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Estimation of Water Surface Temperature by Infrared Remote Sensing at Shiozu Bay in Lake Biwa

Yasumasa ITAKURA and Shuichi ENDOH

ABSTRACT

Thermal infrared mapping can provide useful data on the surface temperature distributions of a restricted observation area, such as a bay in a lake.

This paper describes a method for estimating the surface temperature of the water, in which the estimation of the equivalent background radiation temperature (EBRT) is a key factor. The results from the first field experiment show that the optimal EBRT is 4.4 °C lower than the atmospheric temperature. A comparison of the estimated temperature and the temperature measured by a thermistor towed by a boat shows that the minimum deviation is within 1.1 °C. The second field experiment for measuring water surface temperature at a station in the middle of Shiozu Bay gives a continuous comparison during over 24 hr between the measured temperature and the estimated temperature using the optimal EBRT obtained from the first field experiment. The results show that the deviation is also within 1.1 °C.

Key words : Lake Biwa, temperature estimation, thermal infrared mapping

INTRODUCTION

The numerous useful applications of infrared remote sensing are well known in meteorological and environmental studies in areas such as resources investigations, pollution surveillance and the location of fish. Thermal infrared mapping, one of the infrared remote sensing techniques, can be incorporated into the satellite-borne sensors to obtain ocean surface temperature distributions, which provide data on tidal currents and storms for the meteorological, environmental and fishery sciences (McCLAIN, 1985 ; TAMEISHI, 1985 ; TAKAYAMA and MAEDA, 1990). In addition to the satellite's sensor, airborne sensor and sensors positioned on high buildings or mountaintops can also provide useful data on the surface temperature distributions of a restricted observation area, such as a bay, and enable continuous observation of such an area with high spatial resolution.

Because the water density is primarily determined by the temperature, it is possible to deduce the water movements in freshwater lakes, such as Lake Biwa, from the spatial and temporal variations of the water surface temperature. The movements of water are important not only in their own right, but also for the chemical and biological properties of the lake. The authors have observed water movements by the infrared remote sensing method from the top of a mountain. However, since the sensor has a slanted optical path and is influenced by background radiation, so it is difficult to estimate the surface temperature of the water with exactitude. This paper describes the method and the results of an estimation of surface temperature by thermal infrared mapping sensor with a slanted optical path.

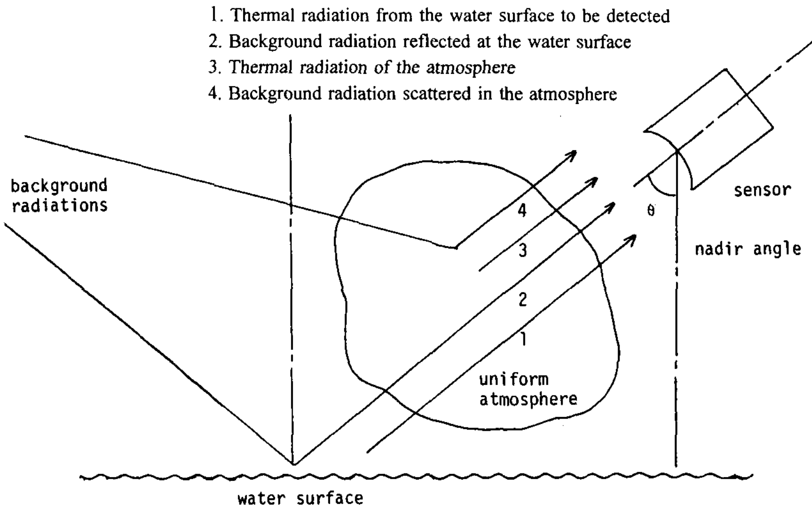

Fig. 1. Infrared remote sensor model (after ITAKURA, 1995).

TEMPERATURE ESTIMATION OF WATER SURFACE

Principle of the estimation

A typical situation of remote sensing of the surface temperature of lake water is depicted in Figure 1, which shows the sensor aiming toward a spot on the lake surface, hence measuring the radiant flux emerging from the earth's atmosphere (ITAKURA *et al.*, 1989 ; ITAKURA *et al.*, 1994 ; ITAKURA, 1995). The received radiant flux $\Phi_0(\phi, \psi)$ corresponding to the pixel at a position (ϕ, ψ) on the display of the thermal infrared mapping sensor contains (1) the thermal radiation of the water surface to be detected, (2) the background radiation reflected at the surface, (3) the thermal radiation of the atmosphere along the optical path of the sensor and (4) the background radiation scattered in the atmosphere also along that path. A real water surface is neither a perfectly diffuse surface nor a perfect specular one. Nevertheless, from the observations shown in Figure 1, it can be assumed that the thermal radiation of the water surface is emitted from a Lambertian diffuse surface with angular dependent emissivity, and that the background radiation is reflected from a specular surface with angular dependent reflectivity. The reflectivity of the water surface, $r(\theta)$, can be calculated by the Fresnel reflection formula as a function of nadir angle θ, and the emissivity, $\varepsilon(\theta)$, is equal to $1-r(\theta)$ by the law of conservation of energy. In calculating the thermal radiation of the atmosphere along the optical path of the sensor, the equivalent emissivity of the atmosphere is equal to $1-\tau_a(\theta)$, where $\tau_a(\theta)$ is the transmittance of the atmosphere. The nadir angle, θ, corresponding to the position (ϕ, ψ) on the display, can be calculated easily from the inclination angle and the view field angle of the sensor. The positions (ϕ, ψ) are points at the horizontal scanning axis and at the vertical scanning axis on the display, respectively. In general, $\varepsilon(\theta)$, $r(\theta)$ and $\tau_a(\theta)$ are functions of the wavelength λ.

The $\Phi_0(\phi, \psi)$ is given by the following equation.

$$\Phi_0(\phi, \psi) = (\pi/4)(A D^2/f^2) \int \tau_0(\theta) \{[\varepsilon(\lambda, \theta) L(\lambda, T_s) + (1-\varepsilon(\lambda, \theta)) L(\lambda, T_b)] \tau_a(\lambda, \theta) + (1-\tau_a(\lambda, \theta)) L(\lambda, T_a)\} d\lambda. \quad (1)$$

where

f : focal length of the optics,
D : aperture diameter of the optics,
A : area of the detector,
$\tau_0(\lambda)$: spectral transmittance of the optics contained in the spectral responsivity of the detector,
$\varepsilon(\lambda, \theta)$: spectral emissivity of the water surface as a function of the nadir angle θ,
$\tau_a(\lambda, \theta)$: spectral transmittance of the atmosphere as a function of the nadir angle θ,
T_s : temperature of the water surface to be measured,
T_a : temperature of the atmosphere,
T_b : equivalent background radiation temperature (EBRT),
λ : wavelength,
$L(\lambda, T) = (c_1/(\pi\lambda^5))/[\exp(c_2/(\lambda T))-1]$: spectral radiance of a Lambertian black body radiator given by Planck's radiation law,
c_1 : first radiation constant, and
c_2 : second radiation constant.

We neglect the background radiation scattered in the atmosphere, the fourth term in Figure 1 (TAKAYAMA and MAEDA, 1990). A detector with an optical filter has a responsivity in a spectral interval, from λ_1 to λ_2, in which $\tau_0(\lambda)$, $\varepsilon(\lambda, \theta)$ and $\tau_a(\lambda, \theta)$ are independent of λ. Thus, the formula $\Phi_0(\phi, \psi)$ is modified as follows :

$$\Phi_0(\phi, \psi) = (\pi/4)(A D^2/f^2)\, \tau_0 \{[\varepsilon(\theta) \int L(\lambda, T_s) d\lambda + (1-\varepsilon(\theta)) \int L(\lambda, T_b) d\lambda]\, \tau_a(\theta) + (1-\tau_a(\theta)) \int L(\lambda, T_a) d\lambda\}. \quad (2)$$

Now, we define that :

$$\Phi_i = (\pi/4)(A D^2/f^2)\, \tau_0 \int L(\lambda, T_i) d\lambda, \quad (3)$$

where sub i means sub o, s, a or b corresponding to "observed," "surface," "atmosphere," or "background," respectively.

We rewrite equation (2) and then calculate the value of $\Phi_s(\phi, \psi)$ to be detected, that is, the radiant flux of thermal radiation from the water surface, as follows :

$$\Phi_s(\phi, \psi) = [\Phi_0(\phi, \psi) - (1-\varepsilon(\theta))\,\tau_a(\theta)\Phi_b - (1-\tau_a(\theta))\,\Phi_a] / (\varepsilon(\theta)\tau_a(\theta)) \tag{4}$$

The surface temperature T_s at a position (ϕ, ψ) can be derived by solving the equation (3) inversely for the value $\Phi s(\phi, \psi)$.

In the above calculating process, the observed temperature T_0 can be calibrated from the value indicated on the display of the sensor, as will be mentioned in the next section. The temperature of the atmosphere T_a can be easily measured by a meteorological thermometer on the assumption of a uniform atmosphere of observation. The value of T_a is obtained by averaging two atmospheric temperatures, one on the sensor-site at the top of mountain and the other on the observation station in the middle of Shiozu Bay. On the other hand, the equivalent background radiation temperature (EBRT) T_b can not be measured directly. In our previous report (ITAKURA, 1995), T_b has been assumed to be equal to T_a ; this is called the first method. However, on this assumption, the estimated temperature T_s did not agree well with the actual temperature of ground-truth checking. Therefore, the value of T_b must be estimated by another method, which aims to minimize the deviation between the actual temperature measured directly by a thermistor towed by a boat and the estimated temperature obtained from equation (4) by changing the value of T_b. This is called the second method. The field experiment shows the superior effectiveness of the second method.

Basic experiments

There are important terms in this paper which we now briefly list (ITAKURA, 1995) : (1) calibration of the thermal infrared mapping sensor, (2) calculation of the emissivity of the water surface as a function of the nadir angle, and (3) calculation of the atmospheric absorption along the optical path of the sensor. The basic experiments have been done by a sensor with one element detector and two mechanical scanning mirrors (ITAKURA *et al.*, 1989 ; ITAKURA, 1995). The specifications of the sensor, "Infra-Eye 560", made by the Fujitu Company, are shown in Table 1. The sensor has a built-in temperature standard of 65 °C ; therefore, the incident radiant flux is converted into a temperature indicated on the display by referring to this standard.

The results of the basic experiments are as follows :

(1) Calibration curve of the sensor :

The temperatures displayed on the sensor are plotted to the temperatures of the blackbody-type source putting at a point of 70 cm from the sensor. The probability error comparing both temperatures is within 0.18%. This

Table 1. Specifications of the infrared mapping sensor.

Temperature range	-20～1600 °C
Minimum detectable temperature difference	0.2 °C
Frame time	3.7 sec
Field of view	horizon 25° vertical 25°
Horizontal resolution	300 lines/frame
Scanning lines	224 lines
Detector	HgCdTe (77K)
Spectral range	9.3～11.35 μm
Range of focus	20 cm～∞

(Fujitsu Co.Ltd. Infra-Eye 560)

calibration has been repeated every year. During every observation period it has been confirmed that the calibration curve does not vary outside the limits of the probability error.

(2) Emissivity calculation :

The value of emissivity $\varepsilon(\theta)$ of the water surface as a function of the nadir angle can be calculated from the index number of fresh water, n=1.2, at the infrared wavelength 10 μm (QUERRY, 1969), using the Fresnel reflection formula. In the infrared wavelength region, the effective optical depth of clear water is very shallow, less than 10 μm, due to the strong absorption of radiation by H_2O molecules (KELLY, 1978).

(3) Calculation of atmospheric transmittance:

The atmospheric transmittance along the optical path of the sensor can be easily calculated by the absorption coefficients of H_2O and CO_2 under the meteorological condition of the observation (HUDSON, 1969 ; ITAKURA, 1995).

FIELD EXPERIMENTS

First field experiment

Temperature estimations of water surface have been done in Shiozu Bay in the northern part of Lake Biwa since 1986. Shiozu Bay is 7 km long on its north-south axis and 4 km long on its east-west axis. The average depth is 30 m. Figure 2 shows the transect lines for a thermistor towed by a boat at a depth of about 30 cm. The thermal infrared mapping sensor was positioned on the top of a mountain about 220 m above the water surface level of Shiozu Bay. Figures 3 (a), (b), (c) and (d) show comparisons of the surface temperature obtained by the two methods along the transect line indicated in Figure 2. In these figures, the thick dotted line indicates the actual temperature obtained by a thermistor towed by a boat. The thermistor has an accuracy of ±0.1 °C and a time constant of 0.8 sec. The thin and thick solid lines show the values deduced by the first method and the second method, respectively. The deviations between the actual temperature and the estimated temperature by changing the value of T_b are calculated every 10 sec along each transect line. Table 2 summarizes the minimum deviation and the optimal EBRT (T_b^0). From Table 2, the water surface temperature can be estimated within 1.1 °C, and T_b^0 is smaller than T_a by about 3 °C to 5 °C, averaging 4.4 °C.

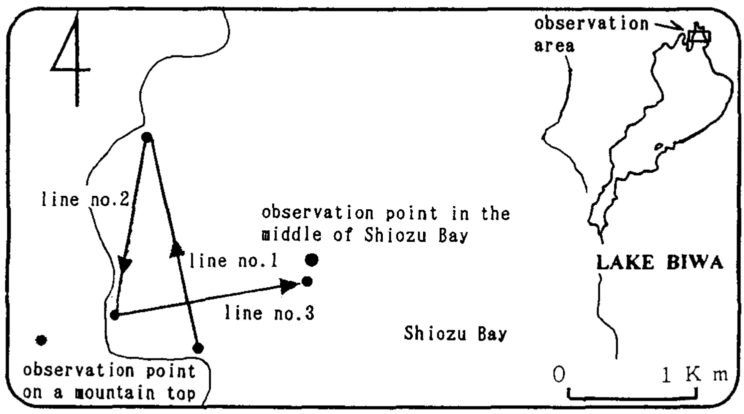

Fig. 2. Transect lines for measuring water surface temperature by a thermistor towed by a boat in Shiozu Bay.

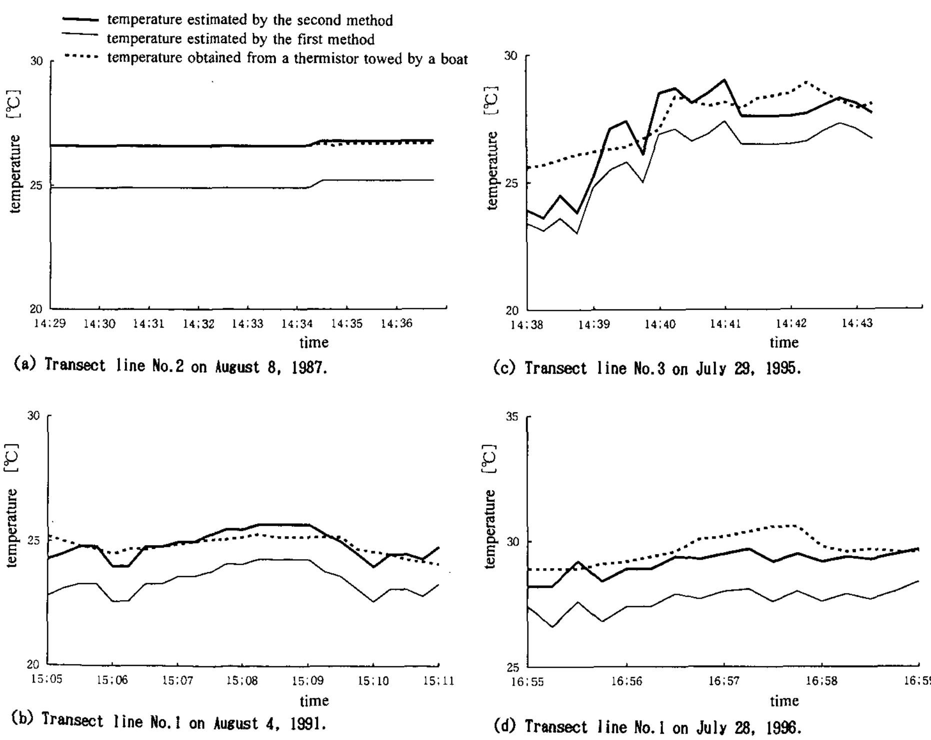

Fig. 3. Comparison of the water surface temperature along each transect line.

Table 2. Estimated optimal equivalent background radiation temperature and the minimum deviation temperature obtained from Figure 3.

	Optimal equibalent background radiation temperature $T_b{}^0$ (°C)	Minimum deviation temperature (°C)	Temperature of the atmosphere T_a (°C)	$T_a-T_b{}^0$ (°C)	Humidity (%)	Weather	Date and time
1987	23.7	0.1	28.4	4.4	83	fine	Aug. 8 14:20 to 14:36
1991	18.1	0.4	23.6	5.5	73	fine	Aug. 4 15:05 to 15:11
1995	27.6	1.1	31.0	3.4	70	fine	July 29 14:24 to 14:42
1996	25.8	1.1	29.9	4.1	70	fine	July 27 16:55 to 16:59

Second field experiment

The optimal EBRT can be estimated as mentioned above. To confirm this value, continuous observations of the surface temperature have been done for several years at a station in the middle of Shiozu Bay (Figure 2) during over 24 hr in summer. The comparisons between the temperature measured by a thermistor thermometer at a depth of 30 cm (KIMURA, 1969 ; TAKASHIMA, 1982) and that estimated by using the value of $T_b{}^0$ are shown in Figures 4 (a), (b) and (c). In these figures, the solid line is the surface temperature calculated by the value of $T_b{}^0$ taken from Table 2, and the dotted line is the temperature of the thermistor thermometer read on the hour. The deviations between these for every hour are summarized in Table 3, and are also within 1.1 °C regardless of the daily variations in the water temperature.

Table 3. Deviation of the surface temperature between the temperature measured by a thermistor thermometer and that estimated by the second method obtained from Figure 4.

	Optimal equivalent background radiation temperature $T_b{}^0$ (°C)	Deviation of the surface temperature (°C)	Weather	Date and time
1991	18.1	0.8	fine	Aug. 3, 9:00 am to Aug. 4, 12:00
1995	27.6	0.9	fine	July 28, 14:00 to July 30, 10:00 am
1996	25.8	1.1	fine	July 27, 10:00 am to July 28, 11:00 am

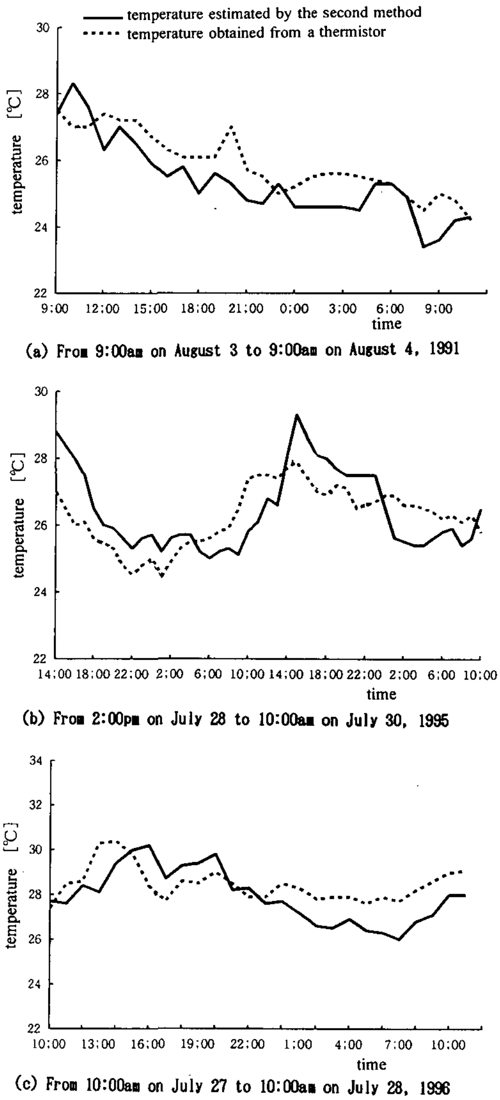

Fig. 4. Comparison of the water surface temperature at a station in the middle of Shiozu Bay.

CONCLUSION

The estimation of water surface temperature using a thermal infrared mapping sensor was examined in the case of a slant observation path in Shiozu Bay in the northern part of Lake Biwa. From the first field experiment, the optimal EBRT was estimated by the second method, which aimed to minimize the deviation between the actual temperature measured directly by a thermistor towed by a boat and the estimated temperature obtained from equation (4) by changing the value of T_b. The optimal EBRT was 4.4 °C lower than the atmospheric temperature. The minimum deviation was within 1.1 °C. The second field experiment at a station in the middle of Shiozu Bay provided a comparison between the surface temperature measured by a thermistor thermometer placed at a depth of 30 cm and that estimated by using the value of the optimal EBRT. The deviation every hour was also within 1.1 °C regardless of daily variations. These data mentioned above were taken under weak wind of less than 2 ms^{-1}. On the other hand, under strong wind, a surface model is needed instead of a specular one.

By estimating more exactly the water surface temperature with a slanted observation path, infrared remote sensing becomes a useful tool for real time monitoring of the water movements of lakes based on temporal variations in the surface temperature distribution. The following observations are expected to provide useful information in lake limnological studies of factors such as water movement in a small bay and near a reed community, river water traces flowing into lake, detection of a cool or warm water mass, and so forth.

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びわ湖塩津湾における赤外線リモートセンシングによる湖面温度の推定

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摘　要

本論文は赤外線リモートセンシングによって湖面の温度を推定する方法について述べている。ここでの赤外線リモートセンシングの対象は琵琶湖の塩津湾で，センサーである赤外線撮像装置は近くの山の上に設置される。この場合，センサーが斜めの光路をとるために湖面の温度推定において背景放射の影響を受けやすいという問題が生じる。すなわち，等価背景放射温度の推定が湖面温度の推定精度を支配する。

最初の野外実験により，ボートで曳航したサーミスタ温度計の値（グランドツルース温度）とその航路に沿って 10 秒毎に赤外線センサーで得た値から湖面温度推定の数式の中で背景放射温度を変化させて算出した湖面温度を比較して，両者の差が最低になる背景放射温度を最適等価背景放射温度として決定した。最適等価背景放射温度は大気温度より平均で 4.4 ℃低いこと，及び，湖面の推定温度と実測値（グランドツルース温度）の最小温度差は 1.1 ℃であること，が明らかにされた。

次の野外実験では，塩津湾のほぼ中央に設置された碇点において 24 時間以上の連続観測を行い，碇点の水面下 30 cm でサーミスタ温度計で測定された水温と最初の野外実験で求めた最適等価背景放射温度を用いて山頂からの赤外線センサーで得た値から推定した湖面温度を比較した。両者は，湖面温度に日変化があるにもかかわらず，1.1 ℃以内の誤差で一致していることが示された。