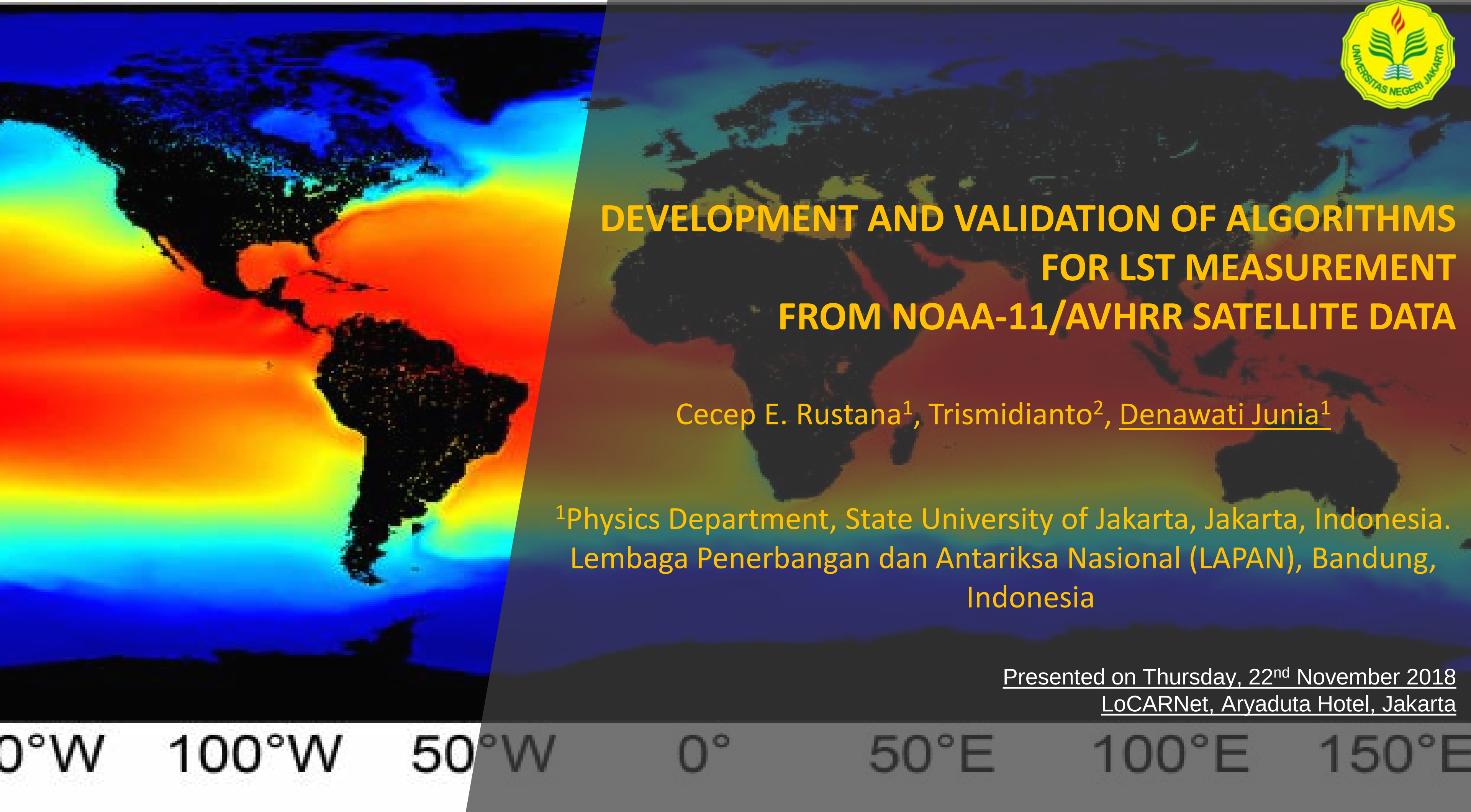


# DEVELOPMENT AND VALIDATION OF ALGORITHMS FOR LST MEASUREMENT FROM NOAA-11/AVHRR SATELLITE DATA

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# LST

Land Surface Temperature (LST), it is potentially valuable in modeling and prediction studies of small scale through to synoptic scale processes. Because of the LST variability, both spatially and temporally (Prata et al, 1990).

Pict. of NOAA Satellite with AVHRR Sensor

The difficulties in accurately determining LST:

1. In-homogeineity of the land surface (Becker, 1987)
2. Variability of surface emissivity and topography
3. Temperature and moisture structure of the overlying atmosphere.

The relative flatness of emissivity for the land surface in the 10 - 12 µm thermal region (Schmugge et al., 1991) encourages the use of the split window approach to correct upwelling radiances for atmospheric water vapor absorption.

# Radiative Transfer Equation in the Thermal Infrared

## LAMBERTIAN REFLECTOR

the radiative transfer equation for the outgoing thermal infrared radiance *Ii* received by channel *i* of a satellite's sensor may be expressed as:

$$I_i(\theta) = \varepsilon_i(\theta) B_i(T_s) \tau_i(\theta) + \int_0^p B_i(T_p) \frac{\partial \tau_i(\theta, p)}{\partial p} dp + [1 - \varepsilon_i(\theta)] \tau_i(\theta) L_i$$

Eq. 1

Surface emissivity

Zenith angle

Surface Temperature

Planck Function

Armospheric Transmittance

Armospheric Temperature At pressure p

Weighting Function

hemispherical down-welling atmospheric radiances at a wavelength *i*

$\rho_I(\theta)$, the hemispherical reflectivity

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# Radiative Transfer Equation in the Thermal Infrared

Simply form of equation 1:

$$I_i = \tau_i\left[\varepsilon_i B_i(T_s) + (1-\varepsilon_i)L_i\right] + \int_p^0 B_i(T_p)\frac{\partial\tau_i(p)}{\partial p}dp$$

Eq. 2

Apply the mean value theorem, yielding:

$$\int_p^0 B_i(T_p)\frac{\partial\tau_i(p)}{\partial p}dp = (1-\tau_i)\bar{B}_i$$

Eq. 3

# Radiative Transfer Equation in the Thermal Infrared

$\bar{B}$ is the Planck radiance averaged over the transmission function. Rewriting (2) using (3), we obtain:

$$I_i = \tau_i \left[ \varepsilon_i B_i (T_s) + (1 - \varepsilon_i) L_i \right] + (1 - \tau_i) \bar{B}_i$$

Eq. 4

where now $\varepsilon_I$ is the band averaged emissivity for channel *i, i* is the band averaged transmittance for channel *i, Li* is the down-welling component of the flux of sky radiance, *Bi(Ts)* is the surface Planck radiation, *Ts* is the surface temperature and *Bi* is the radiance emitted by the atmosphere.

# Split Window Method

Based on the regression scheme proposed by Anding and Kauth (1970), which related window radiance measurements at two adjacent wavelengths to sea surface temperature (SST), McMillin (1971) used the radiative transfer equation to develop a theoretical justification for that method.

Using equation (4) , we may write the up-welling radiance at the satellite in terms of the split window channels 4 and 5 of AVHRR:

$$I_4 = \tau_4\left[\varepsilon_4 B(T_s) + (1-\varepsilon_4)L_4\right] + (1-\tau_4)\bar{B}_i \quad \text{Eq. 5}$$

$$I_5 = \tau_5\left[\varepsilon_5 B(T_s) + (1-\varepsilon_5)L_5\right] + (1-\tau_5)\bar{B}_i \quad \text{Eq. 6}$$

# Split Window Method

by expanding the Planck function to first order about a mean radiance value, we obtain;

$$T_s = \left(\frac{1+\chi}{\varepsilon_4}\right)\left(\frac{1}{1+\chi\tau_5\frac{\Delta\varepsilon}{\varepsilon_4}}\right)T_4 - \left(\frac{\chi}{\varepsilon_4}\right)\left(\frac{1}{1+\chi\tau_5\frac{\Delta\varepsilon}{\varepsilon_4}}\right)T_5 + \left(1-\frac{\frac{1}{\varepsilon_4}}{1+\chi\tau_5\frac{\Delta\varepsilon}{\varepsilon_4}}\right)L_{sky}\left(\frac{\partial B}{\partial T}\right)_{T_s}^{-1} \quad \text{Eq. 7}$$

where:

$$\chi = \frac{1-\tau_4}{\tau_4-\tau_5} \qquad \chi = \frac{1-\tau_4}{\tau_4-\tau_5}$$

$T_4$ = the brightness temperature of AVHHR channel 4.

$T_5$ = the brightness temperature of AVHRR channel 5.

$L_{sky}$ = the sky radiance, assumed to be the same for both channels.

# Split Window Method

The last term in equation (7) generally is small because the sky radiance is low (for clear skies with low water vapour, *Lsky* (11 µm) 60 mW/(m str cm-1), and the emissivity is typically high ( 0.9). With the Planck derivative evaluated for 285K, and the highest expected value for the sky radiance, the term will give *Lsky(B/T)* = 40 (Prata, 1991). Equation (7) above may be simplified further by assuming the spectral emissivity difference is very small, yielding:

$$LST = 40\left(1 - \frac{1}{\varepsilon}\right) + \left(\frac{1+\chi}{\varepsilon}\right)T_4 - \left(\frac{\chi}{\varepsilon}\right)T_5 \quad \text{Eq. 8}$$

$$LST = a + bT_4 + cT_5 \quad \text{Eq. 9}$$

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# Split Window Method

The outcome of a recent study (Axelsson, 1985) indicates that a constraint may be applied to the coefficients in equation (5). Specifically, *b + c = 1*, may be used without any significant increase of the estimated error, especially for SST determination.

$$LST - T_4 = a_o + b_o\left(T_4 - T_5\right)$$ Eq. 10

If the quantity $(T_4 - T_5)$ is set equal to ΔT, then we may regard equation (10) as the first order term of the more general expansion:

$$LST - T_4 = a_o + a_1 \Delta T + a_2 \Delta T^2$$ Eq. 11

# REGRESSION EQUATION COEFFICIENT

Our synthetic study yielded an LST algorithm to first order given by,

$$LST - T_4 = 2.0687 + 2.8093(T_4 - T_5) \quad \text{Eq. 12}$$

And two second order:

$$LST - T_4 = 2.1489 + 2.5961(T_4 - T_5) + 0.1099(T_4 - T_5)^2 \quad \text{Eq. 13}$$

# REGRESSION EQUATION COEFFICIENT

We obtained respectively the LST regression relations for first and second order as follows,

$$LST - T_4 = (1.9745 \pm 0.0297) + (2.7608 \pm 0.0322)(T_4 - T_5)$$

Eq. 14

$$LST - T_4 = (2.1031 \pm 0.0527) + (2.5539 \pm 0.0468)(T_4 - T_5) + (0.0564 \pm 0.0302)(T_4 - T_5)^2$$

Eq. 15

# Expected Algorithm Performance

The synthetic study performed using Alice Springs' (January) climatological data indicates the LST algorithms (equations (12) and (14)) provide accurate estimates of LST. Note that use of regression in deriving the coefficients for equation (10) and (11) minimized the bias errors in the radiative transfer calculation which may arise from air mass dependence. However, this analysis identified that the second order relationships (equations 13 and 15) provided a slightly reduced rms errors when compared to the performance the first order schemes (equation 12 and 14).

# Expected Algorithm Performance

Using the brightness temperatures for channels 4 and 5 for the Alice Springs' data set, the performance, without additive Gaussian noise, gave an rms error of 0.15 °C, for both the first and second order regression schemes. Whereas, an rms errors of about 0.55 °C were determined for the first and second order formulations using the additive Gaussian noise of 0.12 K standard deviation. This study recommends the application of these algorithms for estimating LST yield to an accuracy of about 1°C, providing that the land surface's physical properties are well characterized.

# Expected Algorithm Performance

The expected performance figures quoted earlier were based on how the algorithm estimate LST compared to the LST input to the radiative transfer calculation, with the latter using climatological data. We now describe the performance using NOAA/AVHRR radiances and in-situ LST measurements. We validated our LST retrieval by applying our algorithms (equations 12 -15) to field data measured at the Walpeup Field Site (35*11'58'' S, 142*03'51'' E) located in a wheat growing area in NW Victoria (Australia). The site has been instrumented by CSIRO Division Atmopheric Research with an array of temperature sensors installed over an area roughly 1.1 km by 1.2 km. It is a large uniform field of red sandy soil typical of the inland parts of semi-arid Australia. The field was initially bare, then sown to wheat, then barley and finally left fallow, over a period of 2 years. Measurements used in this study have been made during the whole of the last two years (Prata, 1992).

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# Expected Algorithm Performance

An analysis of in-situ measurement (50 measurements) that are coincident in time with the satellite's measurements, yield overall LSTs of about 1 $^{0}$C accuracy. The analysis also indicates high correlation between satellite and in-situ measurements with a correlation coefficient r2 of about 0.99. The algorithm of equation (12) gave rms error of 1.00 *C with bias of -0.16. Further, rms errors of 0.98 *C with the bias of -0.28 were achieved using the algorirthm described by equation (13). The algorithms of equations (14) and (15) yield respectively rms errors of 0.98 *C with a bias of -0.03, and 0.95 *C with the bias of -0.11. Figures 5 and 6 present the correlation of LSTs for in situ and satellite measurements, for both first and second order regression schemes using data which included Gaussian noise synthetized sensor (equations 14 and 15, respectively).

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# CONCLUSIONS

1. The estimation of LST to acceptable accuracy is very dependent on correctly characterizing the atmosphere.
2. The analysis indicated that using brightness temperature of the thermal channels of AVHRR/NOAA, algorithms may be used to determine LST to an accuracy of order 1°C with a correlation coefficient of about 0.99.
3. The second order regression scheme indicates a possibility for improving LST measurement accuracy.
4. An analysis of in-situ measurement (50 measurements) data from Victoria field station of the CSIRO Division of Atmospheric Research. that are coincident in time with the satellite's measurements, yield overall LSTs of about 1 $^{0}$C accuracy.

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