The second Asia/Oceania Meteorological Satellite User's Conference 6-9, December 2011, Tokyo, Japan

Optimal estimation technique for Sea Surface Temperature Retrieval from Multi Channel Infrared Data

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1. Introduction

The current algorithm used at Meteorological Satellite Center (MSC)/Japan Meteorological Agency (JMA) for SST retrieval from MTSAT data is based on the MCSST method (McClain et.al, 1985). SSTs retrieved with this method have large negative biases in seas where the satellite zenith angles exceed about 50 degrees. For advanced corrections of the atmospheric attenuations, an optimal estimation method (1DVAR) was developed at MSC. This method is going to be implemented in MSC's process of the SST retrieval from MTSAT data.

2. Space-based Data

Space-based data used for this development is the infrared data at the infrared channel 1 (IR1) and 2 (IR2) of the visible and infrared radiometry onboard MTSAT-2 (Fig. 1). The specks and response functions of IR1 and IR2 are shown in Table 1 and Fig. 2. The data is weighted mean of the radiation intensity. Sensor Planck function (eq.(1)-(3)) is used for the calculation of brightness temperatures.

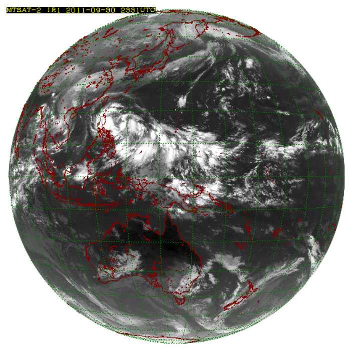

Fig. 1 Brightness temperature calculated from the infrared radiation intensity observed at IR1 (00UTC October 1, 2011)

$$B_i(T_i) \approx B_{\lambda_i}(T_i^e) \quad (1)$$

$$T_i^e = c_{1,i} + c_{2,i} T_i \quad (2)$$

$$B_{\lambda_i}(T) = \frac{2hc}{\lambda_i^5 (e^{\frac{hc}{k_B \lambda_i T}} - 1)} \quad (3)$$

i: channel number, B_i: sensor Planck function, T_i: brightness temperature, T_i^e: effective temperature, λ_i: wave length, c_{1i}, c_{2i}: constant coefficients, B_i: monochromatic Planck function, *h*: Planck constant, *c*: velocity of the right, *e*: base of natural logarithm, k_B: Boltsman constant

Channel	Wave Length (μm)	Central Wave Length	C1 (primary)	C2 (primary)
IR1	10.3 ~ 11.3	10.8	-0.0361	0.9999
IR2	11.5 ~ 12.5	12.0	-0.0976	1.0002
IR4	3.5~4.0	3.8	0.2304	0.9991

Table 1 Infrared Channels of the MTSAT-2
Channels used for SST estimation is shown with its wave range, central wave length and coefficients for sensor Planck function (eq.(2)).

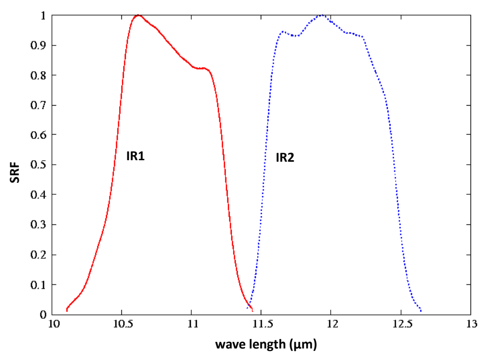

Fig. 2 Sensor Response Function (SRF) for the IR1 (red) and IR2 (blue) of the visible and infrared radiometry on board the MTSAT-2

3. Radiative transfer model

3.1 Atmospheric single layer model

An atmospheric single layer infrared radiative transfer model (hereafter single layer model) is installed (eq. (4)). It is possible to calculate infrared radiation more simply than full speck radiative transfer model. Further more, an emissivity model and a transmittance model are introduced for better calculation in seas far from subsatellite point.

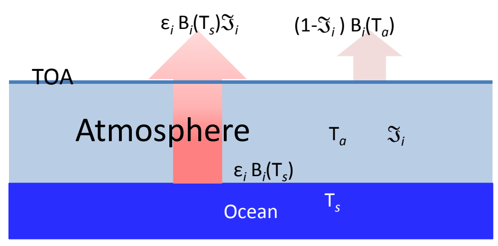

Fig. 3 Atmospheric single layer model for infrared radiation transfer

$$I_i = \varepsilon_i B_i(T_s)\Im_i + (1.-\Im_i)B_i(T_a) \quad (i=1,2) \quad (4)$$

i: channel number, I_i: radiation intensity, ε_i: emissivity of sea surface, B_i: sensor Planck function, T_s: sea surface temperature, $\Im_i$: transmittance, T_a: air temperature

3.2 Emissivity (ε_i)

Emissivity of the sea surface is a function of the emission angle and sea surface roughness. The isotropic Gaussian (IG) model with the Surface-emitted Surface-reflected (SESR) emission by Masuda (Masuda 2006) is adopted (Fig. 4-5, eq. (5)). Regarding wind speed, 6-hour forecast of JMA NWP is used. Fig. 6 shows the emissivity as a function of emission angle and wind speed.

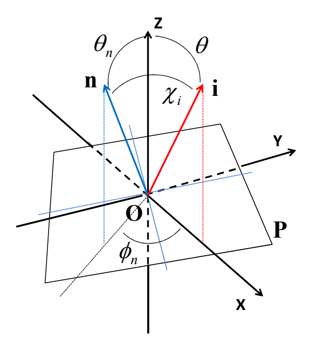

Fig. 4 Emissivity geometry from sea surface

O: an instantaneous point of sea surface, **P**: the wave facet tangent at **O**, **n**, θ_i, Φ_i: the facet unit normal vector, its zenith angle and its azimuth angle, **i**:, θ: unit emission vector and its zenith angle, χ_i: angle between **i** and **n**

$$\varepsilon_i(\theta,\nu) = \frac{1}{\cos\theta}\int_0^1\int_{-\pi}^{\pi}\varepsilon_i^0(\chi_i)\cos\chi_i P(z_x,z_y)\frac{1}{\cos\theta_n}^{-4} d\phi_n d\mu_n \quad (5)$$

i: channel number, ε_i: emissivity, ε_i^0: emissivity of a plane surface, *v*: wind speed, P: probability of the slopes, (Z_x, Z_y): slope component

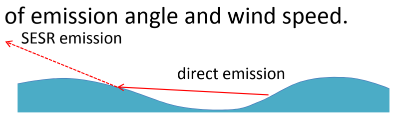

Fig. 5 Direct emission and Surface-emitted Surface-reflectance (SESR) emission

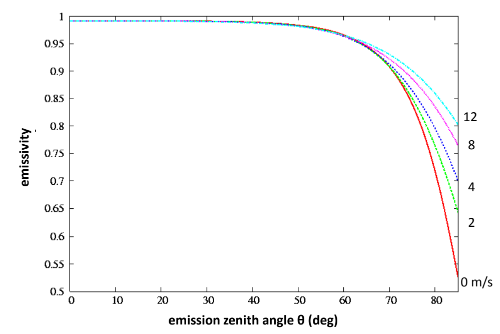

Fig. 6 Emissivity as a function of emission zenith angle (degree) and wind speed calculated with the IG-SESR model. Numbers on the right of each plots shows the wind speed in m/s.

3.3 Transmittance

The absorption by the water vapor which is a major gas for the atmospheric absorption is taken into account for the contribution to transmittance. For the calculation of transmittance, the infrared continuum absorption model by Robert (Robert 1976) is introduced. The transmittance by water vapor is a function of number of water molecules in unit mass, air temperature and pressure, partial pressure of water vapor and radiation path length (eq. (6)-(8)).

$$\Im_i = e^{-C_i^0 \exp(T_0\{\frac{1}{T_a}-\frac{1}{296}\})W_{H2O}\{P_{H2O}+\gamma(P-P_{H2O})\}L} \quad (6)$$

$$C_i^0 = \frac{\int C_\lambda^0 S_i(\lambda)d\lambda}{\int S_i(\lambda)d\lambda} \quad (7)$$

$$C_\lambda^0 = a + b\exp(-\beta\frac{10^4}{\lambda}) \quad (8)$$

i: channel number, $\Im_i$: transmittance, C_i^0: channel averaged absorption coefficient at temperature Ta=296K, T_0: temperature dependence parameter, C_λ^0: absorption coefficient at T_a=296K and wave length λ_i, W_{H2O}: number of water molcules in a unit mass, P,P_{H2O}: air pressure and partial pressure of water vapor, γ: a relative measure of the ambient to self-broadened water continuum term, L: radiation path length, a, b and β: constant coefficents

To simplify the calculation, a parameter σ, which is a function of water molecules, air pressure, partial pressure and radiation path length (eq. (9)), is installed. Then the transmittance is a function of air temperature and σ (eq. 10). Fig. 7 shows the transmittance at σ=0.1.

$$\sigma = W_{H2O}\{P_{H2O} + \gamma(P-P_{H2O})\}L \quad (9)$$

$$\Im_i = e^{-C_i^0 \exp(T_0\{\frac{1}{T_a}-\frac{1}{296}\})\sigma} \quad (10)$$

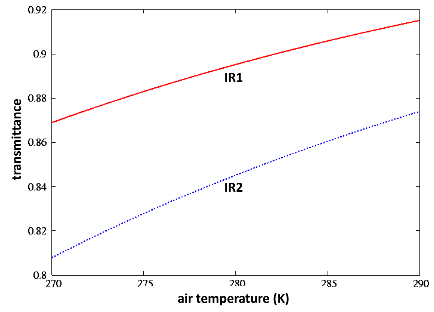

Fig. 7 Transmittance
Transmittance at σ=0.1 as a function of air temperature.

4. 1DVAR

To calculate SSTs with the single layer model, 1DVAR method is installed. SSTs are calculated by minimizing a cost function (eq. (11), (12)). **x** and $\mathbf{x_0}$ are a variable vector and its background state vector, **y** is an observation vector and H(**x**) is a forward operator. **B** and **R** are the error covariance matrix of the background states and the measurement vector **y**. I_1^x and I_2^x are infrared radiation intensities as a function of the **x**. The single layer model (eq. (4)) is applied for the calculation of these I_1^x and I_2^x.

$$J = (\mathbf{x}-\mathbf{x}_0)\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_0) + (\mathrm{H}(\mathbf{x})-\mathbf{y})\mathbf{R}^{-1}(\mathrm{H}(\mathbf{x})-\mathbf{y}) \quad (11)$$

$$\mathbf{x} = (T_s, T_a, \sigma) \quad (12)$$

$$\mathbf{y} = (I_1, I_2) \quad (13)$$

$$H(\mathbf{x}) = (I_1^x, I_2^x) \quad (14)$$

Back ground state is required to calculate the SSTs. T_s, T_a and σ are calculated from buoy data and MTSAT-2 data by solving a simultaneous equations (eq. (15)). The buoy data is collected via GTS and other local networks. Then quality control is conducted. Fig. 9 shows T_a and σ calculated from the data in July 2010 to June 2011. Then each T_a and σ are averaged over the bins of T_1x(T_1-T_2)xθ_z (T_1, T_2 : brightness temperatures at IR1 and IR2, θ_z: satellite zenith angle) and used as the background states.

$$\begin{cases} I_1^{sat} = \varepsilon_1 B_1(T_s^{in\text{-}situ})\Im_1 + (1.-\Im_1)B_1(T_a) \\ I_2^{sat} = \varepsilon_2 B_2(T_s^{in\text{-}situ})\Im_2 + (1.-\Im_2)B_2(T_a) \end{cases} \quad (15)$$

I_1^{sat}, I_2^{sat}: observed radiation intensity at IR1 and IR2, $T_s^{in\text{-}situ}$: buoy data, ε_1, ε_2 : emissivity, B_1, B_2: sensor Planck function, $\Im_1$, $\Im_2$: transmittance, T_a: air temperature

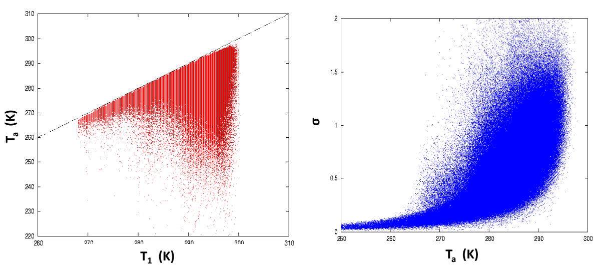

Fig. 9 T_a (left) and σ (right) calculated from buoy data and MTSAT-2 data in July 2010 to June 2011.

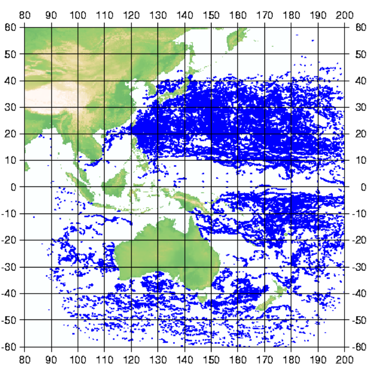

Fig. 8 Buoy Locations
Locations of moored and drifting buoys from July 2010 to June 2011 which used for the calculation background states.

5. Quality

The 1DVAR method was applied for the MTSAT-2 data in five days from October 1-5, 2011. Fig. 10 and Table 2 shows the calculated SSTs and their estimated results against buoy data. Table 3 shows the results of current SST product. BIAS and RMSE of all of the data were improved from -0.44K and1.32K to 0.03K and 0.67K. This is because the correction of emissivity and atmospheric attenuation is improved by introduction of the single layer model and 1DVAR method.

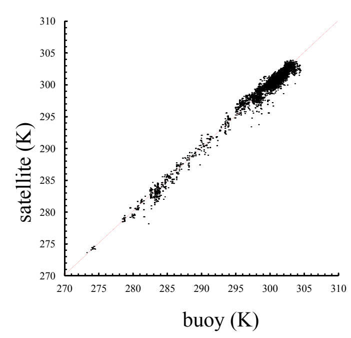

Fig. 10 MTSAT-2 SSTs as a function of buoy data

Table 2 (satellite-buoy)

SST[K]	N	BIAS	RMSE	STD
-283	176	0.13	0.79	0.78
283-293	475	-0.02	0.77	0.77
293-	7883	0.03	0.66	0.66
ALL	8534	0.03	0.67	0.67

Table 3 (current product-buoy)

SST[K]	N	BIAS	RMSE	STD
-283	35	0.46	0.74	0.58
283-293	434	-0.10	1.29	1.28
293-	6516	-0.47	1.33	1.24
ALL	6985	-0.44	1.32	1.24

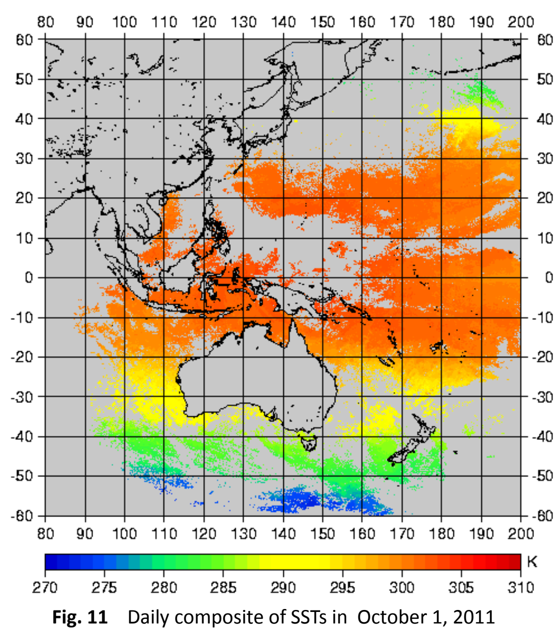

Fig. 11 Daily composite of SSTs in October 1, 2011

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