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
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2006 - Assistant Professor (-2015), Associate Professor (2015-)
Department of Aerospace Engineering, Tohoku University
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Satellite Operation and Ground Station Management

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DOST = Department of Science and Technology, Philippines
UPD = University of the Philippines Diliman
Contents

1. Introduction to Satellite Operations *
2. Communication System *
3. Tutorial: Link Budget Calculation
4. Power Flux Density (PFD) Regulation
5. Conclusion

* = 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
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. 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.
1. Introduction to Satellite Operations

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**

![1st light images by RAIKO](image)
1. Introduction to Satellite Operations

Operation Routine

M = Manned Operations
U = Unmanned Operations
Can be remote ground stations

Command
Telemetry
Mission Data

Make Operation Plan
Upload Command List
Evaluate Status
Unmanned Mission Data Download

Daytime  Night
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)
2. Communication System

Deployment 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

![Deployable Antenna Image]
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

(C) Tohoku Univ.

(C) Tohoku Univ.
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

![Diagram of communication system](C)Tohoku Univ.
2. Communication System

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](image1)

![Dish-Antenna for S-Band](image2)

(C) The University of Tokyo

(C) TU, NO
2. Communication System

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**
3. Link Budget Calculation
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.

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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**.

<table>
<thead>
<tr>
<th>W</th>
<th>dBm</th>
<th>dBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mW</td>
<td>0 dBm</td>
<td>-30 dBW</td>
</tr>
<tr>
<td>10mW</td>
<td>10 dBm</td>
<td>-20 dBW</td>
</tr>
<tr>
<td>100mW</td>
<td>20 dBm</td>
<td>-10 dBW</td>
</tr>
<tr>
<td>1W</td>
<td>30 dBm</td>
<td>0 dBW</td>
</tr>
<tr>
<td>5W</td>
<td>37 dBm</td>
<td>7 dBW</td>
</tr>
</tbody>
</table>

Transmitter

2250MHz
0.1W out
= 20 dBm

* 30 dBm = 0 dBW
3. Link Budget Calculation

Step 2: EIRP

Satellite

- Transmitter
  - 2250MHz
  - 0.1W out
  - = 20 dBm

Cable Loss
- = -1 dB

Antenna
- Gain = 4 dBi

EIRP
- = 20 - 1 + 4
- = 23 dBm

EIRP = Equivalent Isotropic Radiated Power

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3. Link Budget Calculation

Step 3: Space Loss

- EIRP oriented towards the ground station
  - EIRP = 23 dBm

- Space Loss oriented towards the satellite
  - Space Loss = ? dB
  - (depends on orbital height and elevation)

- Received Signal Power
  - Received Signal Power = ? dBm

- Antenna Gain
  - Antenna Gain = ? dBi
  - (depends on dish diameter and frequency)

- Cable Loss
  - Cable Loss = -1 dB

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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.

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

\( L_S \) is free-space loss, \( r \) is the distance, and \( \lambda \) is the wavelength of RF signals.

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

Step 3: Space Loss

- Calculation of distance
  - \( \text{rho} = \text{distance (slant range)} \)
  - \( \text{R}_E = \text{earth radius} \)
  - \( h = \text{orbital height} \)

A = \( \text{EL} + 90\text{deg} \)
\( a = \text{R}_E + h \)
\( b = \text{rho} \)
\( c = \text{R}_E = 6378.137 \text{ km} \)

Law of sine
\( \frac{a}{\sin A} = \frac{c}{\sin C} \)
\( B = 180\text{deg} - (A+C) \)
\( b = \sin B \times (a/\sin A) \)

L_S(dB) = 10 \cdot \log_{10} \left( \left(4 \pi \frac{\rho}{\lambda} \right)^2 \right)
= 20 \cdot \log_{10} \left(4 \pi \rho \right) - 20 \cdot \log_{10} \left(\lambda \right)
= 20 \cdot \log_{10} \left(4 \pi \rho \right) - 20 \cdot \log_{10} \left(\frac{c}{f_{\text{Hz}}} \right)
= 20 \cdot \log_{10} \left(4 \pi \rho \right) - 20 \cdot \log_{10} \left(\frac{c}{f_{\text{MHz}} \cdot 10^6} \right)
= 32.4 + 20 \cdot \log_{10} (\rho_{\text{km}}) + 20 \cdot \log_{10} (f_{\text{MHz}})

<table>
<thead>
<tr>
<th>orbital height h_{km}</th>
<th>rho_{km} @ EL = 5 \text{ deg}</th>
<th>rho_{km} @ EL = 15 \text{ deg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 km</td>
<td>1331</td>
<td>794</td>
</tr>
<tr>
<td>400 km</td>
<td>1805</td>
<td>1175</td>
</tr>
<tr>
<td>500 km</td>
<td>2078</td>
<td>1408</td>
</tr>
<tr>
<td>600 km</td>
<td>2329</td>
<td>1626</td>
</tr>
</tbody>
</table>

L_S(dB) = 32.4 + 20 \cdot \log_{10}(1408) + 20 \cdot \log_{10}(2250) = \text{162.4}
3. Link Budget Calculation

Step 3: Space Loss

\[ h_{km} = 500, f_{MHz} = 2250 \]

**Graph:**

- **EL (deg):** 0, 15, 30, 45, 60, 75, 90
- **L_S (dB):** 152, 154, 156, 158, 160, 162, 164, 166, 168

**Key Points:**
- **Difference:** 12.4 dB
- **Difference:** 8.7 dB

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3. Link Budget Calculation

Step 4: Antenna Gain of Ground Station

### 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,

\[
A_e = \lambda^2 G / 4\pi
\]

*A_e* is the effective aperture,

\[
\eta = A_e / A
\]

*\(\eta\)* is the aperture efficiency (typically 0.5 - 0.7)

\[
G = 4\pi A / \lambda^2
\]

\[
A = \pi \times (D_m/2)^2
\]

\[
A_e = \eta \times A = 0.5 \times \pi \times (D_m/2)^2
\]

\[
\lambda = c / f
\]

\[
G(\text{dBi}) = 10 \times \log_{10}(4 \pi \times A_e / (c/f)^2)
\]

\[
c = 300 \times 1e+6 \text{ m/s}, \ D_m = 2.4, \ f_{\text{MHz}} = 2250
\]

\[
G(\text{dBi}) = 32.0
\]
3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

- EIRP = 23 dBm
- Space Loss = -162 dB
- Antenna Gain = 32 dBi
- Received Signal Power = 23 - 162 + 32 - 1 = -108 dBm

Space Loss oriented towards the satellite (depends on orbital height and elevation)
Antenna Gain oriented towards the ground station (depends on dish diameter and frequency)
Cable Loss = -1 dB

1408 km @ EL = 15 deg

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3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

- Received Signal Power ($C$) = $-108$ dBm
- Carrier to Noise Density Ratio ($C/N_0$) = ? dBHz
- System Noise Temperature = ? K
- Noise Power Spectral Density ($N_0$) = ? dBm/Hz

[!] Next, we proceed to calculate the noise level
3. Link Budget Calculation

Step 5: Carrier to Noise Density Ratio

- **System noise temperature** \((T_{sys})\) 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*

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

\[
C = P_T G_T G_R \left(\frac{\lambda}{4\pi r}\right)^2 \frac{1}{L_A}
\]

- \(C\) 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 \((\leq 1.0)\)
- \(N_0\) 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 \((= 1.380649 \times 10^{-23} \text{ J/K})\)
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.


<table>
<thead>
<tr>
<th></th>
<th>Downlink 2-12 GHz</th>
<th>Uplink 2-12 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Noise</td>
<td>25 K</td>
<td>290 K</td>
</tr>
<tr>
<td>Line Loss Noise (cable noise)</td>
<td>35 K (Line Loss = 0.5dB)</td>
<td>35 K (Line Loss = 0.5dB)</td>
</tr>
<tr>
<td>Receiver Noise</td>
<td>75 K (NF = 1.0dB)</td>
<td>289 K (NF = 3.0dB)</td>
</tr>
<tr>
<td>System Noise</td>
<td><strong>135 K (21.3 dB-K)</strong></td>
<td><strong>614 K (27.9 dB-K)</strong></td>
</tr>
</tbody>
</table>

**Calculation of Noise Power Density \( N_0 \) by System Noise \( T_{sys} \)**

\[
N_0 = kT_{sys}
\]

\[
N_0_{dB} = 10\log_{10}(k) + 10\log_{10}(T_K) = -198.6 + 10\log_{10}(T_K)
\]

Boltzmann constant, \( k = 1.380649 \times 10^{-23} \) (J/K)

\( W = J/s, \quad J = W.s = W/\text{Hz}, \quad k = W/(K.\text{Hz}) \)

\[
10\log_{10}(k) = -228.6 \text{ dBW/(K.Hz)} = -198.6 \text{ dBm/(K.Hz)}
\]

\( T_K = 135, \quad 10\log_{10}(T_K) = 21.3 \text{ dB-K} \)

\[
N_0_{dB} = -198.6 \text{ dBm/(K.Hz)} + 21.3 \text{ dB-K} = -177.3 \text{ dBm/Hz}
\]
3. Link Budget Calculation

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

Received Signal Power (C) = \(-108\) dBm

System Noise = 135 K

Noise Power Density (N0) = \(-177\) dBm/Hz

Receiver (Telemetry Demodulator)

Carrier to Noise Ratio \(C/N0 = 69\) dBHz

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3. Link Budget Calculation

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

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

C = -108 dBm

Eb/N0 = 10 dB (BER = 1e-5)

Req. C/N0 = 60 dBHz

C/N0 = 69 dBHz

N0 = -177 dBm/Hz

BR = 50 dBHz

link margin = 9 dB (9.3 dB)

BER = Bit Error Rate

N = -177 + 50 = -127 dBm

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3. Link Budget Calculation

Step 6: Required Carrier to Noise Density Ratio

Eb/N0 = bit energy to noise power density

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Eb/N0 for BER = 1e-5 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSK</td>
<td>13.3</td>
</tr>
<tr>
<td>BPSK, QPSK</td>
<td>9.6</td>
</tr>
<tr>
<td>BPSK, QPSK + R-1/2 Viterbi Decoding</td>
<td>4.4</td>
</tr>
</tbody>
</table>

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

Step 7: Result of Link Margin and Level Diagram

- 2250MHz
- 0.1W out
- 500km orbit
- 100 Kbps
- with 9.3 dB margin
- @ 15-deg elevation

<table>
<thead>
<tr>
<th>kbps</th>
<th>margin (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>9.3</td>
</tr>
<tr>
<td>200</td>
<td>6.3</td>
</tr>
<tr>
<td>500</td>
<td>2.3</td>
</tr>
<tr>
<td>1000</td>
<td>-0.7</td>
</tr>
<tr>
<td>2000</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

500kbps is also acceptable but, we ignored the pointing error of ground station and satellite.
3. Link Budget Calculation

Step 7: Result of Link Margin and Level Diagram

Level Diagram (Question)

[?] Which dot is which value?
Which line is which gain?
3. Link Budget Calculation

Step 7: Result of Link Margin and Level Diagram

Level Diagram (Answer)

<table>
<thead>
<tr>
<th>Index</th>
<th>Signal Level (dBm)</th>
<th>Req. Level (dBm/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>1</td>
<td>19.0</td>
<td>19.0</td>
</tr>
<tr>
<td>2</td>
<td>23.0</td>
<td>23.0</td>
</tr>
<tr>
<td>3</td>
<td>-139.4</td>
<td>-139.4</td>
</tr>
<tr>
<td>4</td>
<td>-107.4</td>
<td>-107.4</td>
</tr>
<tr>
<td>5</td>
<td>-108.4</td>
<td>-108.4</td>
</tr>
</tbody>
</table>

(C)HU
3. Link Budget Calculation

Step 7: Result of Link Margin and Level Diagram

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

<table>
<thead>
<tr>
<th>kbps</th>
<th>margin (dB) @ EL=15deg</th>
<th>margin (dB) @ EL=75deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>9.3</td>
<td>18.0</td>
</tr>
<tr>
<td>200</td>
<td>6.3</td>
<td>15.0</td>
</tr>
<tr>
<td>500</td>
<td>2.3</td>
<td>11.0</td>
</tr>
<tr>
<td>1000</td>
<td>-0.7</td>
<td>8.0</td>
</tr>
<tr>
<td>2000</td>
<td>-3.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

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

[?] 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)

- **Satellite**
  - Transmitter
    - 2250MHz
    - 0.1W out
    - $\text{EIRP} = 20 - 1 + 4 = 23 \text{ dBm}$

- **Antenna**
  - Gain = 4.0 dBi

Cable Loss
- $= -1.0 \text{ dB}$

$\text{OBW} = 100 \text{ kHz}$
- (@ 100kbps, BPSK)
- [!] 134 kHz will be feasible

$\text{EIRP/OBW} = 23 \text{ dBm} - 50 \text{ dBHz} = -27 \text{ dBm/Hz}$
- (without antenna gain $\Rightarrow -31 \text{ dBm/Hz}$)
4. Power Flux Density (PFD) Regulation

Power Flux Density (PFD) at ground

- Power Flux in spherical surface
  \[ A = 4 \pi h^2 \]

@ 500km height
\[ A = 3.142 \times 10^6 \text{ km}^2 \]
\[ = 125.0 \text{ dB.m}^2 \]

\[ \text{PFD} = \frac{\text{EIRP/OBW}}{A} \times 4\text{kHz} \]
\[ = -27 \text{ dBm/Hz} - 125 \text{ dB.m}^2 + 10 \log_{10}(4000) \text{ dB.Hz} \]
\[ = -116 \text{ dBm/m}^2 = -146 \text{ dBW/m}^2 \]

36.0 dB.Hz
4. Power Flux Density (PFD) Regulation

**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.*

**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
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.