ROBUST HAZE REDUCTION: AN INTEGRAL PROCESSING COMPONENT IN SATELLITE-BASED LAND COVER MAPPING

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ABSTRACT:

Spatially varying haze is a common feature of archival Landsat scenes currently being used for large-area land cover mapping and can significantly affect product quality. Robust haze reduction that is image-based and involves minimal operator intervention, is therefore a necessary a-priori step to information extraction. The practical implementation of a suitable methodology, based on a Haze Optimized Transform (HOT), is described. The approach is being used in a program to map the Great Lakes watershed with archival Landsat Multi-Spectral Scanner (MSS) imagery. The impact of haze reduction is assessed using inter-scene classification consistency as a 'surrogate' measure of user classification accuracy. Consistency comparisons made between sets of raw and haze-reduced scenes indicate that 'rare' class identification is most improved by this procedure.

1.1 Introduction

The last decade has witnessed a number of initiatives, for example the National Land Cover Data (NLCD, Vogelmann et al., 2001) and the GEOCover (Dykstra et al., 2000) programs, involving the derivation of regional and national-scale land cover products from moderate to high-resolution satellite images. The Landsat series of satellites has been a primary data source, since it has provided a continuity of coverage for the past 30 years through its Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced TM sensors. It is desirable, for a given land cover product, that source imagery be limited to a narrow acquisition window in order to encapsulate thematic information at a given 'epoch'. Given the constraints of Landsat orbital characteristics and atmospheric conditions, at least a 3-year window is needed to obtain a comprehensive set of low cloud-cover scenes. Even with this relaxed constraint and especially of early 'epochs' (e.g. 1970s's MSS coverage), scenes with visually apparent, spatially-varying haze must be included. This compromise can significantly degrade subsequent image classification and land cover mapping quality. As a consequence, haze reduction must be viewed as a necessary pre-processing step to information extraction.

The desirable characteristics of an 'operational' haze reduction module include robustness (i.e. applicable to a wide range of haze conditions), ease-of-use (i.e. minimal operator intervention) and that it be image-based since ancillary atmospheric data will be limited for most archival scenes. It should be noted that only 'relative' compensation for haze (e.g. adjustment to the haze level of the clearest portion of a scene) is sought because most image classification algorithms (e.g. unsupervised clustering and supervised maximum likelihood classification) do not require absolute radiometric calibration. Over the past year, research has been undertaken at the Canada Centre for Remote Sensing (CCRS) to formulate and implement such a methodology. This has led to the development of a Haze

Optimized Transform, hereafter referred to as HOT, to capture the spatial distribution of haze over Landsat scenes. An implementation of HOT-based haze reduction has been included within the framework of a proto-type workstation currently being used to map synoptic land cover of the Great Lakes watershed with archival Landsat MSS imagery. In this paper we describe the results of a study to assess the impact HOT-based processing by comparing land cover derived from raw versus haze-reduced scenes.

A detailed description of the formulation of the HOT and its example application to Landsat Thematic Mapper data has been presented elsewhere (Zhang et al., 2002a, Zhang and Guindon, 2002b), however, here we present an overview of its salient features. The transform exploits the fact that, under uniform haze conditions, spectral responses of a broad range of common surface classes are highly correlated in the Landsat visible bands. On the other hand, relative response to the presence of haze is wavelength-dependent, being most acute toward the blue end of the spectrum. In the HOT formulation, the clearest areas of a scene are first used to define a 'clear line', i.e. a thematic response line in visible spectral space (e.g. bands MSS1 vs. MSS2). The transform then quantifies, for a given image pixel, its spectral deviation from this line. The resulting raster overlay of HOT response then encapsulates the spatially-varying haze component relative to the clearest scene areas.

2. Practical aspects of HOT-based haze reduction

Here we present an overview of our haze reduction procedure with particular emphasis on implementation considerations related to the routine processing of Landsat MSS data. As mentioned earlier, automated image-based processing has been sought. Our current procedure is limited to the radiometric adjustment of the two visible bands (MSS1 and MSS2), in part because of their enhanced sensitivity to haze vis a vis the

infrared bands and in part because haze has an additive effect on radiance in this portion of the spectrum.

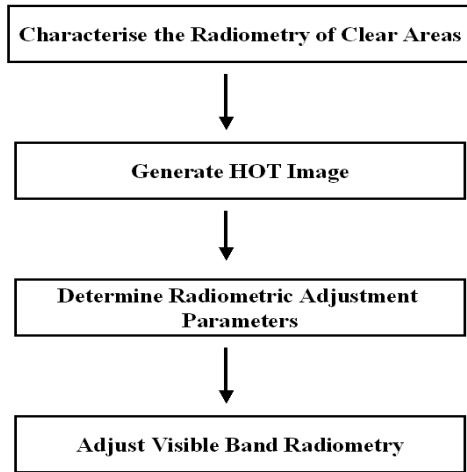Figure 1 shows a schematic of the principal processing steps of the procedure.

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│            Generate HOT Image                 │
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│        Adjust Visible Band Radiometry         │
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Figure 1. Outline of HOT-based haze reduction

2.1 Characterize the Radiometry of Clear Areas

Our haze adjustment procedure is a relative one in the sense that it attempts to normalize a scene to the radiometry of the clearest portion of a scene. As a consequence, the first step in the process involves collecting a sample of pixels from clear areas to be used to parameterize the 'clear area' radiometry. Sample selection is currently done manually (the only manual step in the overall procedure) by delineating rectangular windows in the scene based on a visual estimation of intra-scene clarity. A key objective of this process is the selection of a sample that spans the full visible band reflectance range, i.e. that it includes a mix of vegetated and non-vegetated land cover.

The clear area sample is analyzed in the visible band spectral space, i.e. (MSS1 (green) vs. MSS2 (red)). In this space data is highly correlated and can be characterized by a 'clear line' defined through least-squares regression.

2.2. Generate HOT Image

In the visible band space, hazy pixels will deviate from the clear line since haze has a greater radiometric influence in the green band than in the red band. The HOT transform uses the observed band 1 and band 2 radiances of a given pixel to compute its orthogonal displacement from the clear line. When this is done for each pixel, a HOT image is generated that quantifies the spatial and intensity distribution of haze. In the case of Landsat MSS, this product is noisy because of a combination of low dynamic range and quantization errors in the visible band data. Noise reduction through spatial smoothing is feasible since haze variations tend to be on the scale of kilometers compared to the 80 meter spatial resolution of the MSS sensor. We accomplish smoothing by generating an image pyramid from the HOT image (Schowengerdt, 1997), selecting a suitable level then expanding that level back to the sampling interval of the parent HOT image through bilinear interpolation. For MSS, experience has indicated that the second pyramid level (i.e. 4 times reduction) provides a robust smoothing solution.

2.3. Determine Radiometric Adjustment Parameters

For those pixels exhibiting a HOT response greater than that of the clear areas, a radiance adjustment (i.e. reduction) will be applied. Based on modelling experiments (Zhang et al. 2002a), a linear relationship between radiance adjustment and HOT level serves as a good first approximation. The scale factor of this relationship is determined using a 'dark target' subtraction approach (e.g. Chavez, 1988). For a given visible band, a series of grey level histograms are generated for pixels in HOT intervals ranging from clear to the haziest levels for which adjustment is practical. The rate of increase of histogram lower bound with HOT defines the required scale factor. It should be noted that water bodies with significant sediment content will also trigger a high HOT response. To overcome this problem, a water mask is created by thresholding the MSS4 image and used to exclude water pixels from the histogram analysis described above.
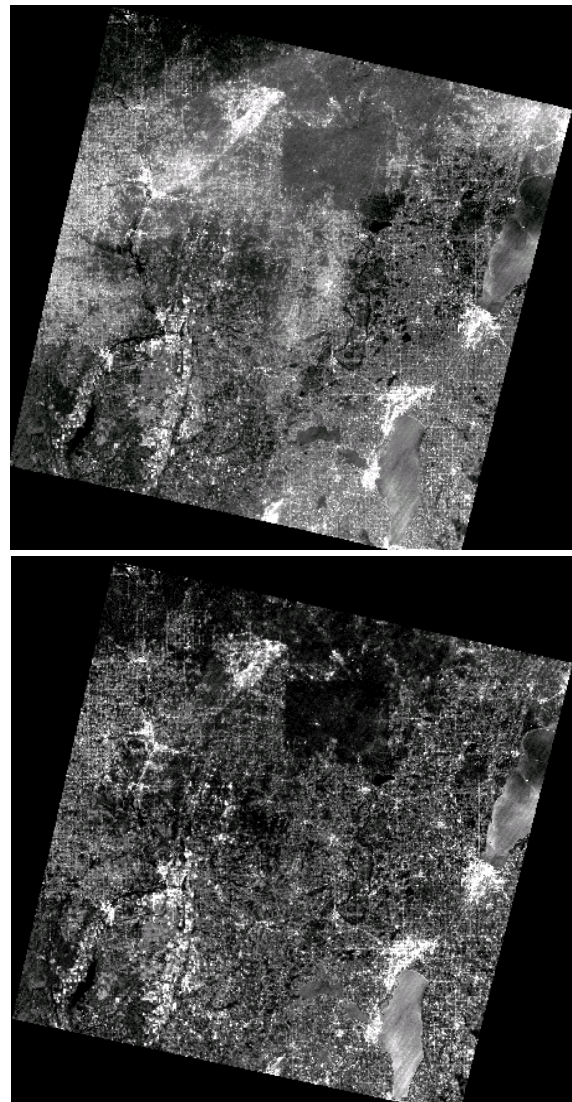

Figure 2. Example of adjustment (lower) from a hazy image (upper)

2.4. Adjust Visible Band Radiometry

With scaling factors in hand, the two visible bands can then be adjusted on a per pixel basis. Water body pixels do not undergo this adjustment. This is not a major limitation since accurate water classification can be achieved even in the presence of high levels of haze. Finally, because of the necessary smoothing operation described above, pixels near the image boundary cannot be correctly processed and must be trimmed from the final product. Figure 2 shows an example MSS1 case with the raw image (top) exhibiting extensive regions of low to moderate level haze that have been successfully suppressed through the adjustment process (bottom image).

3. Classification accuracy impact of haze removal

The assessment described here was conducted as part of a joint project involving the Canada Centre for Remote Sensing and the United States Environmental Protection Agency to generate synoptic land cover products of the Great Lakes watershed. This is being done with archival Landsat MSS data sets for three acquisition epochs, mid 1970's, mid 1980's and early 1990's. Coverage of the complete watershed for each epoch encompasses approximately 50 scenes.

A proto-type system, QUAD-LACC, has been developed to accomplish the mapping task Its methodology is based on independent classification (unsupervised clustering followed by cluster labelling) of each scene and subsequent classification compositing (Guindon and Edmonds, 2002a). In this way, a major feature of Landsat data is exploited, namely, the extensive overlap coverage of scenes from adjacent orbital tracks. This approach was selected for two reasons. First, by utilizing all available imagery, information degradation and loss in individual scenes due to cloud and haze can be partly overcome. Second, classification consistency in overlap regions can be used as an indicator of classification performance that characterizes the spatial distribution of accuracy across large area (i.e. multi-scene) land cover products (Guindon and Edmonds, 2002b).

To assess the impact of haze removal on classification performance, we have selected a set of 35 source scenes from the 1990's epoch and created two sets of classified products, one derived from raw and the other from haze reduced imagery. For the purposes of this study, land cover has been stratified into two broad categories only, forest vs. non-forest land. Within each classified data set, consistency analyses have been undertaken on all cross-track overlap regions. Comparisons have then been made between consistency levels of corresponding overlap regions in the two product sets.

The level of consistency can be quantified in the following manner. Consider the case of the overlap region of two classified scenes, #1 and #2. The consistency of classification of a class A in scene #1 can be defined as the portion of pixels, classed as A in scene #1, that have the same classification in scene #2. For a two-class scenario (classes A and B), the above consistency, C_{1A}, can be expressed as:

$$C_{1A} = \frac{fP_{1A}P_{2A} + (1-P_{1B})(1-P_{2B})}{fP_{1A} + (1-P_{1B})} \qquad (1)$$

where the P's refer to the producer accuracies of each class in each scene (e.g. P_{1A} is the class A producer accuracy in scene #1) and f is the ratio of the numbers of true class A to true class B pixels in the overlap region (Guindon and Edmonds, 2002b). Producer accuracy, P_A, is defined as the probability that a true class A pixel is correctly labelled. This differs from user accuracy, Q_{1A}, which is the probability that a pixel, classed as A, is indeed of true class A. User accuracy can be expressed as:

$$Q_{1A} = \frac{fP_{1A}}{fP_{1A} + (1-P_{1B})} \qquad (2)$$

As has been shown elsewhere and can be seen from a comparison of equations 1 and 2, consistency is a useful surrogate of conventional user accuracy (Guindon and Edmonds, 2002b).

For our rudimentary classes we would expect producer accuracies to be high (typically above 85%). On the other hand, over the Great Lakes watershed, consistency and hence user accuracy can vary significantly because of the variations in f. If we take 'forest' for class A, f can range as low as 0.05 in the largely agricultural/urban south to more than 10 in the boreal forests of the north. In the case of southern scenes, the majority of pixels classed as forest can be commission errors. As a result of commission error randomness, forest consistency can be low (i.e. much less than 0.5) and therefore, as with user accuracy, be very sensitive to even moderate improvements in producer accuracy that may arise from haze reduction.

For a given scene pair and its overlap region, f remains constant but haze processing will alter producer accuracy and hence consistency. While the impact of haze reduction will vary from scene-to-scene and hence overlap-to-overlap region, we can consider some simple scenarios to attempt to gauge its overall impact on the scene population. We will assume that the producer accuracies of the two classes are the same raw imagery and are improved by the same percentage by haze reduction. Initially, four scenarios were considered, namely initial raw producer accuracies (PRAW) of 85 and 90% and incremental improvements (PINC) of 2.5 and 5%. Equation 1 has been used to generate raw-improved consistency 'trajectories' for values of f ranging from 0.05 (low consistency) to 20 (high consistency). The trajectories are shown in Figure 3 along with the unity line (i.e. no change) for reference. All four cases predict similar, moderate levels of consistency improvement.

Figure 4 illustrates the raw versus haze-reduced consistency comparison for the Landsat MSS data set. A number of points can be made regarding these results.

(a) The data set exhibits significant scatter with offsets relative to the unity line which are much larger than those predicted from the four scenarios especially at low consistency levels.

(b) Haze reduction results in significant improvement in all low consistency cases (i.e. cases where raw image consistency was less than 0.5). The impact is more difficult to discern at higher consistency levels from the diagram alone because of scatter. To better understand overall trends, we have grouped data points in intervals of raw consistency and computed the average haze reduced consistency for each. The results, shown in Table 1, indicate that consistency enhancement gradually

diminishes with increasing consistency level and that haze processing may reduce consistency at the highest levels.
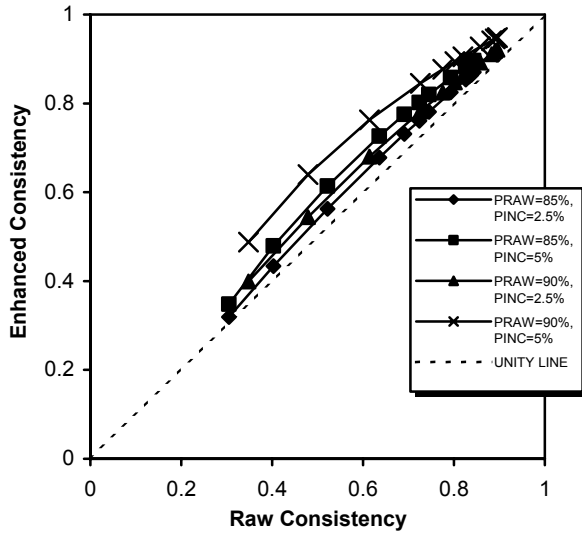

Figure 3. Predicted consistency relationships for model producer accuracy scenarios
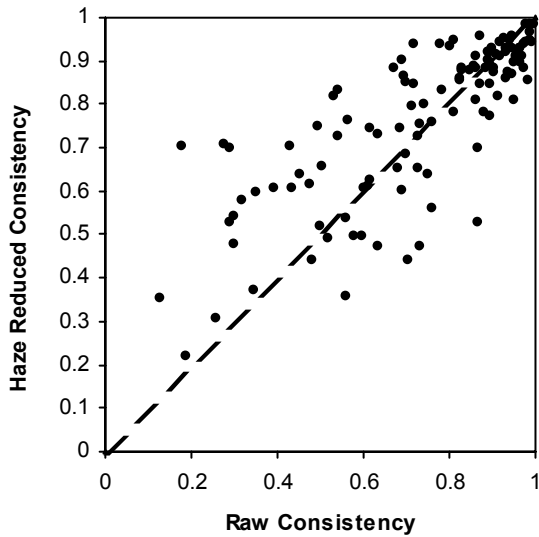

Figure 4. Raw versus haze-reduced consistency for the Landsat MSS data set

(c) Haze reduction results in significant improvement in all low consistency cases (i.e. cases where raw image consistency was less than 0.5). The impact is more difficult to discern at higher consistency levels from the diagram alone because of scatter. To better understand overall trends, we have grouped data points in intervals of raw consistency and computed the average haze reduced consistency for each. The results, shown in Table 1, indicate that consistency enhancement gradually diminishes with increasing consistency level and that haze processing may reduce consistency at the highest levels.

(d) Low consistency is associated with so-called 'rare' classes, i.e. those with small proportional coverage relative to classes with which they are likely to be confused (i.e. low f values). Unless a rare class exhibits a very high level of spectral uniqueness, its producer accuracy will be degraded due to the limitations of the classification process where the goal is to assign a label to a given cluster that is indicative of its dominant class. When a class is under-represented relative other classes of similar spectral properties, many of its member pixels will be members of clusters dominated by other classes thereby reducing its producer accuracy. Based on trial runs using equation 1, we conclude that the observed large improvements at low consistency are explainable by low raw producer accuracies, typically in the range of 50 to 60%, that are increased to the 85% range by haze processing. In addition, as f increases, forest producer accuracy increases to the expected levels of 85 to 90% even in the raw scenes. Consequently, the impact of haze processing gradually diminishes. Independent scene-based classification assessments using ground reference data confirms these model predictions and are being published elsewhere (Guindon and Edmonds, 2002b).

Raw Scene Consistency Range	Mean Haze-Reduced Consistency
0.0 - 0.2	0.43
0.2 - 0.4	0.54
0.4 - 0.6	0.63
0.6 - 0.7	0.72
0.7 - 0.8	0.73
0.8 - 0.9	0.86
0.9 - 1.0	0.92

Table 1. Mean consistency levels of haze-reduced scenes for different ranges of raw scene consistency.

4. Conclusions

Although Landsat data selection has been optimized for many large-area monitoring programs, constituent scenes may be contaminated by haze, thereby jeopardizing effective information extraction. A robust, image-based haze reduction methodology has been described which is suitable for bulk processing applications. Assessment of its impact on Landsat MSS scenes indicate that it can significantly improve inter-scene classification consistency and hence classification accuracy. This is particularly true for classes of low proportional coverage (i.e. 'rare' classes) whose producer accuracies are limited by the framework of the classification methodology.

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