Atmospheric correction method based on HJ-1 CCD data

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Abstract: We proposed a new atmospheric correction approach for HJ-1 CCD datasets, in which the aerosol optical depth (AOD) is acquired based on the relationships between surface reflectance of the blue band and red band over dense dark vegetation (DDV) regions. The atmospheric correction look-up tables (LUTs) were introduced to provide atmospheric correction coefficients under different aerosol loadings and sun-view geometry. The comparison of the results with intraday MODIS (Moderate Resolution Imaging Spectroradiometer) surface reflectance out-puts (MOD09) indicated the proposed atmospheric correction method has preferable accuracy. We did uncertainty analyses from the aspects of AOD retrieval accuracy, radiometric calibration accuracy, altitude impact and atmospheric water vapor con-tent impact.

Key words: HJ-1 CCD, atmospheric correction, look-up tables (LUTs), surface reflectance, MODIS, aerosol optical depth (AOD)

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1 INTRODUCTION

Environment Satellite 1 (HJ-1) launched in September 2008 in China, which is the first satellite used for environmental and disaster monitoring in large-scale dynamical and around-the-clock (Wang, 2010). The features of wide coverage, high spatial resolution and high temporal observation frequency enable it suitable for environmental and disaster monitoring. However, signatures are received by the HJ-1 CCD, which are contaminated by the effects of atmospheric particles as they absorbing and scattering of the solar radiation. These effects normally result in distortion of the actual reflectance and subsequently affect the extraction of information from images. It is necessary to accurate removal of atmospheric effects to retrieve quantitative information from HJ-1 CCD data.

Atmospheric correction is the process of removing the effects of the atmosphere and converting satellite received signature into ground reflectance. According to the characteristics and complexity of frequently-used models, atmospheric correction approaches can be divided into physically-based, image-based and relative correction methods (Had-jimitsis, et al., 2004).

Physically-based method is developed mainly based on principles that electromagnetic waves transfer in atmosphere. These methods are the most complex and highly accurate ones used for retrieving surface reflectance. Yet, they are time-consuming and require in-situ measurements about the atmospheric composition, such as atmospheric water vapor content, aerosol optical characteristics and spatial distribution of ozone concentration in the experimental regions. Different atmospheric profiles may have large influences upon the accuracy of atmospheric correction (Jimenez-Munoz, et al., 2010).

With image-based method, an image can be corrected by imagery itself rather than assisting with in-situ measurements, the method can be used in more sophisticated research designs (Lu, et al., 2002). Dark-object method, also known as the histogram minimum method (Hadjimitsis, et al., 2010; Liang, et al., 2001), which is one of the most commonly used image-based methods, the method presumes that the satellite received signatures from a dark object is mainly contributed by the atmosphere at visible wavelengths. These kinds of methods may not work well if the dense vegetations are not widely distributed in the regions covered by satellite pixels.

Relative atmospheric correction approaches are inherently empirical and ground on the assumption of the existence of simple

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linear relationships among continuous time series images and the dominance of stable features in the scene (Song, et al., 2001). These methods can be used to normalize digital number values among multi-temporal images, which are essentially statistical methods, and useless in removing atmospheric impacts. Thus the relative correction methods are not available for quantitative analysis.

Atmospheric correction is the first critical processing step and may affect subsequent steps in application cases of remotely sensed imagery. Until now, correction of atmospheric effects on satellite imagery has not been achieved operationally (Wang, 1999; Song, et al., 2001). The purpose of this research is to develop an atmospheric correction method for HJ-1 CCD datasets, and to solve general atmosphere and surface conditions and the method is therefore suitable for operational applications. In the settings of HJ-1 CCD cameras, the absorption caused by water vapor and other gases can be ignored (Lu, et al., 2002), thus only atmospheric aerosols need to be considered. Richter (1990) suggested that the estimation of ground reflectance can be achieved via a series of atmospheric correction functions compiled using an RTM for different simulated atmospheres, aerosol loadings, and observed conditions. In this paper, we proposed an atmospheric correction approach based on pre-created look-up tables to provide correction coefficients according to different atmospheric parameters and different sun-view geometrics.

2 CREATION OF LOOK-UP TABLES

It is computationally prohibitive to run a radiative transfer model for every pixel within daily datasets to provide atmospheric correction coefficients. In our research, we created LUTs using 6S (Second Simulation of Satellite Signal in the Solar Spectrum) code to achieve those targets for a variety of sun-view angles and aerosol loadings. The following inputs are necessary: sun-view geometrics, aerosol model (type and concentration), atmospheric model and gaseous components, ground reflectances (type and spectral variation), and spectral conditions (Zhao, et al., 2000).

As atmospheric conditions vary significantly both temporally and spatially merely in virtue of molecular scattering and absorption, it is difficult to specify atmospheric conditions within a large area. Moran, et al. (1992) and Zhao, et al. (2000) reported that the impact on the precision of atmospheric correction by a standard model is comparable to that by an in-situ model. Therefore, we select standard atmospheric models (the middle latitude summer/winter atmospheric model) and standard aerosol model (the continental model) as our inputs on the assumption of homogeneous Lambertian reflectance characteristics.

The quantitative levels of input parameters in 6S code need to be determined by considering the tradeoff between computation accuracy and time required. The influences caused by different settings are discussed before creating LUTs. The simulations were proceeded based on the following original settings: apparent reflectance is 0.3, solar zenith angle is 50°, view zenith angle is 20°, relative azimuth angle is 90°, mid-latitude summer atmospheric model, continental aerosol model and aerosol loadings at 550nm is 0.5. Results illustrate that AOD is the most important uncertainty parameter. Depending on the sensitivity analysis, we set aerosol concentration as 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.8, 1.0, 1.5, and 2.0. Meanwhile, we specified the sun-view geometrical grades as follows: six sensor zenith angles within the observational range of HJ-1 CCD with a step of 6°, eighteen solar zenith angles from 0° to 85° with a step of 5°, nineteen relative azimuth angles from 0° to 180° with a step of 10°. Then LUTs of atmospheric correcting coefficients were installed off-line.

3 AOD RETRIEVAL

Atmospheric correction necessitates the accurate estimation of the effects of multiple scattering, which are strongly dependent on the aerosol size distribution, concentration, and absorption properties (Gordon, 1997). Thus, the accurate retrieval of aerosols is the pivotal step.

Currently, the mostly used AOD retrieval approach over land is the dense dark vegetation (DDV) method in which low surface reflective property in the red and blue bands are utilized to distinguish land surfaces and AOD, especially in shortwave infrared (IR) near the 2.1 μm band. For the blank in shortwave infrared band, determination of surface reflectance for HJ-1 CCD imagery is comparatively difficult, and consequently, the retrieval of AOD distributions (Sun, et al., 2010). Although aerosol loadings can be obtained over some regions from vegetation indexes, such as NDVI, the correction accuracy is still affected significantly by aerosol and the determination of DDV regions has great subjectivity (Kaufman, et al., 1997b). The method proposed by Sun, et al. (2011) is used here to retrieve aerosol loadings, which uses MODIS surface reflectance output (MOD09) as the priori datasets to support HJ-1 CCD aerosol retrieval. The MOD09 was used to provide the percentage of dense vegetation distributions, and AOD was retrieved based on the relationships between surface reflectance of red and blue bands over DDV regions.

AOD usually distributes more smoothly than that of surface reflectance (Hagolle, et al., 2008; Liang, et al., 2001). In a local region, we considered that the variation of sun-view geometry and aerosol loadings have negligible influences on atmospheric correction accuracy. Therefore, we divided the under-corrected image to many pieces and determined the prior AOD value in each piece with the following formulas (take window M for example):

(1)If the window M has at least 10 percent pixels with a suitably positive value, the AOD value of the window needs to be replaced with the median value of the ten values;

(2)Otherwise, take the center pixel of the window as a standard, and search for another window with a size of 10 N×10 N (N =1, 2, 3, …, n) until the new window satisfies condition (1). Then, the median value of these eligible pixel values is used as the aerosol loading in window M;

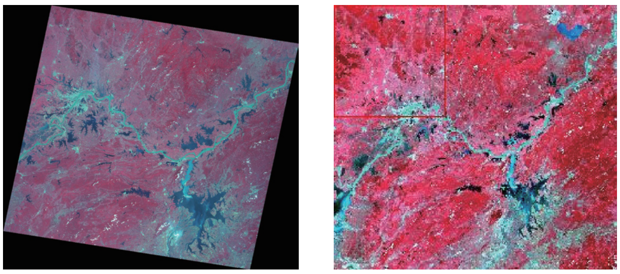
(3)If no aerosol loadings have been determined in the end, the background AOD value of the research area is used in the atmospheric correction.

We finally determined the size of each piece as 20 km×20 km according to the above analysis. With this window size, time required and computation accuracy can get a balance.

4 RESULTS AND EVALUATION

HJ-1 CCD images covering different surfaces were selected to evaluate our method. The absence of concurrent in-situ measurements during HJ-1 satellite over-flight was a main obstacle for a rigorous evaluation of the outputs. MODIS reflectance outputs would reflect the actual reflectivity of the surface more realistically (Liang, et al., 2002). In this paper, we selected them as our validating data.

The comparison between corrected HJ-1 CCD image (obtained on October 4, 2012) and the corresponding MODIS reflectance output is shown in Fig. 1 . After correction, the two images have similar texture distributions. In mountainous regions, slope and altitude variations induce strong changes in irradiance and upwelling radiance (Lenot, et al., 2009), and the surrounding relief can also create shadows and some ground regions may be hidden outside of the sensor view field. In these regions, the assumption of homogeneous Lambertian reflectance characteristics would not hold. The most important reason leading to errors in water regions is the accuracy of radiative calibration. After the offset is adjusted in radiative calibration, this phenomenon will recede and even disappear.

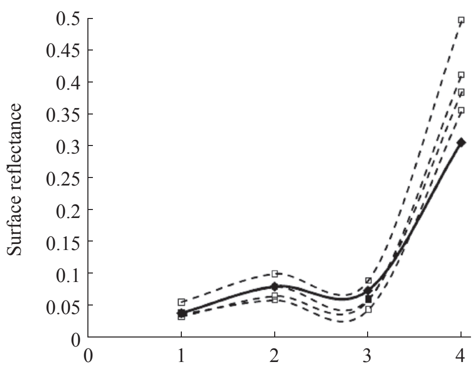


(a) HJ-1 CCD image (b) MODIS reflectance output

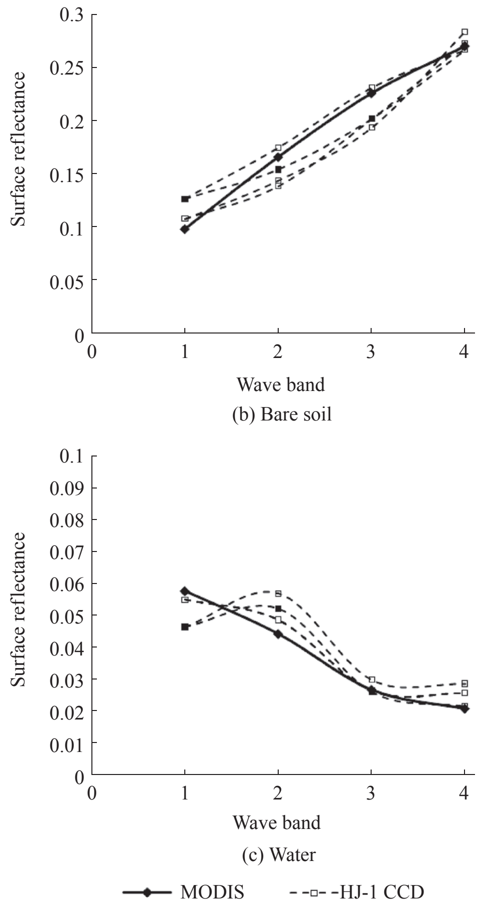
Fig. 1 Comparison between corrected HJ-1 CCD and MODIS reflectance output

4.1 Comparison with MODIS

The comparison of typical surface features (vegetation, bare soil, and water) extracted from HJ-1 CCD and MODIS is shown in Fig. 2. In near-infrared band, satellite received signature is affected by atmospheric water vapor content at a certain degree. HJ-1 CCD reflectance of vegetation at this band is higher than that of MODIS as we ignored the influence of atmospheric water vapor content. The comparison results of water reflectance can be explained by the following reasons: (1) over case 2 waters, chlorophyll, COD, and TSP content can affect atmospheric correcting accu-racy; (2) accuracy of radiometric calibration over water has great bias.



(a) Vegetation



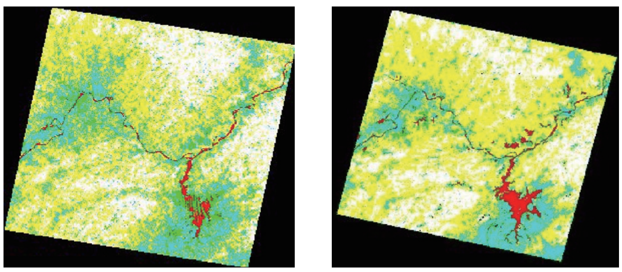
(b) Bare soil

(c) Water

Fig. 2 Surface reflectance comparison of typical surface features

4.2 Normalized difference vegetation index (NDVI)

NDVI can be used to analyze remote sensing measurements, and assess whether the target observed contains live green vegetation or not. From the comparison of NDVI distributions between the corrected images and MODIS products in Fig. 3, we can find that NDVI values would increase after correction. The visible bands are mainly influenced by the atmospheric scattering, which causes image additive effects. Inversely, in the near infrared wavelength, atmospheric scattering results in image subtraction effects.



(a) HJ−1 CCD image (b) MODIS image

Fig. 3 Comparison of NDVI distributions among corrected HJ/CCD image and MODIS image

5 UNCERTAINTY ANALYSIS

Uncertainty would arise in the proposed atmospheric correction owing to many different sources. In this section, some of them would be discussed separately.

(1) AOD retrieval accuracy

Quality of the surface reflectance estimation is mainly dominated by the knowledge of AOD (Vermote, et al., 1999), especially in low surface reflectance regions where the aerosol radiative effect is stronger. The simulated relations between AOD and corrected surface reflectance is shown in Fig. 4. Based on the same apparent reflectance, corrected surface reflectance at each band increases with higher AOD. With the increase of wavelength, atmospheric correcting accuracy would decrease because of AOD.

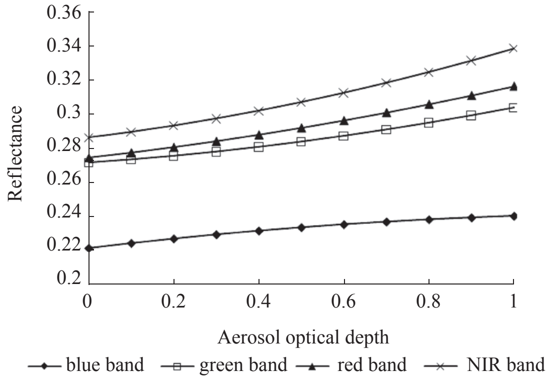


Fig. 4 Relations between corrected reflectance and AOD

There are many factors leading to errors in AOD retrieval: ① accuracy of MODIS surface reflectance outputs; ② effectivity of the aerosol model; ③ matching errors between MODIS and HJ-1 CCD images; ④ differences in observation geometry and surface bidirectional reflectivity; ⑤ and filtering method proposed above.

(2) Atmospheric water vapor content

Fig. 5 is the simulated relations between corrected surface reflectance and atmospheric water vapor content. With band settings of HJ-1 CCD sensor, influence of atmospheric correcting accuracy caused by water vapor content in atmosphere will increase as wavelength increase, and tends to a saturation state when wavelength reaches a certain extent. Within the visible range, this influence can be negligible. In our research, the influence of atmospheric water vapor content has been ignored.

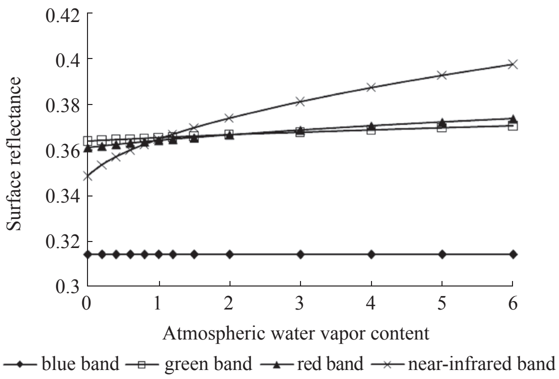


Fig. 5 Relationship between corrected reflectance and atmospheric water vapor content

(3) Radiometric calibration accuracy

Moran, et al. (1995) pointed that sensor sensitivity may degrade after the preflight calibration. Uncertainty of radiometric calibration will affect the accuracy of corrected reflectance (Fig. 6).

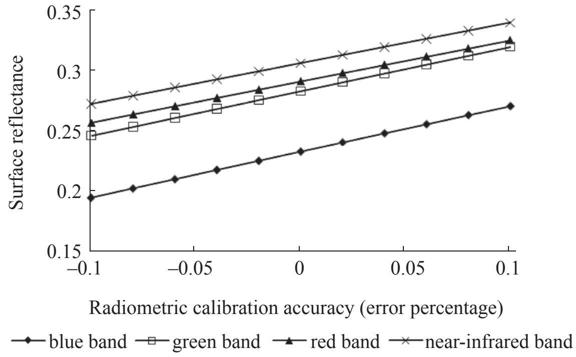


Fig. 6 Relationship between corrected reflectance and radiometric calibration accuracy

(4) Influence of target elevation

Target elevation may influence the solar irradiance, water vapor distribution, and aerosol distribution. A target pixel on the ground is illuminated by both the direct and diffuse solar radiances and the radiances from surrounding pixels areas. To account for the dependence of atmospheric correction accuracy on the surface elevation, simulations are performed separately for different elevations (Fig. 7). The result indicates that surface reflectance would increase as target elevation increases in visible bands with more pronounced behavior in near-infrared bands.

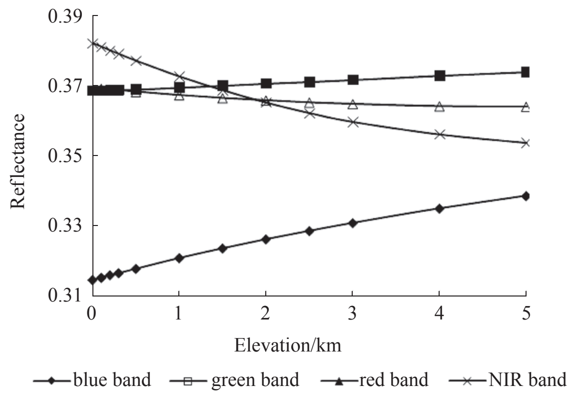


Fig. 7 Influence of elevation changes to atmospheric correction reflectance

Besides the above uncertainty factors, there are some others that may influence the precision of atmospheric correction, such as the so-called "adjacency effect", surface BRDF effects, and look-up table interpolating method.

6 CONCLUSION

Satellite received signature combines the information of land surface and atmosphere, especially aerosols. To extract quantitative information from satellite signature accurately, the atmospheric effects need to be removed. Since the 1970s, many atmospheric correcting methods have been developed, from the earlier empirical line method and flat field method to more recent methods based on rigorous radiative transfer modeling.

In our research, a new method for HJ-1 CCD atmospheric correction has been proposed, which was implemented based on pre-calculated look-up tables providing three atmospheric correction coefficients. In this method, we retrieved AOD values based on the relationships between blue and red bands over dense vegetation areas. The comparison with intraday MODIS surface reflectance outputs indicated that this atmospheric correction approach has a high accuracy. This atmospheric correction approach has been used on HJ-1 CCD datasets operationally. At last, we did uncertainty analyses from the aspects of AOD retrieval accuracy, radiometric calibration accuracy, and influence of target elevation, atmospheric water vapor content and other factors.

Implement of this atmospheric correction approach has great scientific significance. However, this approach cannot be used if the research areas have no dense vegetation distribution. Besides, this method has coarse precision in mountainous and water regions. These problems would be solved in future along with further investigation.

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HJ-1 CCD数据大气校正方法研究

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摘　要：本文开展了HJ-1 CCD相机数据大气校正方法的研究工作。基于辐射传输模型构建了不同大气条件下的大气校正系数查找表；大气校正中用到的气溶胶光学厚度数据基于浓密植被区域红蓝波段地表反射率之间的关系反演得到。与对应当天的MODIS地表反射率数据的对比分析表明，本文提出的大气校正方法具有较高的精度。本文还从气溶胶光学厚度的反演精度、大气水汽含量的变化、辐射定标精度、海拔高度等方面对大气校正的不确定性进行了分析。

关键词：HJ-1 CCD，大气校正，查找表，地表反射率，MODIS，气溶胶光学厚度

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1　引　言

HJ-1卫星于2008年9月发射升空，是中国第一颗用于大尺度、实时动态环境与灾害监测的卫星(王桥 等，2010)。CCD相机是HJ-1 A/B双星上的有效载荷之一，其宽覆盖、高空间分辨率和高时间频次的观测方式，在研究环境效应等方面具有较大的优势。然而，卫星传感器接收到的信号由于受到大气的影响，使得卫星影像在反映地表真实反射率时产生失真。为了从卫星影像中得到真实的地表信息，首先要进行精确的大气效应的去除。

大气校正的目的是消除大气和光照等因素对地物反射的影响，获得真实的地物反射率。针对大气校正过程中使用的模型的不同，可以将大气校正方法分为基于辐射传输模型的方法、基于影像自身信息的方法和相对大气校正方法(Hadjimitsis 等，2004)。

基于辐射传输模型的大气校正方法是利用电磁波在大气中的辐射传输原理建立起来的方法，该类型的方法能够在不同的大气条件下以较高的精度获得真实地表反射率。但是，该类型的大气校正方法需要研究区域的地面实测大气参数，如大气水汽含量、气溶胶光学特性、臭氧含量及空间分布等。大气参数测量的困难，限制了基于辐射传输模型的大气校正方法的应用(Jiménez-Muñoz 等，2010)。

基于影像自身信息的大气校正方法不需要野外实测参数等辅助数据，并且能够适用于历史数据和偏远的研究区域(Lu 等，2002)。黑暗像元法是应用最广泛的一种基于影像自身信息的大气校正方法(Liang 等，2001；Hadjimitsis 等，2010)。该方法在使用时假定待校正的遥感影像上存在着反射率很小的黑暗像元区域，该区域的反射率主要由大气程辐射的影响产生。

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当不同时相遥感影像上存在具有稳定反射率的像元，并且这些像元的反射率存在线性关系时，可以使用基于相对大气校正方法实现影像的大气校正(Song 等，2001)。该类型的大气校正方法可用于对不同时相的遥感影像进行归一化处理，不需要同步的大气参数，但是该类型的方法均是基于统计模型的方法，无法获得真实的地表反射率。

大气校正是各种遥感应用中最关键的一步，但是，发展到现在还没有一种通用的大气校正算法(Wang，1999；Song 等，2001)。在HJ-1 CCD波段范围内，水汽和臭氧等气体对大气校正精度的影响可以忽略(Lu 等，2002)，因此，只需要考虑大气气溶胶光学厚度的影响。Richter (1990)指出地表反射率的计算可以通过在不同的大气和观测条件下求解辐射传输模型获得，由此本文基于查找表的方式实现了HJ-1 CCD相机数据的大气校正，大气校正过程中用到的气溶胶光学厚度基于红蓝波段地表反射率之间的关系反演获得。

2 大气校正查找表构建

本文中HJ-1 CCD数据的大气校正基于查找表的方式实现。利用6S(Second Simulation of Satellite Signal in the Solar Spectrum)进行辐射传输模拟时，需要输入以下参数：(1)观测几何条件；(2)气溶胶参数；(3)大气模式和大气中各种气体的含量；(4)地表信息；(5)传感器的光谱响应(Zhao 等，2001)。

Moran等人(1992)和Zhao等人(2001)的研究表明，分别选用标准大气模式和用户自定义模式进行大气校正时，对大气校正精度的影响可以忽略。因此，查找表构建时，本文选择了6S中预定义的标准模式作为输入，其中，大气模式分别选择中纬度夏季和中纬度冬季两种，气溶胶模式选择大陆型，同时假定地表具有均一的朗伯反射特性。

大气校正系数查找表的构建精度直接影响到大气校正结果的精度。因此，在查找表构建时，基于以下初始设置进行了敏感性分析：大气顶层反射率为0.3；太阳天顶角为50°；观测天顶角为20°；相对方位角为90°；大气模式为中纬度夏季；气溶胶类型为大陆型；550 nm处的气溶胶光学厚度为0.5。分析结果表明：在HJ-1 CCD传感器波段设置范围内，气溶胶光学厚度的确定精度是影响该传感器大气校正精度的最重要的因素。在此基础上，设置550 nm处的气溶胶光学厚度值为：0.0、0.1、0.2、0.3、0.4、0.5、0.8、1.0、1.5、2.0；在CCD相机观测角度范围内设置了6个传感器天顶角；0°—85°范围内以5°为间隔设置了18个太阳天顶角；0°—180°范围内设置了19个相对方位角。

基于以上输入参数，离线构建了不同大气及观测条件下的大气校正系数查找表。

3 大气气溶胶光学厚度反演

大气颗粒物的多次散射效应主要由大气气溶胶粒子的大小、浓度和吸收特性决定(Gordon，1997)。因此，大气校正时需要精确估算气溶胶光学厚度的分布。

当前陆地地区气溶胶光学厚度反演最常用的方法是浓密植被法，该方法主要基于可见光波段地表反射率较低的特性实现气溶胶光学厚度的反演。浓密植被法气溶胶光学厚度反演中已经发展了多种地表反射率的确定方法，其中应用最广泛的是2.1 μm附近短波红外波段的方法。由于HJ-1 CCD传感器缺少2.1 μm附近短波红外波段，使得气溶胶光学厚度的确定变的异常困难(Sun 等，2010)，植被指数的方法可以实现该类型传感器局部区域的气溶胶光学厚度反演，但是植被指数本身随着气溶胶光学厚度的变化而变化，并且浓密植被分布阈值的确定主要依据人的经验，从而限制了该方法的应用 (Kaufman 等，1997)。针对HJ-1 CCD数据气溶胶光学厚度反演困难的问题，Sun等人(2011)提出了一种基于MODIS地表反射率数据确定研究区域浓密植被分布的方法，之后，HJ-1 CCD数据红蓝波段地表反射率之间的关系实现了气溶胶光学厚度的反演。本文方法实现了浓密植被区域气溶胶光学厚度的反演。由于在局部区域内，气溶胶光学厚度的分布相对稳定(Liang 等，2001；Hagolle 等，2008)，因此，将待校正的影像分成若干个窗口，采用以下步骤确定研究区域的气溶胶光学厚度分布情况：

(1)以窗口M为例，若该窗口内有气溶胶光学厚度值的分布，并且像元数多于10个，则取所有满足条件的气溶胶光学厚度值的众数作为该窗口的气溶胶光学厚度值；

(2)若窗口M不满足条件(1)，则以窗口M的中心像

元为中心，按10N×10N(N=1, 2, 3, ···, n)的尺寸扩大窗口大小，在每一个新窗口中以(1)为准则进行判断；

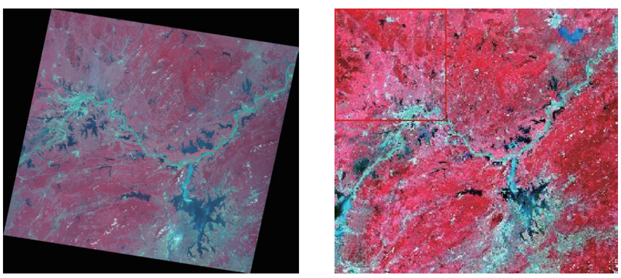
(3)若整景影像中无法找到合适的气溶胶光学厚度值，则以研究区域的本底气溶胶值作为整个研究区域气溶胶光学厚度值的分布，实现HJ-1 A/B CCD相机数据的大气校正。

本文通过试验，确定大气校正窗口大小为20 km×20 km。在该尺寸下，大气校正结果不会出现斑块现象，并且该尺寸下大气校正的精度不会受到影响。

4 结果和验证

本文选择了中国不同地表覆盖类型的HJ-1 CCD数据开展了大气校正方法的研究工作。MODIS地表反射率产品在反映真实地表反射率的变化方面具有较高的精度(Liang 等，2002)，因此，本文选择MODIS地表反射率产品作为基础数据，验证本文提出的大气校正算法的精度。

图1是2010-10-04华东地区的经过大气校正的HJ-1 CCD数据与对应当天的MODIS地表反射率数据的标准假彩色合成图像对比结果。由图可以看出：校正后的HJ-1 CCD数据纹理比较清晰。在地势起伏比较大的山区(如中国台湾)，由于地表朗伯面反射的假设不再成立，使得该类型地区大气校正地表反射率容易出现负值的现象。水体区域大气校正后出现负值主要是由HJ-1 CCD数据本身的定标精度造成的，当对该数据进行重新定标后，出现负值的区域将会明显减少。

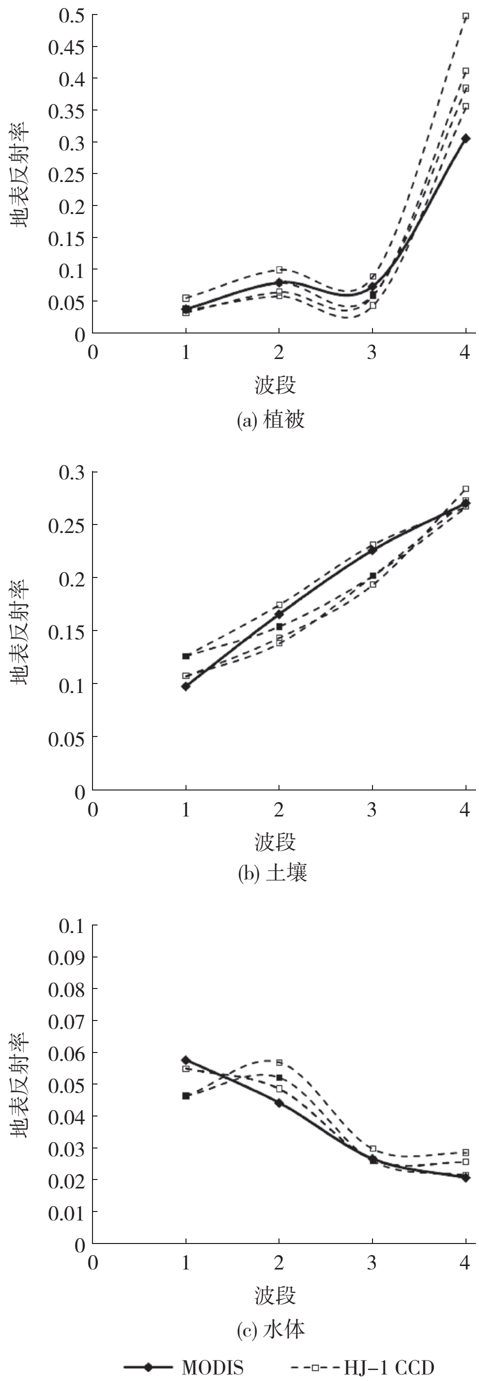


(a) HJ–1 CCD (b) MODIS

图1 HJ-1 CCD数据大气校正结果与对应当天的MODIS地表反射率数据的对比

4.1 HJ–1 CCD与MODIS地表反射率比较

图2为从大气校正后的HJ-1 CCD和MODIS影像中提取的典型地物反射率(植被、土壤、水体)的对比分析图，由图可以看出两者具有较好的一致性。在近红外波段，传感器接收到的信号在一定程度上受到大气水汽的影响，本文提出的大气校正算法中，没有考虑大气水汽含量的变化对大气校正结果的影响，因此，与MODIS地表反射率数据相比，植被区域近红外波段的反射率偏高；水域大气校正反射率与MODIS地表反射率数据偏差比较大的原因主要由以下两点：(1)本文研究的水域为二类水体，水中叶绿素和悬浮颗粒物COD的含量会影响水域大气校正



(a) 植被

(b) 土壤

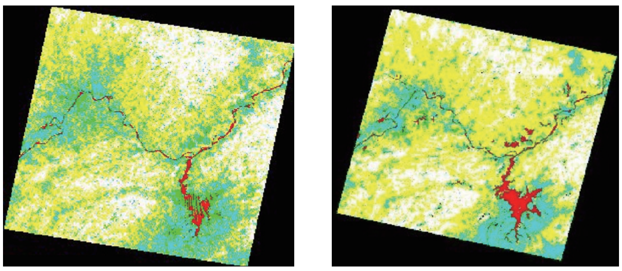
(c) 水体

图2 HJ-1 CCD与MODIS地表反射率对比

的精度；(2)通过对比分析MODIS与HJ-1 CCD辐射定标结果表明：HJ-1 CCD数据水域辐射定标精度不高，基于MODIS数据对HJ-1 CCD数据进行交叉定标之后，HJ-1 CCD数据水域大气校正的精度得到明显改善。

4.2　归一化植被指数

植被指数能够很好地反映地表植被覆盖类型的变化。图3为选取的2010-10-04华东地区的HJ-1 CCD一景影像与对应的MODIS数据的NDVI对比分析图，其中，黑色部分为背景区域，红色为水体，白色为植被指数较大的区域。可以看出，两者的NDVI具有相同的变化趋势。由于大气顶层反射率只考虑了太阳角度、日地距离和太阳辐射的影响，而没有考虑大气散射的影响，而大气的散射效应可以增加可见光波段的反射率、降低近红外波段的反射率，所以经过大气校正后，可见光波段的反射率降低，近红外波段的反射率升高，影像的植被指数呈现增加的趋势。



(a) HJ-1 CCD　　(b) MODIS

图3　NDVI对比

5　不确定性分析

本文从以下几个方面对大气校正过程中的不确定性进行了分析：

(1)大气气溶胶光学厚度

大气校正的精度主要由大气校正过程中用到的气溶胶光学厚度的精度决定(Vermote和Vermeulen, 1999)。当前，浓密植被区域气溶胶光学厚度反演精度为0.1，稀疏植被区域为0.1—0.3。图4为模拟的气溶胶光学厚度对HJ-1 CCD数据大气校正结果的影响，随着传感器波段中心波长的增加，气溶胶光学厚度对大气校正结果的影响逐渐减小。

本文中，气溶胶光学厚度反演的精度会受到以下几个方面的影响：①MODIS地表反射率产品的精度；②气溶胶模型的影响；③MODIS和HJ-1 CCD数据之间的配准误差；④地表二向性反射特性引起的误差；⑤气溶胶光学厚度滤波算法引起的不确定性。

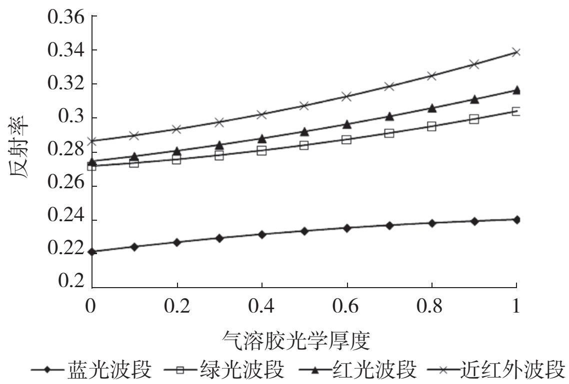


图4　气溶胶光学厚度对校正的地表反射率的影响

(2)大气水汽含量

图5为大气水汽含量对大气校正结果精度的影响，可以看出：在HJ-1 CCD波段设置范围内，随着波段的增加，大气水汽含量对大气校正精度的影响逐渐增加；在可见光波段范围内，大气水汽含量对大气校正精度的影响可以忽略；在近红外波段，大气校正的精度随着大气水汽含量的增加逐渐趋于饱和。本文在开展HJ-1 CCD数据大气校正方法的研究中，没有考虑大气水汽含量的变化。

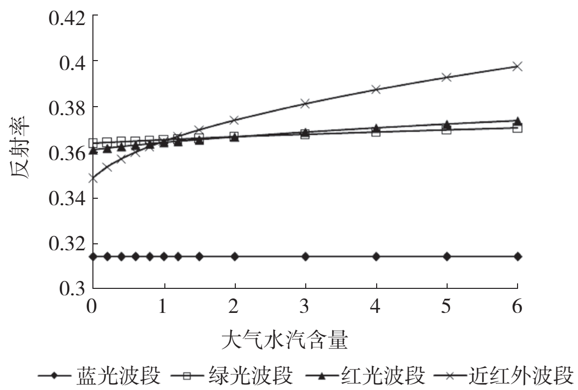


图5　大气水汽含量对校正的地表反射率的影响

(3)HJ-1 CCD辐射定标精度

传感器的灵敏度随着时间的推移会产生衰减。当对传感器的辐射定标结果(辐射亮度)加入不同的误差时，大气校正结果会发生明显变化(图6)。

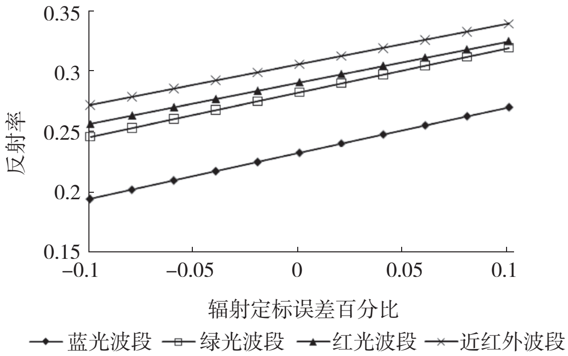


图6　辐射定标误差对校正的地表反射率的影响

(4)地表海拔高度

海拔高度的变化直接影响到传感器接收到的太阳辐射、大气水汽含量和气溶胶光学厚度的分布。在相同的大气层顶反射率的前提下，可见光波段的地表反射率随着海拔高度的增加而增大，且增大的幅度随着波长的增加而减小，在近红外波段，地表反射率随着海拔高度的增加而减小(图7)。

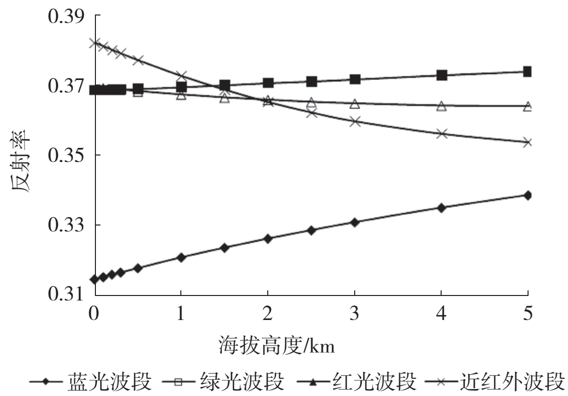


图7　海拔高度对地表反射率的影响

除了以上不确定性因素外，还有很多因素会影响到大气校正的精度，这些因素包括临近像元效应的影响、地表BRDF特性和查找表插值方法等。

6　结　论

卫星传感器接收到的信号既是大气贡献的函数，又是下垫面地表反射率的函数；为了从卫星影像中得到精确的地表信息用于定量遥感的研究，必须去掉大气的影响。从20世纪70年代开始，随着定量遥感技术的发展，各种大气校正算法应运而生。这些大气校正方法从最初的基于线性统计模型的方法发展到现在的基于辐射传输模型的方法。

本文提出了一种针对HJ-1 CCD相机数据的大气校正方法，该方法基于大气校正查找表实现。基于红蓝波段地表反射率之间的关系实现了气溶胶光学厚度的反演，之后经过滤波处理应用于该类型数据的大气校正中，得到了研究区域的高空间分辨率的地表反射率数据。通过与对应的MODIS地表反射率产品的对比分析表明：本文方法具有较高的精度。最后本文对大气校正的不确定性进行了分析。

该方法的实现对于推动中国的环境与灾害监测具有重要的意义，但是，该大气校正方法在无浓密植被分布的区域不具有适用性，并且，在广阔的山区和水域，该方法获得的地表反射率的精度还有待于改进。该算法存在的不足将在以后的研究中进行改进。

志　谢　感谢中国资源卫星应用中心提供了HJ-1 CCD数据支持和在数据辐射定标方面给予的指导；感谢NASA提供高精度的MODIS地表反射率产品用于本文的大气校正算法精度的评价！

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