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
Yuji Sakamoto, Dr.

Position:
2006 - Assistant Professor (-2015), Associate Professor (2015-)
   Department of Aerospace Engineering, Tohoku University
2021 - Associate Professor
   Division of Mechanical and Space Engineering, Hokkaido University

Research Topics:
Design, Assembly, and Evaluation of Micro and Nano Satellites
Satellite Operation and Ground Station Management
1. Introduction
2. Theory
3. Case study I - 50kg microsatellites in SSO
4. Case study II - 2.6kg 2U CubeSat in ISS orbit
5. Conclusion

Tutorial. Example of 1-node analysis for 1U CubeSat
1. Introduction
1. Introduction

1.1 Lecturer's satellite projects

DIWATA-1 was released to space on April 28, 2016 from the ISS

(C)JAXA

(C)JAXA
1. Introduction

1.1 Lecturer's satellite projects

- **2009**
  - SPRITE-SAT
  - Image: (C) TU, HU

- **2012**
  - RAIKO
  - Image: (C) TU

- **2014**
  - RISING-2
  - Image: (C) TU, HU

- **2016**
  - DIWATA-1
  - Image: (C) TU, HU, DOST, UPD

- **2018**
  - DIWATA-2
  - Image: (C) TU, HU, DOST, UPD

- **2019**
  - RISESAT
  - Image: TU, HU (C) JAXA

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

1.2 Bus system of micro/nano satellites

Large Satellites
- ALOS-4
  - 3000 kg
  - MicroSatellite × 50
  - NanoSatellite × 1000

Micro Satellites
- DIWATA-2
  - 57 kg

Nano Satellites
- RAIKO
  - 2.7 kg
1. Introduction

1.2 Bus system of micro/nano satellites

Launch is not a GOAL, it is just a START

1.5 - 3 years
design, assemble

3 - 5 years
3 - 5 years

end of operation

communications, observations
1. Introduction

1.2 Bus system of micro/nano satellites
1. Introduction

1.2 Bus system of micro/nano satellites

- 1. Structure
- 2. Power
- 3. Communication
- 4. Computer
- 5. Thermal
- 6. Attitude
1. Introduction

1.2 Bus system of micro/nano satellites

550 x 350 x 550 mm
52.4 kg
1. Introduction

1.3 Importance to estimate and control the satellite temperature

• If you don't care of the temperature, what will happen?
  • Battery outside of temperature range
    => no charge/discharge of battery current => life is over, mission failure
  • Onboard computers or sensors temperature out of range => mission failure
  • Mechanical parts temperature out of range => mission failure

• Important thing = which items have narrow or severe temperature ranges?
  • We need to estimate the temperature in the preliminary design phase
    => affects the design of the structure, locations of onboard instruments, locations of solar-cell area, and space for additional heat control items
1. Introduction

1.4 Objectives of lecture

- Fundamentals of thermal analysis and control
- Tutorial of 1-node simple thermal analysis for 1U CubeSat
- Case studies of analyses, tests, and flight data
  - 1: microsatellite SPRITE-SAT (2009)
  - 2: nanosatellite RAIKO (2012)
  - 3: microsatellite RISING-2 (2014)
2. Theory
2. Theory

2.1 Elements to decide the temperature of satellite

A. Satellite <-> Environment

\[ mc_p \frac{dT}{dt} = Q_S + Q_I + Q_a - Q_{sp} \]

- Simplified ignoring inside of satellite
- plus => T is increased
- minus => T is decreased
- zero => T is not changed

- \( Q \)
  - \( T_1 > T_2 \)
  - \( Q=0 \)
  - \( T_1 = T_2 \)
2. Theory

2.2 Math model of temperature variation by time

B. Inside of satellite

Full equation for item i

\[ m_i c_{pi} \frac{dT_i}{dt} = Q_i - \sum_{j=1}^{n} C_{ij} (T_i - T_j) - \sum_{j=1}^{n} \varepsilon_i \varepsilon_j F_{ij} A_i \sigma (T_i^4 - T_j^4) \]

- Contact heat transfer
- Radiation heat transfer

Sum of environmental heats and power consumption

Power Consumption

Contact/radiation heat transfer (among of panels and instruments)
2. Theory

2.2 Math model of temperature variation by time

\[ \alpha \text{ solar absorptivity} = 0 \ldots 1 \]

\[ \varepsilon \text{ infrared emissivity} = 0 \ldots 1 \]

\[ \alpha = 0.9 \]

\[ 0.9 \cdot Q_S \]

\[ 1366 \text{ W/m}^2 \]

\[ 0.1 \cdot Q_S \]

Example of radiation to space

\[ Q_{sp} \]

\[ \varepsilon = 0.9 \]

\[ Q_{sp} = 9 \cdot Q_{sp} \]

\[ \varepsilon = 0.1 \]

\[ Q_{sp}' \]
2. Theory

2.2 Math model of temperature variation by time

\[- \sum_{j=1}^{n} C_{ij} (T_i - T_j)\]

simplified to **2 blocks**

**contact** heat transfer

\[Q\]

HOT \rightarrow COLD

**contact** thermal resistance

\[Q_{12} = -C_{12}(T_1 - T_2)\]

\[C_{12} \text{ (W/K)}\]

\[T_1 = T_2\]

\[Q_{12} = 0\]
2. Theory

2.2 Math model of temperature variation by time

\[-n \sum_{j=1}^{n} \epsilon_i \epsilon_j F_{ij} A_1 \sigma (T_i^4 - T_j^4)\]

**simplified to 2 plates**

**Radiation**

Heat transfer

**HOT** \[Q\] **COLD**

Near

= large F

= high radiation

0.6 in view

Far

= small F

= low radiation

0.1 in view

\[Q_{12} = -\epsilon_1 \epsilon_2 F_{12} A_1 \sigma (T_1^4 - T_2^4)\]

\[F\] • view factor = 0 .. 1
2. Theory
2.3 Effect of panel connections

A) direct connection = **high** contact resistance

B) insert insulation plate and washer = **low** contact resistance

![Diagram showing direct connection vs. insulated connection with glass epoxy plates and washers.](image)
2. Theory

2.5 Effect of orbital motion

Sat. in sunshine
input = $Q_S + Q_I + Q_a$

Sat. in eclipse
input = $Q_I$

Earth

90-100 minutes/round
14 .. 15 rounds/day

Sun

"all sunshine"

view from Sun

T

typical

time
2. Theory

2.7 Effect of power generation and consumption

A) charging battery (sunshine)

\[ Q_e = P_{BUS} = 0.1Q_S \]

max. effi. = 30%

\[ P_{BAT} = 0.2Q_S \]

\[ 0.7Q_S \] to heat panel

B) battery full (sunshine)

\[ Q_e = P_{BUS} = 0.1Q_S \]

max. effi. = 30%

\[ 0.9Q_S \] to heat panel

input \[ Q_S \]

input \[ Q_S \]
2. Theory
2.7 Effect of power generation and consumption

C) discharging battery (eclipse)

\[ Q_e = P_{BUS} \]

- input heats \( Q_S \) to panel
  => partly, consumed by bus instruments (sunshine)
  => partly, used to charge battery (sunshine) [!] no heat
  => consumed by bus instruments (eclipse)

no solar light
discharging
2. Theory

2.8 Effect of 4 seasons

<table>
<thead>
<tr>
<th>Season</th>
<th>Solar Constant ($G_s$)</th>
<th>Incident Radiation ($q_I$)</th>
<th>Emissivity ($\alpha$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Solstice</td>
<td>1414</td>
<td>261</td>
<td>0.4</td>
</tr>
<tr>
<td>Summer Solstice</td>
<td>1366</td>
<td>237</td>
<td>0.3</td>
</tr>
<tr>
<td>Autumn Equinox</td>
<td>1318</td>
<td>189</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Reference:
Tutorial

Example of 1-node analysis for 1U CubeSat
Tutorial
Example of 1-node analysis for 1U CubeSat

10cm (each side)
1U CubeSat

surface area =
0.010^2 x 6 = \textbf{0.060 m}^2

\textbf{complex}
cross section area

simplified by \textbf{sphere}
with same-surface area

\textbf{simplified cross section area}

surface area = \textbf{0.060 m}^2
cross section area
= surface area / 4 = \textbf{0.015 m}^2

\textbf{constant cross section area}
**Step 1: Define the alpha and epsilon of the surface**

**Case A)**
- solar cells (8x7cm) + aluminum

<table>
<thead>
<tr>
<th>Material</th>
<th>Occupancy</th>
<th>$\alpha$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar cells</td>
<td>56%</td>
<td>0.920</td>
<td>0.800</td>
</tr>
<tr>
<td>aluminum</td>
<td>44%</td>
<td>0.255</td>
<td>0.025</td>
</tr>
<tr>
<td>polyimide</td>
<td>0%</td>
<td>0.515</td>
<td>0.760</td>
</tr>
</tbody>
</table>

**Case B)**
- solar cells (8x7cm) + polyimide

<table>
<thead>
<tr>
<th>Material</th>
<th>Occupancy</th>
<th>$\alpha$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar cells</td>
<td>56%</td>
<td>0.920</td>
<td>0.800</td>
</tr>
<tr>
<td>aluminum</td>
<td>0%</td>
<td>0.255</td>
<td>0.025</td>
</tr>
<tr>
<td>polyimide</td>
<td>44%</td>
<td>0.515</td>
<td>0.760</td>
</tr>
</tbody>
</table>

**Average**
- Case A: $0.627$, $0.459$
- Case B: $0.742$, $0.782$
Step 2: Define the input heats from Sun and Earth

\[ Q_S = AG_s \alpha \cos \theta_s, \quad Q_l = Aq_I \varepsilon F_e \cos \theta_e, \]

\[ Q_A = AG_s aK_a \alpha F_e \cos \theta_e \]

* Acos\(\theta_s\) = Acos\(\theta_e\) = \(A_{\text{cross}}\) in this sphere model

<table>
<thead>
<tr>
<th>(G_s) direct solar flux</th>
<th>W/m²</th>
<th>1366</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_l) earth infrared emission</td>
<td>W/m²</td>
<td>237</td>
</tr>
<tr>
<td>(a) albedo rate</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Fe@400km alt. view factor of earth</td>
<td></td>
<td>0.885</td>
</tr>
<tr>
<td>Ka@400km alt. for (Q_a) calc.</td>
<td></td>
<td>0.998</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Q_s)</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_l)</td>
<td>12.86</td>
<td>15.20</td>
</tr>
<tr>
<td>(Q_a)</td>
<td>3.41</td>
<td>4.03</td>
</tr>
<tr>
<td>(Q_s+Q_l+Q_a)</td>
<td>17.71</td>
<td>21.69</td>
</tr>
</tbody>
</table>
Step 3: Calculate temperature time rate of change (dT/dt) as example

\[ mc_p \frac{dT}{dt} = Q_s + Q_l + Q_a + Q_e - Q_{sp} \]

\[ = Q \]

heat radiation to space

\[ [!] A = A_{surface} \]

\[ Q_{sp} = \varepsilon A \sigma \left( T^4 - T_{sp}^4 \right) \]

when \( T = 20 \) degC

[!] \( T \) is satellite temperature

other constant values

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>Stephan-Boltzmann constant</th>
<th>W/m².K⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.671E-08</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( m )</th>
<th>satellite mass</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( c_p )</th>
<th>specific heat of aluminum</th>
<th>J/kg.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>879</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( T_{sp} )</th>
<th>temperature of deep space</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| Case A | | | | |
|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Sun/Ecl</th>
<th>T(degC)</th>
<th>T(K)</th>
<th>Q(W)</th>
<th>Qsp(W)</th>
<th>dT/dt(K/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>20</td>
<td>293</td>
<td>17.71</td>
<td>11.53</td>
<td>0.00528</td>
</tr>
<tr>
<td>Ecl</td>
<td>20</td>
<td>293</td>
<td>1.44</td>
<td>11.53</td>
<td>-0.00863</td>
</tr>
</tbody>
</table>

[!] Try to calculate by spread sheet
Tutorial
Example of 1-node analysis for 1U CubeSat

Sunshine ... Eclipse (60 minutes)
* integrated by every 10 seconds

Eclipse .. Sunshine (30 minutes)

[ ! ] find the satellite temperature, which can be same at beginning and end of a single orbital period
The only difference is the external surface materials, but the temperature can be shifted by 37 degC (= 16 - (-21)).

without an insulation concept, satellite temperature can be changed by 16 degC (= 32 - 16) in a single 90-minute period.
3. Case study I - 50kg microsatellites for SSO
### 3. Case study I - 50kg microsatellites for SSO

#### 3.1 Summary of satellite specifications

<table>
<thead>
<tr>
<th></th>
<th>SPRITE-SAT</th>
<th>RISING-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missions</td>
<td>Remote Sensing</td>
<td>Remote Sensing</td>
</tr>
<tr>
<td>Orbit</td>
<td>SSO, <strong>666 km</strong> height</td>
<td>SSO, <strong>628 km</strong> height</td>
</tr>
<tr>
<td>Mass</td>
<td><strong>45.3 kg</strong></td>
<td><strong>43.2 kg</strong></td>
</tr>
<tr>
<td>Size</td>
<td>50 x 50 x 50 cm (total)</td>
<td>50 x 50 x 50 cm (total)</td>
</tr>
<tr>
<td></td>
<td>* 50 x 50 x 42 cm (panels)</td>
<td>* 50 x 50 x 42 cm (panels)</td>
</tr>
</tbody>
</table>
3. Case study I - 50kg microsatellites for SSO

3.2 Outside/Inside appearance

<table>
<thead>
<tr>
<th>SPRITE-SAT</th>
<th>RISING-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common</strong></td>
<td></td>
</tr>
<tr>
<td>6 external panels + center pillar (4 panels)</td>
<td>aluminum grid panels</td>
</tr>
<tr>
<td>* most of instruments are attached on the center pillar</td>
<td>* fabrication speed and cost merits</td>
</tr>
<tr>
<td>* center pillar is thermally insulated from external panels</td>
<td>* heavier than SPRITE-SAT</td>
</tr>
<tr>
<td><strong>External panel material</strong></td>
<td></td>
</tr>
<tr>
<td>aluminum skin/core honeycomb panels</td>
<td></td>
</tr>
</tbody>
</table>

(C)TU,HU

SPRITE-SAT

(C)TU,HU

RISING-2

(C)TU,HU

SPRITE-SAT

(C)TU,HU

RISING-2

(C)TU,HU
3. Case study I - 50kg microsatellites for SSO

3.3 Concept of inside heat connection model

<table>
<thead>
<tr>
<th>SPRITE-SAT</th>
<th>RISING-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface of internal panels and instruments</td>
<td>Aluminum <em>(no paints)</em></td>
</tr>
<tr>
<td>Heat radiation transfer with ext. panels</td>
<td>Small <em>(or Negligible)</em></td>
</tr>
<tr>
<td>Black</td>
<td></td>
</tr>
<tr>
<td>Large <em>(complex thermal analysis</em></td>
<td></td>
</tr>
<tr>
<td>* negative for center insulation concept*)</td>
<td></td>
</tr>
</tbody>
</table>
3. Case study I - 50kg microsatellites for SSO

3.4 Concept of outside heat connection model

Case of SPRITE-SAT

![Image of SPRITE-SAT panels]

Table: Heat specifications of elements and panels

<table>
<thead>
<tr>
<th>Element</th>
<th>( \alpha )</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar cell*</td>
<td>0.68</td>
<td>0.80</td>
</tr>
<tr>
<td>aluminum**</td>
<td>0.26</td>
<td>0.03</td>
</tr>
<tr>
<td>MLI</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Polyimide</td>
<td>0.52</td>
<td>0.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Panel</th>
<th>A(m²)</th>
<th>( \alpha )</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>top</td>
<td>0.2397</td>
<td>0.463</td>
<td>0.619</td>
</tr>
<tr>
<td>side</td>
<td>0.1862</td>
<td>0.517</td>
<td>0.652</td>
</tr>
<tr>
<td>bottom</td>
<td>0.2397</td>
<td>0.118</td>
<td>0.078</td>
</tr>
</tbody>
</table>

* original value was 0.85 w/o power generation
** A7075 with Alodine 1000

[ ! ] Area, avg. alpha and epsilon values are summarized in each panel

Adjustment of Polyimide area is an easy method to control heat balance
- average temperature can be decreased by a larger Polyimide area
- Polyimide area (0.76 epsilon) can emit the larger heat from aluminum surface (0.03 epsilon)

[!] Exact alpha, epsilon values are different depending on the coating method or tape thickness, they must be measured by special instruments
3. Case study I - 50kg microsatellites for SSO

3.5 Method of 2-node analysis

Environment of Sun, Earth, Space

0. satellite surface panels

1. radiation heat transfer

2. contact heat transfer

(C)TU,HU

(C)TU,HU

satellite inside structure
3. Case study I - 50kg microsatellites for SSO

3.5 Method of 2-node analysis

Node: ①
Satellite Surface Panels
Q1
Consumption Power (on ext. panels)
R
Radiation Heat Transfer Coefficient

Node: ②
Satellite Inside Structure
Q2
Consumption Power (on inside panels)
C
Contact Heat Transfer Coefficient

surface specs: A, α, ε
3. Case study I - 50kg microsatellites for SSO

3.6 Analysis result and flight data for SPRITE-SAT

Temperature of central pillar

- SPRITE-SAT

**estimate** = **16.5 degC** (in winter)

Estimation was included in flight data range (15-20 degC)

(C) TU,HU
3. Case study I - 50kg microsatellites for SSO

3.7 Analysis result and flight data for RISING-2

- SPRITE-SAT and RISING-2 have similar external dimensions, but RISING-2 average temperature is higher than SPRITE-SAT
  - power generation efficiency of solar cell is higher -> typical power consumption of inside is increased
  - heat radiation among inside parts are insulated w/o black paint

![Temperature estimation graphs]

- winter = 16.5 degC
- winter = 24.3 degC

about +8 degC is estimated (better for battery)

(C) TU,HU
3. Case study I - 50kg microsatellites for SSO

3.8 Purpose of thermal vacuum chamber test

- **1. Thermal Test** for onboard instruments and harness
  - all the instruments must work normally in the lowest and highest temperature
    - example) troubles by unstable oscillator clocks
  - mandatory for deployable mechanisms to ensure the safe temperature range

- **2. To decide the coefficients of heat transfer**
  - dummy mass aluminum blocks can be also applied
  - number of unknown variables should be decreased
  - epsilon of radiation heat transfer can be measured by other instruments

- **SPRITE-SAT**
- **RISING-2**

(C)TU,HU

JAXA’s item (C)TU,HU

complex of radiation model

no radiation = good to decide contact coefficients
3. Case study I - 50kg microsatellites for SSO

3.8 Purpose of thermal vacuum chamber test

To measure solar absorption \( \alpha \)

To measure emissivity \( \varepsilon \)

Portable Spectral Solar Absorptance Measurement System PM-A2

Thermo Fisher Scientific Nicolet iS50 FT-IR

Photos: Hokkaido University
https://f3.eng.hokudai.ac.jp/microsat.html
4. Case study II - 2.6kg 2U CubeSat for ISS orbit

KiboCUBE Academy
4. Case study II - 2.6kg 2U CubeSat for ISS orbit

4.1 Summary of satellite specifications

- **RAIKO**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missions</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Orbit</td>
<td>ISS, <strong>400 km</strong> height</td>
</tr>
<tr>
<td>Mass</td>
<td><strong>2.66 kg</strong></td>
</tr>
<tr>
<td>Size</td>
<td>10 x 10 x 22.7 cm (total)</td>
</tr>
</tbody>
</table>

- No special treatment for thermal analysis
- No insulation concept, the entire structure and instruments are simply connected by stainless bolts
- No paint for internal instruments
4. Case study II - 2.6kg 2U CubeSat for ISS orbit

4.4 Analysis result and flight data for RAIKO

- Single node analysis (no insulation concept)
  -> **43** degC in all-sunshine phase
  -> **+4 .. +15** degC in winter phase
  -> **-10 .. +3** degC in summer phase

- Battery temp. was from **-5degC to +13degC**

[!] Lessons Learned: at least battery module must have been insulated. minus degC is risk for battery charge/discharge and lifetime
5. Conclusion
5. Conclusion

• **Section 1.3)** importance of estimating the satellite temperature and adjusting it.
  - battery temperature should be in normal temp. range
  - computers, sensors, mechanical parts also important

• result of the thermal analysis have an effect on the design of structure, location of onboard instruments, necessity of heaters
  - in early the phase of design, we need to start the analysis

• **Section 2)** theories are needed in thermal analysis
  - balance of heat input from the Sun and the Earth, and heat radiation to space
  - consumption power, concept of insulation
  - 2.3: insulation method, 2.4: radiation control by surface material, 2.7: power generation
5. Conclusion

- **Section 3)** case studies of 50 kg microsatellites
  - first satellite (SPRITE-SAT) had an ambiguous concept (insulation, black paint)
  - insulation concept is one of many thermal concepts, suitable method is different in each satellite

- **Section 4)** case study of CubeSat
  - battery temperature was often in lower than 0 degC
  - battery wasn't discharged normally in very cold situation => not a successful example
  - Lessons Learned: insulation to battery was necessary in this case => high temperature in all-sunshine phase is a risk
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.