Thermal Analysis of Spacecraft using Data Assimilation

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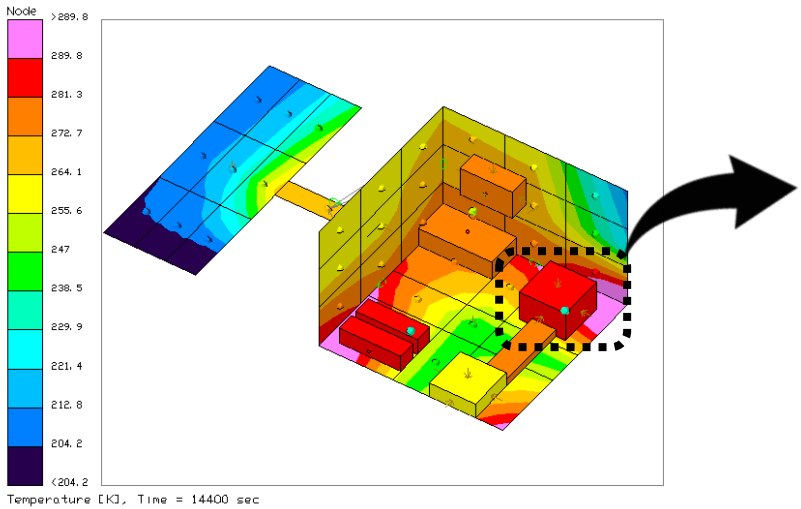
Research Background

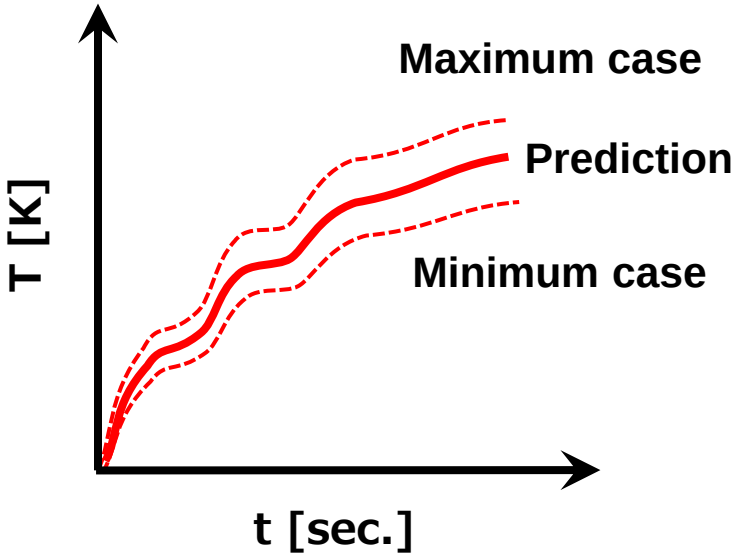
Thermal analysis of the Spacecraft

✓ 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



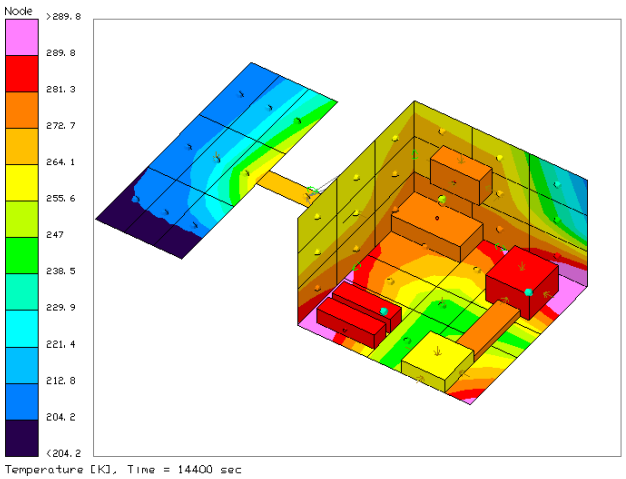
Temperature Prediction



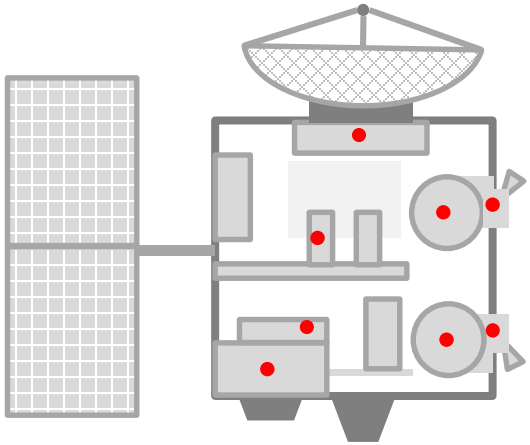
Uncertainty of TMM

Research Background

Temperature Estimation using “Data Assimilation”



Thermal Analysis by TMM



- Temperature monitoring

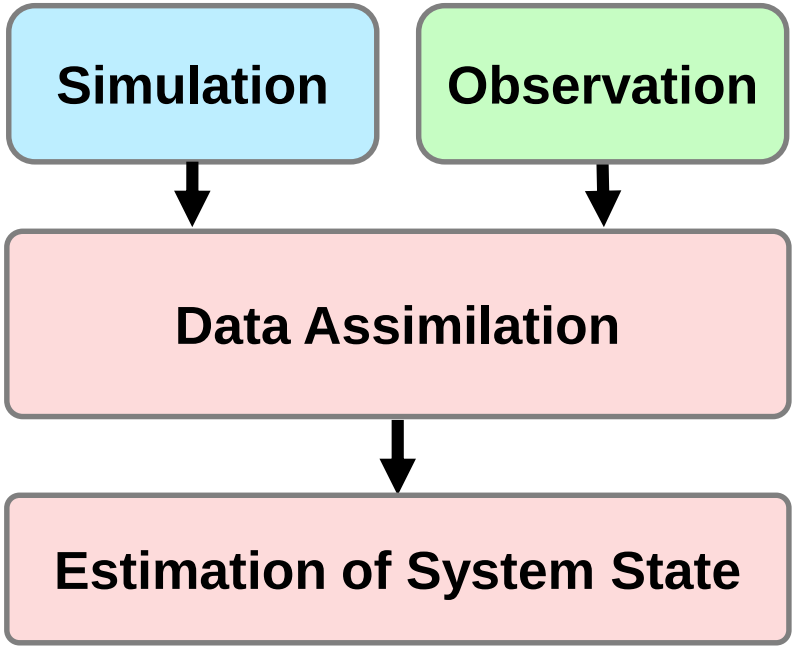
Flight Data

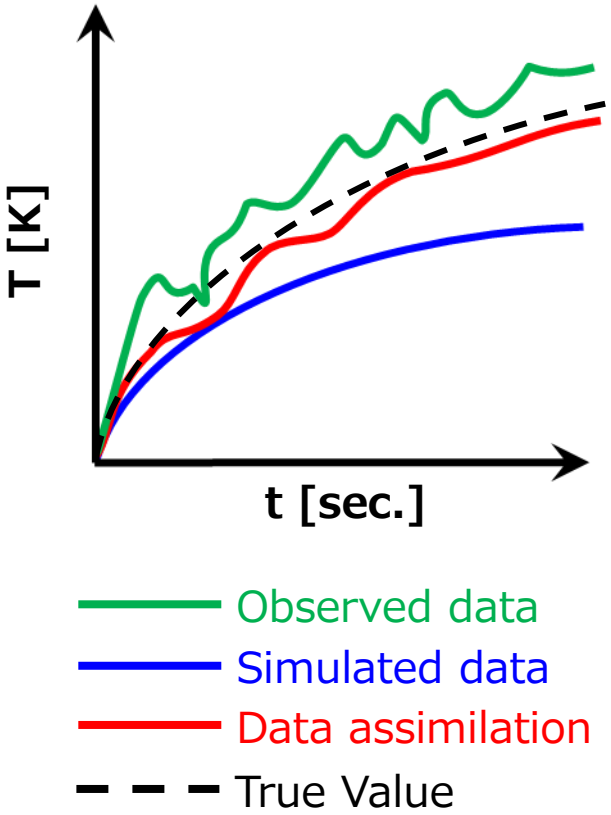
➢ <u>By using flight temperature datasets</u>, estimate the thermal state in higher accuracy than conventional TMM analysis

Research Background

Data assimilation technique

✓ Statistic approach to combine observed data and simulated data





Objective

✓ 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 / Ensenble Kalman Filter

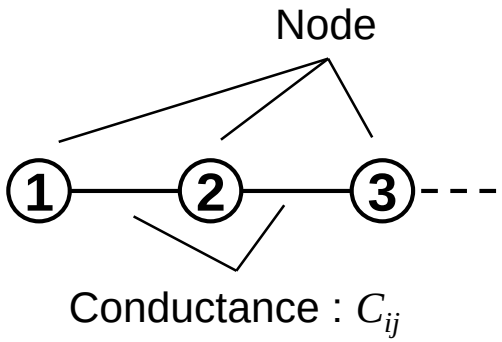
Methodology

1. Thermal Mathematical Model (TMM)

TMM consists of…

✓ Node : heat generation / temperature / heat capacity

✓ Path : thermal conductance

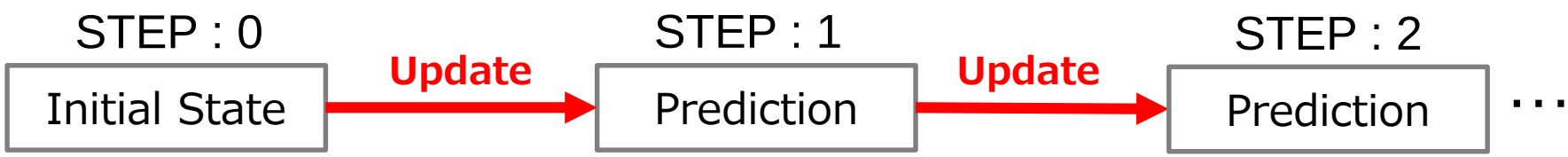


Governing equation

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

Heat balance between nodes

Temperature distribution



Methodology

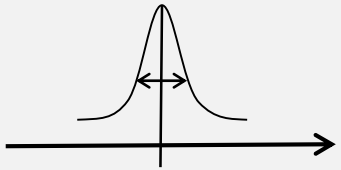
2. Ensemble Kalman Filter (EnKF)

Kalman Filtering

$$\mathbf{X}_{est} = \mathbf{X}_{simu} + \mathbf{K} \times (\mathbf{X}_{simu} - \mathbf{Y})$$

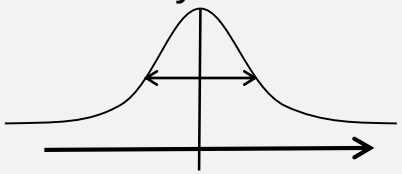
- $\mathbf{X}_{est}$: Estimated data
- $\mathbf{X}_{simu}$: Simulated data
- $\mathbf{Y}$: Observed data
- $\mathbf{K}$: Kalman gain

Estimation variance



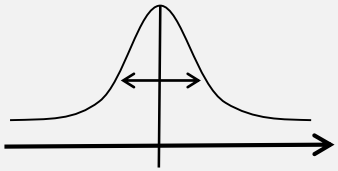
$\mathbf{X}_{est}$: Estimated data

σ^2 : System Noise



$\mathbf{X}_{simu}$: Simulated data

σ^2 : Observation Noise

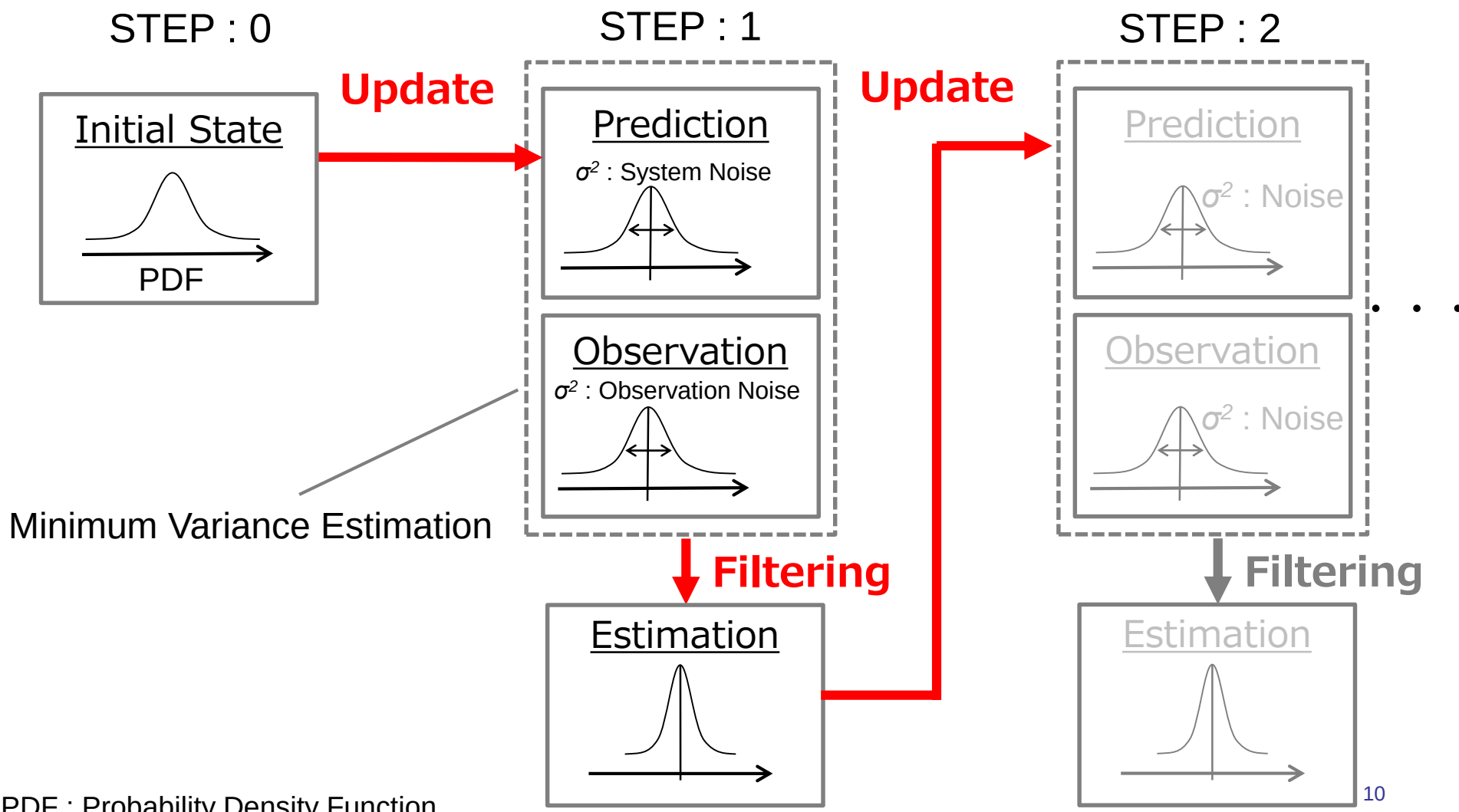


$\mathbf{Y}$: Observed data

- ✓ Simulated data is modified by difference between simulation and observation
- ✓ Kalman gain “K” is calculated from Variance of X_{simu}

Methodology

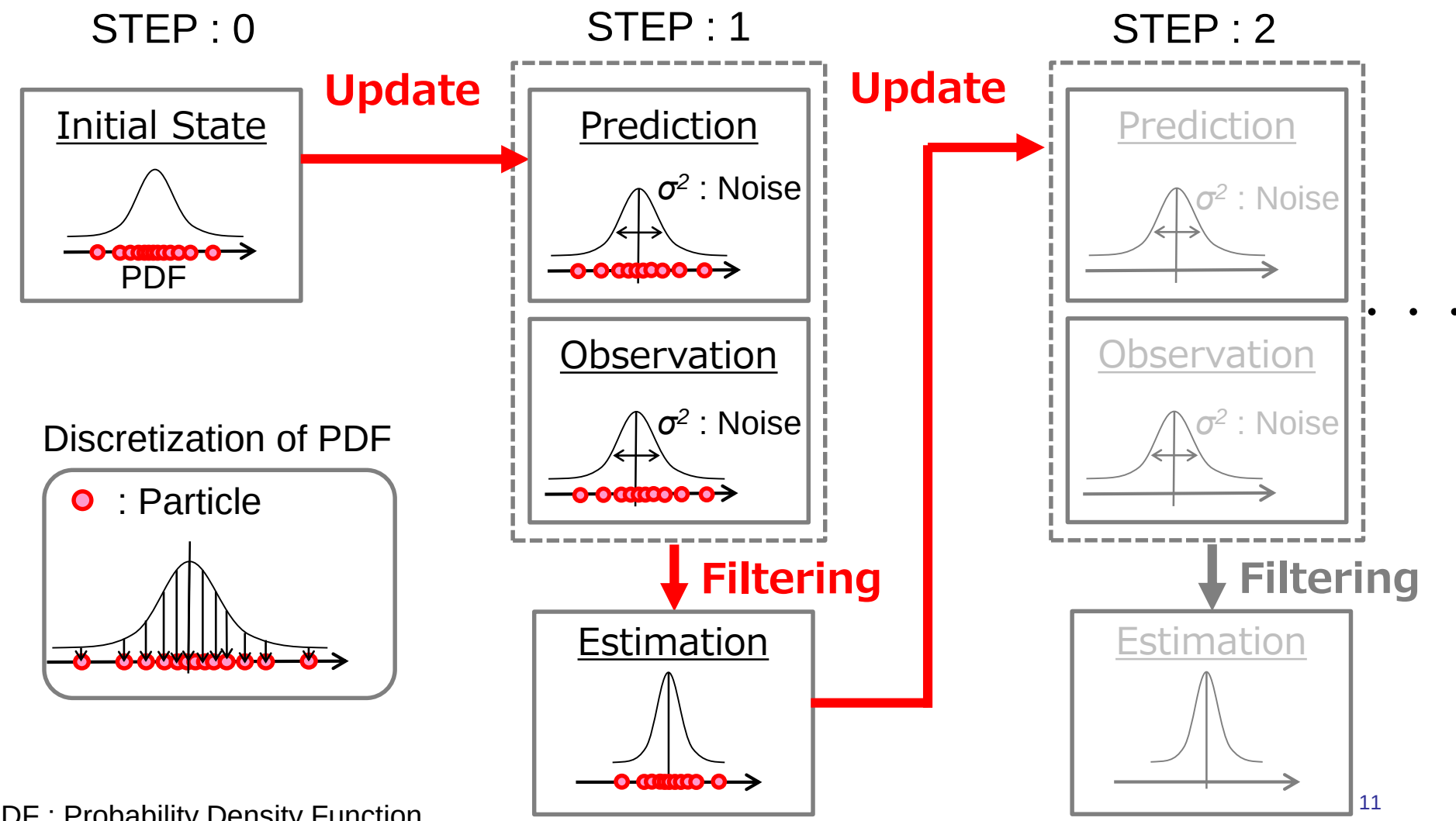
2. Ensemble Kalman Filter (EnKF)



PDF : Probability Density Function

Methodology

2. Ensemble Kalman Filter (EnKF)



PDF : Probability Density Function

Experiment

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

Experiment

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

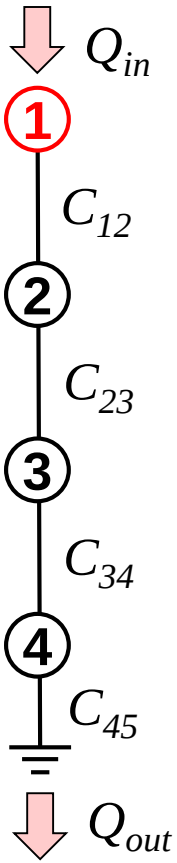
EnKF Assisted TMM Analysis

Compare the Accuracy of Temperature Estimation

Experiment

2. Building a TMM

➢ Built a simple and high uncertain thermal model



Governing Equation

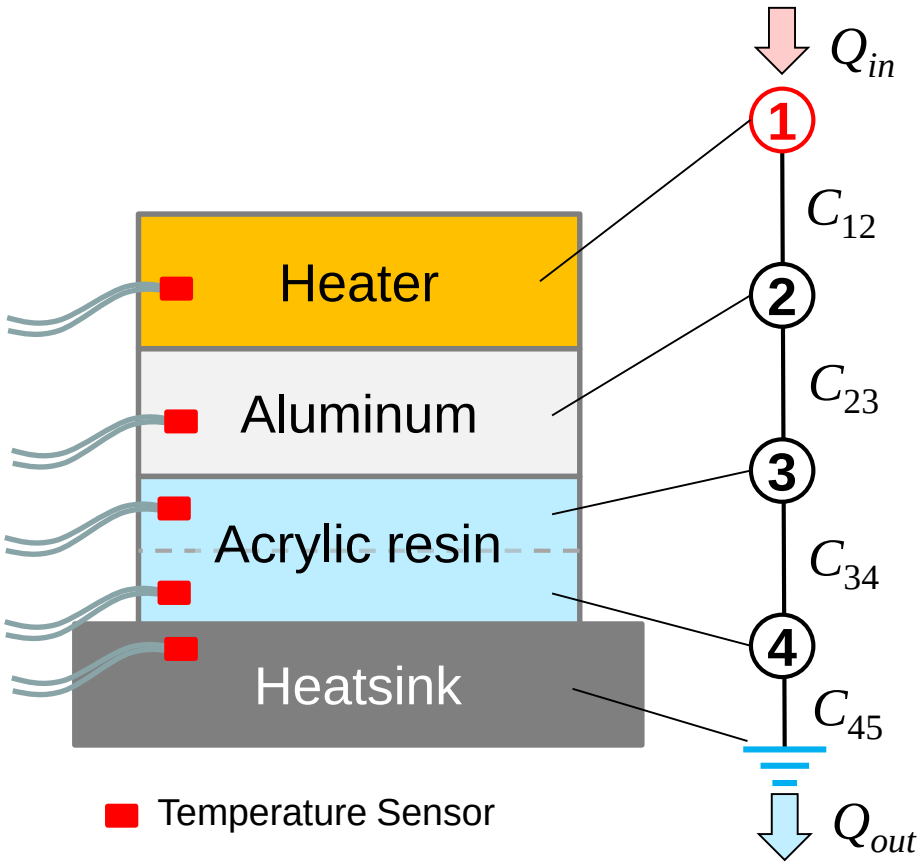
✓ 1-Dimensional thermal mathematical model

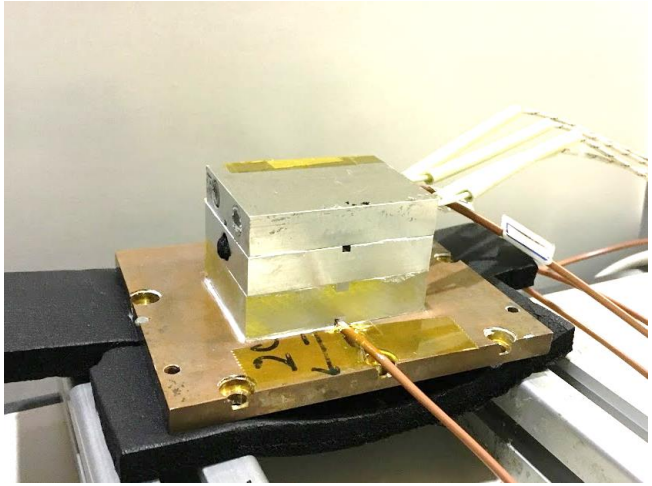
✓ Each conductance C_{ij} has different uncertainty

✓ Heat input and output Q have uncertainty

Experiment

3. Thermal Test



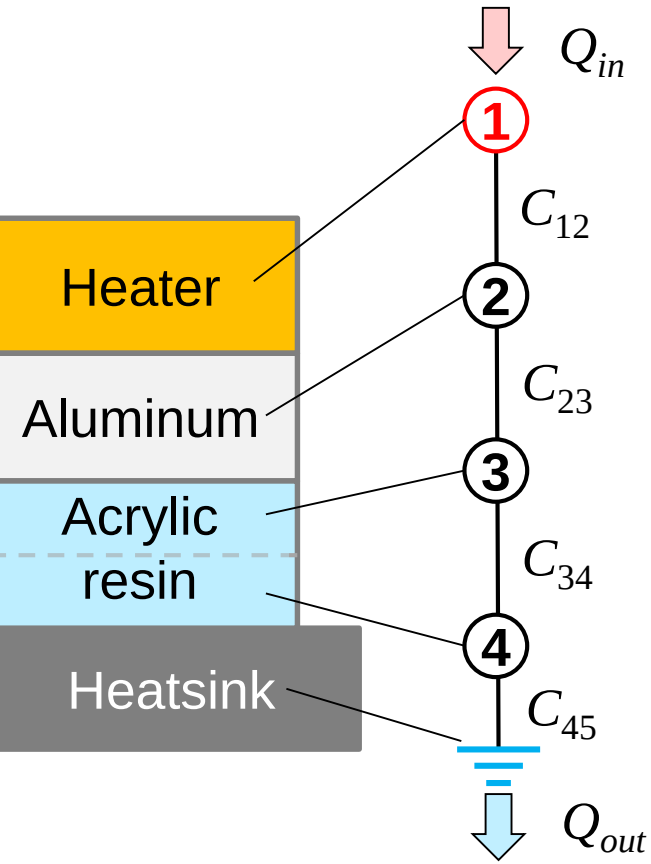


Test Model

Node No.	Content
1	Heater
2	Aluminum
3	Acrylic resin / upper part
4	Acrylic resin / lower part
-	Heatsink

3. Thermal Test

Uncertainty of the Thermal Test



Model Uncertainty

Parameter	Factor	$\pm 3\sigma$
Q_{in}	Heat generation : Q_{heater}	± 15 %
Q_{out}	Heatsink temperature : $T_{heatsink}$	± 0.45 K
C_{12}	Contact conductance : h_{12}	± 50 %
C_{23}	Contact conductance : h_{23}	± 50 %
C_{34}	Thermal conductivity : k_{resin}	± 0.04 W/(m·K)
C_{45}	Contact conductance : h_{45}	± 50 %

Experiment

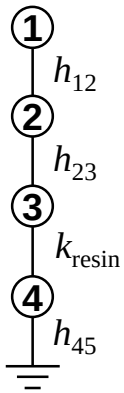
4. Correlation and Uncertainty Analysis of TMM

Thermal Test Result

① Test A (Ground Test Simulation)

Test Condition	Value
Q_{heater}	2.0 W
$T_{heatsink}$	383.2 K
Measurement Error (3σ)	± 1.0 K

② Model-Test Correlation result

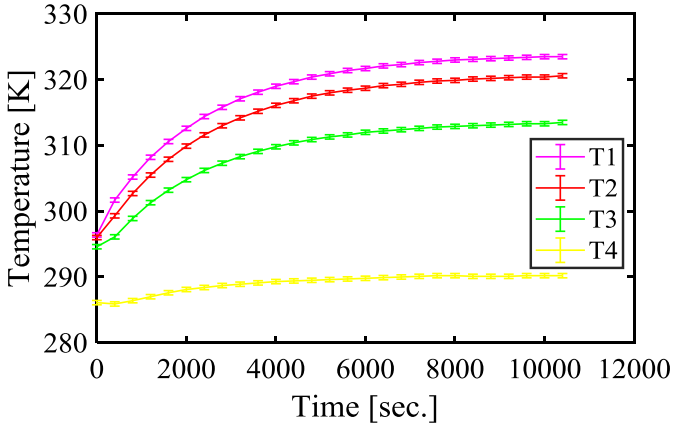


Content	Value
h_{12}	300 W/(m²·K)
h_{23}	500 W/(m²·K)
k_{resin}	0.26 W/(m·K)
h_{45}	10000 W/(m²·K)

③ Test B (Flight Data Simulation)

Test Condition	Value
Q_{heater}	2.4 W
$T_{heatsink}$	383.2 K
Measurement Error (3σ)	± 1.0 K

④ Thermal Analysis



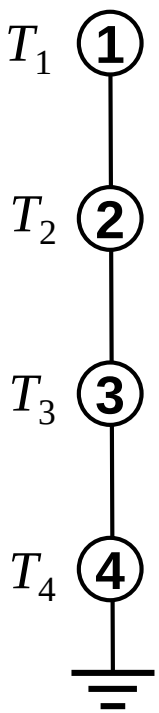
Result and Discussion

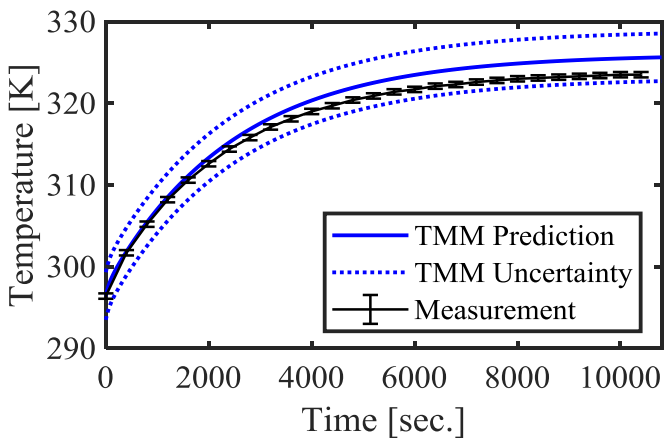
1. Conventional TMM Analysis
2. EnKF Assisted TMM Analysis
3. Comparison of Two Methods

Result and Discussion

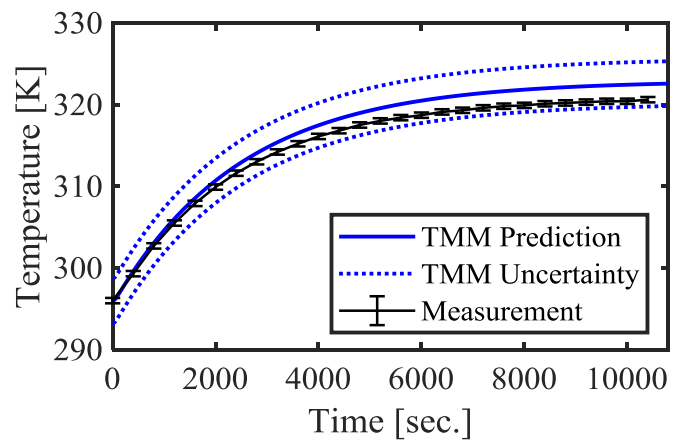
1. Conventional TMM Analysis

Thermal Analysis by TMM

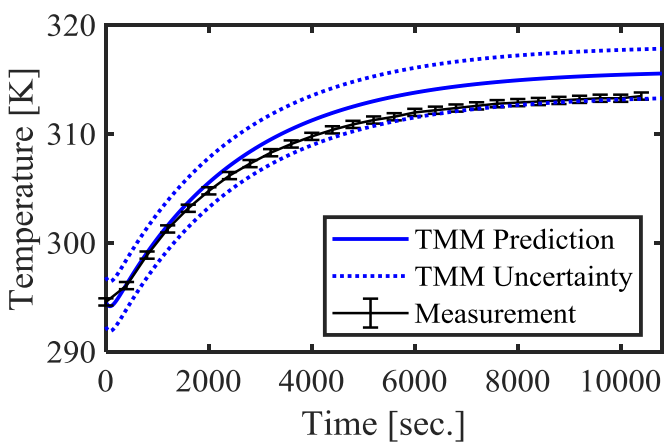




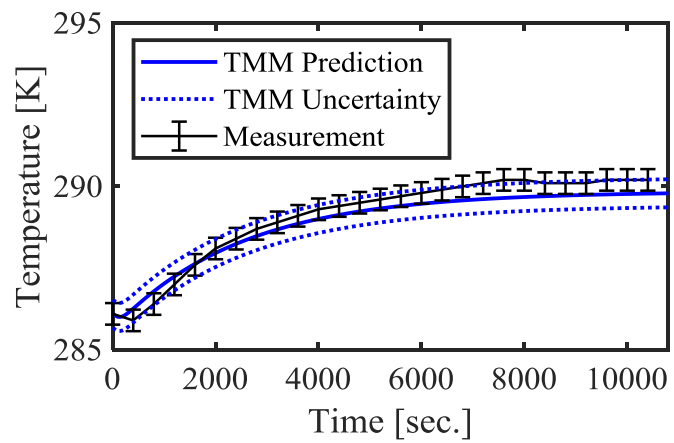
T_1 Transition



T_2 Transition



T_3 Transition

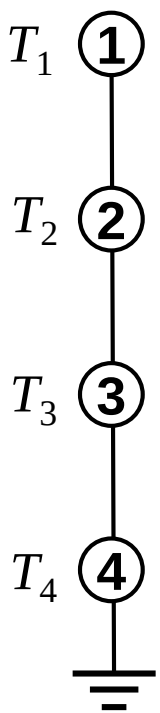


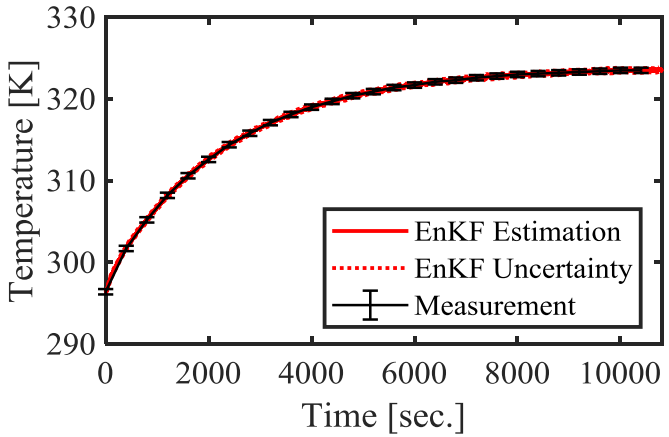
T_4 Transition

Result and Discussion

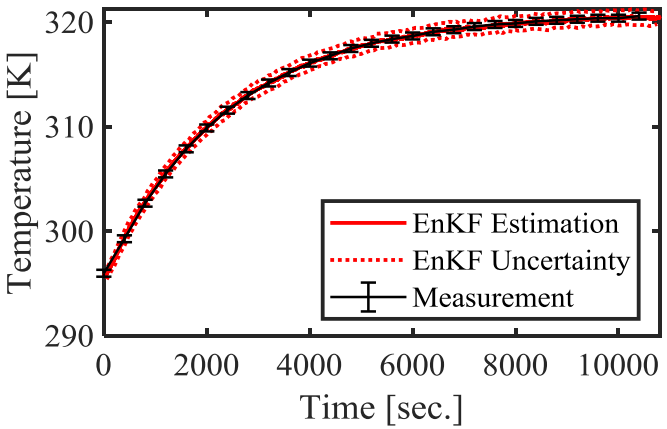
2. EnKF Assisted TMM Analysis

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

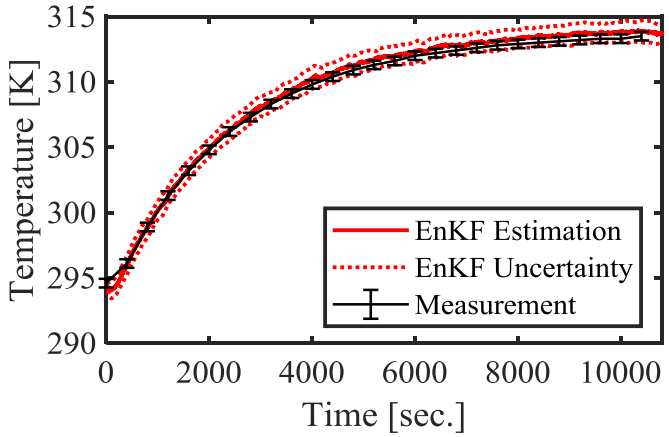




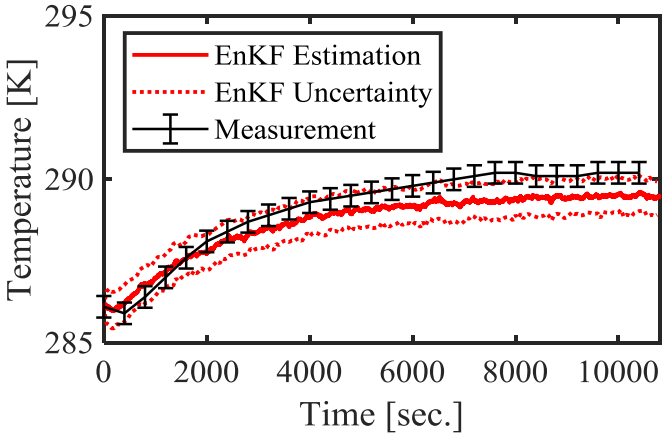
T_1 Transition / observing T_1



T_2 Transition / observing T_1



T_3 Transition / observing T_1

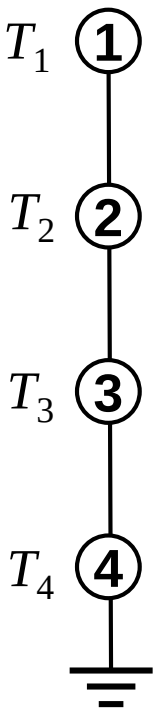


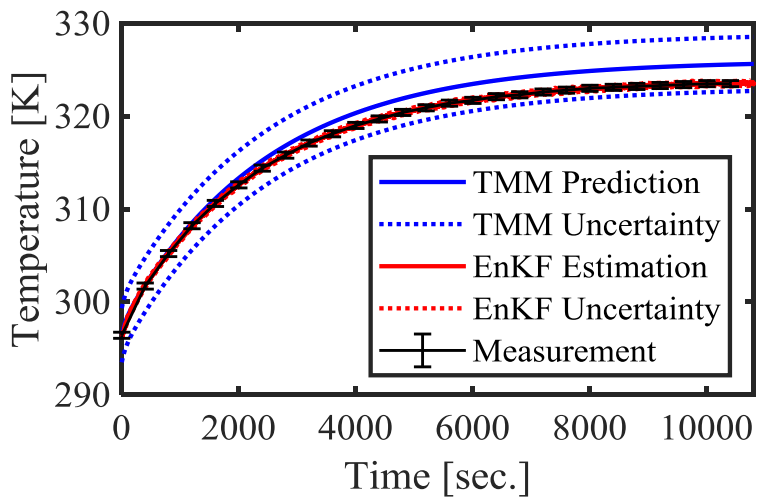
T_4 Transition / observing T_1

Result and Discussion

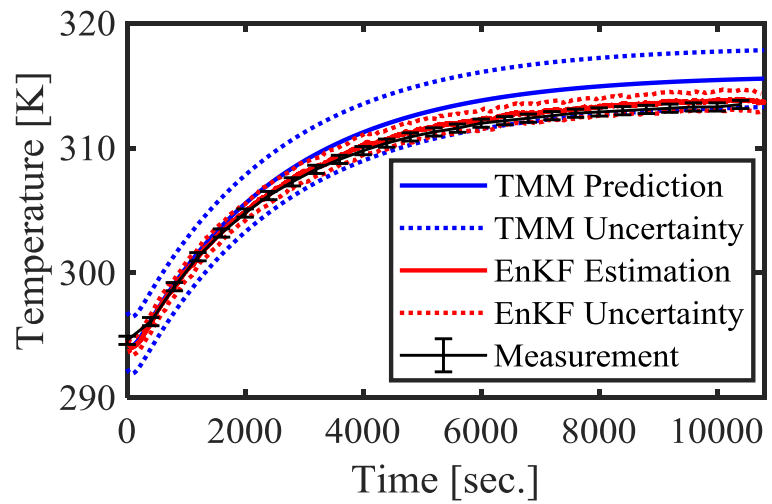
3. Comparison of Two Methods

Comparison with "Conventional TMM" & "EnKF assisted TMM"





T_1 Transition / observing T_1



T_3 Transition / observing T_1

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

Result and Discussion

3. Comparison of Two Methods

Difference from Measured Temperature

	TMM	EnKF assisted TMM (T_1 Observation)
T_1	2.13 K	0.00 K
T_2	1.96 K	0.08 K
T_3	2.07 K	0.37 K
T_4	- 0.41 K	-0.43 K

Standard Deviation of Analysis Result

	TMM	EnKF assisted TMM (T_1 Observation)
T_1	2.91 K	0.27 K
T_2	2.74 K	0.68 K
T_3	2.28 K	0.75 K
T_4	0.43 K	0.55 K

- ➢ Difference from measured data is decreased by data assimilation
- ➢ The uncertainty of the analysis is decreased by data assimilation
- ➢ T_4 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