Haze detection, perfection and removal for high spatial resolution satellite imagery

Title description: An innovative haze removal technique for multi-spectral satellite imagery, unnecessary of aerosol transparent bands and suitable for urban remote sensing.

Abstract: We present a technique to remove spatial varying haze contamination for high spatial resolution satellite imagery, which is comprised of three steps: haze detection, haze perfection, and haze removal. Background suppressed haze thickness index (BSHTI) in haze detection is used to indicate relative haze thickness. ‘Fill sink’ and ‘flatten peak’ routines in haze perfection are applied to correct some spurious background effects. Virtual cloud point (VCP) method based on BSHTI is used in haze removal. Case study using two Quickbird images (hazy and clear) of Shenyang City in China proves the effectiveness of this technique except for those regions too hazy. Comparison of the overlapped region between hazy and clear images using 76 paired polygon samples shows that squared correlation coefficient of each band between the two image becomes larger than 0.7. The advantages of this technique are unnecessary of aerosol transparent bands and suitability for urban remote sensing.
1 Introduction

In recent years high spatial resolution satellite imagery such as Quickbird, IKONOS, and Orbview have been widely used to obtain more detailed spatial information than is possible to achieve from low resolution imageries. Though a high resolution image is available in several days’ revisit time, availability of a high-quality image often depends on luck. Cloud and haze are two atmospheric effects that cause image contamination. Cloud cover blocks almost all reflected radiation from the surface so substitution using another image is the only information loss recovery method available (Lu, 2007). Haze partially obscures the ground, so it is theoretically possible to be removed using atmospheric correction techniques.

Homogeneous haze can be removed using many existing atmospheric correction techniques (Hadjimitsis et al., 2004), such as corrections that use independent data for atmospheric optical conditions, image-based atmospheric corrections assuming existence of a certain stable land cover type (Chavez, 1988; Kaufman and Sendra, 1988; Kaufman et al., 1997; Teillet and Fedosejevs, 1995). However, these techniques were not developed for ever-present spatial varying haze contamination, since the unavailability of aerosol distribution.

To remove spatial varying haze contamination in a scene, Liang et al. (2001, 2002) proposed a cluster matching technique for TM based on an assumption that each land cover cluster (unsupervised classified using infrared bands) has the same visible reflectance in both clear and hazy regions. However, cluster matching technique has a precondition that aerosol transparent bands are available, which makes it impractical for high resolution satellite imagery, since visible bands and the near-infrared band are contaminated by haze more or less.

Some relative atmospheric correction techniques using only visible bands have been developed to change a heterogeneous hazy image to a homogeneous hazy image that can be corrected using existing atmospheric correction techniques. It was noted that haze seems to be a
major contributor to the fourth component of Tasselled Cap (TC) transformation (Crist and Ci-
cone, 1984; Richter, 1996). Zhang et al. (2002) proposed the haze optimized transformation
(HOT) for haze detection, which is an improved two-band version (TM bands 1 and 3) of TC
transformation. HOT combined with dark object subtraction (DOS) has been shown to be an
operational relative atmospheric correction technique for TM and high-resolution satellite data
(Dal Moro and Halounova, 2007; Zhang et al., 2002). However, the limitation of this method is
the precondition of high correlation between blue band and red band, which is sometimes inac-
curate. Furthermore, an overcorrection and undercorrection problem of some land cover types
needs further research.

In this paper, we present a novel relative atmospheric correction technique to solve spatial
varying haze contamination. This technique is comprised of three steps in sequence: haze detec-
tion, haze perfection, and haze removal detailed in the following sections. To show the benefit
and cost of this technique and to provide an assessment, we take two Quickbird multispectral
images (one hazy and one clear) as a case study.

2 Methods

Flow chart of the method is shown in Fig. 1 and will be detailed in sequence.

Fig. 1. Flow chart of the method for solving spatial varying haze contamination including hu-
man intervention. Rectangles are main process steps of this method, round corner rectangles are
some settings necessary, and the rest are image data.

2.1 Haze detection

The first step to remove spatial varying haze in a scene, the first step is to retrieve spatial
varying haze thickness using spectral information. Until now, high resolution imageries always
have only several visible bands and one near-infrared band, which are all more or less possibly
contaminated by haze. Accordingly, aerosol transparent band based techniques are not suitable.
Haze optimized transform (HOT) using blue and red bands lights hope for haze removal techniques using only visible bands (Zhang et al., 2002). But HOT seems not that robust, since blue and red band is not always highly correlated according to our test on 23 hazy TM images (Fig. 2). Most of correlation coefficients are lower than 0.9, while some of them even lower than 0.8.

Fig. 2. Correlation coefficient between TM1 and TM3 of clear region in 23 TM images in ascending sequence.

In this step, our goal is to detect haze and treat all the land cover types as background. Therefore, we need an index that can not only describe haze thickness, but also suppress background noise caused by land cover types. Here, we propose a background suppressed haze thickness index (BSHTI) for spatial varying haze detection (Eq. 1).

\[
BSHTI = k_1 \times \text{band1} + k_2 \times \text{band2} + k_3 \times \text{band3} + k_4
\] (1)

Where \( \text{band1/2/3} \) is the digital number (DN) of blue/green/red band respectively. \( k_1,k_2,k_3,k_4 \) are four parameters whose values are determined through maximizing the score function.

Score function: \( M_{BSHTI\_TR}/SD_{BSHTI\_CR} \)

\[ s.t. M_{BSHTI\_CR} = 0 \]

Where \( M_{BSHTI\_TR} \) is mean of BSHTI in a thick haze region (TR) manually delineated, \( M_{BSHTI\_CR} \) is mean of BSHTI in a clear region (CR) manually delineated, \( SD_{BSHTI\_CR} \) is standard deviation of BSHTI in CR.

Maximizing the score function can be achieved through solving the equations below (Eq. 2):

\[
\frac{\partial \text{score}}{\partial k_1} = \frac{\partial \text{score}}{\partial k_2} = \frac{\partial \text{score}}{\partial k_3} = 0 \Rightarrow KS = M_{\_\_CR} - M_{\_\_TR}
\] (2)

Where \( K \) is the 1\times3 vector \((k_1,k_2,k_3)\), \( S \) is the 3\times3 covariance matrix of band1/2/3 calcu-
lated from pixels in the clear region, and $KS$ is a $1 \times 3$ vector. $M_{CR}$ and $M_{TR}$ are mean $band1/2/3$ values of pixels in CR and TR respectively, which are both $1 \times 3$ vectors. If $K$ is known, $k4$ can be easily calculated from the constraint expression: $M_{BSHTI\_CR} = 0$. Considering the ununiqueness of solution of Eq. 2, we set the norm of vector $K$ to be 1 for a unique solution.

BSHTI is derived from an optimal statistical decision and describes haze thickness well in accord with visual perception based on experience. However, we recognize that some spurious land cover types may cause severe bias that is statistically abnormal. Therefore, we need the following haze perfection step to resolve this problem or overcorrection and undercorrection will occur on the final result after haze removal.

2.2 Haze perfection

The haze perfection step is a tradeoff between correct BSHTI preservation and spurious BSHTI correction by using spatial information. So this step should be based on difference between correct BSHTI and spurious BSHTI (note: hereafter, we use term ‘BSHTI_low’ and ‘BSHTI_high’ to refer to spurious BSHTI lower and higher than true value respectively). Here, we assume that correct BSHTI varies slowly and continuously with location. If we regard the BSHTI image as a DEM (Fig. 3), the hazy region forms a continuous peak, the clear region forms a flat background, a BSHTI_low forms a sink and a BSHTI_high forms a sudden peak. We correct BSHTI_low and BSHTI_high separately through filling sink and flattening peak operations respectively.

Fig. 3. Simplified description of correct BSHTI and spurious BSHTI in hazy and clear regions. BSHTI_low and BSHTI_high mean spurious BSHTI lower and higher than true value respectively.


2.2.1 BSHTI_low correction

In hydrology, sink (also: depression, catchment basin) is a very important component of surface topology (Jenson and Domingue, 1988). In large-scale geomorphology, small sink is usually considered as erroneous data. So far, some robust algorithms have been proposed to detect and fill sink, among them Planchon’s which is simple and fast (Planchon and Darboux, 2002). Actually, Planchon’s ‘fill sink’ routine is a special interpolation method. For each sink, it detects and masks the sink and then replace it by the minimum of its border pixels. We find it a coincidence that his routine is almost the same as the morphological reconstruction operation in mathematical morphology using a user-defined marker, which is available in the software MATLAB (function ‘imfill’). We simplify the ‘fill sink’ routine into four steps (Fig. 4). According to the algorithm, correct BSHTI will be changed by mistake only when a sink is formed by haze itself, where a region is encircled by hazier ringed region forming a crater. Fortunately, this situation is unusual.

Fig. 4. Flowchart of BSHTI_low correction and pseudo code of ‘fill sink’ routine. A is any large value larger than the maximum of BSHTI, B is any small value smaller than the minimum of BSHTI.

2.2.2 BSHTI_high correction

Haze and BSHTI_high both form peaks, while the former is continuous peak and the latter is sudden peak. We should keep the former and flatten the latter. We develop a four-step ‘flatten peak’ routine based on the sudden change on the borders (Fig. 5). In this routine, users define ‘N’ that should be large enough to remove all BSHTI_high by morphological erosion, which can not be recovered by the latter morphological reconstruction. The maximal change represents the sudden change on the borders. BSHTI_high whose corresponding maximal change is larger than the user defined ‘MC’ will be masked and interpolated.
Fig. 5. Flowchart of BSHTI_high correction and pseudo code of ‘flatten peak’ routine. B and n
are both user defined parameters.

After BSHTI_low correction and BSHTI_high correction, M_BSHTI_CR is no longer zero.
To adjust the bias, Mean_BSHTI_CR is subtracted from the whole BSHTI image.

2.3 Haze removal

To remove spatial varying haze based on HOT, Zhang sliced the HOT image and applied
DOS method to each slice (Zhang et al., 2002). Visually, a hazy image can be deblurred effi-
ciently, but aerosol multiple scattering is not considered. Aerosol scattering not only increases
apparent surface reflectance over dark objects but also reduces the apparent surface reflectance
over bright objects (Fraser and Kaufman, 1985). The histogram match method may be better
than DOS method on multiplicative effect, but it is only suitable when each slice has enough
pixels and land cover composition is almost the same as that in the clear region. We therefore
propose a virtual cloud point (VCP) method based on BSHTI, considering both the lower-bound
and upper-bound value of each BSHTI slice (Fig. 6).

Fig. 6. Virtual cloud point method, taking blue band for example. a is the virtual cloud point
(VCP), which is the point of intersection of the two regression lines of upper bound and lower
bound. b is an example hazy pixel, and c is b after haze removal. In this scatterplot, BSHTI slice
interval (SI) is 1, BSHTI valid slices (VS) for regression is from 15 to 100.

The approach for each band consists of the following steps:

1. Choose a hazy region (HR) that has spatially homogenous land cover composition
   and spatial varying haze over it. If that region does not exist, use the whole image
   region instead.

2. Slice the BSHTI of the hazy region with a proper slice interval (SI).
3. Find the lower-bound and upper-bound DN value of histogram in each slice. Considering the unstableness of minimum and maximum value (Dal Moro and Hlounova, 2007), we choose the BPth and (100-BP)th percentile as lower-bound and upper-bound value respectively.

4. Set a proper BSHTI range as valid slices (VS), If BSHTI is smaller than lower limit of VS, it is mainly contributed by background noise, while if BSHTI is larger than upper limit of VS, pixel number in a slice is quite small that lower-bound and upper-bound values are not reliable.

5. Regress the two bounds respectively and find the point of intersection (BSHTIvcp, DNvcp) for each band as the thickest haze (cloud), which can be considered as VCP.

6. Centrally project all pixels (BSHTI, DN) onto the vertical line (BSHTI=0) to get the dehazed image using Eq. 3.

\[
DN_{\text{result}} = \frac{DN \times BSHTI_{\text{vcp}} - BSHTI \times DN_{\text{vcp}}}{BSHTI_{\text{vcp}} - BSHTI} \quad (3)
\]

3 A case study

3.1 Study area and data

Two Quickbird multispectral images (One clear and one hazy) of Shenyang City in China were acquired on 19 and 24 August 2006 respectively. Landscape in the two images is urban landscape, which is complex and challenging. We assume that only atmospheric effects cause DN difference between them in this five days’ interval. Overlapped region of the clear Quickbird image can be used to test our technique implemented on the hazy Quickbird image.

Most of the hazy Quickbird image is covered by spatial varying haze (Fig. 7a). Considering space limitation, we degrade the image for overview and select three typical hazy samples and one clear region to show details. All the three hazy samples show much haze variation and contain diverse urban and suburban land cover types beneath the haze. Sample1 is an inner-urban...
landscape with a large park surrounded by residential blocks, where haze contamination is the most severe in the hazy Quickbird image. Sample2 is a suburban landscape with farmland and industrial factories. Sample3 is a suburban landscape under urbanization with a river, farmland, bare soil. The clear region is present as reference to show whether and how our technique will distort what is not supposed to be changed. Though the upper-left and lower-right part of the clear region is slightly hazy, compared with other hazy samples, we still believe it clear enough.

### 3.2 Human intervention

Before implementing the method, users must define regions including TR, CR, HR (optional) and parameters including MC, N, SI, BP, and one range VS (Fig. 1). In this case, TR is shown in sample1 in Fig. 7a, CR is the clear region in Fig. 7a, HR is not defined. Location of the two regions is manually delineated in the whole image in Fig. 7a. MC is 5, N is 30, SI is 1, BP is 2 and VS is from 15 to 100.

### 3.3 Results

In the haze detection step, optimized four parameters $k1$–$k4$ are 0.935, -0.001, -0.353, -225. Correlation coefficients of band1/2, band1/3, band2/3 are 0.970, 0.898, 0.962. Green band is highly correlated with blue and red bands and contributes little in BSHTI calculation. $M_{BSHTI\_TR}$ is 123 and $SD_{BSHTI\_CR}$ is 12.4. BSHTI of the hazy Quickbird image is shown in Fig. 7b. From an inspection of the whole image, we find that severe bias happens on colorful and bright white man-made objects.

Visually, haze perfection can efficiently correct spurious BSHTI (Fig. 7cd). After BSHTI_low correction and BSHTI_high correction, $M_{BSHTI\_TR}$ falls slightly from 123 to 122, and $SD_{BSHTI\_CR}$ falls from 12.4 to 7.02. Background is more suppressed while haze information is maintained after haze perfection.

In haze removal step, to each of the four bands, the correlation coefficient of lower-bound values with BSHTI is larger than that of upper-bound values with BSHTI (Table 1). This situa-
tion is caused by the fact that shadow and water representing low DN is widely distributed in the urban environment. So lower-bound values of slices are mostly from shadow or water pixels. On the other hand, upper-bound values of slices depend on land cover type composition under haze, and the correlation coefficient is determined by homogeneity of land cover distribution.

Table 1. Virtual cloud point information of each band in our case study.

Fig. 7e shows the final result of our relative atmospheric correction technique. Visually, it proves effectiveness of this technique except for the region covered by too thick haze in sample1. Colorful and bright white man-made objects keep their original color after haze removal. Quantitative assessment will be presented in the next section.

Fig. 7. A hazy Quickbird multispectral image as a case study and four typical regions (sample1/2/3, clear region) for detail show. Thick haze region (TR) in sample1 and the clear region (CR) are used for calculating background suppressed haze thickness index (BSHTI). (a) original hazy image (431 band composition). (b) BSHTI. (c) BSHTI after BSHTI_low correction. (d) BSHTI after BSHTI_low correction and BSHTI_high correction. (d) dehazed image (431 band composition).

3.4 Benefit and cost assessment

Assessment of our relative atmospheric correction technique is implemented through two ways: comparison of the overlapped region with another clear image (benefit assessment) (Fig. 8bc) and comparison of the clear region before and after haze removal (cost assessment). The former aims at assessing how effective to recover true spectral information under haze, while the latter aims at assessing how a clear region is distorted after haze removal, which is a negative side effect of our technique. We emphasize that though a clear region can be manually
masked to keep intact in our developed software, our aim here is to present signal-to-noise ratio for objective assessment.

Fig. 8. The overlapped region for benefit assessment (in black and white averaged by band1/3/4).

(a) hazy Quickbird before haze removal, dark points indicate 76 polygon samples for benefit assessment, (b) hazy Quickbird after haze removal, (c) clear Quickbird.

3.4.1 Benefit assessment

Since the satellite azimuth angles between the hazy Quickbird image and the clear Quickbird image are different, we delineate 76 paired polygon samples with BSHTI from -30 to 120 in the overlapped region in either image for polygon-to-polygon comparison (Fig. 11a). Each sample represents one homogeneous land cover, and the mean value of pixels in a polygon sample is used for comparison to avoid the geometric problem.

After haze removal, the squared correlation coefficient of each band between dehazed Quickbird and clear Quickbird becomes larger than 0.7, which is much better than that before haze removal (Fig. 12). The reason for using the correlation coefficient instead of RMSE is that our technique is an image based relative atmospheric correction technique. It is clear that our technique can ameliorate the hazy Quickbird imagery significantly.

Fig. 9. Scatter plot of hazy Quickbird (before and after haze removal) vs clear Quickbird using 76 paired polygon samples in the overlapped region.

3.4.2 Cost assessment

Statistical summary of the comparison of clear region before and after haze removal is shown in Table 2. For each band after haze removal, mean is increased by 3~5, standard deviation is decreased by about 2~4, mean absolute error (MAE) is about 5~8, and root mean square error (RMSE) is about 7-11.
Table 2. Statistical summary for comparison of clear region in the hazy Quickbird before and after haze removal.

4 Conclusion

In this paper, we present a novel three-step relative atmospheric correction technique using only visible bands to remove spatial varying haze contamination. The first step is haze detection using background suppressed haze thickness index (BSHTI). The second step is haze perfection to correct spurious BSHTI. The third step is haze removal using a virtual cloud point (VCP) method based on BSHTI.

Although it is illustrated using QuickBird imagery in this paper, this technique is designed for any high resolution satellite imagery that is more and more popular in detailed spatial information extraction. The main advantages of this technique are:

(a) Aerosol transparent bands are not needed. Since the visible bands and near-infrared band are possibly contaminated by haze, therefore, this advantage is essential for high resolution satellite imagery that usually does not have mid-IR bands.

(b) It is suitable for urban remote sensing. Since urban environments are very complex and challenging, few atmospheric correction techniques have been very effective for urban remote sensing.

The disadvantages are:

(a) Though VCP has considered the effect of aerosol multiple scattering, it is based on linear hypothesis. Adding complex mechanical models of aerosol scattering may help.

(b) Our proposed technique continues to require human intervention. Further search should aim at automation of this technique.
Reference


Fig. 1. Flow chart of the method for solving spatial varying haze contamination including human intervention. Rectangles are main process steps of this method, round corner rectangles are some settings necessary, and the rest are image data.

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BSHTI after BSHTI_low correction and BSHTI_high correction. (d) dehazed image (431 band composition).
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Fig. 9. Scatter plot of hazy Quickbird (before and after haze removal) vs clear Quickbird using 76 paired polygon samples in the overlapped region.
Table 1. Virtual cloud point information of each band in our case study.

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<th>Correlation coefficient</th>
<th>BSHTI_vcp</th>
<th>DN_vcp</th>
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<td>upper-bound</td>
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*BSHTI_vcp and DN_vcp are x and y coordinates of VCP

Table 2. Statistical summary for comparison of clear region in the hazy Quickbird before and after haze removal.

<table>
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*SD is standard deviation, MAE is mean absolute error, RMSE is root mean square error.