Sensitivity Analysis on Sea Surface Temperature Estimation Methods with Thermal Infrared Radiometer Data through Simulations

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***Abstract*—Sensitivity analysis on Sea Surface Temperature: SST estimation with Thermal Infrared Radiometer: TIR data through simulations is conducted. Also Conjugate Gradient Method: CGM based SST estimation method is proposed. SST estimation error of the proposed CGM based method is compared to the conventional Split Window Method: SWM with a variety of conditions including atmospheric models. The results show that the proposed CGM based method is superior to the SWM.**

***Keywords*—SST estimation; Split Window; Conjugate Gradient; MODTRAN; atmospheric model**

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, sensitivity analysis results are described. SST estimation accuracy, in general, depends on relative humidity, air temperature, meteorological range, wind speed, aerosol type, and so on. Sensitivity of these factors on SST estimation accuracy is clarified in order to make clear that how does component influencing to SST estimation accuracy.

The following section describes the method for sensitivity analysis together with some theoretical background followed by some experiments. 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. Method for Sensitivity Analysis

By using MODTRAN of radiative transfer software code with six default atmospheric models, Tropic, Mid. Latitude Summer and Winter, Sub Arctic Summer and Winter, and 1976 US standard atmosphere, brightness temperature of the assumed spectral bands in Thermal Infrared wavelength regions can be estimated. Therefore Root Mean Square Error: RMSE of SST estimation error can be estimated for the assumed SST estimation method.

D. Assumed SST Estimation Method

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

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

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 perceptible water while m denotes slant length between sea surface and TIR instrument onboard satellites. In the TIR wavelength region, perceptible 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. 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 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

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.

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

The unknown factors are as follows,

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

Namely, sea surface temperature, perceptible 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,

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

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

$$
\begin{aligned}
I_i &= \frac{c1c_{1i}}{\lambda^3 \exp(\frac{c2}{\lambda T_s}) - 1} \exp\Big\{ -(c_{2i} + \frac{c3i}{\cos\theta}) u^{c_{4i} + \frac{c5i}{\cos\theta}} \Big\} \\
&+ \Big[1 - c_{1i} \exp\Big\{ -(c_{2i} + \frac{c_{3i}}{\cos\theta}) u^{c_{4i} + \frac{c5i}{\cos\theta}} \Big] (C_{1i} + C_{2i} I_{ak})
\end{aligned}
\quad (14)
$$

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

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

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

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

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

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

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

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

$c2 : ch/k = 1.43889$

Then the unknown variables are estimated through iterations. Also Root Mean Square Error: RMSE can be evaluated.

$$
\begin{aligned}
RMSE &= \sqrt{\frac{\sum_{k=1}^{N} (e_k)^2}{N}} \\
e_k &= T_s - T_s'
\end{aligned}
\quad (23)
$$

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

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

Also the second derivatives are represented as follows,

$$
\begin{aligned}
\frac{\partial^2 J}{\partial T_s^2} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial T_s \partial u} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial T_s \partial I_{ak}} &= 2 \sum_{i=1}^{3} \Big\{ \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}} \Big\} \\
\frac{\partial^2 J}{\partial u \partial T_s} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial u^2} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial u \partial I_{ak}} &= 2 \sum_{i=1}^{3} \Big\{ \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}} \Big\} \\
\frac{\partial^2 J}{\partial T_s \partial T_s} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial I_{ak} \partial u} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\} \\
\frac{\partial^2 J}{\partial I_{ak}^2} &= 2 \sum_{i=1}^{3} \Big\{ \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} \Big\}
\end{aligned}
\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

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

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

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

E. Assumed Spectral Bands

Spectral bands of ADEOS/OCTS (Advanced Earth Observing Satellite / Ocean Color and Temperature Scanner) are assumed as typical spectral bands for SST estimation which are 10300-11360nm for Band 4, and 11360-12500nm for Band 5, respectively.

III. Experiments

F. Simulation 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]

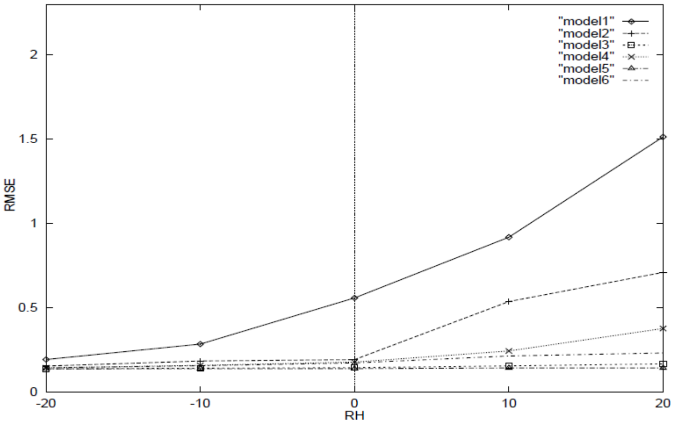
Then SST is estimated with the proposed method and the conventional split window method using the calculated at sensor radiance.

G. Evaluation of RMSE for the Proposed CGM

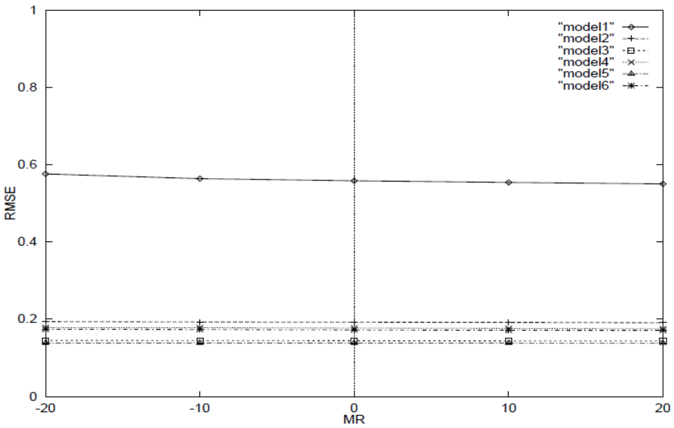
SST estimation error for the proposed CGM can be evaluated with RMSE which is expressed in equation (23) by using MODTRAN derived at sensor radiance of TIR bands.

Figure 1 show RMSE of CGM as functions of (a) relative humidity, (b) meteorological range, (c) air temperature, (d) observation zenith angle, (e) sea surface temperature, and (f) wind speed for six atmospheric models. In accordance with increasing of relative humidity, meteorological range, observation zenith angle, sea surface temperature, and wind speed, RMSE increased. RMSE is, on the other hands, decreases in accordance with increasing of air temperature. Meanwhile, Figure 2 (a) shows the relation between meteorological range and RMSE as parameters of different types of aerosol for the Mid.

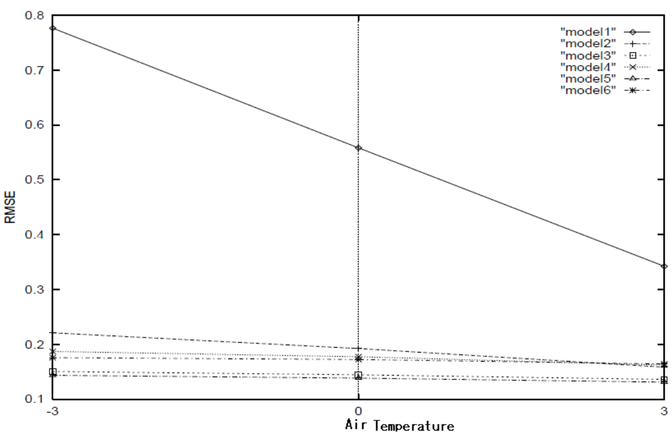
Latitude Summer of atmospheric model. RMSE for Navy Maritime shows the greatest followed by Maritime, Desert, and Troposphere aerosol. Figure 2 (b) shows RMSE for the six different aerosol types, Navy Maritime, Maritime, Urban, Desert, Rural, and Troposphere aerosol types at the meteorological range of 23 km. Figure 2 (c) shows RMSE as function of altitude for Desert aerosol. Figure 3 shows RMSE of the representative radiance from the atmosphere for the six different atmospheric models. It does not show monotonic relation between relative humidity and RMSE. Therefore, the representative radiance from the atmosphere has to be estimated precisely.



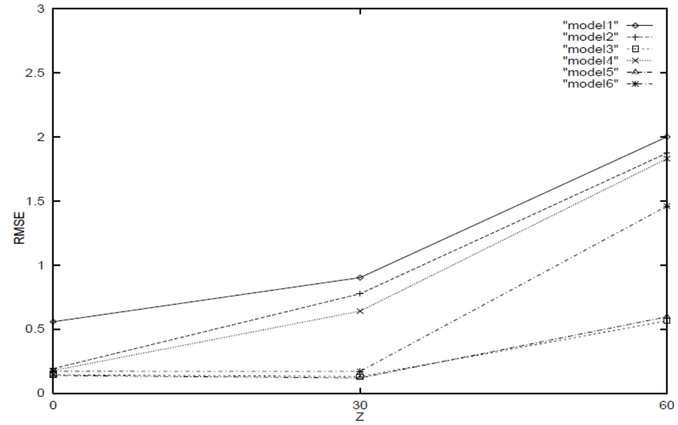
(a)Relative Humidity



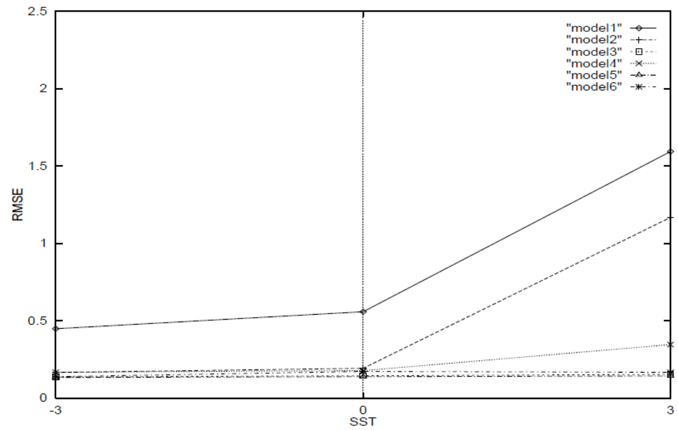
(b)Meteorological Range



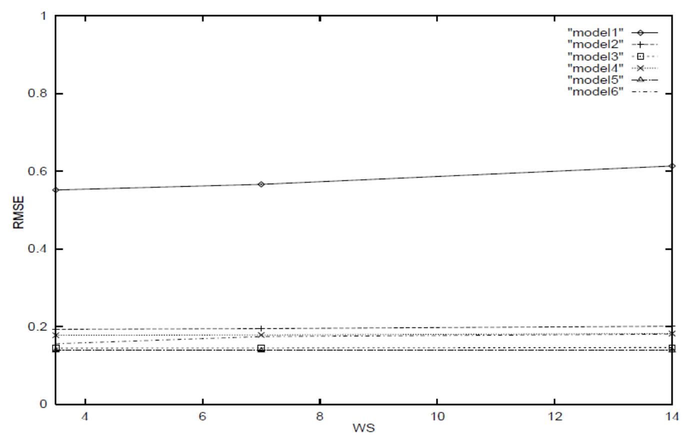
(c)Air Temperature



(d)Observation Zenith Angle

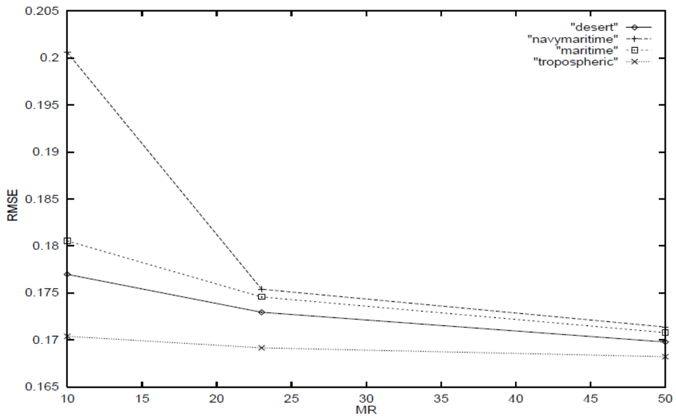


(e)Sea Surface Temperature

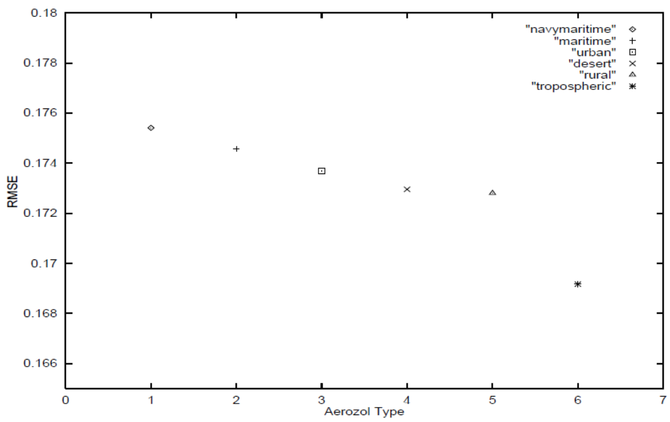


(f)Wind Speed

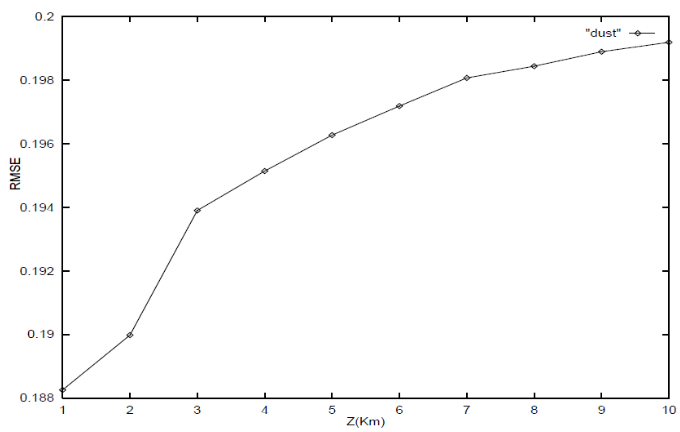
Fig. 1. RMSE of CGM as functions of (a) relative humidity, (b) meteorological range, (c) air temperature, (d) observation zenith angle, (e) sea surface temperature, and (f) wind speed for six atmospheric models



(a)Aerosol Type



(b)Aerosol Type



(c)Altitude (Desert type of aerosol)

Fig. 2. RMSE as function of aerosol types

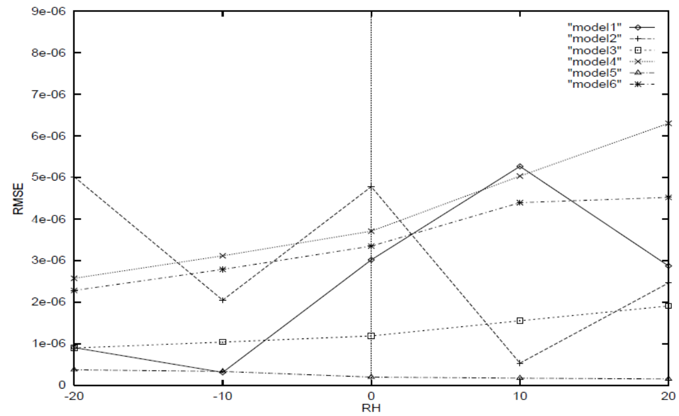
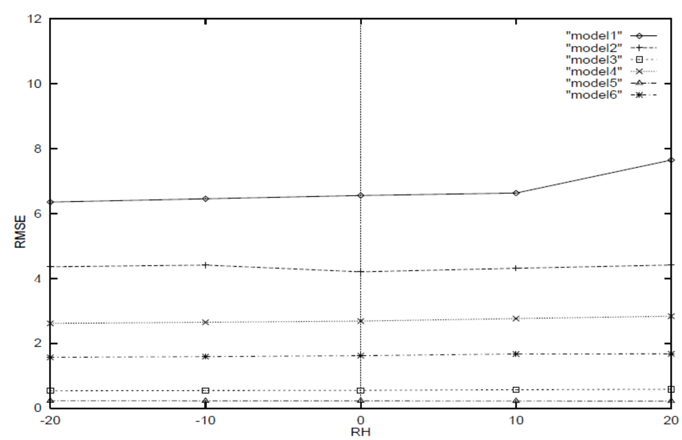


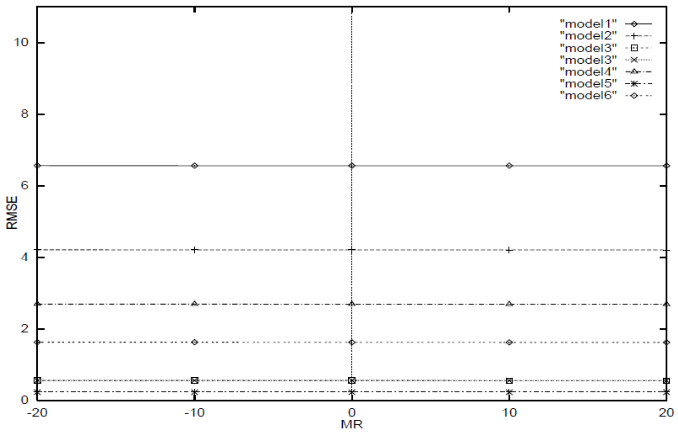
Fig. 3. RMSE of the representative radiance from the atmosphere for the six different atmospheric models

H. Evaluation of RMSE for the Conventional Split Window

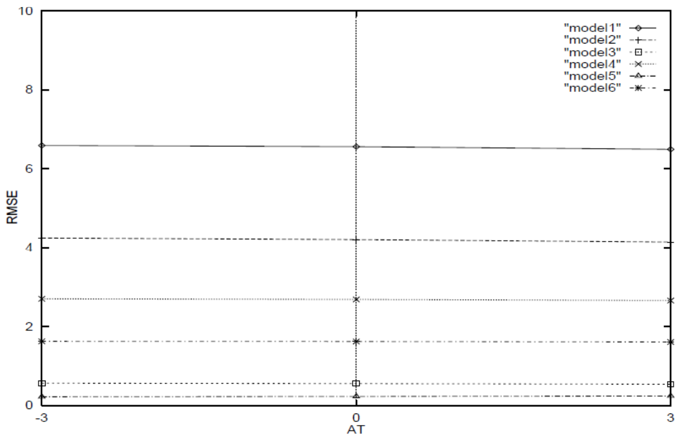
SST estimation error for the conventional split window can be evaluated with RMSE which is expressed in equation (23) by using MODTRAN derived at sensor radiance of TIR bands. Figure 4 shows RMSE of Split Window as functions of (a) relative humidity, (b) meteorological range, (c) air temperature, (d) observation zenith angle, (e) sea surface temperature, and (f) wind speed for six atmospheric models. RMSE of the conventional Split Window is much larger than that of CGM. In accordance with increasing of relative humidity, meteorological range, observation zenith angle, sea surface temperature, and wind speed, RMSE increased. RMSE is, on the other hands, decreases in accordance with increasing of air temperature.



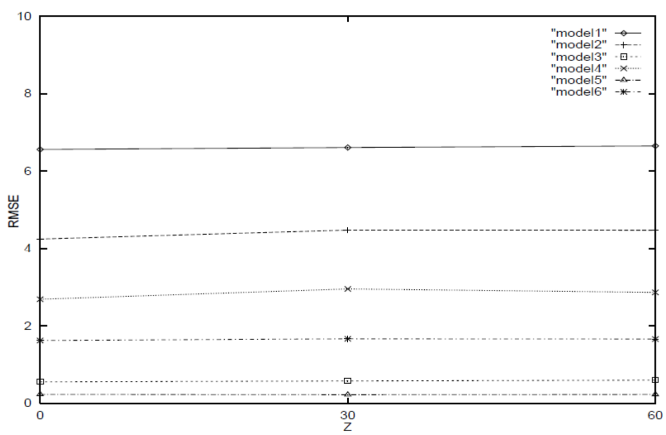
(a)Relative Humidity



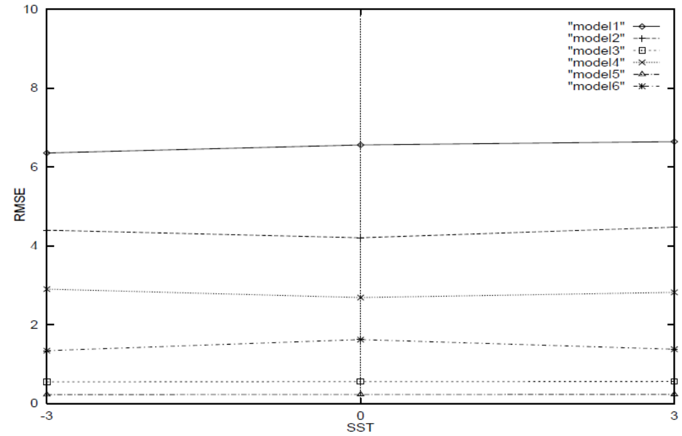
(b)Meteorological Range



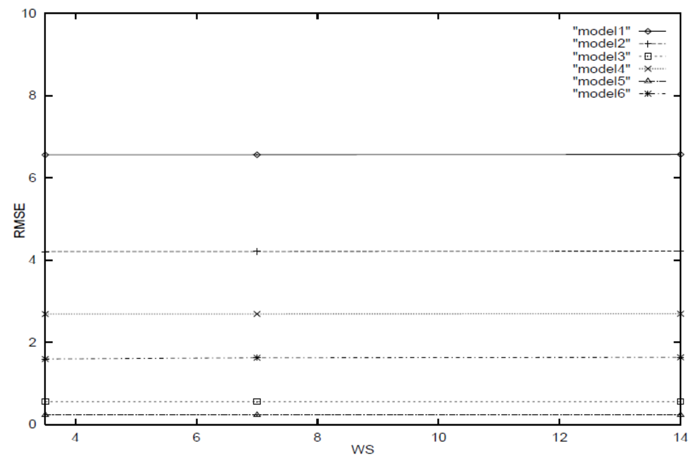
(c)Air Temperature



(d)Observation Zenith Angle



(e)Sea Surface Temperature



(f)Wind Speed

Fig. 4. RMSE of the conventional Split Window as functions of (a) relative humidity, (b) meteorological range, (c) air temperature, (d) observation zenith angle, (e) sea surface temperature, and (f) wind speed for six atmospheric models

I. Comparison of RMSE between Split Window and CGM

Overall RMSE of the conventional Split Window and the proposed CGM is shown in Table 3.

Although depending on the atmospheric model, RMSE between both are different, RMSE of the proposed CGM is lower than that of Split Window. Therefore, CGM is superior to Split Window.

TABLE III. OVERALL RMSE OF THE CONVENTIONAL SPLIT WINDOW AND THE PROPOSED CGM

	Split Window	Conjugate Gradient
Tropic	1.195	0.864
Mid. Latitude Summer	0.702	0.479
Mid. Latitude Winter	0.472	0.408
Sub Arctic Summer	0.641	0.596
Sub Arctic Winter	0.483	0.317
1976 US Standard	0.505	0.478
Average	0.726	0.559

J. Influence Due to Observation Noise

In order to evaluate influence due to observation noise on SST estimation accuracy, RMSE with and without of random number derived noise is evaluated. The normal distribution of random number with 10^{-6} of variance and with zero mean is generated by using Messene Twister. The random number is added to the at sensor radiance of the simulated TIR bands data. Then SST is estimated based on the proposed conjugate gradient method. Table 4 shows the result.

TABLE IV. INFLUENCE DUE TO OBSERVATION NOISE ON SST ESTIMATION ACCURACY

	Without noise	With 10^-6 of noise
Tropic	0.4386	0.7214
Mid. Latitude Summer	0.1924	0.6012
Mid. Latitude Winter	0.1446	0.2871
Sub Arctic Summer	0.1774	0.5624
Sub Arctic Winter	0.1384	0.2601
1976 US Standard	0.1724	0.3631

IV. IV. CONCLUSION

Sensitivity analysis on Sea Surface Temperature: SST estimation with Thermal Infrared Radiometer: TIR data through simulations is conducted. Also Conjugate Gradient Method: CGM based SST estimation method is proposed. SST estimation error of the proposed CGM based method is compared to the conventional Split Window Method: SWM with a variety of conditions including atmospheric models. The results show that the proposed CGM based method is superior to the SWM.

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