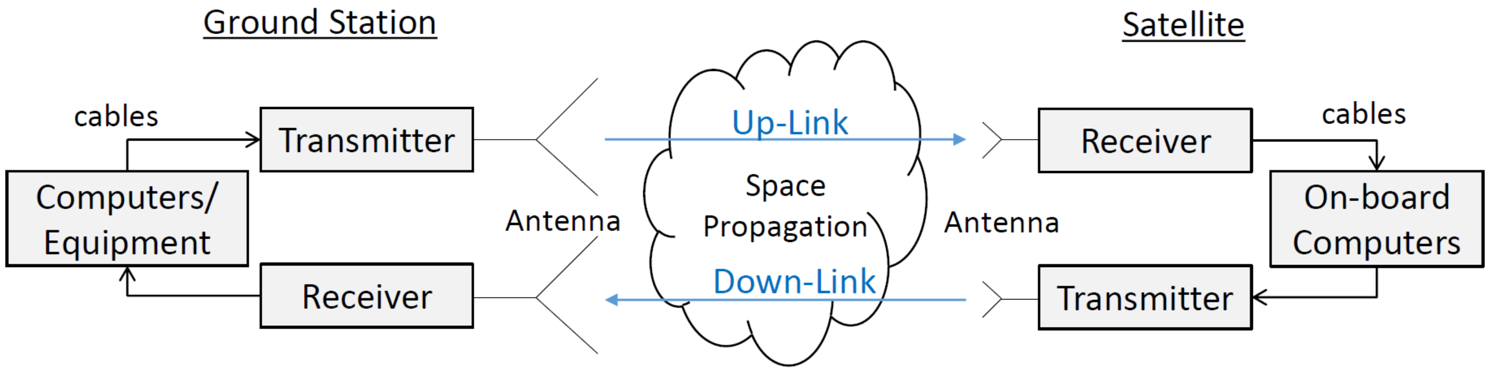
2. Communication System

Introduction to Communication System

- Communication system is required for:

- upload commands

- download house-keeping data and mission data



- Typical frequencies:

- VHF (around 144 MHz, amateur radio)

- UHF (around 435 MHz, amateur radio)

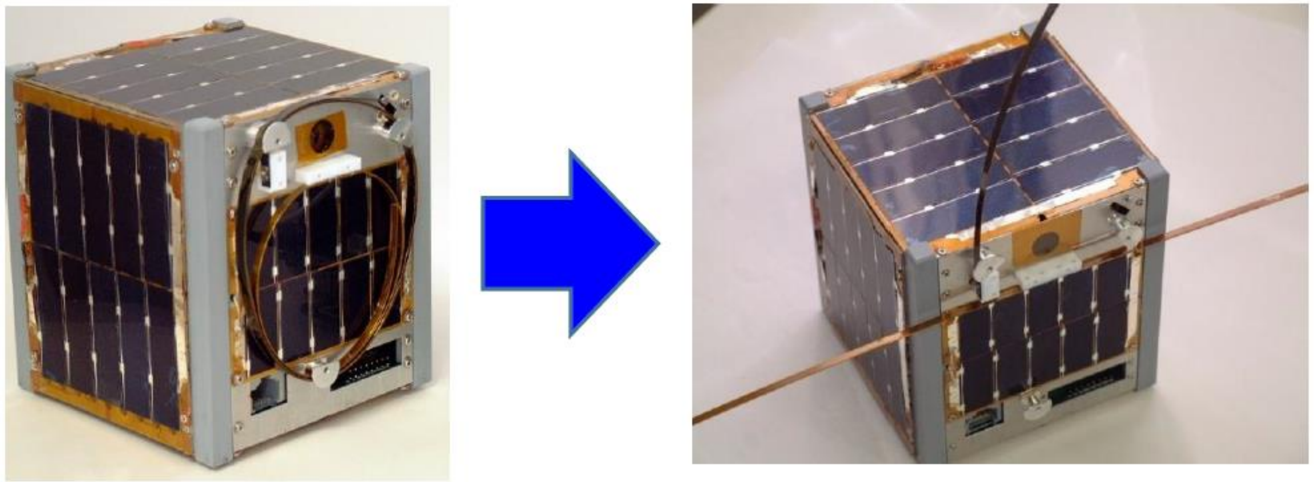
- S-band (around 2 GHz)

- X-band (around 8 GHz)

Typical CubeSat RF Transmitter and Receiver © Addnics corp.

Deployable Antenna

- **Lower frequency** bands require **longer antennas**.
- Typical frequencies: **UHF** (around 144MHz) and **VHF** (around 435MHz)
- Merit: **reasonable prices** for the setup of amateur radio **ground station**
- Data rate can be slow (**1.2kbps, 9.6kbps, 38.4kbps**, etc.)
  - limited assigned band width
- **Folded antennas must be automatically deployed** for communications



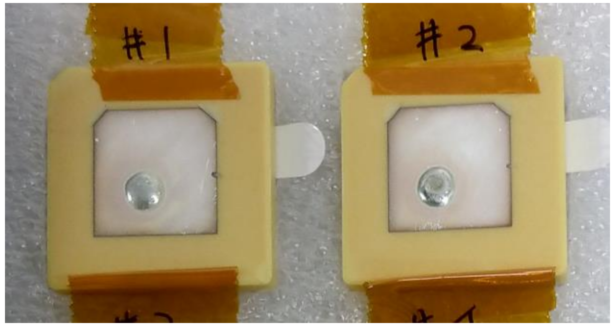
XI-IV © University of Tokyo

2. Communication System

Patch Antenna

- **S-band (2GHz)** and **X-band (8GHz)** will be used for **high-speed data** communications
  - example, **2Mbps** (0.5W out) by S-band, **20Mbps** (1.0W out) and more by X-band
  - **wide assigned bandwidth** especially for X-band
- **Demerit**: ground station **cost** (large parabola antenna system)
- **No deployment mechanism** required => low risk of communication failure

patch antennas



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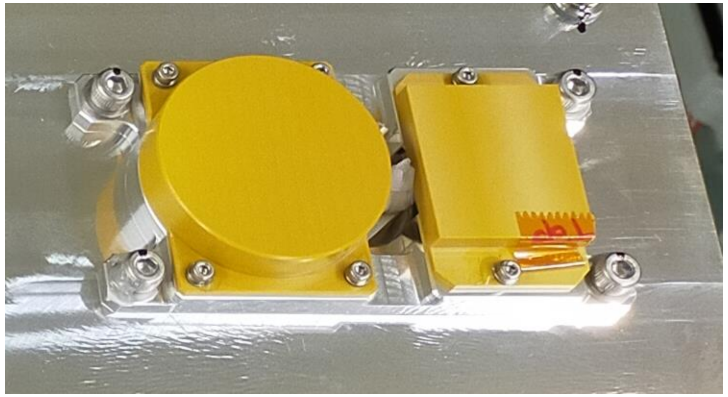
assembly



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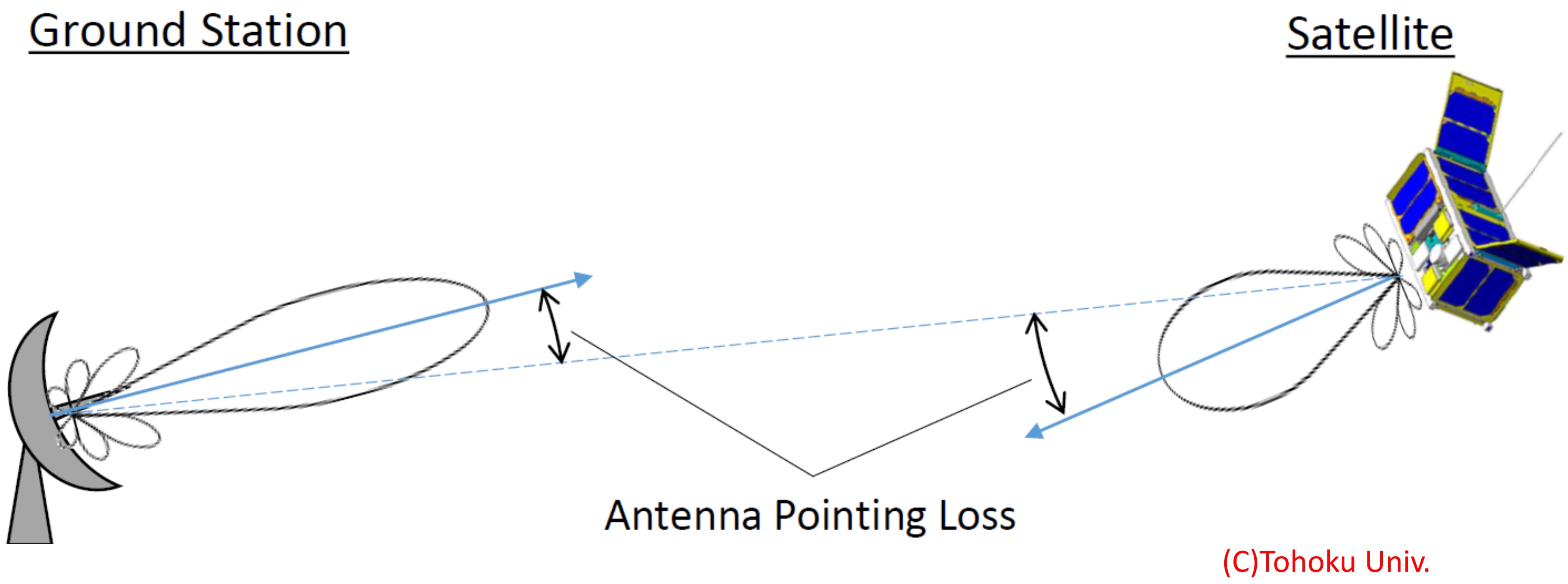
patch antennas
with covers
(for GPS and S-band uplink)

2. Communication System

High Gain Antenna

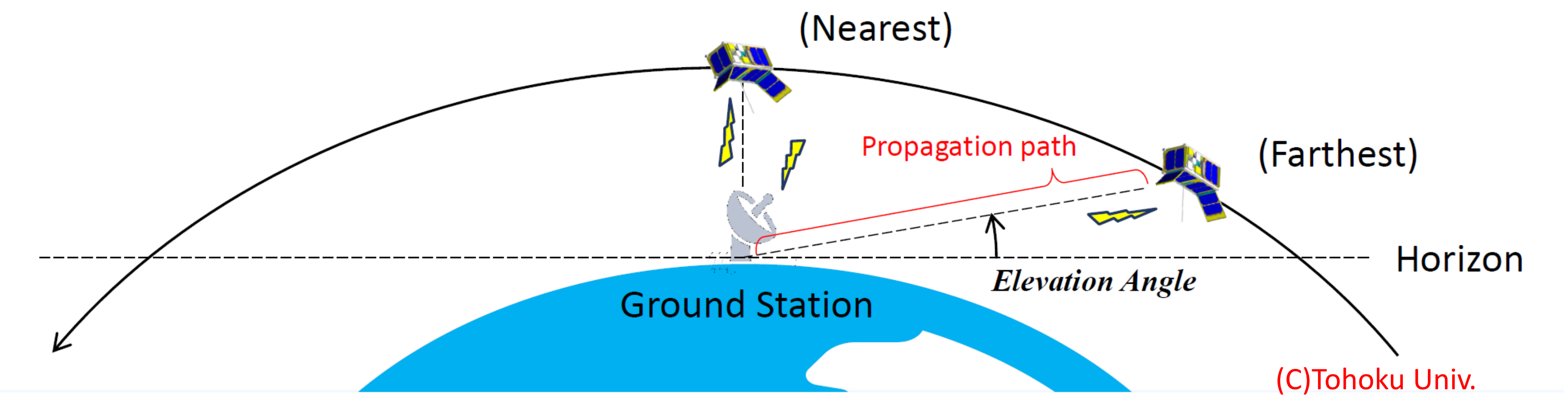
- **High gain antennas** require **pointing control** to satellite or ground station
- **Narrow beam** width can achieve **higher gain**
- **Power resource is required** for both **transmission** amp and **attitude control** components



Link Budget Design

- **Specs** of communication system can be designed by **link budget** analysis. Acceptable **data rate** (10kbps, 100kbps, 1Mbps, etc.) can be **calculated** by the **balance of hardware specs**.

1. Hardware specs of **both satellite and ground station**: **antenna** (size and gain), **transmitter** (output power), **receiver** (minimum input signal levels)
2. Data **modulation**: modulation type (FSK, BPSK, QPSK, etc.)
3. Orbit: **distance** at **nearest** and **farthest** (satellites around horizon)



2. Communication System

Types of Ground Stations

- **Ground station antenna** must be **controlled** to point toward the satellite during observation chance
- **Future satellite position** can be **calculated**
- **Satellite orbits** at reference times are **available in the Two Line Element (TLE)** format, which are distributed by celestrak.com etc.

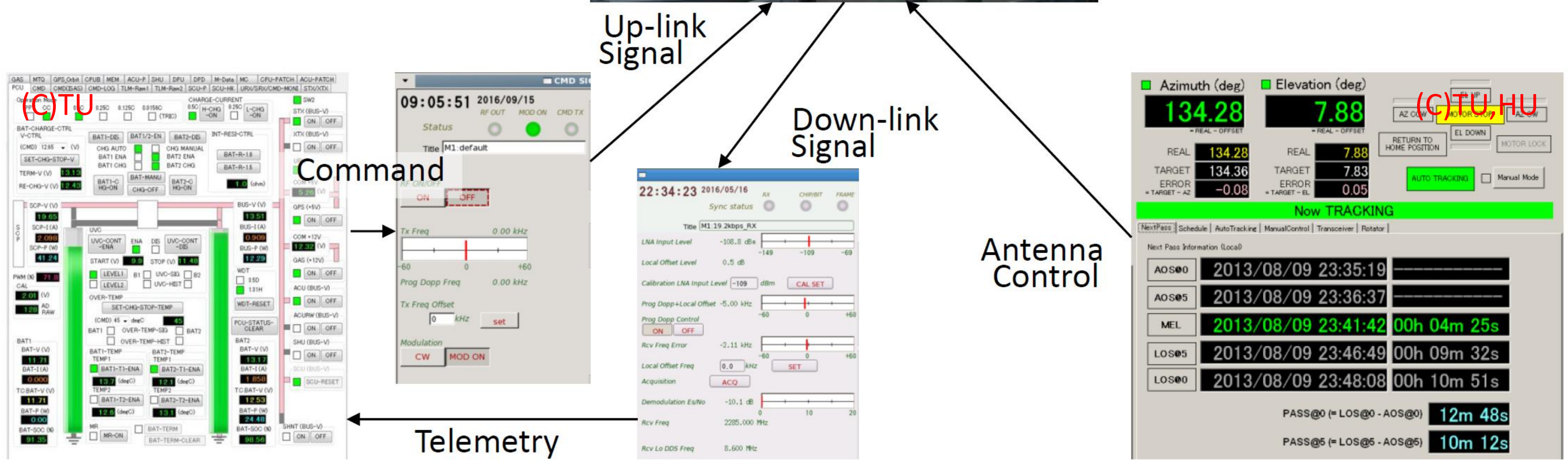
Yagi-Antenna for VHF-band

Dish-Antenna for S-Band

Items for Ground Station

1. **Antenna** with **controllable motors**
2. **Transmitter** and **receiver** with functions of suitable **modulation/demodulation** and **coding/decoding**
3. Operation **software**

Operation Room



Satellite Control Software

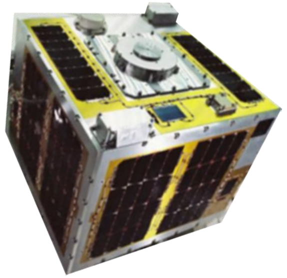
Dish-Antenna for S-Band

3. Link Budget Calculation

Introduction to Link Budget Calculation

- **Link budget calculation** is the task of analyzing **how much link margin is existing** between the **four conditions** including **orbit, antenna specs, transmission power, and communication data speed**.

- Example) **Calculate the communication data speed (bitrate)** that can be achieved at an 15-deg elevation angle when the orbit, antenna specs, and transmission power are given.



2250MHz
0.1W out

500km orbit

2.4m dish

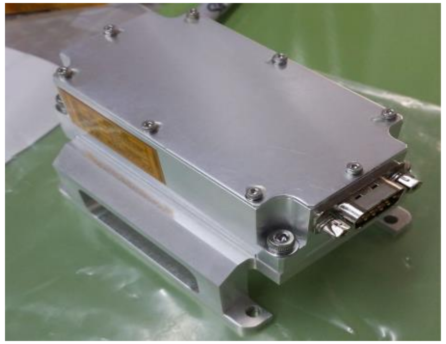
bitrate ?
@ 15-deg elevation

(C)HU

3. Link Budget Calculation

Step 1: Transmitter

- We use **dBm** (dBmW) or **dBW** as the power unit: Convenient for calculating **amplification** or **attenuation** of RF signal level by **addition and subtraction**
- In decibel power calculations, **+3dB is 2x**, **-3dB is 1/2**, and **+7dB is 5x**.



Transmitter
2250MHz
0.1W out
= 20 dBm

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* 30 dBm = 0 dBW

W	dBm	dBW
1mW	0 dBm	-30 dBW
10mW	10 dBm	-20 dBW
100mW	**20 dBm**	**-10 dBW**
1W	30 dBm	0 dBW
5W	37 dBm	7 dBW

3. Link Budget Calculation

Step 2: EIRP

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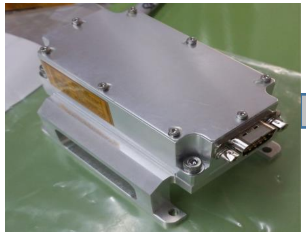
Satellite

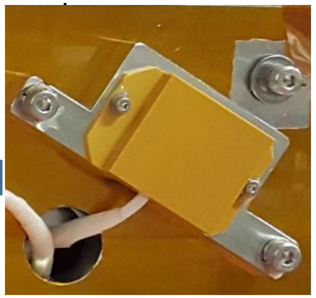


Transmitter
2250MHz
0.1W out
= 20 dBm

Cable Loss
= - 1 dB

(depends on product, frequency, length. See datasheet.)

Antenna
Gain = 4 dBi



EIRP
= 20 - 1 +4
= 23 dBm

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EIRP = Equivalent Isotropic Radiated Power

Step 3: Space Loss

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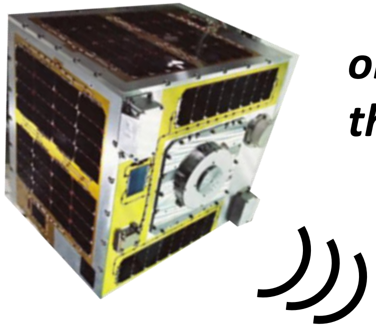

oriented towards the ground station

EIRP = 23 dBm

distance ?

Space Loss = ? dB

(depends on orbital height and elevation)

oriented towards the satellite

Received Signal Power = ? dBm

Cable Loss = - 1 dB

Antenna Gain = ? dBi

(depends on dish diameter and frequency)

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3. Link Budget Calculation

Step 3: Space Loss

- The power of RF signals is **attenuated** in proportion to the **square of the distance r**.
- Also, it is attenuated in proportion to the **square of the frequency** (= speed of light / wavelength).

=> If the frequency is the same, the **longer the distance**, the **greater the attenuation**.

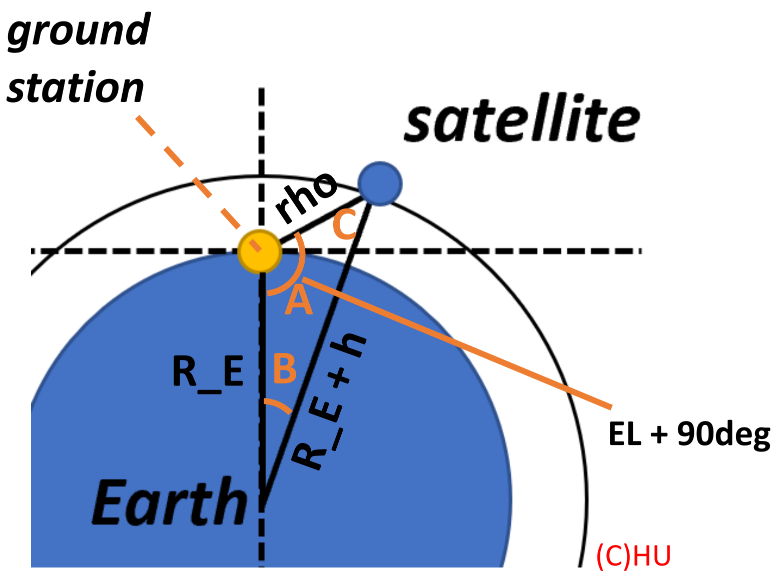
=> At the same distance, the **higher the frequencies**, the **greater the attenuation**.

Reference: Spacecraft Systems Engineering, 4th Edition, Chapter 12 - Telecommunications, 12.2.10 The Link Budget

$$L_S = \left(\frac{4\pi r}{\lambda}\right)^2$$

L_S is free-space loss, r is the distance, and λ is the wavelength of RF signals.

Step 3: Space Loss



calculation of distance
rho = distance (slant range)
R_E = earth radius
h = orbital height

A = EL + 90deg
a = R_E + h
b = rho
c = R_E = 6378.137 km
law of sine
a / sinA = c / sinC
B = 180deg - (A+C)
b = sinB x (a/sinA)

L_S(dB) = 10.log10{(4.pi.rho/lambda)^2}
= 20.log10(4.pi.rho) - 20.log10(lambda)
= 20.log10(4.pi.rho) - 20.log10(c / f_Hz)
= 20.log10(4.pi) + 20.log10(rho_km) - 20.log10(c_km_s) + 20.log10(f_Hz)
= 21.984 + 20.log10(rho_km) - 109.536 + 20.log10(f_MHz * 1e+6)
= **32.4 + 20.log10(rho_km) + 20.log10(f_MHz)**

orbital height h_km	rho_km @ EL = 5 deg	rho_km @ EL = 15 deg
250 km	1331	794
400 km	1805	1175
500 km	2078	**1408**
600 km	2329	1626

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L_S(dB) = 32.4 + 20.log10(1408) + 20.log10(2250) = **162.4**

3. Link Budget Calculation

Step 3: Space Loss

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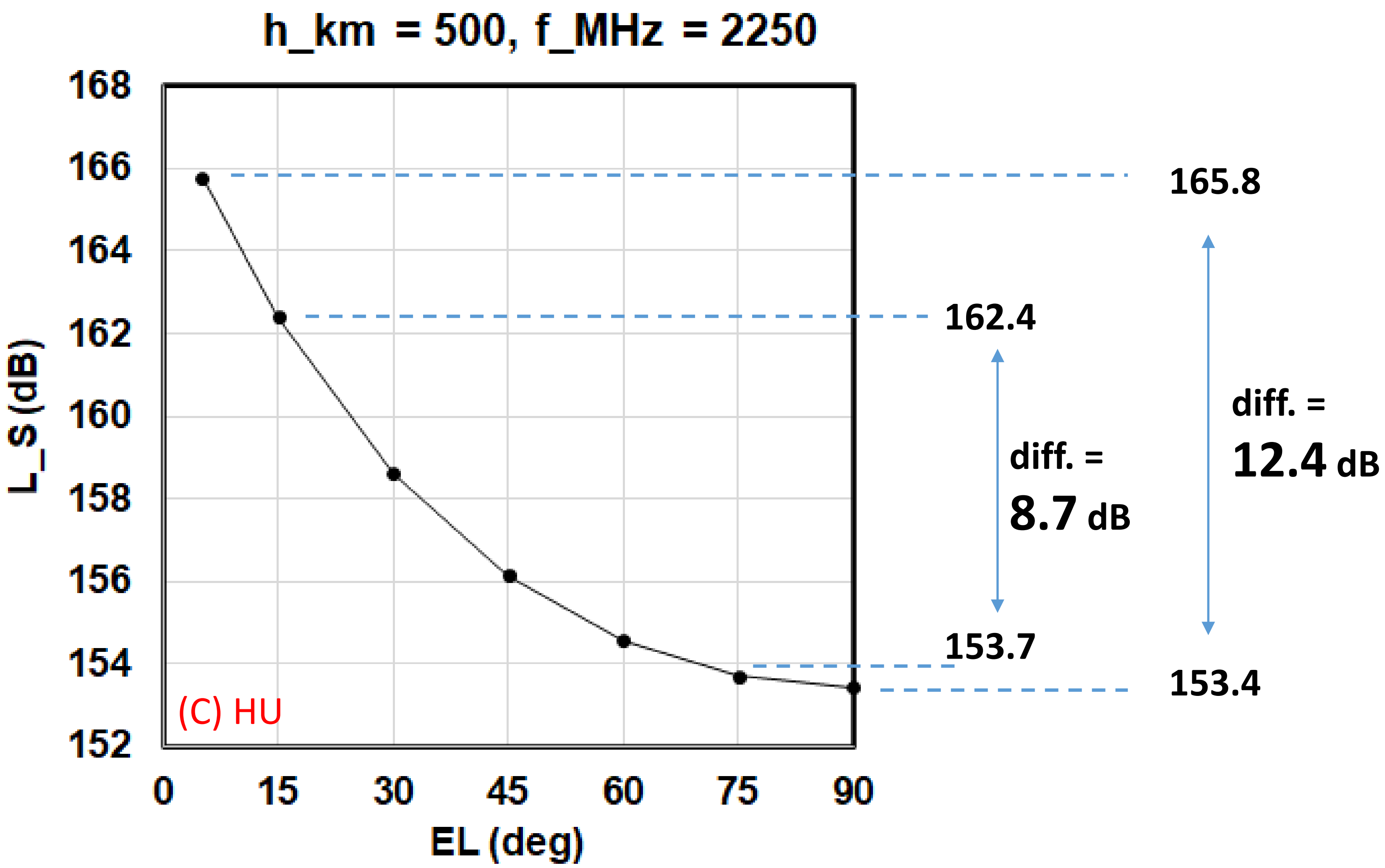

3. Link Budget Calculation

Step 4: Antenna Gain of Ground Station

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Reference: Spacecraft Systems Engineering, 4th Edition, Chapter 12 - Telecommunications, 12.2.8 Antennas

$$G = \frac{4\pi A}{\lambda^2}$$

G is the directive gain at the centre of the main beam,

A is the physical area of uniformly illuminated antenna,

$$A_e = \lambda^2 G / 4\pi$$

A_e is the effective aperture,

$$\eta = A_e / A$$

η is the aperture efficiency (typically 0.5 - 0.7)

G = 4.pi.A / lambda^2
A = pi x (D_m/2)^2
A_e = eta x A = 0.5 x pi x (D_m/2)^2
lambda = c / f
G(dBi) = **10 x log10(4 x pi x A_e / (c/f)^2)**

c = 300 x 1e+6 m/s, D_m = 2.4, f_MHz = 2250

G(dBi) = **32.0**

3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

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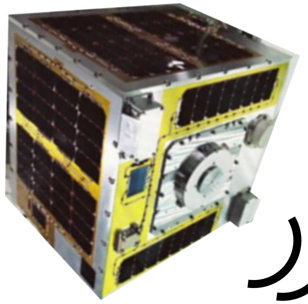

oriented towards the ground station

EIRP
= 23 dBm

1408 km@EL=15deg

Space Loss
= - 162 dB

(depends on orbital height and elevation)

oriented towards the satellite

Received Signal Power
= 23 - 162 + 32 - 1
= -108 dBm

Cable Loss
= - 1 dB

Antenna Gain = 32 dBi

(depends on dish diameter and frequency)

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3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

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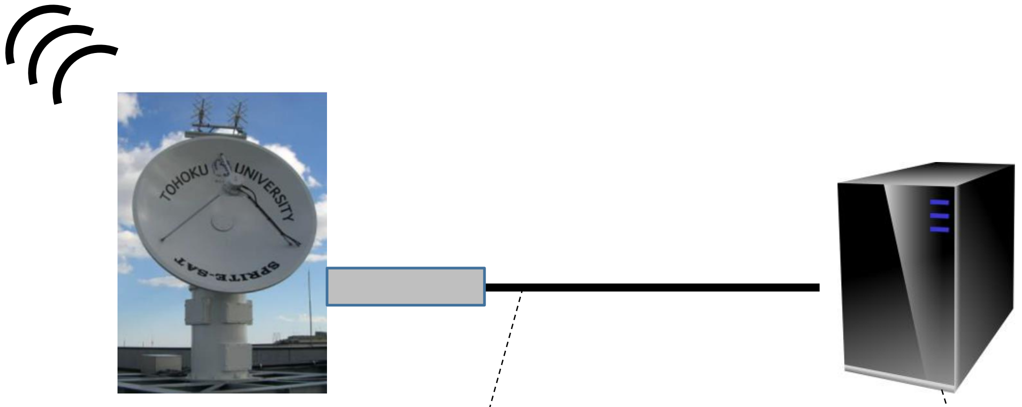


Received Signal Power (C) = -108 dBm

Carrier to Noise Density Ratio
C/N0 = ? dBHz

System Noise Temperature = ? K
Noise Power Spectrul Density (N0) = ? dBm/Hz

(C)HU

[!] Next, we proceed to calculate the noise level

3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

- **System noise temperature** (Tsys) is equivalent to the **thermal noise power** generated by the **resistance at an absolute temperature** T(K).

Reference: Spacecraft Systems Engineering, 4th Edition, Chapter 12 - Telecommunications, 12.2.10 The Link Budget

$$C = P_T G_T G_R (\lambda/4\pi r)^2 (1/L_A)$$

$$\frac{C}{N_0} = P_T G_T (\lambda/4\pi r)^2 (1/L_A)\left(G_R/T_{sys}\right)(1/k)$$

$$N_0 = kT_{sys}$$

C is the signal power at the input to the receiver,

P_T is the transmitter output power,

G_T is the transmitting antenna gain,

G_R is the receiving antenna gain,

L_A is the atmospheric attenuation factor (≤ 1.0)

N_0 is the noise power density,

T_{sys} is the system noise temperature,

C/N_0 is the signal-to-noise-power-density ratio,

k is the Boltzmann constant (= 1.380649 x 1e-23 J/K)

3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

- The **system noise** temperature is the sum of the **antenna noise** temperature, **cable noise** temperature, and **receiver noise** temperature.

Reference: Space Mission Analysis and Design Third Edition (SMAD III) Section 13.3 Link Design, TABLE 13-10.

	Downlink 2-12 GHz	**Uplink 2-12 GHz**
Antenna Noise	25 K	**290** K
Line Loss Noise (cable noise)	35 K (Line Loss = 0.5dB)	35 K (Line Loss = 0.5dB)
Receiver Noise	75 K (NF = 1.0dB)	289 K (NF = 3.0dB)
System Noise	**135 K (21.3** dB-K)	**614 K** (**27.9** dB-K)

calculation of Noise Power Density (N0) by System Noise Tsys

$$N_0 = kT_{sys}$$

N0_dB = 10.log10(k) + 10.log10(T_K) = **-198.6** + 10.log10(T_K)

Boltzmann constant, k = 1.380649 × 1e−23 (J/K)
W = J/s, J = W.s = W/Hz, k = W/(K.Hz)

10.log10(k) = -228.6 dBW/(K.Hz) = -198.6 dBm/(K.Hz)

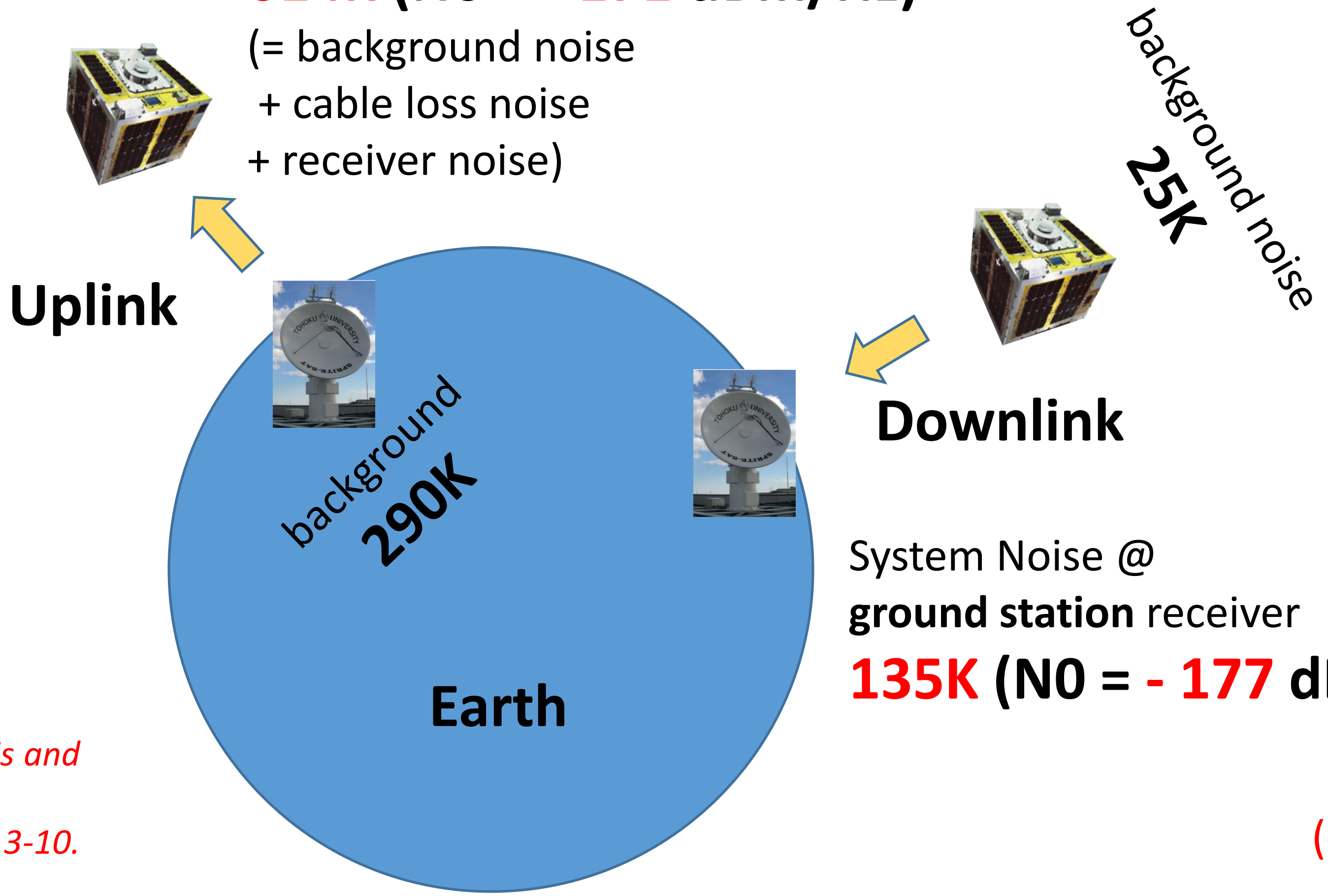
T_K = **135**, 10.log10(T_K) = 21.3 dB-K

N0_dB = -198.6 dBm/(K.Hz) + 21.3 dB-K = **-177.3** dBm/Hz

Step 5: Carrier to Noise Density Ratio

- **Uplink requires +6 dB margin** for same communication data speed as Downlink because of **higher system noise at receiver**

System Noise @ **satellite** receiver
614K (N0 = - 171 dBm/Hz)
(= background noise
+ cable loss noise
+ receiver noise)

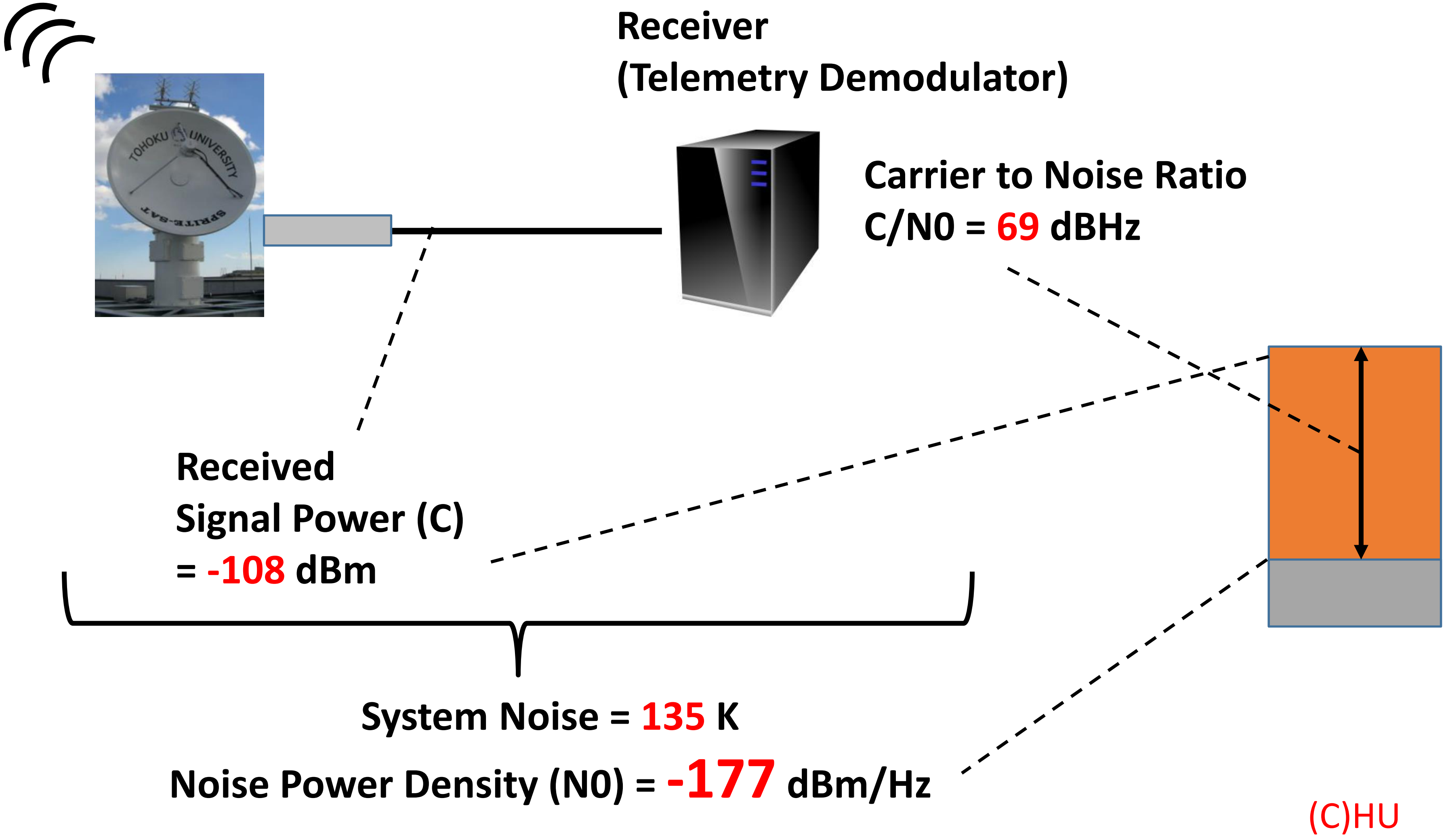


System Noise @ **ground station** receiver
135K (N0 = - 177 dBm/Hz)

Reference: Space Mission Analysis and Design Third Edition (SMAD III) Section 13.3 Link Design, TABLE 13-10.

3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio



Step 6: Required Carrier to Noise Density Ratio

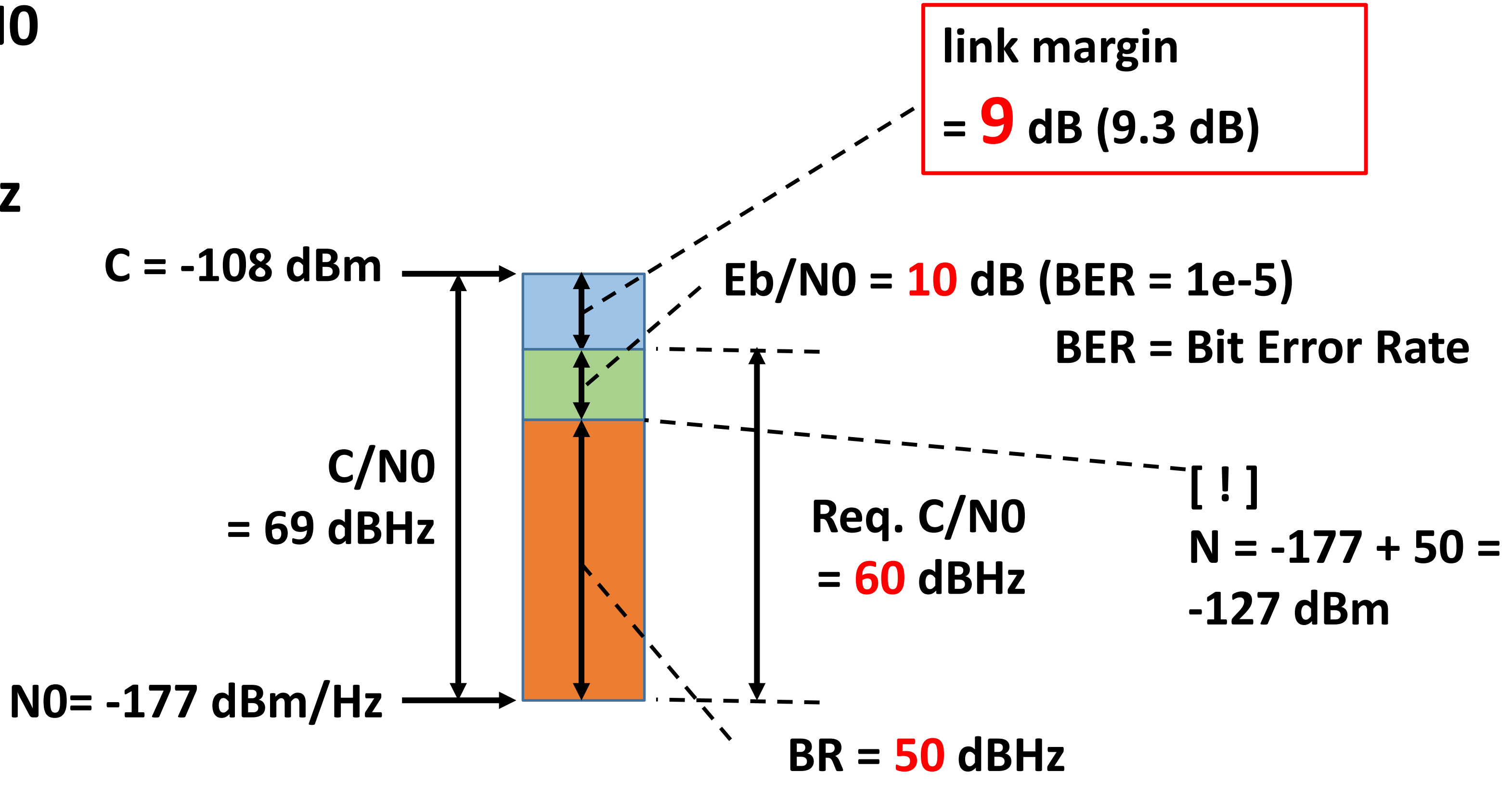
- **Required C/N0**
  = bitrate (BR) x Required Eb/N0

BR = **100 kbps**

BR (dBHz) = 10.log10(100 000) = **50.0 dBHz**

Required Eb/N0
= **9.6 dB** for BPSK
Eb/N0 = bit energy to noise power density

Required C/N0
= 50.0 dBHz + 9.6 = **59.6** dBHz



3. Link Budget Calculation

Step 6: Required Carrier to Noise Density Ratio

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Eb/N0 = bit energy to noise power density

SMAD III, TABLE 13-11. Modulation	**Eb/N0 for BER = 1e-5 (dB)**
FSK	13.3
BPSK, QPSK	**9.6**
BPSK, QPSK + R-1/2 Viterbi Decoding	**4.4**

Reference:
Space Mission Analysis and Design Third Edition (SMAD III)
Section 13.3 Link Design
TABLE 13-10.

Step 7: Result of Link Margin and Level Diagram

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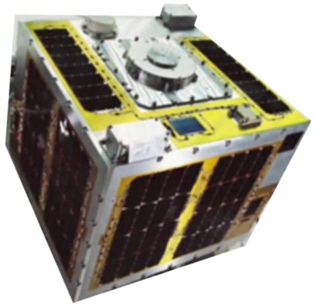

2250MHz
0.1W out

500km orbit

100 Kbps
with 9.3 dB margin
@ 15-deg elevation

2.4m dish

(C)HU

for other bitrate (C)HU

kbps	margin (dB)
100	**9.3**
200	6.3
500	**2.3**
1000	-0.7
2000	-3.7

500kbps
is also acceptable
but, we **ignored the pointing error**
of ground station and satellite

Step 7: Result of Link Margin and Level Diagram

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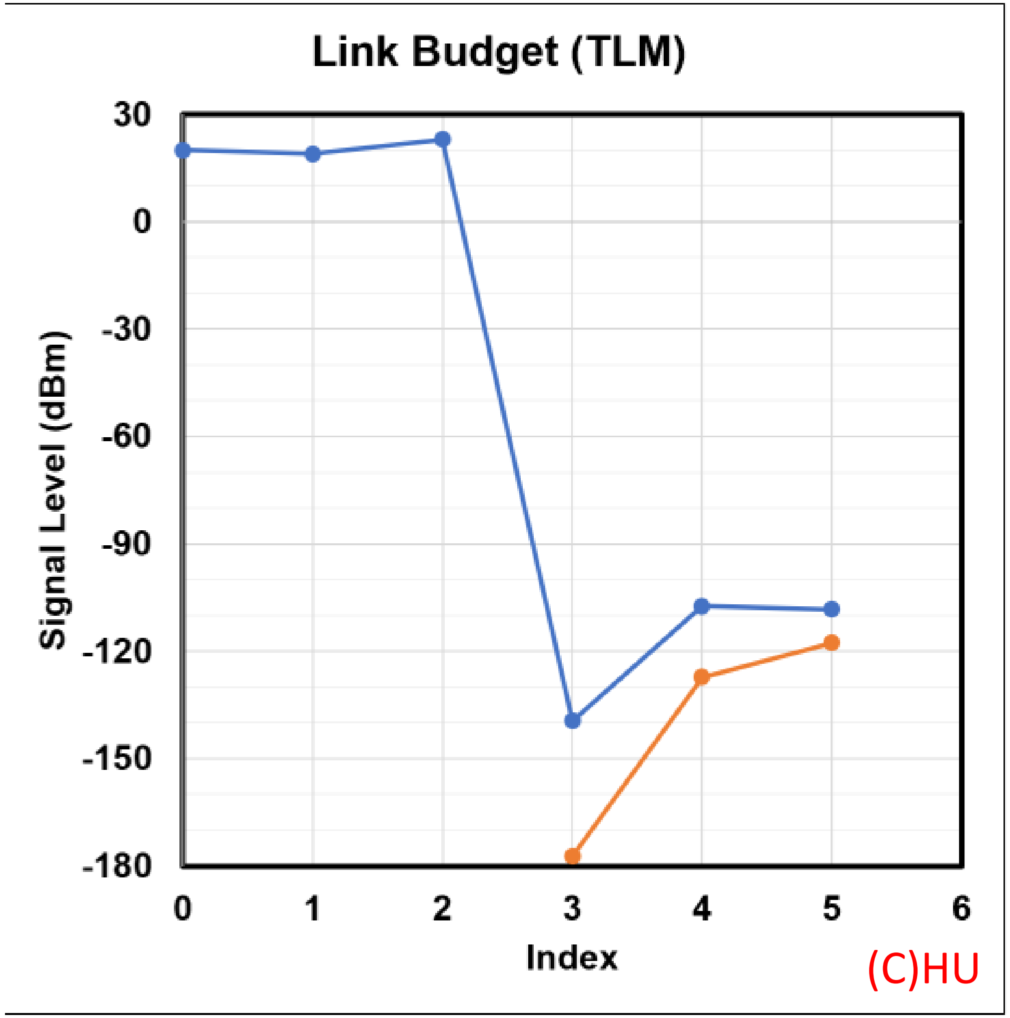
Level Diagram (Question)

[?] Which dot is which value ?
Which line is which gain ?



Step 7: Result of Link Margin and Level Diagram

Level Diagram (Answer)

	Index	Signal	Req.	
Pt	0	20.0		dBm
- Ltc	1	19.0		dBm
+ Gta (= EIRP)	2	23.0		dBm
- Ls (= Pa)	3	-139.4		dBm
+ Gra	4	-107.4		dBm
- Lrc (= C)	5	**-108.4**		dBm
N0	3		-177.3	dBm/Hz
+ BR (= Ns)	4		-127.3	dBm
+ Req. Eb/N0 (= Creq)	5		**-117.7**	dBm

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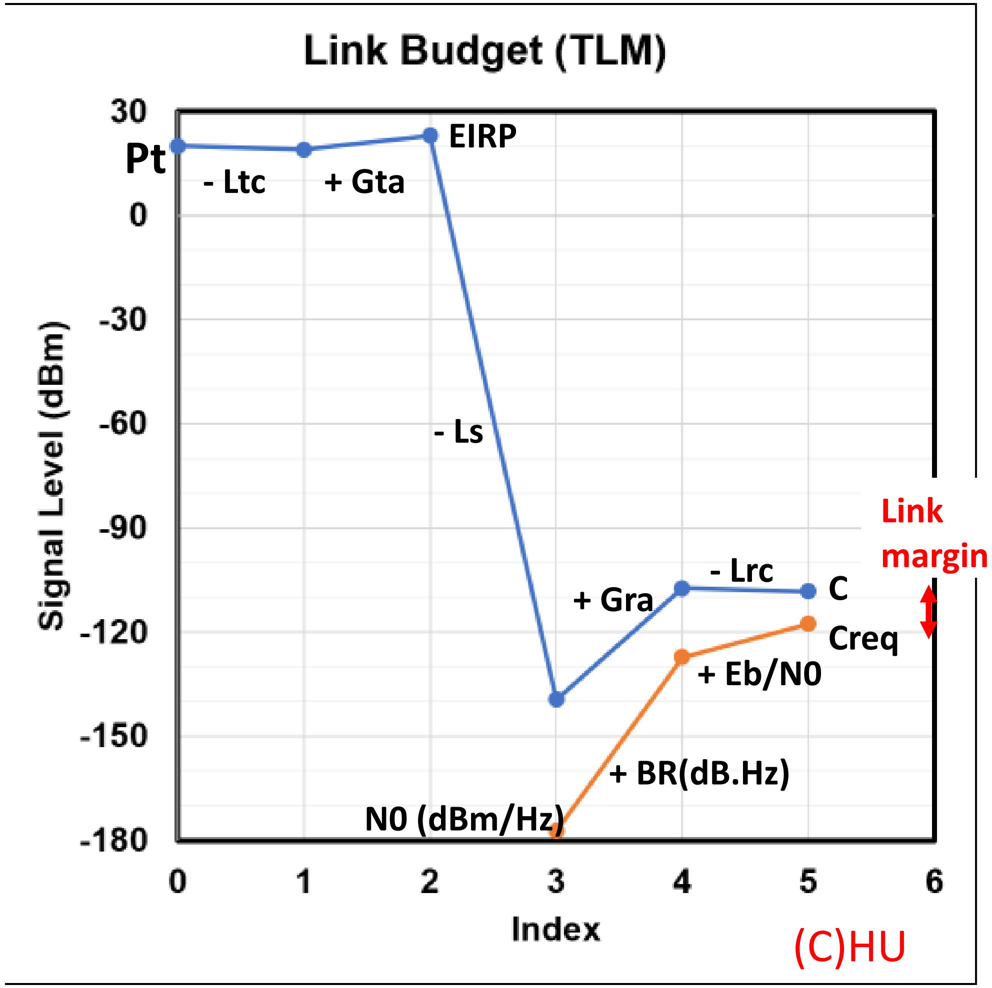
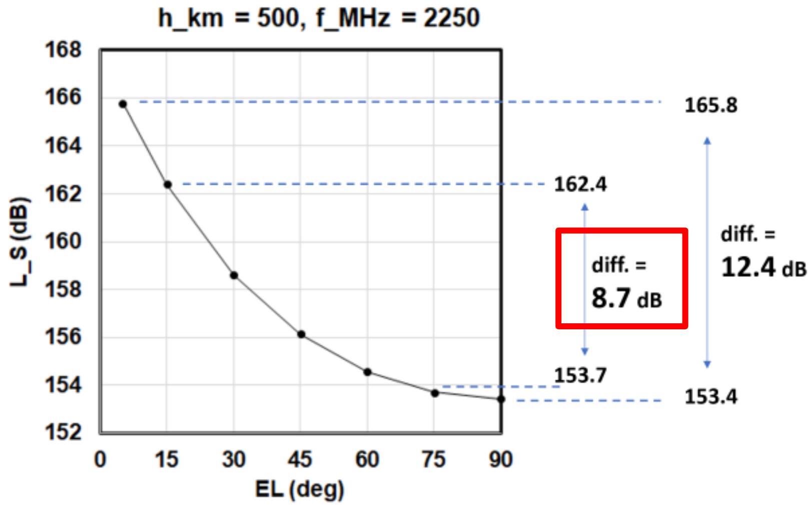


Step 7: Result of Link Margin and Level Diagram

- **Easy Conversion (Case of 15deg EL => Case of 75deg EL)**



kbps	margin (dB) @ EL=15deg	margin (dB) @ EL=75deg
100	9.3	18.0
200	6.3	15.0
500	2.3	11.0
1000	-0.7	**8.0**
2000	-3.7	**5.0**

We can start with 100kbps
in low elevation,
and switch to higher bitrate

Other error sources:
pointing error = 3dB (ground stn.)
pointing error = 3dB (satellite)
8.0 dB ---> **2.0 dB**

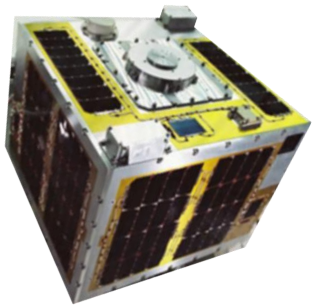
4. Power Flux Density (PFD) Regulation

4. Power Flux Density (PFD) Regulation

Introduction

- **[!]** This regulation applies to **S-band communications**.
- **Not applicable for VHF, UHF**.

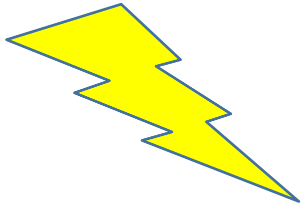
PFD Regulation



2250MHz

0.1W out

500km orbit



2.4m dish

[?] Can we increased to 1W ? 10 W ?

=> We must keep the PFD (Power Flux Density) in regulation level

4. Power Flux Density (PFD) Regulation

Power Spectrum Density (PSD)

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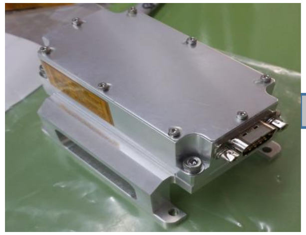
Satellite

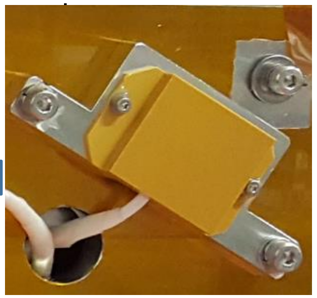


Transmitter
2250MHz
0.1W out
= 20.0 dBm

Cable Loss
= - 1.0 dB

(depends on
product, frequency, length.
See datasheet.)

Antenna
Gain = 4.0 dBi



OBW = 100 kHz
(@ 100kbps, BPSK)
[!] 134 kHz will be feasible

EIRP
= 20 - 1 +4
= 23 dBm

EIRP/OBW = 23 dBm - 50 dBHz = - 27 dBm/Hz
(without antenna gain => -31 dBm/Hz)

4. Power Flux Density (PFD) Regulation

Power Flux Density (PFD) at ground

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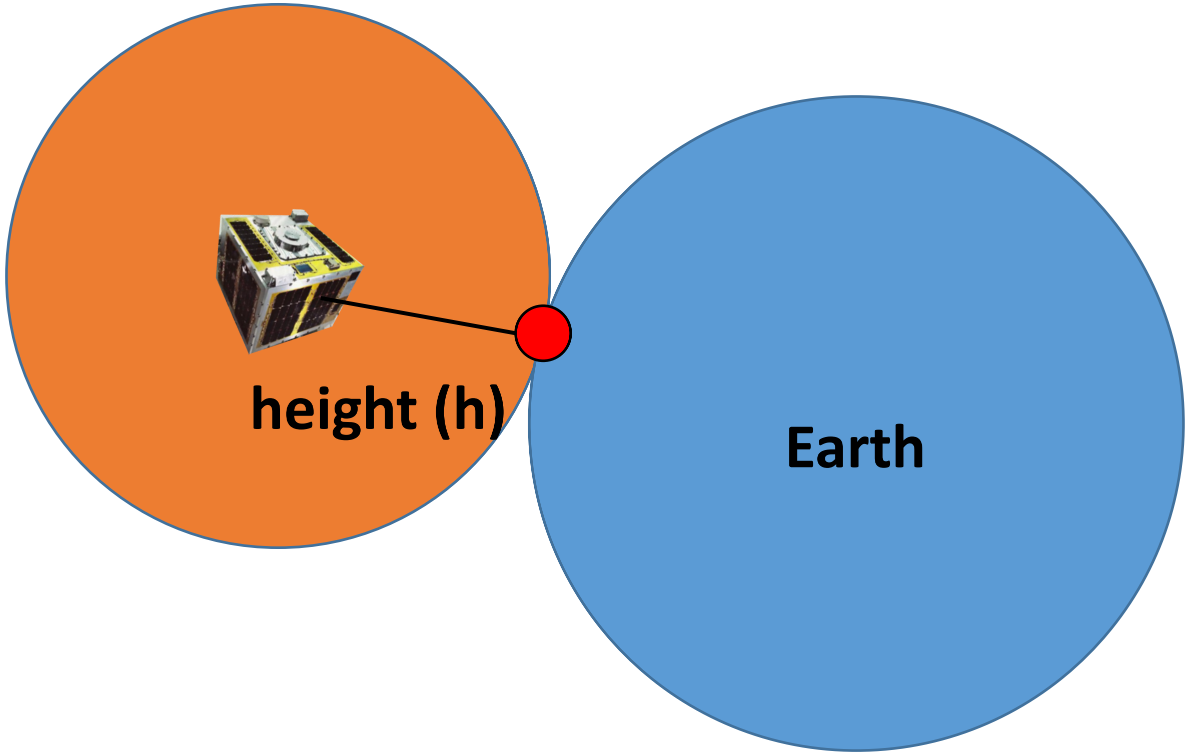

Power Flux
in spherical surface

A = 4 x pi x h^2

@ 500km height
A = 3.142 x 1e+6 km^2
= 125.0 dB.m^2

36.0 dB.Hz

PFD = EIRP/OBW / A x 4kHz
= - 27 dBm/Hz - 125 dB.m^2 + 10.log10(4000) dB.Hz
= - 116 dBm/m^2 = - 146 dBW/m^2

4. Power Flux Density (PFD) Regulation

ITU Radio Regulations

- **International Telecommunication Union (ITU):** The ITU manages the specifications of **global satellite communications** and imposes the **strict regulations**.
- Reference: https://itu.int/pub/R-REG-RR-2020/
  - Please download "English (or other lang.) zipped pdf"
- Important article:
  - **ARTICLE 21** Terrestrial and space services sharing frequency bands above 1 GHz
  - **Section V** – Limits of power flux-density from space stations
  - **TABLE 21-4** (Rev.WRC-19)
- **Referred from RR-2020-00013-Vol.I-EA5:** *The power flux-density at the Earth's surface produced by emissions from a space station, (omission), shall not exceed the limit given in Table 21-4.*

the limit given in Table 21-4

2 200-2 300 MHz
5deg => -154 dBW/m^2
90deg => **-144** dBW/m^2
Reference bandwidth = 4 kHz

8 025-8 500 MHz
5deg => -150 dBW/m^2
90deg => **-140** dBW/m^2
Reference bandwidth = 4 kHz

[!] Tutorial result - 146 dBW/m^2 satisfy the regulated limit

5. Conclusion

7. Conclusion

- Skills of **link budget calculation are important** to decide the operation method and the specifications of communication system.
  - We need to get used to **calculating in "dB" unit**.
  - Important items are **transmitting power, EIRP, space loss, receiving antenna gain, carrier to noise density ratio (C/N0), and required C/N0** by data speed and modulation type.
- Link margin can be expressed by **level diagram**, and we can check **how the margin increase/decrease** by adjusting the specification values.
- Link design **must follow the ITU regulations** such as limit of power flux density (PFD).

Thank you very much.

[Disclaimer]
The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the United Nations.