SELECTION OF DIFFERENT EXTRATERRESTRIAL SOLAR SPECTRAL IRRADIANCE DATASETS AND ITS EFFECTS ON MEAN SOLAR EXOATMOSPHERIC IRRADIANCE

Hu Shunshi[*1], Zhang Lifu[2], Su Yu[1] and Liu Li[1]
[1]Graduate Student, Institute of Remote Sensing Applications Chinese Academy of Sciences, 20 north of Datun Road, Chaoyan district, Beijing, China; Tel: +86 64839450;
E-mail: hufrank@163.com

[2]Professor, Institute of Remote Sensing Applications Chinese Academy of Sciences, 20 north of Datun Road, Chaoyan district, Beijing, China; Tel: +86 64839450;
E-mail: zhanglf@irsa.ac.cn

KEY WORDS: Extraterrestrial Solar Spectral Irradiance; Mean Solar Exoatmospheric Irradiance of Each Band; Thuillier; SBDART; MODTRAN

ABSTRACT: Extraterrestrial Solar Spectral Irradiance (ESSI) is an important parameter for calculating Mean Solar Exoatmospheric Irradiance (MSEI) of each band for a given satellite. In order to find optimal ESSI dataset for calculation of MSEI, 5 ESSI datasets from MODTRAN4.0 software and ESSI dataset simulated by Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) tool were selected to compute MSEI of each band for HJ-1A CCD1, CEBERS02 CCD, Landsat TM5(band1~band4) and ASTER(band1~band9). Comparisons between the calculated MSEI and the published MSEI were made. It is found that ESSI dataset simulated by SBDART tool and MODTRAN oldkur.dat dataset are best suitable for calculation of MSEI and the MSEI results are consistent with published MSEI. There are big errors using MODTRAN thkur.dat and newkur.dat datasets to compute MSEI for these satellites, so that they are not recommended to calculate MSEI for given satellites.

1. INTRODUCTION

As the only source of Earth's energy, Sun maintains all life on Earth, energy transformation and circulation between atmosphere and surface, and it is also a stable source of electromagnetic radiation for satellite remote sensing. Extraterrestrial solar spectral irradiance (ESSI) means how much solar radiation energy a blackbody obtains per unit time and unit area, at the top of the earth's atmosphere, on the average Sun-Earth distance and perpendicular to the direction of the sun incident. It is a constant value about $1.36 \times 10^3 \mathrm{W}/m^2$ in the whole solar spectrum range. According to Planck's Law, extraterrestrial solar irradiance is roughly approximate to blackbody radiation with a temperature of about 6000K, and about 97.5% of all solar radiation energy is covered within 0.31∼5.6μm spectrum range, where VIS accounts for 43.5% and NIR 36.8% respectively (Zhao, 2003). Mean solar exoatmospheric irradiance (MSEI) is the convolution of the band's spectral response function with the ESSI dataset. MSEI is a constant value for a given satellite and is important for calculation of TOA reflectance.

VIS/NIR and SWIR spectral ranges are commonly used for optical satellite detecting and remote sensing applications, in which most of the solar radiation energy is concentrate. It is crucial to use accurate ESSI retrieving quantitative parameters, such as TOA reflectance and surface reflectance. There are 5 ESSI datasets in MODTRAN 4.0 software. ESSI dataset could also be simulated by SBDART and Pan used that dataset to retrieve MSEI of CEBERS02 CCD and achieved excellent performance (Pan, 2008). This study is mainly focused on finding the best ESSI dataset for calculation of MSEI for given satellites. 6 ESSI datasets, 5 of them from MODTRAN4.0 and 1 was simulated by SBDART, were selected to compute MSEI. Comparison between the calculated MSEI and the published MSEI is presented subsequently and a summary of the main findings is provided finally.

2. CALCULATION OF MSEI FOR EACH BAND

MSEI, referred as E_0, is the integration of ESSI dataset and corresponding spectral response function. Spectral response function is spectral sensitivities of a given sensor to incoming solar radiation energy and provided by sensor manufacturer. E_0 could be calculated following formula (1).

$$E_0 = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda)S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda} \tag{1}$$

where $E(\lambda)$ is the ESSI, $S(\lambda)$ is the spectral response function for a given satellite sensor, λ_1, λ_2 is the lower and upper wavelength for specific band respectively. If $E(\lambda)$ and $S(\lambda)$ are known, MSEI could be calculated. Generally $E(\lambda)$ could be simulated by tool or from a dataset and $S(\lambda)$ may be provided by sensor manufacturer.

3. SELECTION OF ESSI DATASETS

3.1 MODTRAN ESSI Datasets

MODTRAN is a tool for solar radiative transfer and is popular and widely used. There are 5 ESSI datasets, cebchkur.dat, chkur.dat, newkur.dat, oldkur.dat and thkur.dat, in the installation directory ".\Bin\Data". These ESSI datasets spectral region range from 50 to $50000 cm^{-1}$ at $1 cm^{-1}$ resolution and with unit of $W/cm^2/sr/cm^{-1}$. Details of the 5 ESSI datasets are shown in Table 1.

Table 1 MODTRAN ESSI datasets

Name	Database File	Solar Constant（W/m^2）
Cebula + Chance database	cebchkur.dat	1362.12
Chance database	chkur.dat	1359.75
Corrected Kurucz database	newkur.dat	1368.00
Older Kurucz database	oldkur.dat	1373.01
Thullier+corrected Kurucz database	thkur.dat	1376.23

Of the 5 ESSI datasets, solar constant which is integration of wavelength and solar radiation energy is different from each other, and the difference of maximum and minimum solar constant is about $16.48 W/m^2$. Due to these reasons, using different ESSI datasets to calculate MSEI may produce various results. Of the 5 ESSI datasets, cebchkur.dat is similarly to chkur.dat and the biggest difference between them is only about $2.3459 \times 10^{-6} W/cm^2/sr/cm^{-1}$, and they are completely identical when wavelength is greater than 0.417μm. Fortunately, spectrum region used in remote sensing generally ranges from VIS, roughly 0.43μm, to SWIR, roughly 2.50μm. In this study, chkur.dat is selected only from these 2 datasets to calculate MSEI. All of the ESSI curves are shown in Figure 1.

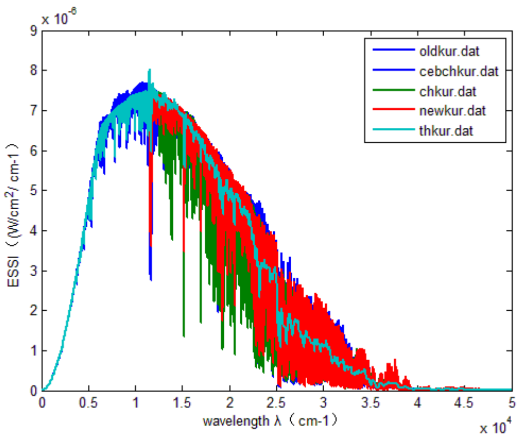


Figure 1 ESSI selected from MODTRAN4.0

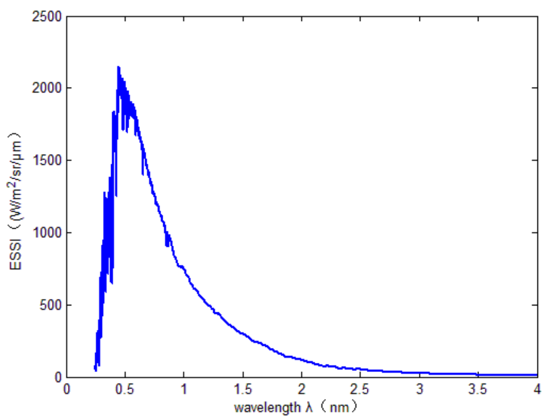


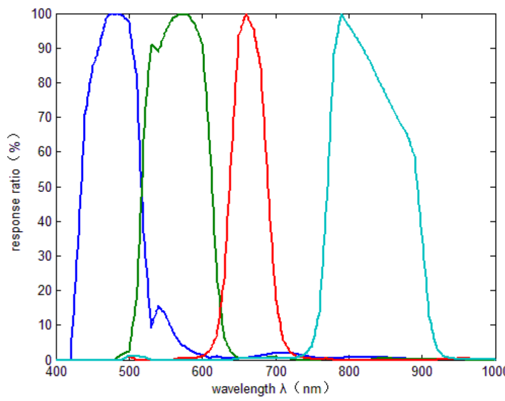
Figure 2 ESSI simulated by SBDART web tool

3.2 ESSI Simulated by SBDART Tool

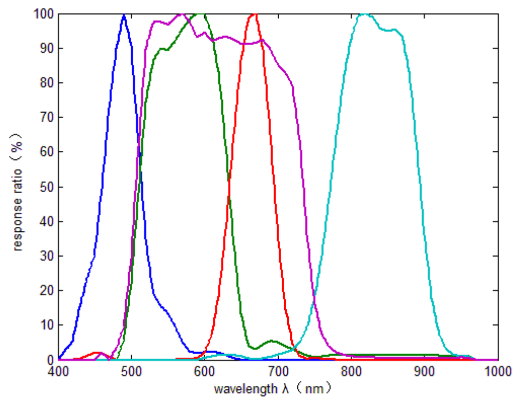
SBDART is a tool that can solve solar radiative transfer problems in remote sensing and atmospheric energy budget studies. It is based on a collection of highly developed and reliable physical models, which have been developed by the atmospheric science community over the past few decades (Paul, introduction; Paul, etc., 1998).
By setting relevant solar geometry, atmospheric profile, aerosol parameters and cloud parameters, users could achieve down, up or direct solar irradiance at the TOA or at the surface. Users could select shortwave (0.25~4.0μm), longwave(4.0~100μm) or entire spectrum(0.25~100μm) to simulate flux with maximum step reach to 1nm resolution. In this study, ESSI is simulated by SBDART web tool, where solar zenith angle is 0, wavelength step is 1nm. The simulated ESSI is shown in Figure 2.

4. SATELLITES AND ITS SPECTRAL RESPONSE FUNCTION

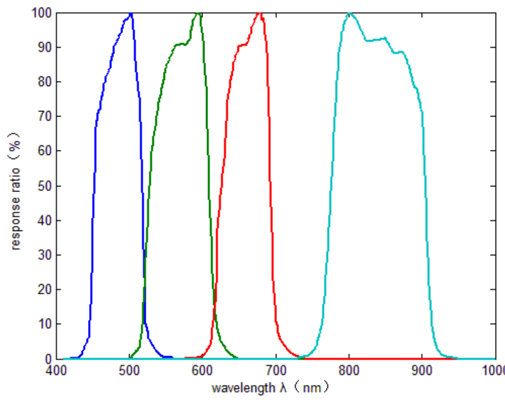
Of these on-orbit satellites, HJ-1A CCD1 (b1-b4), CEBERS02 CCD (b1-b5), Landsat TM5 (b1-b4) and ASTER (b1-b9) are selected to validate which ESSI dataset is appropriate for calculating MSEI. The spectral response functions for these satellites are shown in Figure 3.



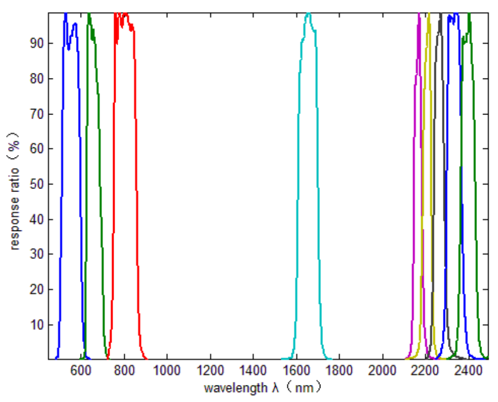
(a) HJ-1A CCD1(b1-b4) (CCRSDA HJ)



(b) CBERS02 CCD(b1-b5) (CCRSDA CBERS)



(c) Landsat TM5(b1-b5)



(d) ASTER(b1-b9) (Alistair)

Figure 3 spectral response function for selected satellite sensors

5. CALCULATION OF MSEI

According to formula (1), E(λ) and S(λ) are needed to calculate MSEI. Four ESSI datasets selected from MODTRAN4.0 with $1cm^{-1}$ spectral resolution and unit of $W/cm^2/sr/cm^{-1}$ and one ESSI dataset simulated by SBDART with 1nm spectral resolution and unit of $W/m^2/sr/\mu m$ were adopted to calculate MSEI for aforementioned satellite sensors. The spectral resolution of $S(\lambda)$ is 1nm. Due to inconsistent unit for these two kinds of ESSI datasets, unit conversion is carried on firstly. Wavelength unit is converted from cm^{-1} to μm, followed by formula (2), irradiance unit from $W/cm^2/sr/cm^{-1}$ to $W/m^2/sr/\mu m$, followed by formula(3).

$$1\mu m = 10^4/1cm^{-1} \quad (2)$$

$$1\,W/m^2/sr/\mu m = 1\,(W/cm^2/sr/cm^{-1}) \times \upsilon^2 \quad (3)$$

Adopted ESSI datasets from MODTRAN4.0, we took the following steps to calculate MSEI:

a) Unit conversion. Wavelength unit shall be converted into μm, ESSI shall be converted into $W/m^2/sr/\mu m$.

b) Interpolating the aforementioned satellite sensor spectral response functions to $1cm^{-1}$ spectral resolution.

c) Integration of spectral response function, from b), and MODTRAN ESSI dataset followed by formula (1).

Utilized ESSI dataset simulated by SBDART, the specific steps for calculating MSEI as follows:

a) Unit conversion. Wavelength unit for both spectral response function and ESSI database file shall be converted into μm and ESSI shall be converted into $W/m^2/sr/\mu m$.

b) Integration of spectral response function and SBDART simulated ESSI dataset followed by formula (1).

6. RESULTS AND DISCUSSION

Followed chapter 2 and 5, we calculated MSEI for each band for aforementioned satellites. The final results are shown in Table 2.

Table 2 MSEI for each band

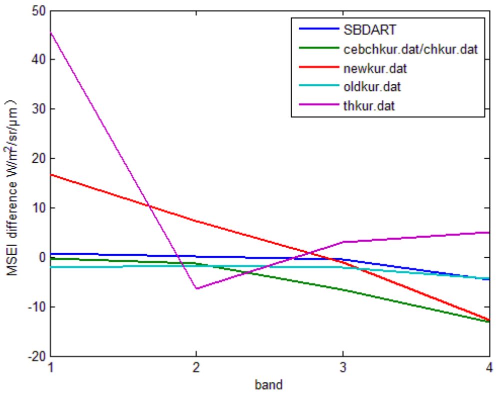
Satellites	ESSI Datasets	Calculated MSEI（$W/m^2/sr/\mu m$）
HJ-1A CCD1	cebchkur.dat/chkur.dat	[1914.142, 1824.161, 1536.068, 1060.604]
	newkur.dat	[1931.137, 1832.664, 1541.509, 1061.005]
	oldkur.dat	[1912.210, 1823.799, 1540.602, 1069.393]
	thkur.dat	[1960.022, 1819.025, 1545.685, 1078.967]
	SBDART	[1915.091, 1825.544, 1542.195, 1069.313]
CEBERS02 CCD	cebchkur.dat/chkur.dat	[1928.054, 1781.298, 1540.030, 1055.759, 1656.236]
	newkur.dat	[1950.907, 1786.989, 1545.862, 1056.615, 1667.362]
	oldkur.dat	[1926.428, 1781.324, 1544.664, 1065.722, 1662.222]
	thkur.dat	[1972.710, 1778.273, 1551.493, 1077.169, 1667.053]
	SBDART	[1928.413, 1782.758, 1546.321, 1065.378, 1663.543]
Landsat TM5	cebchkur.dat/chkur.dat	[1957.618, 1826.928, 1550.880, 1036.102]
	newkur.dat	[1987.999, 1838.018, 1554.482, 1036.183]
	oldkur.dat	[1955.852, 1827.159, 1554.699, 1046.700]
	thkur.dat	[2009.383, 1820.980, 1558.824, 1055.225]
	SBDART	1957.545 1828.715 1556.442 1046.402
ASTER	cebchkur.dat/chkur.dat	[1845.046, 1548.938, 1114.566, 223.662, 86.169, 81.382, 74.045, 65.846, 59.455]
	newkur.dat	[1853.842, 1552.308, 1115.746, 223.662, 86.169, 81.382, 74.045, 65.846, 59.455]
	oldkur.dat	[1844.066, 1552.840, 1118.560, 225.558, 86.135, 81.276, 73.544, 65.752, 59.605]
	thkur.dat	[1841.244, 1558.243, 1133.689, 223.662, 86.169, 81.382, 74.045, 65.846, 59.455]
	SBDART	[1846.090, 1554.447, 1119.167, 231.046, 79.074, 74.455, 70.432, 59.523, 56.263]

The published MSEI for HJ-1A CCD1, CEBERS02 CCD, Landsat TM5 and ASTER are shown in Table 3.

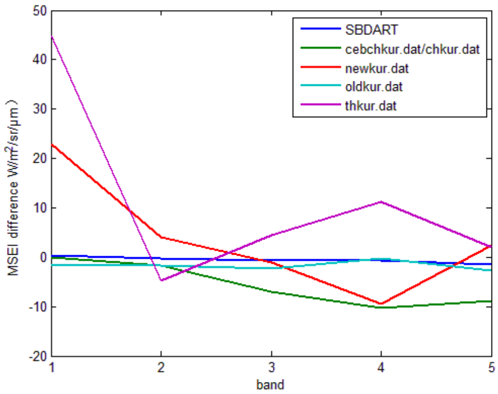
Table 3 Published MSEI for each band

Satellites	Published MSEI（$W/m^2/\text{sr}/\mu m$）
HJ-1A CCD1	[1914.324, 1825.419, 1542.664, 1073.826]
CEBERS02 CCD	[1928, 1783, 1547, 1066, 1665]
Landsat TM5	[1957, 1829, 1557, 1047]
ASTER	[1845.99, 1555.74, 1119.47, 231.25, 79.81, 74.99, 68.66, 59.74, 56.92]

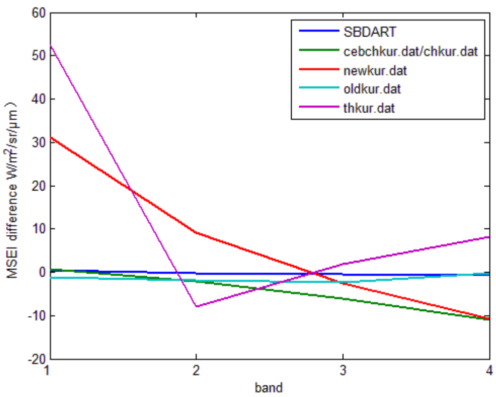
To investigate the degree of accuracy achievable using these different ESSI datasets, the calculated MSEI results were compared with the published MSEI and differences (also referred as error) between of them were also calculated. The errors are shown in Figure 4.



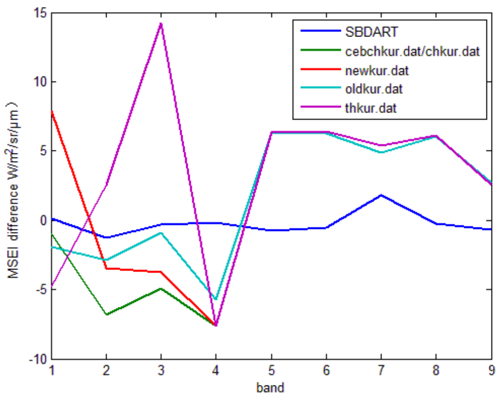
(e) HJ-1A CCD1(b1-b4)



(f) CBERS02 CCD(b1-b5)



(g) Landsat TM5(b1-b4)



(h) ASTER(b1-b9)

Figure 4 Errors between of calculated MSEI and published MSEI for listed satellite sensors

It can be seen from Figure 4 that calculated MSEI using SBDART simulated ESSI dataset are closet to published MSEI. It is found that all of the calculated MSEI results are within $\pm 0.77 W/m^2/\text{sr}/\mu m$ in error compared with published data, except for 4th band of HJ-1A CCD1, which is about -4.513$W/m^2/\text{sr}/\mu m$, 5th band of CEBERS02 CCD, which is about -1.457$W/m^2/\text{sr}/\mu m$, and 2th and 7th band of ASTER, which is about -1.293$W/m^2/\text{sr}/\mu m$ and 1.772$W/m^2/\text{sr}/\mu m$ respectively. It is also found that calculated MSEI using oldkur.dat could gain acceptable results with maximum error for the 5th band of ASTER, which is about 6.325$W/m^2/\text{sr}/\mu m$, and most of other bands within $\pm 2.5 W/m^2/\text{sr}/\mu m$ in error. The calculated MSEI results using chkur.dat are similarly with published MSEI in blue and green bands, while there are big error in other bands, which is exceed 5$W/m^2/\text{sr}/\mu m$ and the maximum error is 13.22$W/m^2/\text{sr}/\mu m$. Calculated MSEI results using thkur.dat and newkur.dat dataset are seriously deviated from the published MSEI, and therefore these two datasets are not suitable for calculating MSEI for aforementioned satellite sensors and need to be revised.

In addition, the calculated result is referred as “observed” data and the published MSEI data is referred as “standard” data, root mean square deviation (RMSE) is measured between of them. The RMSE result is shown in Table 4.

Table 4 RMSE between observed data and published data

Satellite sensor	root mean square deviation（RMSE）				
	SBDART	chkur.dat	newkur.dat	oldkur.dat	thkur.dat
HJ-1A CCD1	2.0587	6.6324	10.009	2.4898	20.807
CEBERS02 CCD	0.79999	6.8289	11.275	1.9252	20.835
Landsat TM5	0.45765	5.6727	15.268	1.4207	23.997
ASTER	0.83413	5.6054	5.7627	4.6196	7.012

As can be seen from Table 4, SBDART results are excellent and have minimum RMSE error, followed by MODTRAN oldkur.dat database file, while there is a big error by using the other 4 MODTRAN database files.

7. CONCLUSION

In this study, five ESSI datasets form MODTRAN4.0 software and one ESSI dataset simulated by SBDART web tool were adopted to calculate MSEI for HJ-1A CCD1, CEBERS02 CCD (band 1- 5), Landsat TM5 (band 1-4) and ASTER (band 1-9). According to analysis of calculated MSEI, conclusions could be drawn as follows:

1) ESSI could be simulated by SBDART tool with high accuracy, and the simulated ESSI could be used to calculating MSEI for a given satellite sensor and the result is excellent.
2) There are 5 ESSI database files in MODTRAN4.0 software with spectral resolution of $1\mathrm{cm}^{-1}$ and with unit of $W/cm^2/cm^{-1}$. Unit conversion should be preceded before calculating MSEI and satellite sensor spectral response function should be interpolate into $1\mathrm{cm}^{-1}$ spectral resolution.
3) Of the MSEI results calculated by using MODTAN4.0 datasets, MSEI result by using oldkur.dat is closest to published MSEI, while other results are not good, especially for thkur.dat and newkur.dat. It can be conclude that oldkur.dat describes solar radiation distribution with high accuracy, while thkur.dat and newkur.dat may inaccurate and need to be revised. So that thkur.dat and newkur.dat are not recommended to calculate MSEI.
4) Solar radiation distribution is identical for cebchkur.dat and chkur.dat when wavelength is greater than 0.417μm, so the calculated MSEI is similar for general satellite sensor. The calculated MSEI results using these two datasets have high accuracy in blue and green bands, while big errors in NIR band.

8. REFERENCES

Alistair M.S. Smith. How to convert ASTER radiance values to reflectance--An Online Guide. In: http://www.cnrhome.uidaho.edu/default.aspx?pid=85984

China Centre for Resources Satellite Data and Application (CCRSDA HJ).HJ-1A CCD1 Spectral response functions download. In: http://www.cresda.com/n16/n1115/n1522/n2118/9626.html

China Centre for Resources Satellite Data and Application (CCRSDA CEBERS).CEBERS-02 CCD Spectral response functions download. In: http://www.cresda.com/n16/n1115/n1522/n2118/9620.html

Pan Zhiqiang,2008. Retrieval and application of band mean solar irradiance of CBERS-02 CCD. Geo-information science,10(1),pp.109-113.

Paul Ricchiazzi,etc,1998. SBDART: A Research and Teaching Software Tool for Plane-Parallel Radiative Transfer in the Earth's Atmosphere. Bulletin of the American Meteorological Society,79(10),pp.2101-2114.

Paul Ricchiazzi,etc. SBDART tool introduction.In:http://arm.mrcsb.com/sbdart/html/sbdart-intro.html

Paul Ricchiazzi,etc. SBDART Web Tool. In: http://paulschou.com/tools/sbdart/

Zhao,Yinshi,2003.The Principle and Method of Analysis of Remote Sensing Application. Science Press,Beijing,pp.16-17.