A new method for retrieving land surface temperature from HJ-1B data and the temporal influences

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Abstract. According to radiation transfer equation (RTE), it is an ill-conditioned problem to obtain land surface temperature (LST) accurately from the HJ-1B thermal infrared channel. Several algorithms have been proposed to resolve this problem. However, some accurate inputs (e.g. atmospheric parameters and land surface emissivity) always inaccessible to common users are indispensable to their applications. An innovative approach (named MTSC method) based on multi-temporal data was described in this paper, by means of which the LSTs are able to be estimated readily and directly from the radiometrically corrected thermal images, even without any other accurate information. To demonstrate its capability, four HJ-1B images (acquired on Nov 28, Dec 10, Dec 18 and Dec 22, 2011, respectively) mainly covering the Pearl River Delta region were selected for LSTs estimation. The LSTs retrieved by the MTSC method were then compared with the near time MODIS surface temperature products, and the samples were collected through a proper procedure. The preliminary assessments demonstrated that accurate results were obtained by using this new method. For example, for the retrieved results of Dec 22, the systematic errors for land cover and sea area were approximate to 1K and 0.5K, respectively. Further comparisons show that the temporal influence was negligible in this experiment, mainly because of the moderate impacts arisen from the atmospheric variation on the surface thermal property, which was acceptable for the MTSC method. However, modifications and improvements are still necessary to enable the full usage of this new approach.

1. Introduction
Land surface temperature (LST), widely considered as a key indicator influencing the environment and ecological system, is involved in many land surface processes. Currently, owing to their high sampling rate and repetitive basis over large and heterogeneous regions, sensors with thermal infrared channel onboard satellite platforms provide feasible way to measure the spatial and temporal LST variations, at both regional and global scales.

Two satellites named HJ-1A and HJ-1B (mainly proposed by the Ministry of Environmental Protection and National Committee for Disaster Reduction, China) were launched on September 6, 2008, being intended for environment and disaster monitoring and forecasting. The infrared scanner (IRS) onboard HJ-1B has one thermal infrared band, of which the radiometric resolution is better than 1.0 K. The nadir spatial resolution of the thermal band is 300 m and the swath width is 720 km，thus the repeat cycle is four days (*http://www.cresda.com/n16/index.html*). At present, to retrieve surface temperature from the single thermal band, several solutions have been proposed [1-4], and the

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modified versions for HJ-1B IRS have also been developed [5]. For these current methods, the atmospheric water vapour content, surface air temperature and surface emissivity are important and indispensible inputs. Generally, acceptable results are able to be obtained given that these inputs are accurate. Nevertheless, for common users, it is difficult. For example, the adequate and accurate collections of atmospheric parameters are inaccessible in most cases.

The purpose of this study is to introduce and assess a new approach (named MTSC), particularly for HJ-1B IRS data. The MTSC method is intended to estimate LSTs directly from the sensor detected radiances. Followed by some experiments and assessments, refinements for this method are also discussed.

2. Methodology

Assuming the Earth's surface as a Lambertian emitter-reflector, the radiance observed in a specific thermal band, can be simply expressed as follow:

$$(L^s)_P^t = \varepsilon_P^t \tau_P^t (B(T_s)_P^t) + (\tau_P^t (1-\varepsilon_P^t) L^{atm\downarrow t}{}_P + L^{atm\uparrow t}{}_P) \tag{1}$$

Where, L^s is the top-of-atmosphere radiance detected by sensor, τ is the atmospheric transmissivity and $L^{atm\uparrow}$ is the up-welling atmospheric radiance, while $L^{atm\downarrow}$ is the down-welling one, ε is the surface emissivity, T_s is the surface temperature and $B(T_s)$ is the blackbody radiance given by the Planck's law. Additionally, 't' marked superscript is a temporal indicator, while 'P' subscript is a spatial indicator. Here, the impacts caused by the observing geometry are ignored.

A parameter called 'totally atmospheric impacts parameter' (denoted as A_{atm}) was defined, in this paper. Furthermore, the surface emissivity and atmospheric transmissivity were considered as an integrated variable ($\varepsilon\tau$). Accordingly, the equation (1) for each pixel (P) at a specific time (t) can be expressed as the simplified form:

$$(L^s)_P^t = (\varepsilon\tau)_P^t (B(T_s)_P^t) + (A_{atm})_P^t = f((\varepsilon\tau)_P^t, B(T_s)_P^t, (A_{atm})_P^t) \tag{2}$$

There are still three variables, including $(\varepsilon\tau)_P^t$, $(A_{atm})_P^t$ and $B(T_s)_P^t$ or $(T_s)_P^t$, needing to be resolved with the known variable $(L^s)_P^t$. Conventionally, it is an ill-conditioned problem to estimate three variables from one equation simultaneously.

A new methodology called MTSC (multi-temporal and spatial single channel method) was proposed to tackle the retrieving issue. The MTSC method is mainly based on three assumptions:

- For a target pixel (P_0), there are N similar pixels (P_1, P_2,···, P_{N-1}, P_N) locating around it. In this paper, similar pixels are selected according to spectral similarity in view of the reflectance property. The spectral similarity is measured by means of the root mean square deviation (RMSD). By the way, the neighbourhood is defined as a moving window around P_0 with the extent of Win_M×Win_M pixels (in this paper, it was set to 7).
- At a specific time (t), the similar pixels and P_0 have an identical emissivity, and the spatial heterogeneity of atmospheric condition within a moving window is negligible.
- Given that there are none obvious changes in atmospheric conditions between two acquisition times (t_i and t_j), the similar pixels and P_0 change in the same way, both in surface temperature and emissivity (denoted as ΔT_s and $\Delta\varepsilon$, respectively). Particularly, it is rational to assume that the emissivity does not change (that is, $\Delta\varepsilon = 0$), if the acquisition times are close enough.

According to these, an equation set (equation (3)) combined by the two time's (t_i and t_j) radiance equations of the target pixel and the N similar pixels is obtained, which includes 2(N+1) equations and N+6 unknown parameters. The unknown parameters include N+1 LSTs ($(T_s)_{P_0}^{t_i}, (T_s)_{P_1}^{t_i}, \cdots, (T_s)_{P_N}^{t_i}$), two integrated values ($(\varepsilon\tau)^{t_i}, (\varepsilon\tau)^{t_j}$), two integrated atmospheric parameters ($(A_{atm})^{t_i}, (A_{atm})^{t_j}$) and the ΔT_s. It suggests that, ideally, this equation set is able to be resolved when the number of similar pixels is no less than 4 (namely $N \geq 4$). In the current version, the equation set is resolved by means of optimizing a nonlinear equation with constraints.

$$
\begin{cases}
(L^s)_{P_0}^{t_i} = f((\varepsilon\tau)^{t_i}, B(T_s)_{P_0}^{t_i}, (A_{atm})^{t_i}) \\
(L^s)_{P_1}^{t_i} = f((\varepsilon\tau)^{t_i}, B(T_s)_{P_1}^{t_i}, (A_{atm})^{t_i}) \\
\qquad\qquad \ldots \\
(L^s)_{P_N}^{t_i} = f((\varepsilon\tau)^{t_i}, B(T_s)_{P_N}^{t_i}, (A_{atm})^{t_i}) \\
(L^s)_{P_0}^{t_j} = f((\varepsilon\tau)^{t_j}, B(T_s + \Delta T_s)_{P_0}^{t_j}, (A_{atm})^{t_j}) \\
(L^s)_{P_1}^{t_j} = f((\varepsilon\tau)^{t_j}, B(T_s + \Delta T_s)_{P_1}^{t_j}, (A_{atm})^{t_j}) \\
\qquad\qquad \ldots \\
(L^s)_{P_N}^{t_j} = f((\varepsilon\tau)^{t_j}, B(T_s + \Delta T_s)_{P_N}^{t_j}, (A_{atm})^{t_j})
\end{cases}
\tag{3}
$$

For application, the retrieving processes are generally divided into three parts: inputting，retrieving and outputting. In the retrieving, a loop procedure is implemented, estimating the preliminary surface black body radiance pixel-by-pixel. Proper procedures should be implemented to identify the outliers in the preliminary results and revise them consequently. Then, LST results can be retrieved from the revised radiances through the inversion of Plank's law or its simple version [6], and the method information for each pixel is provided simultaneously.

3. Datasets
In this paper, our interested area is the Pearl River Delta (PRD) locating around the coat of South China Sea. Four HJ-1B IRS images acquired on Nov 28, Dec 10, Dec 18 and Dec 22, 2011, respectively were selected. Three CCD images, acquired by HJ-1A or HJ-1B, with the same or similar acquisition time to these IRSs were selected correspondingly, specifically on Dec 10, Dec 18, and Dec 25, 2011 respectively. By the way, the HJ-1B CCD image acquired on Dec 10 is the most close and available one to the HJ-1B IRS data of Nov 28. It is reasonable to assume the thermal conditions of these four HJ-1B acquisitions are generally similar, in the same season (winter). For assessing the accuracy of the retrieved results, the MODIS sea surface temperature products (SST) (obtained from *http://oceancolor.gsfc.nasa.gov/*) and the MODIS land surface temperature product (MOD 11) (obtained from *https://lpdaac.usgs.gov/*) were used. In addition, the MODIS atmospheric products (MOD 05) were also used to get the knowledge about atmospheric water vapour content.

4. Results and discussion
MODIS Terra passes over our study area nearly the same as HJ-1B does. The surface temperature products of MODIS Terra may provide a chance to test the retrieved results from HJ-1B IRS data. Particularly, the sea surface temperature can be accurately obtained from MODIS Terra with minor error ($0.2 \pm 0.26K$) (Minnett et al, 2002) [7]. To eliminate the influences caused by the spatial resolution differences between MODIS and HJ-1B, the proper sampling procedure was applied for accuracy assessment [8], to select the relatively homogeneous samples. In addition, for the comparisons among different cases, the commonly selected samples were lastly determined. Then, the validation results based on the commonly selected samples were analyzed. In this paper, three error measurements usually used were applied, including root mean square error (RMSE), systematic error (SE) and absolute median error (MAE) [8].

The MTSC method was initially proposed to retrieve LSTs from two HJ-1B IRS imageries acquired on adjacent days, during which there are none abrupt changes either in meteorology or atmosphere. It is desirable to explore the potential impacts and possible refinements on the MTSC method, when the ideal condition is not met. Taking into account the number of images, in this study, for each HJ-1B IRS image there are totally three chances for being possibly used as inputs. It is necessary to find out which combination is superior to others.

For achieving these goals, comparisons were conducted, and just parts of the results will be discussed due to the lack of space. Setting the results from Dec 22 for example, the potential impacts of different temporal combinations were assessed, specifically with combing the data acquired on Nov

28, Dec 10 and Dec 18 respectively (the combinations were denoted T22_28, T22_10 and T22_18, respectively). Accordingly, the combination T22_18 is supposed to be the ideal one (figure 1).
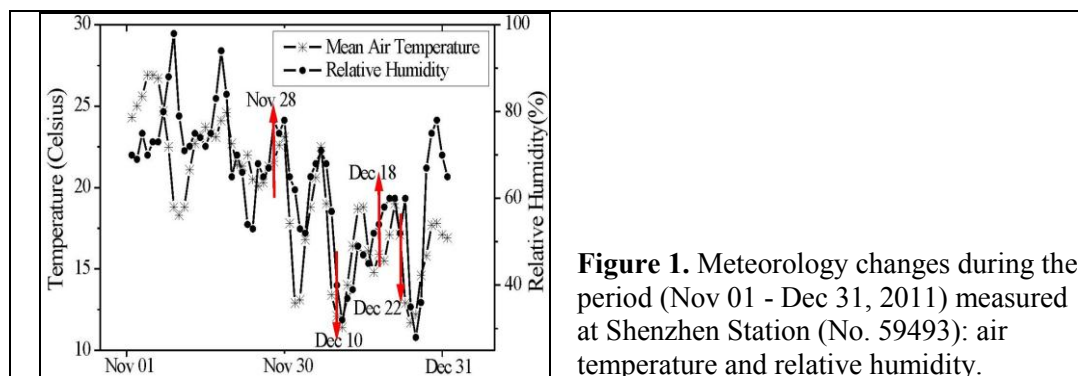

Figure 1. Meteorology changes during the period (Nov 01 - Dec 31, 2011) measured at Shenzhen Station (No. 59493): air temperature and relative humidity.

The accuracy assessment results (table 1) show that the error indicators for the retrieved results are less than 1K (about 0.5K) when compared with the MODIS SST products, no matter which combination was used. Meanwhile, for land cover, when compared with MOD 11 product, the errors are more obvious, specifically with the mean bias about -1K and RMSE about 1.5K. Actually, as shown in table 1, the approximate error measurements among different choices, may suggest that the temporal influence is negligible in this experiment. As figure 1 shows, the meteorological condition varied more or less during this period, but there was none obvious precipitation. That is to say, this kind of atmospheric variation with moderate impacts on the surface thermal property is acceptable for the MTSC method, so that the temporal influences would be negligible.

Table 1. Accuracy assessment results, for general settings

	SST			LST		
	SE	RMSE	MAE	SE	RMSE	MAE
T22_28	-0.38	0.66	0.25	-0.60	1.21	0.66
T22_10	-0.40	0.68	0.30	-1.14	1.55	0.95
T22_18	-0.60	0.79	0.46	-0.96	1.44	0.84

It is worth to mention, for case T22_18, compared with the previous study (in press), there are slight differences in accuracy measurements here, which is probably resulted from the sampling criteria and the differences in the last samples.

However, refinements are still necessary to improve the MTSC's performance. For instance, improvements will be achieved through perfecting the initial settings in the retrieving procedure. For its current version, the initial settings are necessary, including the valid and possible ranges for surface temperature, atmospheric water vapour content, surface emissivity and the surface radiance variation. In previous experiments, according to the climatologic condition of the study area, the surface temperature range was set as (280~310K), while the emissivity was (0.95~1.0) and the atmospheric water vapour content was (1~3g/cm^2). In addition, the settings of possible and valid radiance variation are also desirable. The records shown in figure 1 indicate the different meteorological and atmospheric conditions in these four imagery acquisition days. Considering the facts, the surface radiance variations were roughly estimated according to the daily meteorological records and brightness temperatures observed, in this study. With these general settings, results were obtained properly with acceptable accuracy (table 1). However, that general framework for initial settings has potential ineffectiveness. Therefore, more reasonable specifics should be necessary. For example, the spatial distribution of atmospheric water vapour content varied obviously among these days, as shown in MOD 05 products. It suggests that the previously general setting for atmospheric water vapour content might be problematic. The refined results were then obtained by redefining the initial settings based on other auxiliary information and assumptions (called specific settings). Significant improvements were

achieved by the specific settings, particularly for the land cover (not mentioned here). More detailed discussions on this issue are worthy; however, we just mentioned it briefly in this paper, mainly due to the space limitation. One retrieved result with specific settings (T22_18) was shown in figure 2. It is clear that the result retrieved from HJ-1B IRS is spatially consistent with the MODIS product; furthermore, it shows more details on surface temperature variation mainly due to its relatively higher spatial resolution.
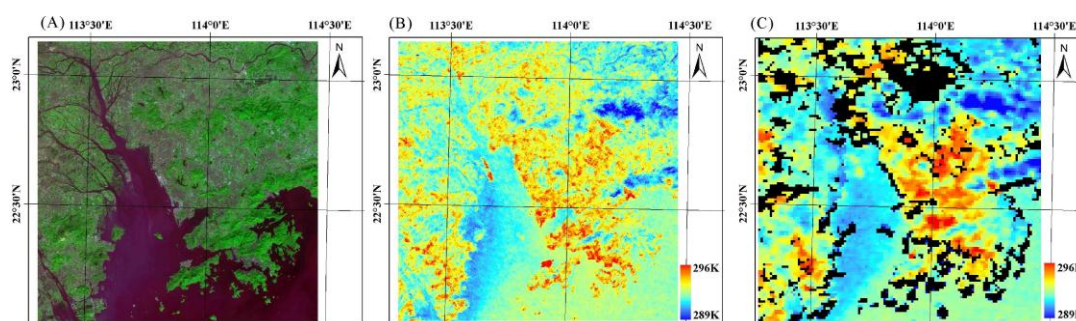

Figure 2. The study area and surface temperature (A):The study area; (B): Surface temperature results retrieved from HJ-1B, on Dec 22, using the MTSC method with specific settings, and the spatial resolution is 300m; (C) Combined results from MODIS LST/SST products with spatial resolution of 1km (areas filled with black color are provided with invalid data).

5. Conclusions

Presently, there have been several methods (e.g. the mono-window algorithm and single-channel method[1-5]) proposed for estimating surface temperature from remotely sensed imagery with one thermal band, such as Landsat TM/ETM+, CBERS and HJ-1B. They are able to perform well given that accurate information about atmosphere and surface emissivity is prepared. However, for common users, that accurate information is always impossible to obtain. To tackle this kind of problem, the MTSC method was developed, initially to obtain surface temperature from HJ-1B IRS data, even without any accurate information related to the atmospheric parameters and land surface emissivity. According to the experiments discussed in this paper, the MTSC method provides a good way for retrieving surface temperature from HJ-1B data, in addition to the already existing methods. At the same time, if atmospheric variation is moderate, the temporal influences on the MTSC would be negligible. Obviously, for common users, the advantage of this new approach relies on the fact that accurate and simultaneous information on atmosphere and surface emissivity is unnecessary. However, improvements are still necessary to refine the MTSC method, especially by perfecting the initial settings on more reasonable bases, so as to enable its full usage. By the way, this innovative methodology may also be suitable for other sensors, including Landsat TM/ETM+.

6. Acknowledgements

7. References

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