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Sea surface temperature estimation from remote measurement of the thermal radiation

Kazuhiko MIMA, Makoto SATOH, Masao MORIYAMA, Takakazu ISHIMATSU
Dpt. Mechanical Systems Eng., Faculty of Eng., Nagasaki Univ.,
1 - 14 Bunkyo-machi Nagasaki 852 JAPAN.

Abstract

To establish the sea surface temperature estimation scheme for the upcoming advanced remote sensor, the *quasi-analytical solution of the approximated radiative* transfer equation is derived. In this method, at first, the radiative transfer equation which express the radiative transfer process of the radiant energy radiated from the sea surface to the satellite is approximated into the non-linear equation. To solve the simultaneous approximated radiative transfer equation at each channel, the constrained non-linear optimization technique is adopted. To define the coefficients of the approximated radiative transfer equation and the constraints, the satellite detected radiance and the total transmittance are computed from the 1350 kinds of simulated atmosphere / surface models via radiative transfer code. The verification from the simulated data show the sufficient result.

1 INTRODUCTION

The sea surface temperature is one of the most important parameters for the environmental science such as meteorology, oceanography, and so on. The present status of the sea surface temperature estimation based on the regression analysis between the satellite observed data and the *in-situ* observation data [1]. For the upcoming advanced remote sensors which have multiple (up to 3 channels) spectral channels in the thermal infrared spectrum, the regression analysis has no advantage to improve the estimation accuracy because the correlation between the spectral channels is large [2].

To make an accurate estimation from the multiple channel sensor data, the quasi-analytic method which solve the radiative transfer equation is proposed. To solve the radiative transfer equation, at first, the approximation of the radiative transfer equation at each channel is made. To solve the simultaneous approximated radiative transfer equation, the constrainted non-linear optimization is adopted. Based on the simulated atmosphere / surface condition, the coefficients of the approximated radiative transfer equation and the constraints are defined and the verification of this method is conducted.

2 APPROXIMATION OF THE RADIATIVE TRANSFER EQUATION

2.1 Radiative Transfer Equation in Thermal IR Spectrum

Under the clear and negligible solar radiation and the scattering effect, the satellite detected spectral radiance at wavenumber ν: I_ν in the case of blackbody surface can be expressed by the following equation [2].

$$\begin{aligned} I_\nu &= B[\nu, T_S]\tau(\nu, 0, Z, \theta) \\ &+ \int_0^Z B[\nu, T(z)]\frac{\partial \tau(\nu, z, Z, \theta)}{\partial z}dz. \end{aligned} \quad (1)$$

where $B[\nu, T]$, $\tau(\nu, z_1, z_2, \theta)$, T and $T(z)$ are spectral Planck function at temperature T, spectral transmittance from altitude z_1 to z_2 at observation zenith angle (0 means nadir) θ at wavenumber ν, surface temperature and air temperature at z, respectively. The detected radiance at each spectral channel: I_i can be written in the weighted average of the normalized response function: $\phi_i(\nu)$ of each spectral channel and the I_ν as follows.

$$I_i = \int_{\nu_{Li}}^{\nu_{Ui}} I_\nu \phi(\nu) d\nu. \quad (2)$$

where ν_{Li} and ν_{Ui} are lower and upper boundary of the response at each spectral channel, respectively. Sea surface temperature can be estimated as the solution of these equation, however, it is difficult because there are so much unknown parameters such as air temperature / absorbar amount profile, surface temperature and so on.

2.2 Assumptions

2.2.1 Spectral averaging of the Planck function and transmittance

Instead of the spectral averaging of the radiance, the spectral averaging of Planck function and transmittance at each spectral channel are adopted [3].

$$B_i[T] = \int_{\nu_{Li}}^{\nu_{Ui}} B[\nu, T]\phi(\nu) d\nu, \quad (3)$$

$$\tau_i(z_1, z_2, \theta) = \int_{\nu_{Li}}^{\nu_{Ui}} \tau(\nu, z_1, z_2, \theta)\phi(\nu) d\nu, \quad (4)$$

Thus, the channel-wise radiative transfer equation are established.

$$I_i = B_i[T_S]\tau_i(0, Z, \theta) + \int_0^Z B_i[T(z)]\frac{\partial \tau_i(z, Z, \theta)}{\partial z}dz, \quad (5)$$

2.2.2 Assumption for the atmospheric radiation

To compute the atmospheric radiation term (the integration term in the radiative transfer equation), it is necessary to know the atmospheric profile. For the sea surface estimation, the atmospheric radiation is the *noise* term, so it is convenient to simplify the atmospheric radiation term as follows [3]

$$\int_0^Z B_i[T(z)]\frac{\partial \tau_i(z, Z, \theta)}{\partial z}dz = [1 - \tau_i(0, Z, \theta)]\, I_{ai} \quad (6)$$

The term I_{ai} is named the representative atmospheric radiation.

On the basis of the spectral dependence of the atmospheric radiation, the representative atmospheric radiation at each channel: I_{ai} is assumed to be the linear function of that at the certain channel: I_{ak}.

$$I_{ai} = F_i(I_{ak}) = C_{1i} + C_{2i}I_{ak}, \quad (7)$$

where C_{1i} and C_{2i} are the regression coefficients

2.2.3 Assumption for the total transmittance

For the earth surface observation, the small atmospheric extinction spectrum (atmospheric window spectrum) is selected, and in this spectrum, the water vapor can be the dominate absorber [2]. In the computation of the total transmittance at each channel: $\tau_i(\theta)$ is assumed to be the exponential function of only the precipitable water: u (total water vapor amount).

$$\begin{aligned} \tau_i(\theta) &= \tau_i(0, Z, \theta) \quad (8) \\ &= c_{1i}\exp\left[-(c_{2i} + c_{3i}m)u^{(c_{4i}+c_{5i}m)}\right], \\ m &= sec(\theta). \quad (9) \end{aligned}$$

where c's are the regression coefficients.

2.3 Approximated Radiative Transfer Equation

To adopt the previous assumptions, the approximated radiative transfer equation can be established.

$$I_i = B_i[T_S]\tau_i(\theta) + [1 - \tau_i(\theta)]F_i(I_{ak}) \quad (10)$$

In this equation, there are 3 unknown variables, surface temperature: T_S, precipitable water: u and the representative atmospheric radiation at the certain channel: I_{ak}, and this equation can be solved in the case of 3 spectral channels data.

3 SOLUTION OF THE RADIATIVE TRANSFER EQUATION

3.1 Non-linear Optimization

To solve the simultaneous approximated radiative transfer equation, the non-linear optimization is adopted. As the cost function: J, the square sum of the difference between observed and calculated radiance are selected.

$$J = \sum_i \left|I_i^{obs} - I_i^{calc}\right|^2, \quad (11)$$

the solution minimizes this cost function.

3.2 Constraints

To avoid the converge into the undesirable solution such as negative temperature or precipitable water, the upper and lower boundary of each unknown variable are defined from numerical simulation. Thus this problem becomes the constrainted non-linear optimization (iterative computation).

4 VERIFICATION

4.1 Target Sensor

To verify the above scheme, OCTS (Ocean Color and Temperature Scanner) onboard ADEOS (ADvanced Earth Observation System) will be launched at 1996 by NASDA / Japan is selected as the target sensor. OCTS has 3 channels in 8.5 - 12.5 [μm]. The specification of OCTS thermal IR channels are in Table 5.

4.2 Definition of the Regression Coefficients

The regression coefficients are defined from the numerical simulation under the 1350 kinds of atmosphere / surface condition.

4.2.1 Atmosphere / surface condition

Simulated condition is based on the **Standard model** catalogued in LOWTRAN 7 which is the radiative transfer computation code developed by US AIR FORCE GEOPHYSICAL LAB. [4].

Fundamental conditions: Tropic, midlatitude summer / winter, Subarctic summer / winter, 1976 US standard.

Surface temperature: ±0, ±3, ±6 [K]

Relative humidity: x1.0, x1.1, x1.2, x0.9, x0.8 (0-10 km)

Air temperature: ±0, ±3 [K] (0-10 km)

observation angle: 0, 30, 60 [deg.]

4.2.2 Computation scheme of several values

Precipitable water Precipitable water is computed from each model.

Satellite detected Radiance At first the satellite detected spectral radiance: I_ν is computed by LOWTRAN 7 and after, the satellite detected radiance at each channel: I_i is computed.

Transmittance From the precipitable water, the total transmittance: $\tau_i(\theta)$ is computed.

Representative atmospheric radiation The representative atmospheric radiation at each channel: I_{ai} is computed as follows.

$$I_{ai} = \frac{I_i - B_i[T_S]\tau_i(\theta)}{1 - \tau_i(\theta)} \quad (12)$$

Spectral dependence of the representative atmospheric radiation In this case, the representative atmospheric radiation at channels 10 and 12 is the function of that of channel 11 (10.3 – 11.4 [μm]): I_{a11}. **Regression coefficients** Each regression coefficients are defined from linear / non-linear least square method [5].

4.3 RMS Error of the Approximated Radiative Transfer Equation

Table 5 shows the RMS error between computed radiance from LOWTRAN 7 and the approximated radiative transfer equation in the brightness temperature unit. All of the RMS error is comparable with the NEΔT, this show the accuracy of the approximated radiative transfer equation is sufficient.

4.4 Definition of the Initial Values and the Constraints

Similar as the coefficient definition, the initial values and the constraints of the unknown variables are defined from the simulated condition. The initial values are defined from the regression analysis between the model value and the observed radiance, especially in the case of sea surface temperature, this method is called the SPLIT WINDOW METHOD [1] [2]. It is noticed that in actual case, they have to be defined from the observed data which contain the observation noise. So in this case, the Gaussian noise which standard deviation is the NEΔT are added to the observed brightness temperature and in some case, this values is converted into the observed radiance. The following formulae are established and the superscript * show the initial value.

$$\begin{aligned} T_S^* &= 0.994TB_{11} + 2.43(TB_{11} - TB_{12}) \quad (13) \\ &+ 0.168(TB_{11} - TB_{10}) + 1.38[K], \\ I_{a11}^* &= 1.38I_8 + 1.12 \times 10^{-6}[W/cm^2/sr], \quad (14) \\ \log(u^*) &= 2.54\log(I_8) + 13.8[cm]. \quad (15) \end{aligned}$$

$$T_S^* - 4.0 \le T_S \le T_S^* + 8.0 \quad (16)$$

$$I_{a11}^* - 2.00 \times 10^{-6} \le I_{a11} \le I_{a11}^* + 1.50 \times 10^{-6} \quad (17)$$

$$\log(u^*) - 0.50 \le \log(u) \le \log(u^*) + 0.1 \quad (18)$$

The RMS error between the initial value and the model value are shown in Table [illegible]. That of precipitable water is relatively large so it is expexted that the precipitable water estimation accuracy becomes worse.

4.5 Sea Surface Temperature Estimation

Also sea surface temperature estimation is conducted based on the simulated condition and noise contaminated satellite detected radiance. As the non-linear optimization algorithm, the quasi-Newton method is used [5]. In Table 5, the results of sea surface temperature and the precipitable water are shown and in Figure 1 and 2, the comparison between the model and estimated values of sea surface temperature and precipitable water are shown. These results are improved from the initial values even the approximation error of the radiative transfer equation is effected. Furthermore, this method can involve the other knowledge such as the meteorological observation data in terms of the constraints, so in such condition, the estimation accuracy is supposed to be improved.

5 CONCLUSION

The previous results lead the following conclusions. To solve the approximated radiative transfer equation by the constrainted non-linear optimization, it is expected that the estimated accuracy will be improved. And this method has the potential to involve the other knowledge to make more accurate estimation.

References

[1] Matsumoto M. and K. Tsuchiya, "Sea surface temperature and precipitable water estimation using MOS-1/VTIR data", *J. Remote Sending Soc. Japan*, vol. 10, No. 1, 19 – 28, 1991. (In Japanese)

[2] Tsuchiya K. *et al*, "Remote sensing", Asakura Pub. Co. pp.326, 1990. (In Japanese)

[3] Matsumoto-Moriyama M. and K. Arai, "A simplified expression of the radiative transfer equation in thermal IR window spectrum", *Proc. IGARSS 93*, vol. 2, 673-675, Tokyo Japan., 1993.

[4] Kneizeys, F. X. *et al*, "Users guide to LOWTRAN 7", AFGL-TR-88, pp. 137, 1988.

[5] Konno H. and H. Yamashita, "Non-linear Programming", Nikka-Giren Pub. Co., pp. 355, 1982. (In Japanese)

Table 1: Specification of the OCTS TIR channels.

Ch.	Wavelength [μm]	NEΔT [K]
10	8.25 – 8.80	0.15
11	10.3 – 11.4	0.15
12	11.4 – 12.5	0.20

Table 2: RMS error of the approximated RTE.

Ch.	RMS [K]
10	2.00e-01
11	7.87e-03
12	1.84e-01

Table 3: RMS error of initial values.

Variable	RMS
T_S	1.02e-00 [K]
u	9.51e-01 [cm]
I_{a11}	5.79e-07 [W/cm^2/sr]

Table 4: RMS error of estimation.

Variable	RMS
T_S	8.04e-01 [K]
u	8.36e-01 [cm]

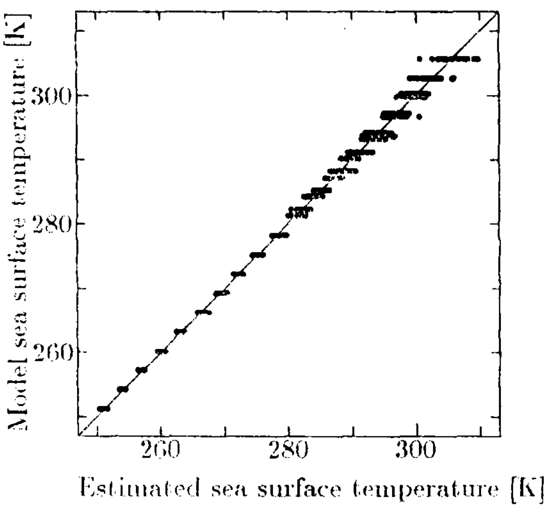

Figure 1: Comparison between model and estimated sea surface temperature

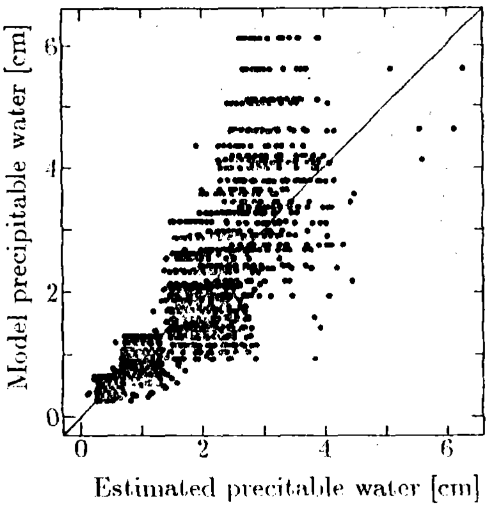

Figure 2: Comparison between model and estimated precipitable water