Continuous Moving Measurement Method for Thermal Environmental Distributions in Streets

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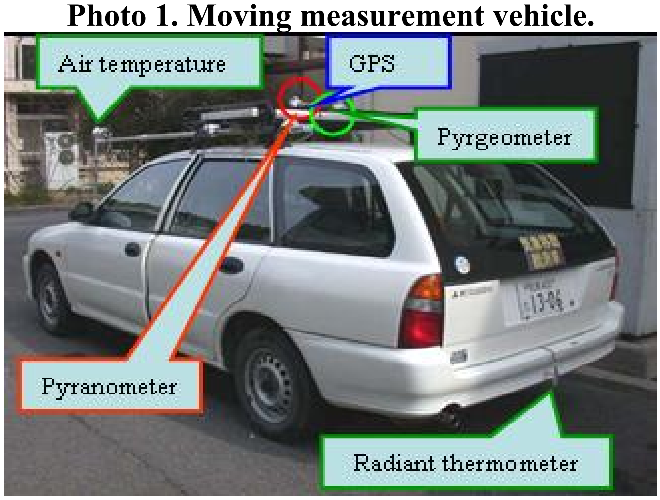
ABSTRACT

While a continuous moving measurement method for urban thermal environment can render data of many more spatial points compared to the fixed point measurement method, the time lag of each sensor causes a measurement error in the spatial distribution. In order to decrease the measurement error, we formulated a moving measurement model with two parameters, which are the time constant of each sensor and the speed of the vehicle. Further we introduced an estimation system from the model. Field experiments were carried out and it was shown that the measurement error was decreased using this estimation system.

1. Introduction

The measurement methods used for measuring urban thermal environment are a fixed point measurement method and a moving measurement method. Depending on the purpose of the measurement, the suitable method is chosen. Although the fixed point measurement method is suitable for measuring time-series changes of a specific point, in order to understand a finely detailed spatial distribution, the spatial density of the measurement points has to be increased. On the other hand, the continuous moving measurement method (W. Kuttler. 1997) is effective to efficiently increase measuring points and to understand the spatial distribution. Due to the spread of GPS (Global Positioning System) technology, this method is often applied to measure the urban thermal environment (Photo 1). However, when a slow response sensor is used for measurement, there will be an error between the actual measured data and true spatial value.

Photo 1. Moving measurement vehicle.

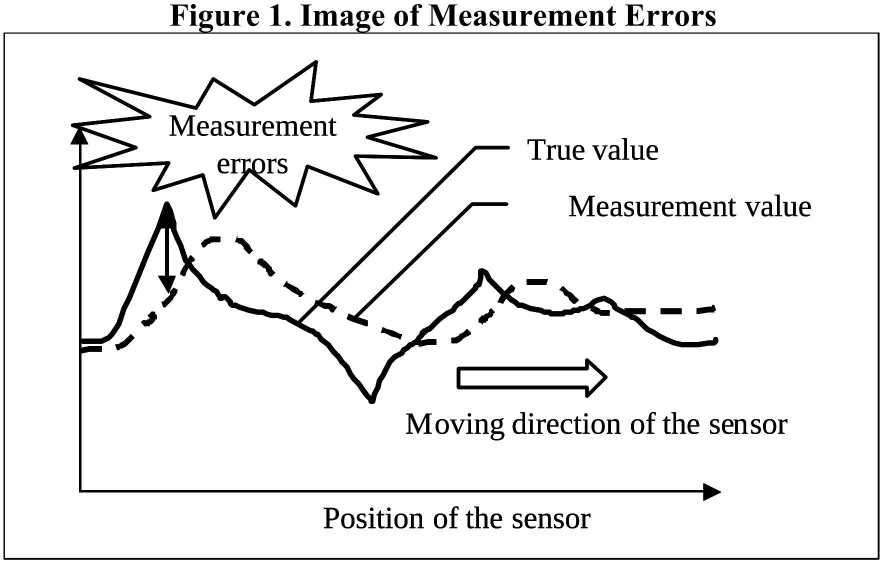


In previous research of air temperature distribution in large areas and urban heat island intensity, the measurement error in the spatial distribution caused by the slow response of the sensor is not considered an important issue. However, with the thermal environment at street level as the subject and the amount of solar radiation and the amount of infrared radiation as the measured properties , the correlation of the correct positions with the measurement values needs to be exact because it is strongly related to the shape of the buildings along the street. The measurement error caused by the sensor response lag is also related to the speed of the vehicle on which the sensor is installed. By using a sensor of which the response characteristic is known, it is possible to estimate the spatial distribution utilizing the information of the response characteristic and the speed of the vehicle.

2. Moving measurement error of the spatial distribution

The moving measurement error in the spatial distribution is thought to be derived from a time lag of the sensor and a delay time in the terminals' position identification process through the GPS. The measurement error is indicated in Figure 1. In the case of a time lag of a sensor, for example, if a sensor with thermal capacity is used to measure temperature, there will be a first-order lag in measuring. Since the sensor is moving, by trying to estimate the spatial distribution from the time series data of measured temperatures, the high frequency of spatial frequency characteristics will be diminished (Figure 1).

Figure 1. Image of Measurement Errors



The GPS delay is caused by the elapsed time in the operational process from receiving signals from the satellites to outputting the positioning information. Because of this delay time, the receiving point of the wave and the recording point of the positioning information are thought to possibly be different. However, when the spatial distribution is calculated from the data which is measured at a recording point that is recorded at that point, shifted data will be obtained that is opposite to the vehicle's actual traveling direction. When the delay time is constant, the error will be avoided by shifting the measurement time.

3. Moving measurement model and estimation system of the spatial distribution

Moving measurement model is assumed to be steady state and distributed in one-dimensional space. The estimation system in this paper is the method used to estimate the spatial distribution of the measurement subject from the detected data obtained from the sensor which moves along with the measurement subject at a fixed speed.

Nomenclature

t : Time

t_o : Initial time

t_d : GPS delay time from receiving signals from the satellites to outputting the positioning information

x_o : Initial position of the sensor

x_p : The sensor position at time t

x : Data measuring position at time t

T : The time constant of the sensor

V : Moving speed of the sensor

$u(t)$: True value of the measured property at time t

$f(x)$: True value of the measured property at the positon x

$F(x)$: Estimated value of the measured property at the positon x

$g(t)$: Instantaneous value of the data measured by the sensor at time t

The sensor position x_p at time t is a shifting point changing in the sensor's direction of movement, $V(t-t_0)$, as per the following equation.

$$x_p = x_0 + V(t-t_0) \tag{1}$$

Considering the GPS time lag, for data at time t, the measurement position x (different position from the sensor) is at the position Vt_d shifted to the reverse of the direction of movement of the sensor.

$$x = x_0 + V(t-t_0) - Vt_d \tag{2}$$

The measurement value $g(t)$ of the sensor is the result (Figure 2) of the input of the true value $f(x)$ of the spatial distribution, or u(t) of the time domain as regards to the measured property at position x. The task is to estimate the true value $f(x)$ of the spatial distribution from the measurement value $g(t)$ of the sensor. From the measurement value $g(t)$ of the sensor, in order to compensate for the response lag of the sensor, an input signal $u(t)$ is estimated (Figure 3) by an inverse system of response characteristics of the sensor. Also, it transforms the input signal $u(t)$ of the sensor to the spatial distribution $f(x)$ (Figure 4). Assuming the sensor response as a first-order lag system, the solution to the following equation (3) is equation (4).

$$T\frac{dg(t)}{dx}+g(t)=u(t) \qquad (3)$$

$$g(t)=\exp\{-(t-t_0)/T\}g(t_0)+\int_{t_0}^{t}\exp\{-(t-s)/T\}/T\times u(s)ds \quad (4)$$

Assume $u(t)$ is constant regarding the interval $\Delta t=t-t_0$, equation (4) is transformed to the discrete system (5) .

$$g(t+\Delta t)=e^{-\frac{\Delta t}{T}}g(t)+(1-e^{-\frac{\Delta t}{T}})u(t) \qquad (5)$$

The inverse system of the equation (5) will be the following equation.

$$u(t)=\left\{g(t+\Delta t)-e^{-\frac{\Delta t}{T}}g(t)\right\}/(1-e^{-\frac{\Delta t}{T}}) \qquad (6)$$

$u(t)$, which is calculated by equation (6), will apply a moving average as per below such that it will decrease noise amplified by differential calculus.

$$\bar{u}(t)=\sum_{i=-N}^{N}u(t+i\Delta t)/(2N+1) \qquad (7)$$

Also, a transformation from time to space is made using equation (2)
That is, by substituting

$$t=t_0+(x-x_0+V\,t_d)/V \qquad (8)$$

From equations (6), (7) the estimated spatial distribution $F(x)$ will be obtained.

$$F(x)=\bar{u}(t_0+(x-x_0+V\,t_d)/V) \qquad (9)$$

Figure 2. Input/output of the sensor

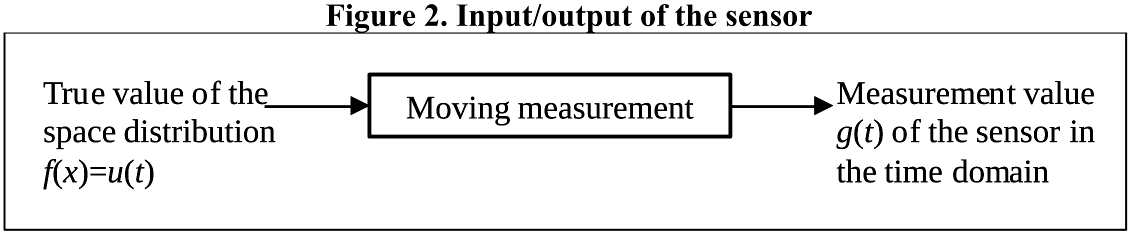


Figure 3. An Inverse system of response characteristics of the sensor

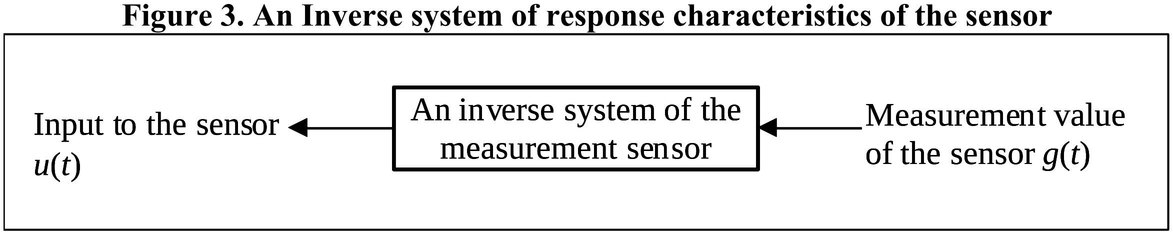


Figure 4. Moving average

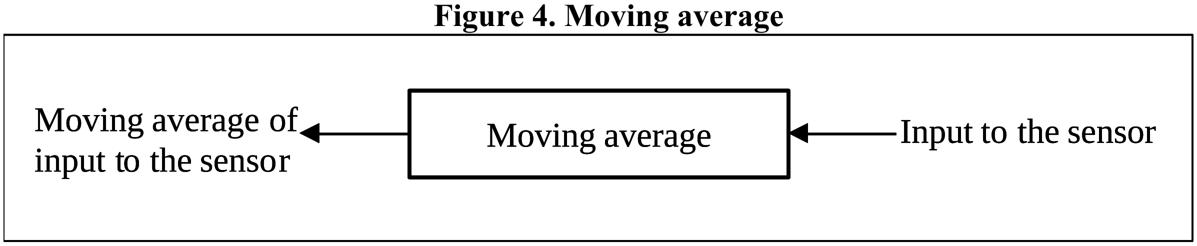
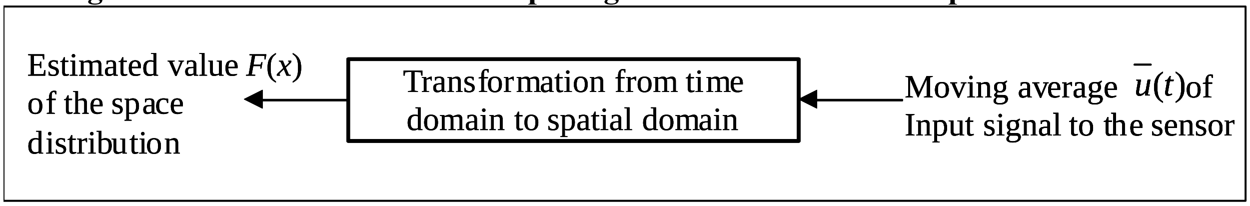


Figure 5. Transformation of the input signal of the sensor to the spatial distribution



4. Experimental Verification

4.1 Time constant measurement of the sensor.

In regards to the pyranometer, pyrgeometer (IR radiometer), infrared thermometer, and thermocouple which are used to measure the thermal environment in an open space, the results of the step response experiments are shown from Figure 6 to Figure 9. The dynamical characteristics of each sensor are expressed as a first-order lag system. The experimental data and the step response of the first-order lag system almost coincide. The time constants of the sensor are shown in Table 1.

Figure 6. Step response of the pyranometer

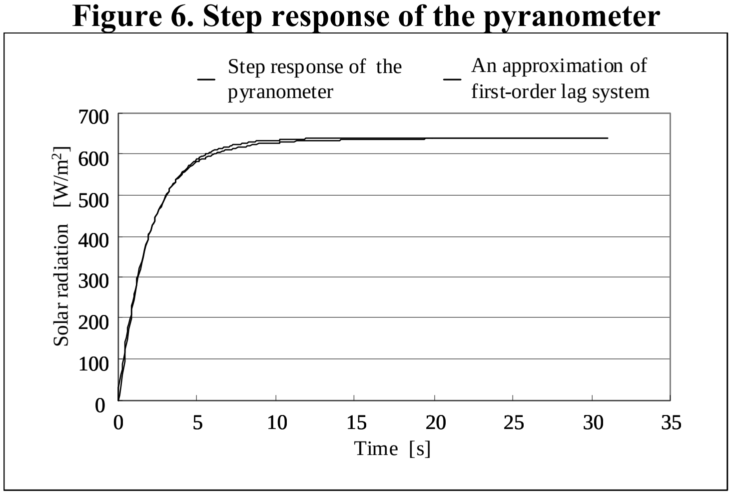


Figure 7. Step responses of the pyrgeometer(IR radiometer)

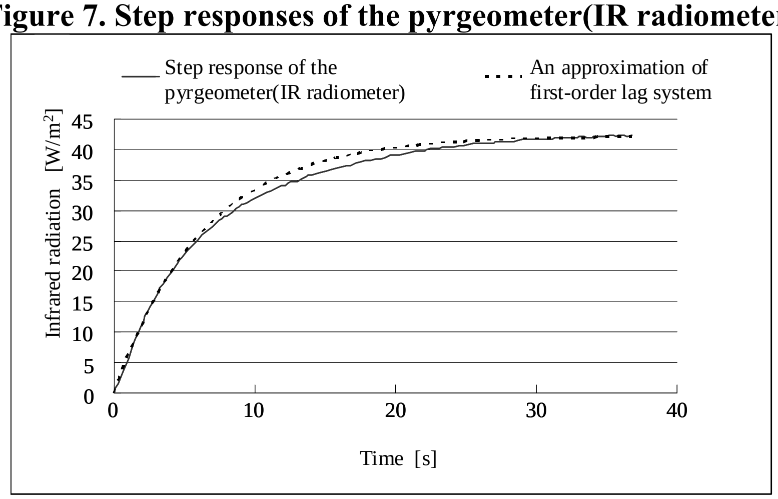


Figure 8. Step responses of the infrared thermometer

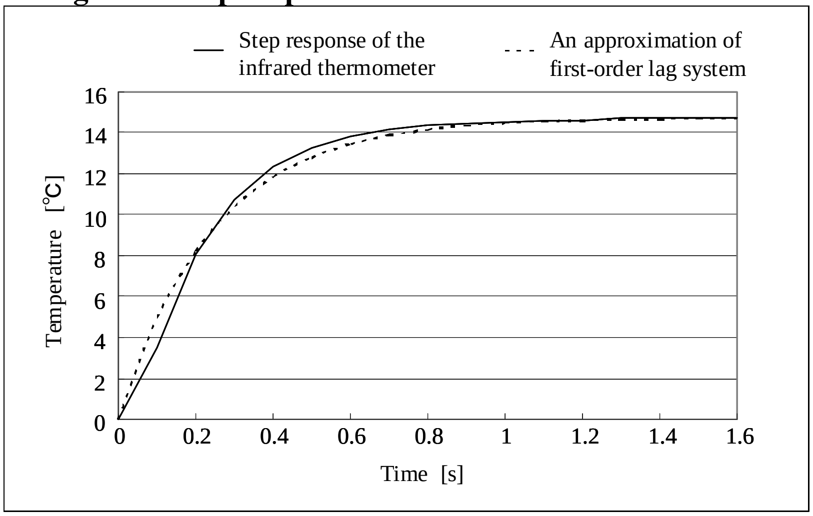


Figure 9. Step responses of the thermocouple

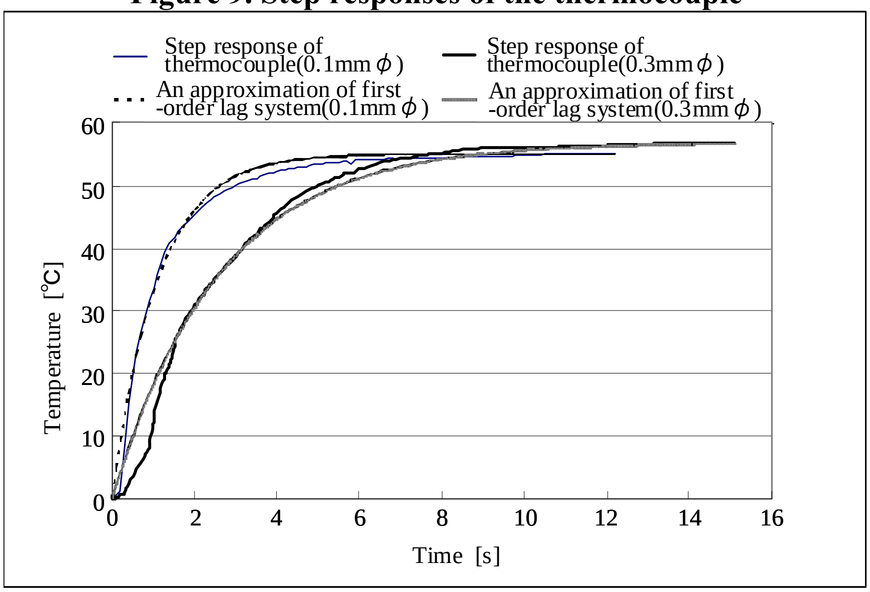


Table 1. Time constants of the sensors

Instruments		Time constant[s]
Pyranometer MS-802		2
he pyrgeometer(IR radiometer) MS-20		6.7
Infrared thermometer IRTS-P		0.25
T type thermocouple	φ0.1	1.1
	φ0.3	2.6

4.2 Experiment of moving measurement

The moving measurement experiment was conducted in street runs from east to west (Photo 2). There were roadside trees along the street. Figure 10 shows the installation positions of the sensors on the vehicle. A 10 km/h experiment started at 11:00am on October 12th, 2005, and experiments were repeated at 20 km/h and 5 km/h (slow speed). The last experiment was run with a speed of 40 km/h at 11:19am. As examples, the measurement value of the pyranometer with a time constant of 2.0 seconds and the measurement value of the pyrgeometer (IR radiometer) with the longest time constant of 6.7 seconds in Table 1, are accordingly shown in Figures 11, and 12. The horizontal axis was positioned in an east-west direction on the vehicle (Measurement value of longitude by the GPS). The vertical axis is the measurement value of the time when the GPS output the location signal. In the figure, a solid line indicates when the measuring vehicle is moving at the low speed of 5 km/h. In the case where the measuring vehicle is moving at this slow speed, the measurement value is considered as the true value $f(x)$.

Next, when the vehicle moved repeatedly at speeds of 10, 20, and 40 km/h, the measuring data $g(t)$was shown against the moving distance position of the sensor. The difference between the spatial distribution of the measurement value and that of the true value (at 5km/h of moving speed) was larger for the pyrgeometer (IR radiometer) which has a larger time constant (Figure 12). On the other hand, the difference was smaller for the pyranometer which has a smaller time constant (Figure 12). However, because the measurement was done repeatedly by changing the speed of the vehicle on the same road and it took almost 20 minutes from the start to the end of the experiment, there is a possibility that the measured properties were not in a steady state. In the case of pyrgeometer (IR radiometer), changes in infrared radiation level were observed during the experiment.

Figure 10. Installed positions of the sensors

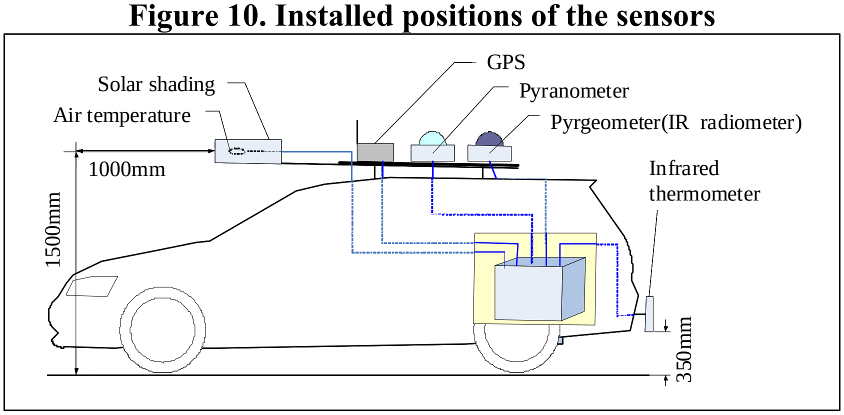


Photo 2. Where the moving measurement experiment was conducted

Figure 11. Moving measurement result of the pyranometer

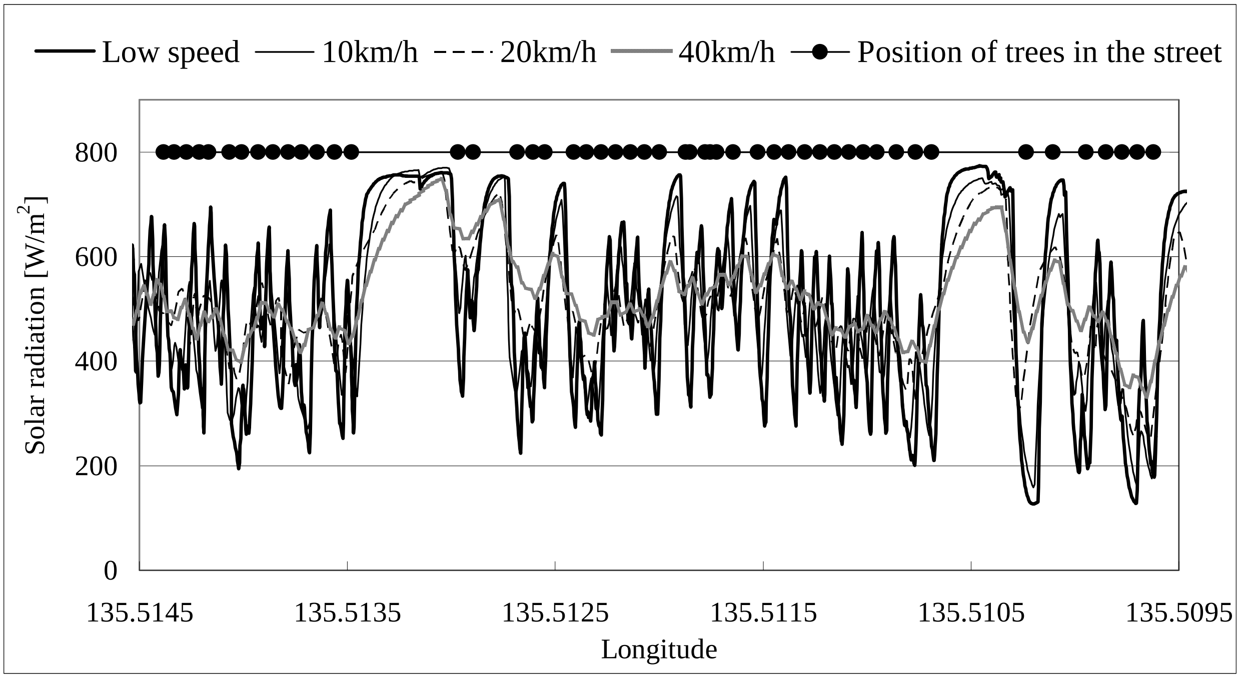
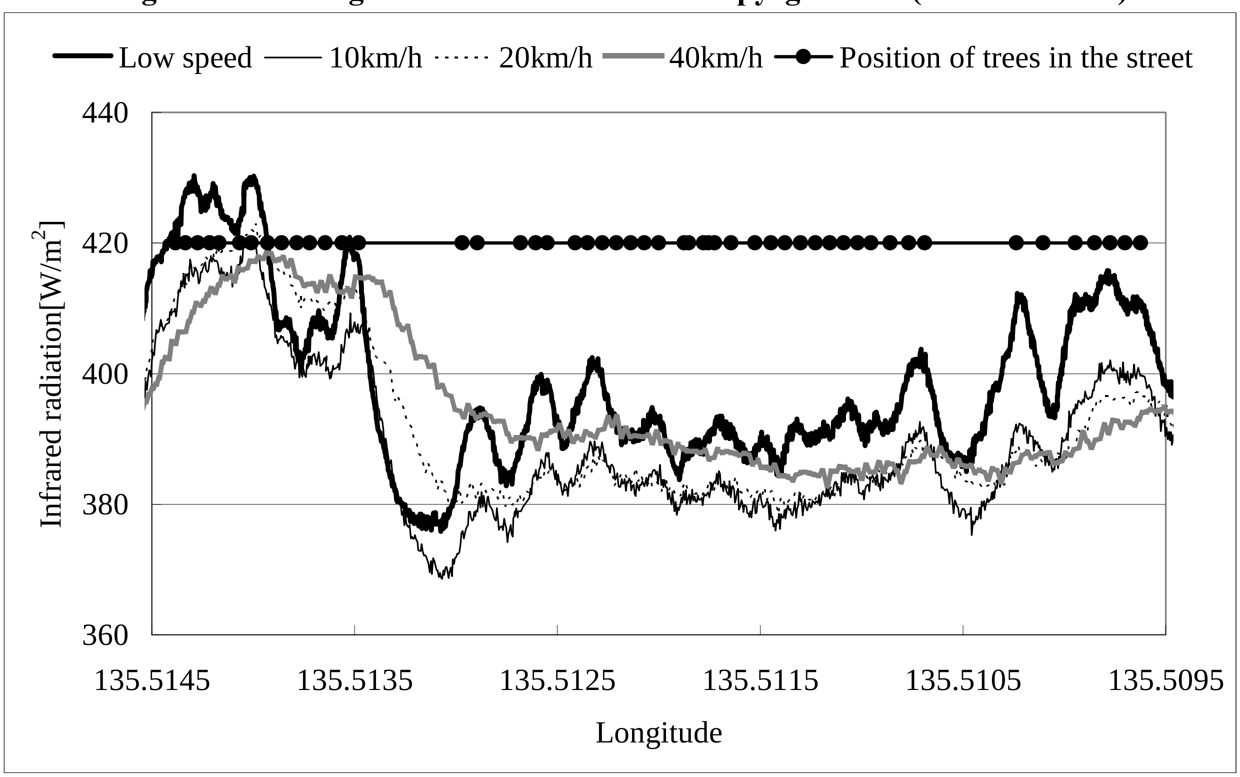


Figure 12. Moving measurement result of the pyrgeometer(IR radiometer)



4.3 Estimated result of the spatial distribution and evaluation

The spatial distribution $f(x)$ is shown by the dashed line in Figure 13 and 14 which was estimated from equation (6) for the inverse system, equation (7) for a moving average to eliminate noises, and equation (9) for spatial changes. When the time constant of the pyranometer is 2.0 seconds, extremely favorable estimated results were obtained. In the case of the pyrgeometer (IR radiometer), although the estimated error became larger because of the large response lag as the time constant is 6.7 seconds, by taking into consideration the response lag of the sensor, the error was decreased. The fluctuation of the estimated value shows the features of fluctuations of the true value fairly well. However, the average level of estimated value is different from that of the true value, which seems to be caused by the fact that both measurements were not carried out simultaneously. Because the time constant of the infrared thermometer is as short as 0.25 seconds, it is not necessary to apply this estimation method when the moving speed of the vehicle is 40 km/h or less.

Figure 13. Comparative result of the moving measurement value, the true value and the estimated value of the pyranometer

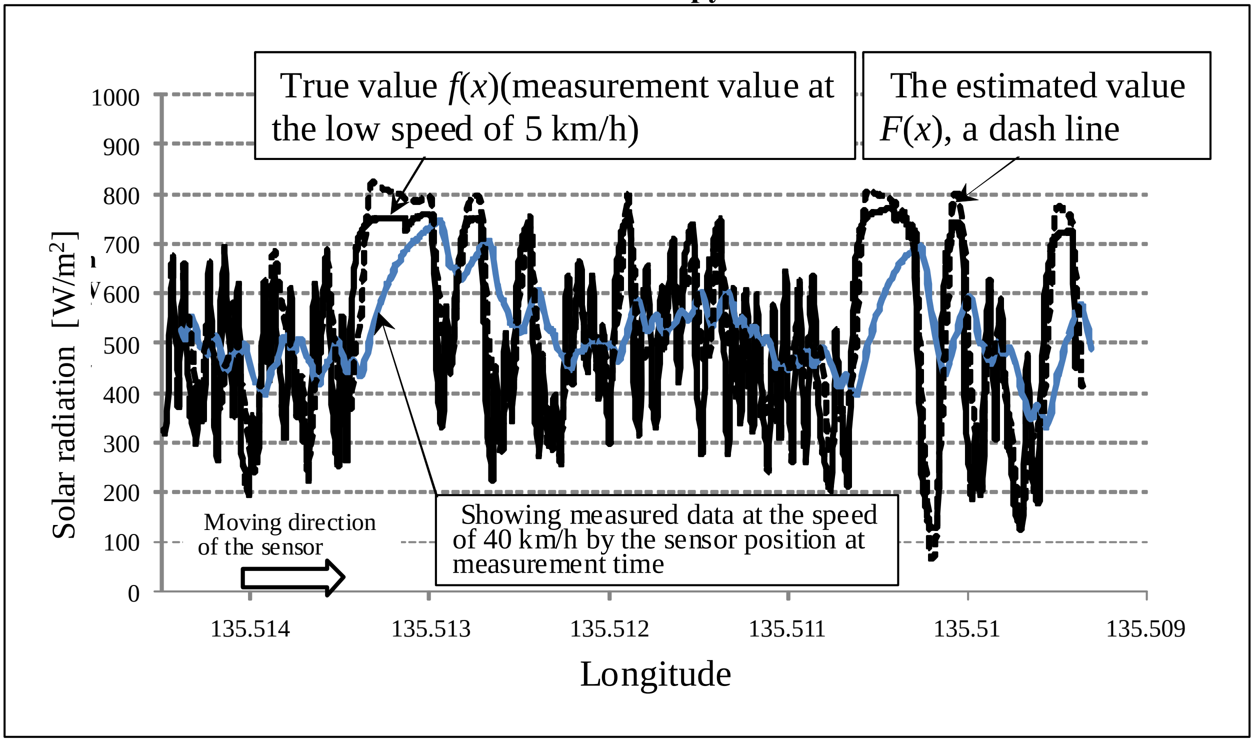
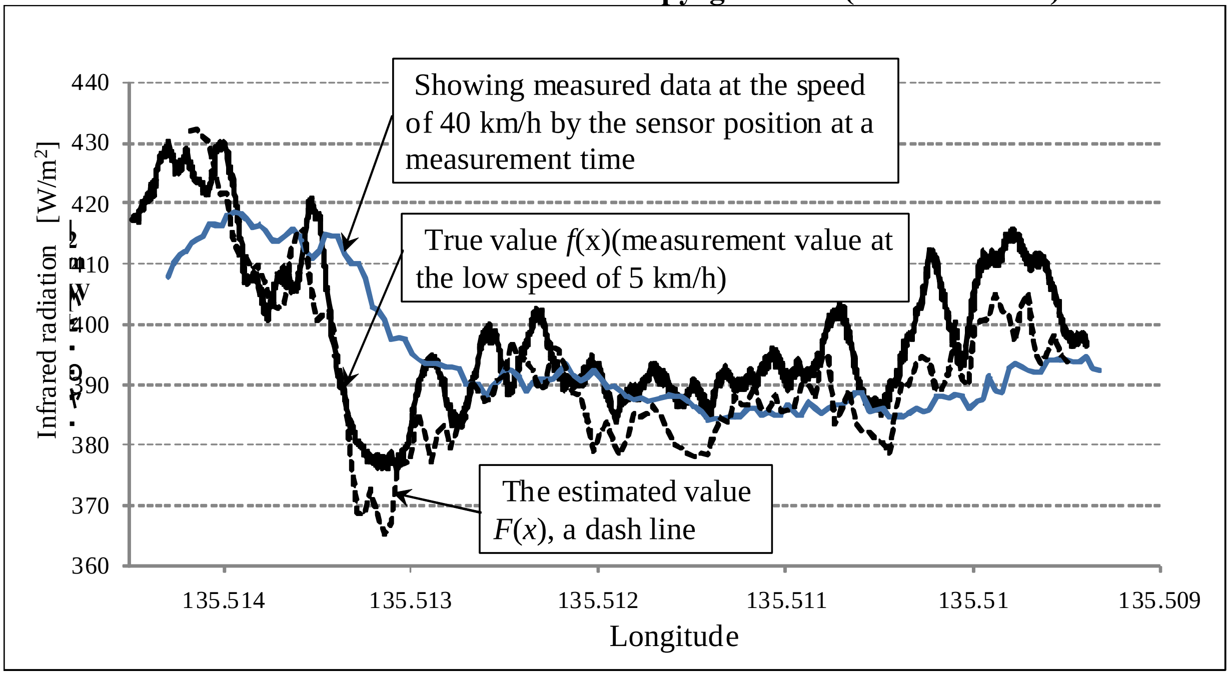


Figure 14. Comparative result of the moving measurement value, the true value and the estimated value of pyrgeometer (IR radiometer)



5. Conclusion

We suggested a method to estimate the spatial distribution from data which was obtained by continuously measuring the spatial thermal environmental distributions in streets, using sensors which have a response lag and GPS which has a time delay. In a street with roadside trees, the moving measurement was conducted at a continuous steady speed of 40 km/h using a pyranometer and a pyrgeometer (IR radiometer) of which both have different response lags. As we estimated the spatial distribution from the measured data, the measured error of the pyranometer with a 2.0-second time constant was extremely small. There is also an estimated error with the pyrgeometer (IR radiometer) which has a comparably large 6.7-second time constant, but by applying this method, it became obvious that measurement error is effectively decreased.

References

W. Kuttler. 1997. "Climate and Air Hygiene Investigations for Urban Planning." ACTA CLIMATOLOGICA. Universitatis Szegediensis, Tom. 31A