Thermal Analysis of Spacecraft using Data Assimilation

Hiroto TANAKA¹, Hiroki NAGAI¹ and Takashi Misaka²
¹Tohoku University, Japan
²AIST, Japan

Presented By
Hiroto TANAKA
1. Research Background
2. Objective
3. Methodology
4. Experiment
5. Result and Discussion
6. Conclusion / Future Work
Research Background

Thermal analysis of the Spacecraft

✓ Temperature prediction of TMM has uncertainty due to “model incompleteness” and “disturbance of boundary condition”

✓ In deep space missions, estimating **thermal state of entire system** is difficult due to limited temperature data

Temperature Prediction

Maximum case

Minimum case

Prediction

Uncertainty of TMM
By using flight temperature datasets, estimate the thermal state in higher accuracy than conventional TMM analysis.
Data assimilation technique

✓ Statistic approach to combine observed data and simulated data

Simulation  
Observation  

Data Assimilation  

Estimation of System State  

T [K] vs. t [sec.]

- Green: Observed data
- Blue: Simulated data
- Red: Data assimilation
- Dashed: True Value
✓ Apply the data assimilation technique to the TMM in order to improve the temperature estimation accuracy

✓ Confirm the availability of data assimilation assisted TMM and compare its performance with conventional thermal analysis

Thermal Mathematical Model + Limited Temperature Datasets = Better Temperature Estimation?
Methodology

1. Thermal Mathematical Model (TMM)
2. Ensemble Kalman Filter (EnKF)
3. Data Assimilation / Ensemble Kalman Filter
Methodology

1. Thermal Mathematical Model (TMM)

TMM consists of…

✓ Node : heat generation / temperature / heat capacity
✓ Path : thermal conductance

Governing equation

\[
T_i(t+1) = T_i(t) + \Delta t \left[ Q_i(t) - \sum_{j=1}^{n} C_{ij} (T_i(t) - T_j(t)) - \sum_{j=1}^{n} R_{ij} \sigma (T_i^4(t) - T_j^4(t)) \right]
\]

Heat balance between nodes

Temperature distribution

STEP : 0
Initial State

Update

STEP : 1
Prediction

Update

STEP : 2
Prediction

⋯
2. Ensemble Kalman Filter (EnKF)

Kalman Filtering

\[ X_{\text{est}} = X_{\text{simu}} + K \times (X_{\text{simu}} - Y) \]

- \( X_{\text{est}} \): Estimated data
- \( X_{\text{simu}} \): Simulated data
- \( Y \): Observed data
- \( K \): Kalman gain
- \( \sigma^2 \): System Noise
- \( \sigma^2 \): Observation Noise

✓ Simulated data is modified by difference between simulation and observation

✓ Kalman gain “K” is calculated from Variance of \( X_{\text{simu}} \)
2. Ensemble Kalman Filter (EnKF)

**Methodology**

**STEP : 0**
- **Initial State**
  - PDF

**STEP : 1**
- **Prediction**
  - $\sigma^2$: System Noise
- **Observation**
  - $\sigma^2$: Observation Noise
- **Estimation**

**STEP : 2**
- **Prediction**
  - $\sigma^2$: Noise
- **Observation**
  - $\sigma^2$: Noise
- **Estimation**

Update

**Update**

Minimum Variance Estimation

Filtering

Filtering

PDF: Probability Density Function
Methodology

2. Ensemble Kalman Filter (EnKF)

STEP : 0
Initial State

Discretization of PDF
○ : Particle

STEP : 1
Prediction
σ² : Noise

Observation
σ² : Noise

Estimation

STEP : 2
Prediction
σ² : Noise

Observation
σ² : Noise

Estimation

PDF : Probability Density Function

Update
Filtering
1. Overview
2. Building a TMM
3. Thermal Test Setup
4. Correlation and Uncertainty Analysis of TMM
1. Overview

Build a Simple Thermal Mathematical Model

Thermal Test A  (Ground Test Data)

Model - Test Correlation

Thermal Test B  (Flight Data)

Conventional TMM Analysis

EnKF Assisted TMM Analysis

Compare the Accuracy of Temperature Estimation
2. Building a TMM

Built a simple and high uncertain thermal model

1. Dimensional thermal mathematical model

✓ Each conductance $C_{ij}$ has different uncertainty

✓ Heat input and output $Q$ have uncertainty
3. Thermal Test

Test Model

<table>
<thead>
<tr>
<th>Node No.</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heater</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum</td>
</tr>
<tr>
<td>3</td>
<td>Acrylic resin / upper part</td>
</tr>
<tr>
<td>4</td>
<td>Acrylic resin / lower part</td>
</tr>
<tr>
<td>-</td>
<td>Heatsink</td>
</tr>
</tbody>
</table>

\[ Q_{in} \]
\[ Q_{out} \]
3. Thermal Test

Uncertainty of the Thermal Test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor</th>
<th>± 3σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{in}$</td>
<td>Heat generation : $Q_{heater}$</td>
<td>± 15 %</td>
</tr>
<tr>
<td>$Q_{out}$</td>
<td>Heatsink temperature : $T_{heatsink}$</td>
<td>± 0.45 K</td>
</tr>
<tr>
<td>$C_{12}$</td>
<td>Contact conductance : $h_{12}$</td>
<td>± 50 %</td>
</tr>
<tr>
<td>$C_{23}$</td>
<td>Contact conductance : $h_{23}$</td>
<td>± 50 %</td>
</tr>
<tr>
<td>$C_{34}$</td>
<td>Thermal conductivity : $k_{resin}$</td>
<td>± 0.04 W/(m·K)</td>
</tr>
<tr>
<td>$C_{45}$</td>
<td>Contact conductance : $h_{45}$</td>
<td>± 50 %</td>
</tr>
</tbody>
</table>
# Experiment

## 4. Correlation and Uncertainty Analysis of TMM

### Thermal Test Result

#### ① Test A (Ground Test Simulation)

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{heater}}$</td>
<td>2.0 W</td>
</tr>
<tr>
<td>$T_{\text{heatsink}}$</td>
<td>383.2 K</td>
</tr>
<tr>
<td>Measurement Error (3σ)</td>
<td>± 1.0 K</td>
</tr>
</tbody>
</table>

#### ② Model-Test Correlation result

<table>
<thead>
<tr>
<th>Content</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{12}$</td>
<td>300 W/(m²·K)</td>
</tr>
<tr>
<td>$h_{23}$</td>
<td>500 W/(m²·K)</td>
</tr>
<tr>
<td>$k_{\text{resin}}$</td>
<td>0.26 W/(m·K)</td>
</tr>
<tr>
<td>$h_{45}$</td>
<td>10000 W/(m²·K)</td>
</tr>
</tbody>
</table>

#### ③ Test B (Flight Data Simulation)

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{heater}}$</td>
<td>2.4 W</td>
</tr>
<tr>
<td>$T_{\text{heatsink}}$</td>
<td>383.2 K</td>
</tr>
<tr>
<td>Measurement Error (3σ)</td>
<td>± 1.0 K</td>
</tr>
</tbody>
</table>

#### ④ Thermal Analysis

![Temperature vs Time Graph](attachment:image.png)
1. Conventional TMM Analysis
2. EnKF Assisted TMM Analysis
3. Comparison of Two Methods
1. Conventional TMM Analysis

Thermal Analysis by TMM

- $T_1$ Transition
- $T_2$ Transition
- $T_3$ Transition
- $T_4$ Transition
2. EnKF Assisted TMM Analysis

Thermal Analysis by EnKF applied TMM / Observation Node : Node 1

- **Transition / observing $T_1$**
  - $T_1$
  - $T_2$
  - $T_3$
  - $T_4$

- **Graphs**
  - EnKF Estimation
  - EnKF Uncertainty
  - Measurement

- $T_1$ Transition / observing $T_1$
- $T_2$ Transition / observing $T_1$
- $T_3$ Transition / observing $T_1$
- $T_4$ Transition / observing $T_1$
3. Comparison of Two Methods

Comparison with “Conventional TMM” & “EnKF assisted TMM”

- The data assimilation result agrees with measured data very well.
- The uncertainty of the temperature estimation decrease drastically comparing with conventional TMM analysis.
3. Comparison of Two Methods

<table>
<thead>
<tr>
<th>Difference from Measured Temperature</th>
<th>TMM</th>
<th>EnKF assisted TMM (T₁ Observation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁</td>
<td>2.13 K</td>
<td>0.00 K</td>
</tr>
<tr>
<td>T₂</td>
<td>1.96 K</td>
<td>0.08 K</td>
</tr>
<tr>
<td>T₃</td>
<td>2.07 K</td>
<td>0.37 K</td>
</tr>
<tr>
<td>T₄</td>
<td>-0.41 K</td>
<td>-0.43 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard Deviation of Analysis Result</th>
<th>TMM</th>
<th>EnKF assisted TMM (T₁ Observation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁</td>
<td>2.91 K</td>
<td>0.27 K</td>
</tr>
<tr>
<td>T₂</td>
<td>2.74 K</td>
<td>0.68 K</td>
</tr>
<tr>
<td>T₃</td>
<td>2.28 K</td>
<td>0.75 K</td>
</tr>
<tr>
<td>T₄</td>
<td>0.43 K</td>
<td>0.55 K</td>
</tr>
</tbody>
</table>

➢ Difference from measured data is decreased by data assimilation
➢ The uncertainty of the analysis is decreased by data assimilation
➢ T₄ result was not improved very well due to observation position and dominant effect of heatsink
Conclusion

Content of the presentation

✓ Data assimilation technique was introduced

✓ Data assimilation was applied to TMM and node temperature was estimated using partial measured data

✓ Performance of conventional TMM and data assimilation assisted TMM were compared

Result

➢ The data assimilation result agreed with measured data

➢ The uncertainty of the temperature estimation decreased drastically comparing with conventional TMM analysis

➢ We confirmed an availability of data assimilation on thermal analysis by simple model and thermal test