Comparative Study on Sea Surface Temperature Estimation with Thermal Infrared Radiometer Data among Conventional MCSST, Split Window and Conjugate Gradient Based Methods

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***Abstract*— Comparative study on Sea Surface Temperature: SST estimations among the conventional Multi-Channel Seat Surface Temperature: MCSST, split window method and the proposed Conjugate Gradient based method: CGM with Thermal Infrared Radiometer: TIR data through simulations is conducted. Utilizing the proposed linearized inversion of radiative transfer equation, SST can be estimated. SST estimation accuracy of the proposed method is compared to the conventional regression based method (Split Window and MCSST method). Through the simulation study, it is found that the proposed CGM based method is superior to the conventional regression based method.**

Keywords-Sea Surface Temperature; radiative transfer equation; regression; conjugate gradient; MCSST; split window.

I. Introduction

Sea Surface Temperature: SST estimation with thermal infrared radiometer onboard satellites is well known and widely used in a variety of research fields, in particular climate changes, global warming, etc. SST estimation methods are proposed [1]-[4]. Most of these are based on regressive analysis and use several spectral bands in Thermal Infrared: TIR wavelength region. The most dominant atmospheric factor is precipitable water. Using the different wavelength TIR bands whose influences due to water vapor are different, it is possible to reduce the influence. The most popular method is Multi Channel Sea Surface Temperature: MCSST [5]. Also previously proposed SST estimation methods are summarized by I. Barton [6]. In the same time, comparative study among the previously proposed methods is well reported [7].

Based on radiative transfer equation, inversion based SST estimation method is proposed [8]. Nonlinear radiative transfer equation is linearized then optimum combination of wavelength regions are selected [9]. Other than that, Geographic Information System: GIS based neural network is proposed for SST estimation method [10]. In this paper, linearized inversion based SST estimation method is utilized. Conjugate gradient method is applied to solve the linearized radiative transfer equation.

The following section describes the proposed SST estimation method with some theoretical background followed by some experiments with the conventional regression based methods. Then conclusion is described together with some discussions.

II. Proposed Method

A. Theoretical Background on SST Estimation with Thermal Infrared Radiometer Data

Radiation from a blackbody with physical temperature of T is expressed in equation (1)

$$B_\nu(T) = \frac{2hc^2}{\lambda^5(\exp(\frac{hc}{\lambda kT}) - 1)} \quad [W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}] \qquad (1)$$

Where

k : Boltzman constant $[J/K]$

h : Plank constant $[J \cdot s]$

c : Light speed $[m/s]$

λ : Wavelength at wave number ν

The contribution from the atmosphere can be expressed as follows,

$$\tau(\theta, z_\infty, z) = \exp\left\{-\int_z^{z_\infty} \frac{\rho(z)k(z)}{\cos(\theta)}dz\right\} \qquad (2)$$

Where

θ : Observation zenith angle

ρ : Density of atmospheric continuents

k : Volume extinction coefficient

And

$$\int_z^{z_\infty} \frac{\rho(z)k(z)}{\cos(\theta)}dz$$

Is called as optical depth of the atmosphere.

B. At Sensor Radiance of Thermal Infrared Radiometer

For sea surface observation with TIR radiometers onboard remote sensing satellites, radiance includes three components, the contribution from sea surface, the contribution from the reflected radiance at sea surface and the contribution from the atmosphere.

$$I(\theta) = \int_{\lambda_1}^{\lambda_2} \Phi(\lambda) \left[\{\epsilon_\lambda B_\lambda(T_s) + (1-\epsilon_\lambda) \int_{z_s}^{\infty} B_\lambda[T(z)] \frac{\partial \tau(\theta, z_\infty, z)}{\partial z} dz\} \cdot \tau(\theta, z_\infty, z_s) + \int_{z_s}^{\infty} B_\lambda[T(z)] \frac{\partial \tau(\theta, z_\infty, z)}{\partial z} dz \right] d\lambda \quad (3)$$

Where

T_s : Sea surface temperature[K]

Φ : Spectral response function

ϵ : Emissivity

τ : Transparency

Spectral response function means spectral sensitivity function of spectral bands of TIR onboard satellites. In general, emissivity of sea surface in TIR wavelength region is almost 1. Therefore, the second term of the equation (3) can be neglected.

$$I(\theta) = \int_{\lambda_1}^{\lambda_2} \Phi(\lambda) \left\{ \epsilon_\lambda B_\lambda(T_s) \tau(\theta, z_\infty, z_s) + \int_{z_s}^{\infty} B_\lambda[T(z)] \frac{\partial \tau_\lambda(\theta, z_\infty, z)}{\partial z} dz \right\} d\lambda \quad (4)$$

C. Approximation of At Sensor Radiance

Assuming spectral response function in the spectral wavelength region of spectral band is 1, then the equation (4) and be rewritten as follows,

$$I(\theta) = B_\lambda(T_s) \tau(\theta, z_\infty, z_s) \cdot + \int_{z_s}^{\infty} B_\lambda[T(z)] \frac{\partial \tau_\lambda(\theta, z_\infty, z)}{\partial z} dz \quad (5)$$

The second term of equation (5) can be approximated as follows,

$$\int_{z_s}^{\infty} B_i[T(z)] \frac{\partial \tau_i(\theta, z_\infty, z)}{\partial z} dz = [1 - \tau_i(\theta, z_\infty, z)] I_{ai} \quad (6)$$

Where I_{ai} denotes representative of spectral band *i* of radiance. Atmospheric transparency can be rewritten as follows,

$$\tau_i(u,\theta) = c_{1i} \exp[-1(c_{2i} + c_{3i} m) u^{c_{4i} + c_{5i} m}] = c_{1i} \exp[-(c_{2i} + \frac{c_{3i}}{\cos\theta}) u^{c_{4i} + \frac{c_{5i}}{\cos\theta}}]$$
$$m \approx 1/\cos\theta \quad (7)$$

Where *u* denotes precipitable water while *m* denotes slant length between sea surface and TIR instrument onboard satellites. In the TIR wavelength region, precipitable water is major absorbing continuants in the atmosphere. Through simulation studies with radiative transfer code of MODTRAN with six atmospheric models (Tropic, Mid. Latitude Summer, Mid. Latitude Winter, Sub Arctic Summer, Sub Arctic Winter and 1976 US Standard Atmosphere), the coefficients are obtained as shown in Table 1.

TABLE I. COEFFICIENTS OF EQUATION (7) OBTAINED WITH MODTRAN OF ATMOSPHERIC SOFTWARE CODE

	c_{n1}	c_{n2}	c_{n3}
c_{1i}	0.8507924	0.9356485	0.9253728
c_{2i}	-0.0754923	-0.03505476	-0.03752114
c_{3i}	0.175898	0.08923810	0.1261287
c_{4i}	1.451688	1.739096	1.679308
c_{5i}	-0.2339985	-0.1563839	-0.1293923

Then I_{ai} is calculated as follows,

$$I_{ai} = F_i(I_{ak}) = A_{1i} + A_{2i} I_{ak} \quad (8)$$

The coefficients in the equation (8) are calculated with MODTRAN in the same manner which is mentioned above. Table 2 shows the results.

TABLE II. COEFFICIENTS OF EQUATION (8) OBTAINED WITH MODTRAN OF ATMOSPHERIC SOFTWARE CODE

	A_{n1}	A_{n2}	A_{n3}
A_{1i}	-0.88610×10^{-6}	0.0	0.75270×10^{-6}
A_{2i}	0.62180	1.0	1.0590

Consequently, radiance of spectral band *i* can be expressed as follows,

$$I_i = B_i[T_s] \tau_i(u,\theta) + [1 - \tau_i(u,\theta)] F_i(I_{ak}) \quad (9)$$

In order to avoid divergence of the solution, the following conditional equation is introduced.

$$X = \frac{X_{max} + X_{min}}{2} + \frac{X_{max} - X_{min}}{\pi} \arctan \xi \quad (10)$$

D. Iteration Method for SST, Precipitable Water, and Representative Radiance

The unknown factors are as follows,

$$\boldsymbol{x} = (T_s, u, I_{ak}) \quad (11)$$

Namely, sea surface temperature, precipitable water, and representative radiance. The following cost function is introduced,

$$J(\boldsymbol{x}) = \sum_{i=1}^{3} (I_i - \hat{I}_i)^2 \quad (12)$$

Then iteration is stopped when the cost function is below the designated value,

$$J(\boldsymbol{x}) \le \varepsilon \quad (13)$$

Radiance of the spectral band *i* can be rewritten as follows,

$$I_i = \frac{c1 c_{1i}}{\lambda^3 \exp(\frac{c2}{\lambda T_s}) - 1} \exp\left\{ -(c_{2i} + \frac{c3i}{\cos\theta}) u^{c_{4i} + \frac{c5i}{\cos\theta}} \right\} + \left[1 - c_{1i} \exp\left\{ -(c_{2i} + \frac{c_{3i}}{\cos\theta}) u^{c_{4i} + \frac{c5i}{\cos\theta}} \right] (C_{1i} + C_{2i} I_{ak}) \quad (14)$$

Then the following updating equation is introduced,

$$\boldsymbol{x}^{(n+1)} = \boldsymbol{x}^{(n)} + \beta^{(n)} A^{(n)} \nabla J[\boldsymbol{x}^{(x)}] \quad (15)$$

It is rewritten in matrix and vector as follows,

$$\begin{pmatrix} T_s \\ u \\ I_{ak} \end{pmatrix}^{(n+1)} = \begin{pmatrix} T_s \\ u \\ I_{ak} \end{pmatrix}^{(n)} + \beta^{(n)} \begin{pmatrix} \frac{\partial^2 J}{\partial T_s^2} & \frac{\partial^2 J}{\partial T_s \partial u} & \frac{\partial^2 J}{\partial T_s \partial I_{ak}} \\ \frac{\partial^2 J}{\partial u \partial T_s} & \frac{\partial^2 J}{\partial u^2} & \frac{\partial^2 J}{\partial u \partial I_{ak}} \\ \frac{\partial^2 J}{\partial I_{ak} \partial T_s} & \frac{\partial^2 J}{\partial I_{ak} \partial u} & \frac{\partial^2 J}{\partial I_{ak}^2} \end{pmatrix}^{-1} \begin{pmatrix} \frac{\partial^2 J}{\partial T_s} \\ \frac{\partial^2 J}{\partial u} \\ \frac{\partial^2 J}{\partial I_{ak}} \end{pmatrix}^{(n)} \quad (16)$$

Where

$$\beta^{(n)} = 1/2^n \quad (17)$$

E. Conjugate Gradient Method

In general,

$$\nabla f(x) = (\frac{\partial f(\boldsymbol{x})}{\partial x_1}, \frac{\partial f(\boldsymbol{x})}{\partial x_2}, \cdots, \frac{\partial f(\boldsymbol{x})}{\partial x_n})^{\tau} \quad (18)$$

And

$$\nabla^2 f(x) = \begin{pmatrix} \frac{\partial^2 f(x)}{\partial x_1^2} & \frac{\partial^2 f(x)}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f(x)}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f(x)}{\partial x_2 \partial x_1} & \frac{\partial^2 f(x)}{\partial x_2^2} & \cdots & \frac{\partial^2 f(x)}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f(x)}{\partial x_n \partial x_1} & \frac{\partial^2 f(x)}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f(x)}{\partial x_n^2} \end{pmatrix} \quad (19)$$

Therefore, the cost function can be rewritten as follows,

$$J = f(x), H_n = \nabla^2 f(s) \quad (20)$$

Where

$$H_n = \begin{pmatrix} \frac{\partial^2 J}{\partial T_s^2} & \frac{\partial^2 J}{\partial T_s \partial u} & \frac{\partial^2 J}{\partial T_s \partial I_{ak}} \\ \frac{\partial^2 J}{\partial u \partial T_s} & \frac{\partial^2 J}{\partial u^2} & \frac{\partial^2 J}{\partial u \partial I_{ak}} \\ \frac{\partial^2 J}{\partial I_{ak} \partial T_s} & \frac{\partial^2 J}{\partial I_{ak} \partial u} & \frac{\partial^2 J}{\partial I_{ak}} \end{pmatrix} \quad (21)$$

is called Hessian or Hesse matrix.

Equation (1) can be rewritten as follows,

$$B_\nu(T_s) = \frac{c_i}{\exp(\frac{c_0 i}{T_s}) - 1}$$

$$B_\nu(T) = \frac{c1}{\lambda^3(\exp(\frac{c2}{\lambda T}) - 1)} \quad (22)$$

where

$$c_i : 2hc^2/\lambda_i^5$$

$$c_{0i} : ch/\lambda_i k$$

$$c1 : 2hc = 1.191126^{-12}$$

$$c2 : ch/k = 1.43889 \quad (23)$$

Then the unknown variables are estimated through iterations.

F. Estimation of Hessian

The first derivatives of the cost function are expressed as follows,

$$\frac{\partial J}{\partial T_s} = -2\sum_{i=1}^{3}(I_i - \hat{I}_i)\frac{\partial \hat{I}}{\partial T_s}$$

$$\frac{\partial J}{\partial u} = -2\sum_{i=1}^{3}(I_i - \hat{I}_i)\frac{\partial \hat{I}}{\partial u}$$

$$\frac{\partial J}{\partial I_{ak}} = -2\sum_{i=1}^{3}(I_i - \hat{I}_i)\frac{\partial \hat{I}}{\partial I_{ak}} \quad (24)$$

Also the second derivatives are represented as follows,

$$\frac{\partial^2 J}{\partial T_s^2} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial T_s}\frac{\partial \hat{I}_i}{\partial T_s} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial T_s^2}\right\}$$

$$\frac{\partial^2 J}{\partial T_s \partial u} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial u}\frac{\partial \hat{I}_i}{\partial T_s} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial T_s \partial u}\right\}$$

$$\frac{\partial^2 J}{\partial T_s \partial I_{ak}} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial I_{ak}}\frac{\partial \hat{I}_i}{\partial T_s} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial T_s \partial I_{ak}}\right\}$$

$$\frac{\partial^2 J}{\partial u \partial T_s} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial T_s}\frac{\partial \hat{I}_i}{\partial u} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial u \partial T_s}\right\}$$

$$\frac{\partial^2 J}{\partial u^2} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial u}\frac{\partial \hat{I}_i}{\partial u} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial u^2}\right\}$$

$$\frac{\partial^2 J}{\partial u \partial I_{ak}} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial I_{ak}}\frac{\partial \hat{I}_i}{\partial u} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial u \partial I_{ak}}\right\}$$

$$\frac{\partial^2 J}{\partial T_s \partial T_s} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial T_s}\frac{\partial \hat{I}_i}{\partial I_{ak}} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial I_{ak} \partial T_s}\right\}$$

$$\frac{\partial^2 J}{\partial I_{ak} \partial u} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial u}\frac{\partial \hat{I}_i}{\partial I_{ak}} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial I_{ak} \partial u}\right\}$$

$$\frac{\partial^2 J}{\partial I_{ak}^2} = 2\sum_{i=1}^{3}\left\{\frac{\partial \hat{I}_i}{\partial I_{ak}}\frac{\partial \hat{I}_i}{\partial I_{ak}} - (I_i - \hat{I}_i)\frac{\partial^2 \hat{I}_i}{\partial I_{ak}^2}\right\} \quad (24)$$

The first derivatives of radiance are expressed as follows,

$$\frac{\partial I_i}{\partial T_s} = \frac{c_i c_{0i} c_{1i}}{T_s^2\{\exp(\frac{c_{0i}}{T_s})-1\}^2}\exp\left\{\frac{c_{0i}}{T_s}-\alpha_1 u^{\alpha_2}\right\}$$

$$\frac{\partial I_i}{\partial u} = c_{1i}\alpha_1\alpha_2\alpha_3 u^{\alpha_2-1}\left\{(C_{1i}+C_{2i}I_{ak})-\frac{c_i}{\exp(\frac{c_{0i}}{T_s})-1}\right\}$$

$$\frac{\partial I_i}{\partial I_{ak}} = C_{2i}\{1-c_{1i}\exp(-\alpha_1 u^{\alpha_2})\} \quad (25)$$

Also the second derivatives of radiance is represented as follows,

$$\frac{\partial^2 I_i}{\partial T_s} = \left[c_i c_{0i} c_{1i}\exp\{-\alpha_1 u^{\alpha_2}\}\right]$$
$$\left\{\frac{-c_{0i}e^{\frac{c_{0i}}{T_s}}-2T_s e^{\frac{c_{0i}}{T_s}}}{T^4(e^{\frac{c_{01}}{T_s}}-1)^2}+\frac{2c_{0i}e^{\frac{c_{0i}}{T_s}}}{T^4(e^{\frac{c_{01}}{T_s}}-1)^3}\right\}$$

$$\frac{\partial^2 I_i}{\partial T_s\partial u} = -\frac{c_i c_{0i} c_{1i}}{T_s^2\{\exp(\frac{c_{0i}}{T_s})\}^2}\exp\{\frac{c_{0i}}{T_s}-\alpha_1 u^{\alpha_2}\}\alpha_1\alpha_2 u^{\alpha_2-1}$$

$$\frac{\partial I_i}{\partial T_s\partial I_{ak}} = 0$$

$$\frac{\partial^2 I_i}{\partial u\partial T_s} = -\frac{c_i c_{0i} c_{1i}}{T_s^2\{\exp(\frac{c_{0i}}{T_s})-1\}^2}\alpha_1\alpha_2$$
$$\exp\left\{\frac{c_{0i}}{T_s}-\alpha_1 u^{\alpha_2}\right\}u^{\alpha_2-1}$$

$$\frac{\partial^2 I_i}{\partial u^2} = c_{1i}\alpha_1\alpha_2\left\{(C_{1i}+C_{2i}I_{ak})-\frac{c_i}{\exp(\frac{c_{0i}}{T_s})-1}\right\}$$

$$\frac{\partial^2 I_i}{\partial u\partial I_{ak}} = c_{1i}C_{2i}\alpha_1\alpha_2\alpha_3 u^{\alpha_2-1}$$

$$\frac{\partial^2 I_i}{\partial I_{ak}\partial T_s} = 0$$

$$\frac{\partial^2 I_i}{\partial I_{ak}\partial u} = c_{1i}C_{2i}\alpha_1\alpha_2\alpha_3 u^{\alpha_2-1}$$

$$\frac{\partial^2 I_i}{\partial I_{ak}^2} = 0 \quad (26)$$

where

$$\alpha_1 = c_{2i}+\frac{c_{3i}}{\cos\theta}$$

$$\alpha_2 = c_{4i}+\frac{c_{5i}}{\cos\theta}$$

$$\alpha_3 = \exp\{-\alpha_1 u^{\alpha_2}\}$$

G. Conventional Regression Based Method of Split Window

Split window method is based on regression with some training dataset which consists of truth data of SST and TIR spectral band data.

Namely, once regression analysis is made, then SST can be estimated with TIR spectral band data (TIR_i). Regression analysis uses the following regressive equation,

$$T_S = \sum_i c_i TIR_i \quad (27)$$

Where c_i denotes regressive coefficients for spectral band *i*.

H. Conventional MCSST

Multi Channel Sea Surface Temperature: MCSST is the method for SST estimation with NOAA/AVHRR (National Oceanic and Atmospheric Administration / Advanced Very High Resolution Radiometer) data. MCSST is based on split window method. AVHRR consist five channels, two channels in visible band, one channel in shortwave infrared band, and two channels in thermal infrared bands (Band 4 and 5). In general, MCSST is expressed in equation (28).

$$\begin{aligned} T_s &= A\cdot TB_4 + B(TB_4 - TB_5) + C(TB_4 - TB_5)(\sec(\theta)-1) \\ &+ D(\sec(\theta)-1)+E \end{aligned} \quad (28)$$

where

T_s : Sea Surface Temperature
TB_i : Brightness Temperature of Band i
θ : Observation Zenith Angle
A, B, C, D, E : Regression Coefficients

In accordance with Kidwell, 1991, MCSST is expressed as follows,

$$T_S = 0.9731T_4 + 2.6353(T_4 - T_5) - 265.4789 \quad \text{for daytime},$$
$$T_S = 0.9994T_4 + 2.7057(T_4 - T_5) - 0.27(T_4 - T_5)(\sec\theta_z - 1)$$
$$+0.73(\sec\theta_z - 1) - 273.0323 \quad \text{for nighttime}, \quad (29)$$

where T_S is given in °C and T_4 and T_5 are in Kelvin. The RMSE and the bias is 1.03°C and -0.51°C for daytime, and 0.73°C and 0.19°C for nighttime, respectively.

III. EXPERIMENT

A. Experimental Conditions

The following parameters are set for the experiments with MODTRAN obtaining at sensor radiance of spectral TIR band data.

Atmospheric Model: Tropic, Mid.Latitude Summer, Mid.Latitude Winter, SubArctic Summer, SubArctic Winter, 1976 US Standard Atmosphere

Constraint: ± 2[K]

Meteorological Range: $\pm 0\%$, $\pm 10\%$, $\pm 20\%$

Relative Humidity: Default x1.0,x.1.1,x1.2,x0.9,x0.8

Air-Temperature: Default $\pm 0, \pm 3$ [K]

Sea surface temperature: Default $\pm 0, \pm 3$ [K]

Wind speed: 3.5, 7.0, 14.0 [m/s]

Aerosol Model: Navy Maritim,Maritim,Tropospheric,Desert

Observation Zenith Angle: 0, 30, 60[deg]

Then SST is estimated with the proposed method and the conventional split window method using the calculated at sensor radiance.

B. Example of Solution Behavior

RMSE is estimated with a variety of precipitable water and representative radiance of TIR band. One of the examples of solution behavior is illustrated in Figure 1.

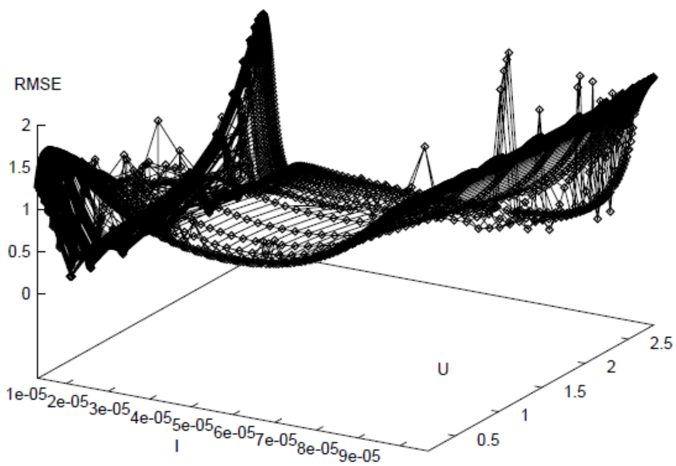
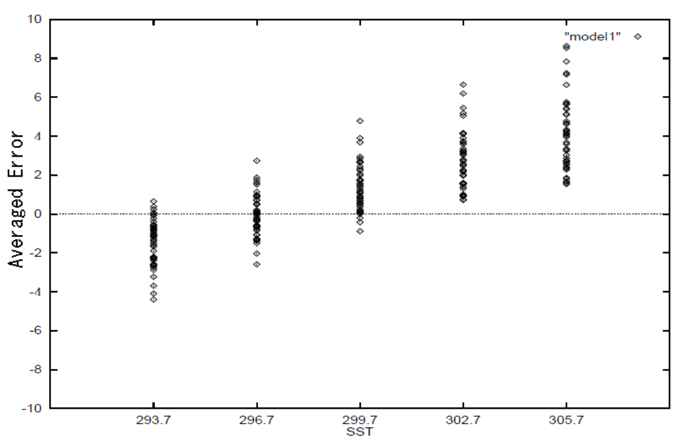
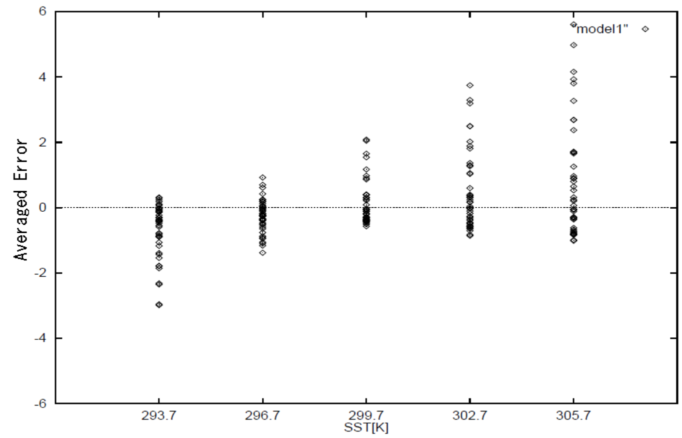


Fig.1. Example of solution behavior in solution space

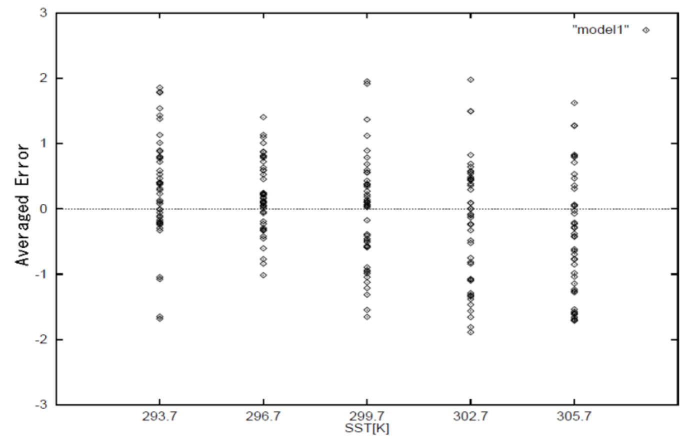
In general, RMSE (SST estimation error) is proportional to the precipitable water. On the other hands, the relation between representative radiance of TIR band and RMSE shows complicated characteristics, in particular for small representative radiance regions. This implies that it is not easy to find the global optimum in the solution space. In other words, it is easy to fall in one solution of local minima.



(a)MCSST

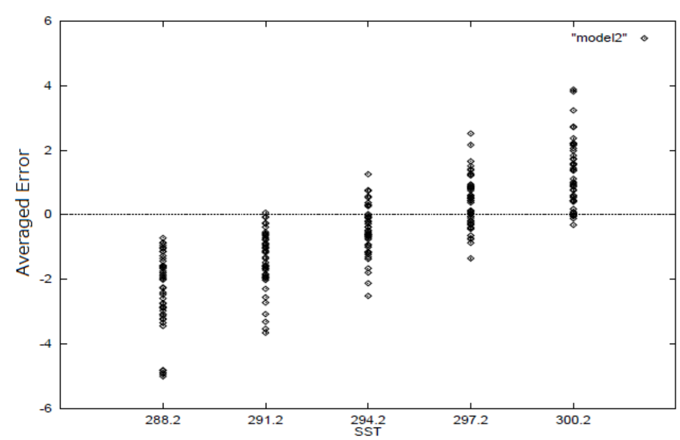


(b)Split Window

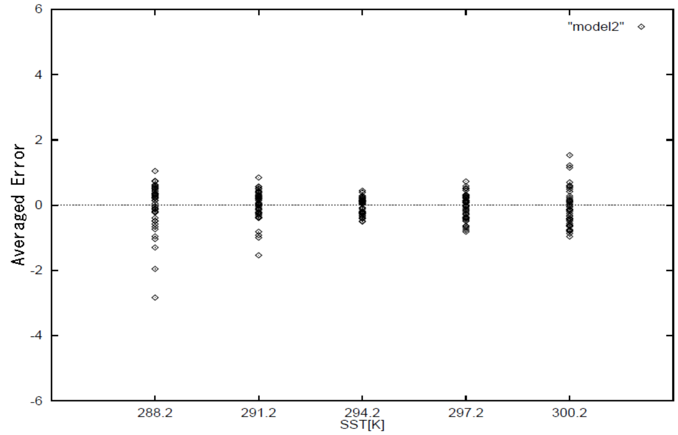


(c)Conjugate Gradient

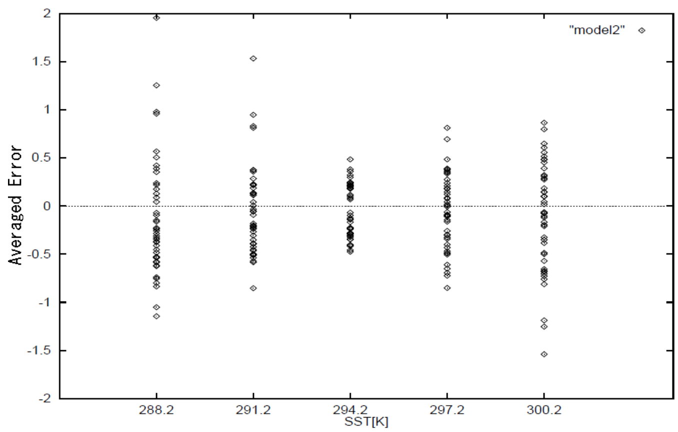
Fig.2. Averaged SST estimation error for Tropic atmosphere model



(a)MCSST

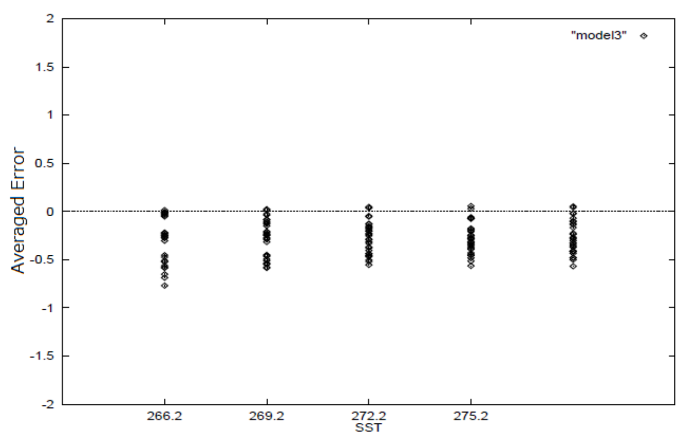


(b)Split Window

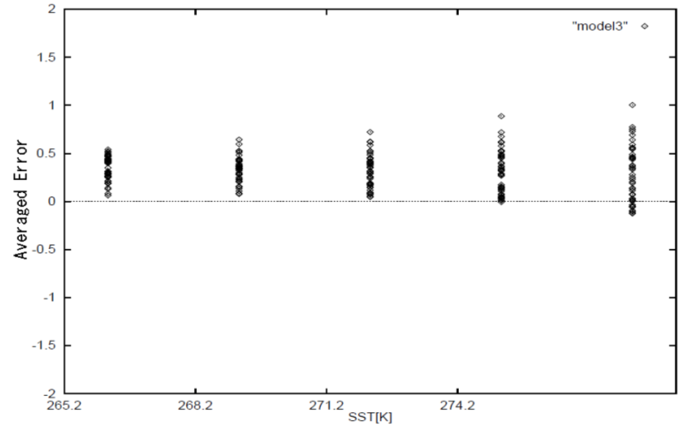


(c)Conjugate Gradient

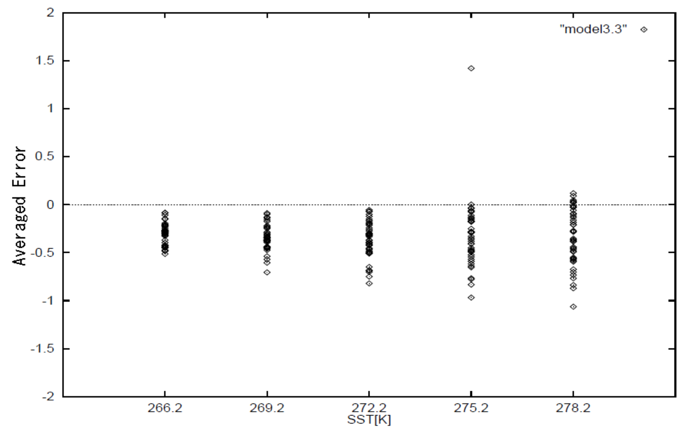
Fig.3. Averaged SST estimation error for Mid. Latitude Summer atmosphere model



(a)MCSST

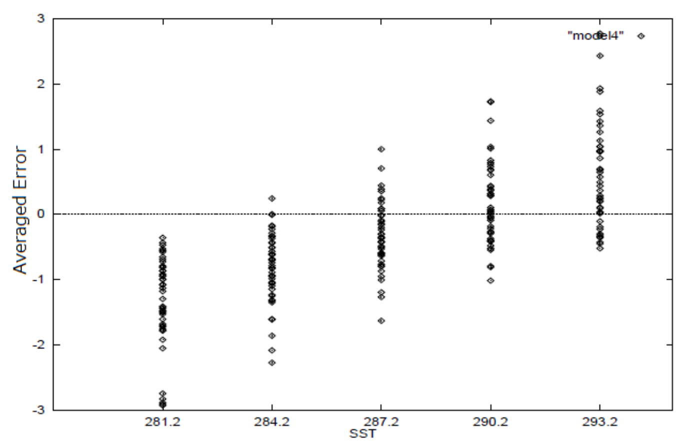


(b)Split Window

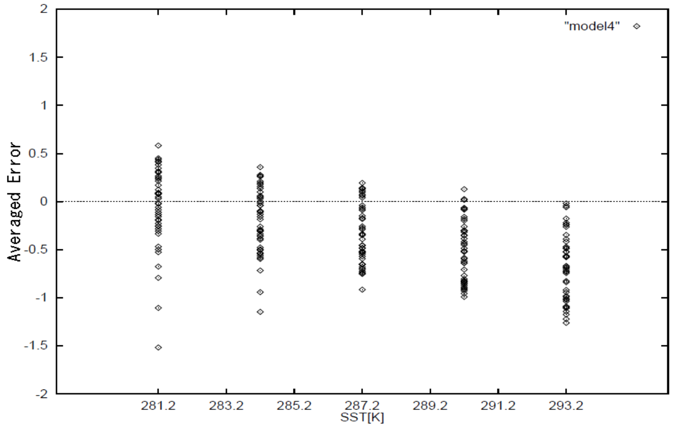


(c)Conjugate Gradient

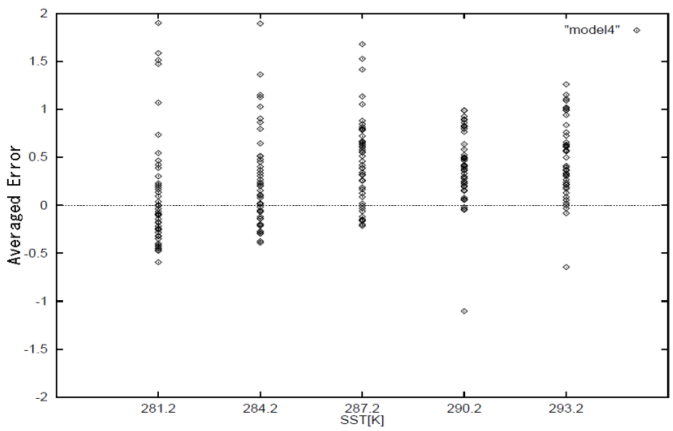
Fig.4. Averaged SST estimation error for Mid. Latitude Winter atmosphere model



(a)MCSST

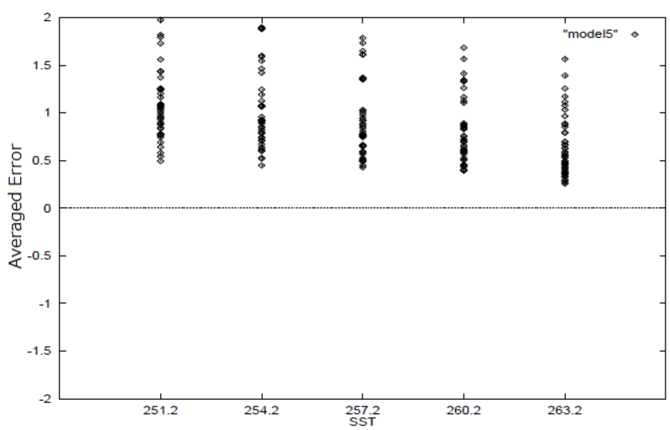


(b)Split Window

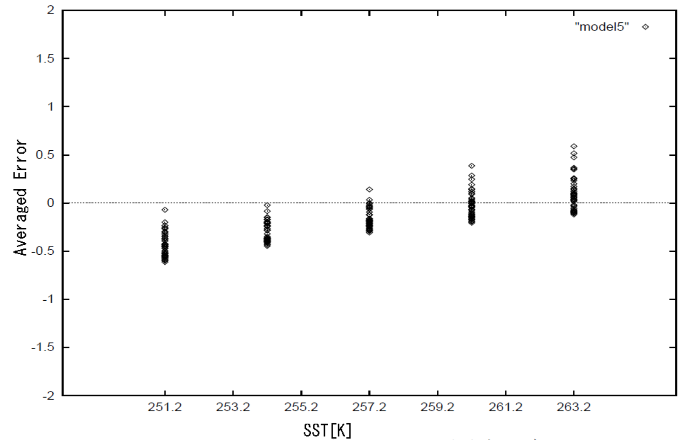


(c)Conjugate Gradient

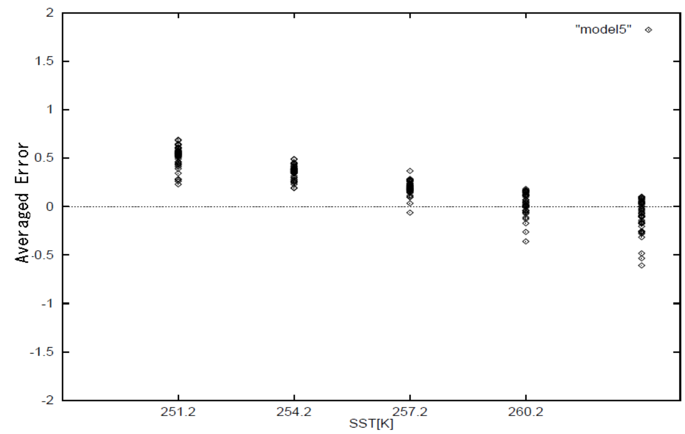
Fig.5. Averaged SST estimation error for Sub Arctic Summer atmosphere model



(a)MCSST

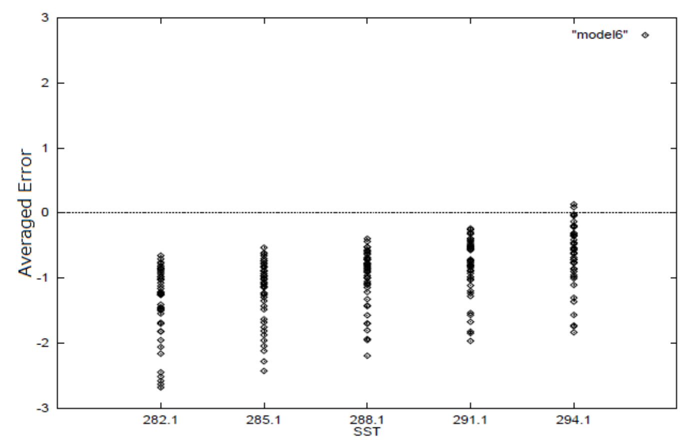


(b)Split Window

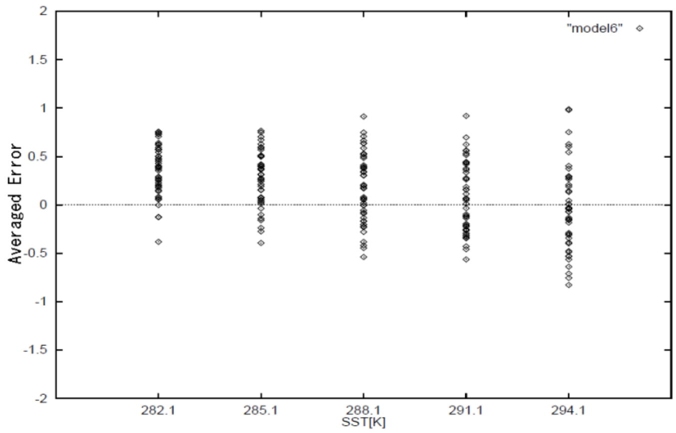


(c)Conjugate Gradient

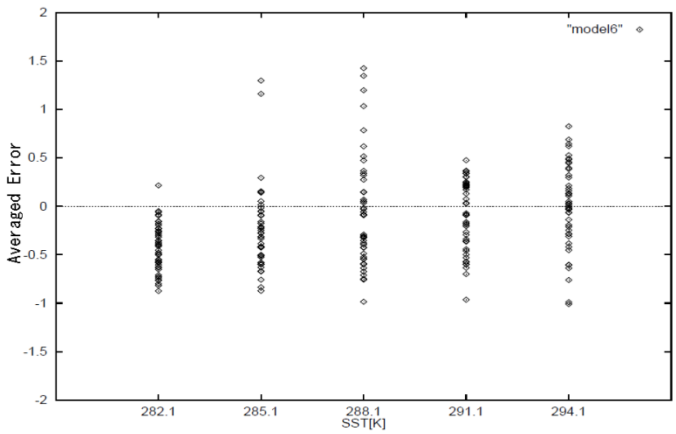
Fig.6. Averaged SST estimation error for Sub Arctic Winter atmosphere model



(a)MCSST



(b)Split Window



(c)Conjugate Gradient

Fig.7. Averaged SST estimation error for 1976 US standard atmosphere model

TABLE III. RMSE OF SST ESTIMATION FOR THE CONVENTIONAL MCSST, SPLIT WINDOW AND CONJUGATE GRADIENT METHOD FOR THE DIFFERENT ATMOSPHERIC MODELS

Atmospheric Model	MCSST(K)	Split Window(K)	CGM Method(K)
Tropic	2.77	1.195	0.864
Mid. Latitude Summer	1.67	0.702	0.479
Mid. Latitude Winter	0.72	0.472	0.408
Sub Arctic Summer	1.01	0.641	0.596
Sub. Arctic Winter	0.99	0.483	0.317
1976 US Standard	1.15	0.505	0.478
Average	1.53	0.726	0.559

C. Evaluated Averaged SST Estimation Error

Averaged SST estimation error of MCSST method, Split Window method, and Conjugate Gradient method for the basic atmospheric models, Tropic (Figure 2), Mid. Latitude Summer (Figure 3) and Winter (Figure 4), Sub Arctic Summer (Figure 5) and Winter (Figure 6) as well as 1976 US standard atmosphere (Figure 7).

For all cases, the proposed conjugate gradient method is superior to the other conventional methods of MCSST and Split Window, in particular for thick atmosphere (precipitable water rich atmosphere). Furthermore, MCSST has systematic errors of which the SST estimation error increases in accordance with increasing of SST.

Although only the difference between MCSST and Split Window methods is the regression coefficients, Split Window method is superior to the MCSST method because the regression coefficients are different among the atmospheric models for Split Window method; MCSST method uses the same coefficients for all atmospheric models.

IV. CONCLUSION

Comparative study on Sea Surface Temperature: SST estimations among the conventional Multi-Channel Seat Surface Temperature: MCSST, split window method and the proposed Conjugate Gradient based method: CGM with Thermal Infrared Radiometer:

TIR data through simulations is conducted. Utilizing the proposed linearized inversion of radiative transfer equation, SST can be estimated. SST estimation accuracy of the proposed method is compared to the conventional regression based method (Split Window method and MCSST).

Through the experiments, it is found that the proposed conjugate gradient method is superior to the other conventional methods of MCSST and Split Window for all cases, in particular for thick atmosphere (precipitable water rich atmosphere).

Furthermore, MCSST has systematic errors of which the SST estimation error increases in accordance with increasing of SST. Although only the difference between MCSST and Split Window methods is the regression coefficients, Split Window method is superior to the MCSST method because the regression coefficients are different among the atmospheric models for Split Window method; MCSST method uses the same coefficients for all atmospheric models.

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