AUTOMATED PRODUCTION OF CLOUD-FREE AND CLOUD SHADOW-FREE IMAGE MOSAICS FROM CLOUDY SATELLITE IMAGERY

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ABSTRACT:

The humid tropical region is always under partial or complete cloud covers. As a result, optical remote sensing images of this region always encounter the problem of cloud covers and associated shadows. In this paper, an operational system for producing cloud-free and cloud shadow-free image mosaics from cloudy optical satellite imagery is presented. The inputs are several cloudy images of the same area acquired by the IKONOS or SPOT satellites. By mosaicking the cloud-free and cloud shadow-free areas in the set of images, a reasonably cloud-free and cloud shadow-free composite scene can be made. This technique is especially valuable in tropical regions with persistent and extensive cloud cover.

1. INTRODUCTION

Cloud cover is a big problem in optical remote sensing of the earth surfaces, especially over the humid tropical regions. This problem can usually be solved by producing a cloud-free mosaic from several multi-date images acquired over the same area of interest. In this method, an image containing the least cloud covers is taken as the base image. The cloudy areas in the image are masked out, and then filled in by cloud-free areas from other images acquired at different time. It is equivalent to the manual "cut-and-paste" method. The cloud-masking process can be automated by intensity-thresholding to discriminate the bright cloudy areas from cloud-free areas. However, simple thresholds cannot handle thin clouds and cloud shadows, and often confuse bright land surfaces as clouds.

In this paper, we present an automated procedure for producing cloud-free and cloud shadow-free image mosaic from cloudy optical imagery, that is able to overcome the pitfalls encountered by the simple thresholding method. This method works for both multispectral and panchromatic images. In this procedure, the pixels are classified into clouds, vegetation, buildings or bare soil based on the pixel intensity, colour, size and shape features. Cloud shadows are automatically located from the knowledge of the imaging geometry and the intensity gradients at cloud edges. Each pixel/patch in each of the images is then ranked according to some predefined ranking criteria. The highest ranked pixels/patches are preferably used to compose the mosaic.

2. DESCRIPTION OF THE ALGORITHM

Figure 1 shows a schematic diagram of the system for operational production of cloud-free and cloud shadow-free mosaics from optical satellite imagery.

2.1 Input Images

The inputs to the system are multispectral/panchromatic images of the same region acquired within a specified time interval. The images are co-registered before being fed into the system.

2.2 Balancing of Grey Level

The brightness of pixels at the same location from two different scenes will be slightly different due to the atmospheric effects, sun angles and sensor look angles during acquisition. This disparity is especially prominent in low-albedo vegetated areas. Therefore, it is necessary to balance the intensity of the patches so as to minimize the variation. An image from the set of input images is chosen as the reference image. The pixel values of all other images in the same set are adjusted according to

$$P = E_{ref} + (S - E) \quad (1)$$

where P is the output pixel value, S is the input pixel value, E_{ref} is the mean pixel value of an overlap area around the mask patch being processed from the reference image, E is the mean pixel value of the same overlap area from the image to be balanced. Please note that the grey-level balancing procedure must be applied to each band.

2.3 Cloud and Cloud-Shadow Masking

Initial cloud and cloud shadow masks are produced using simple intensity thresholds. However, bright pixels of bare soil or building may be confused with cloud pixels. Such confusions are resolved by making use of size, shape and colour information of the bright pixel clusters. Clouds that need to be masked out are much larger than individual buildings. Man-made features such as buildings and bare soil normally have simple geometric shapes. An automatic method has been developed not only to calculate the size of bright patches but also to detect the lines, simple shapes and colour of the bright land surface in order to eliminate improper masking of these buildings and bare soil as clouds by the initial intensity thresholds. We employ a technique based on a geometric model, solar illumination direction and sensor viewing direction, as well as the intensity gradient to automatically predict the approximate location of cloud shadows near to the cloud edges.

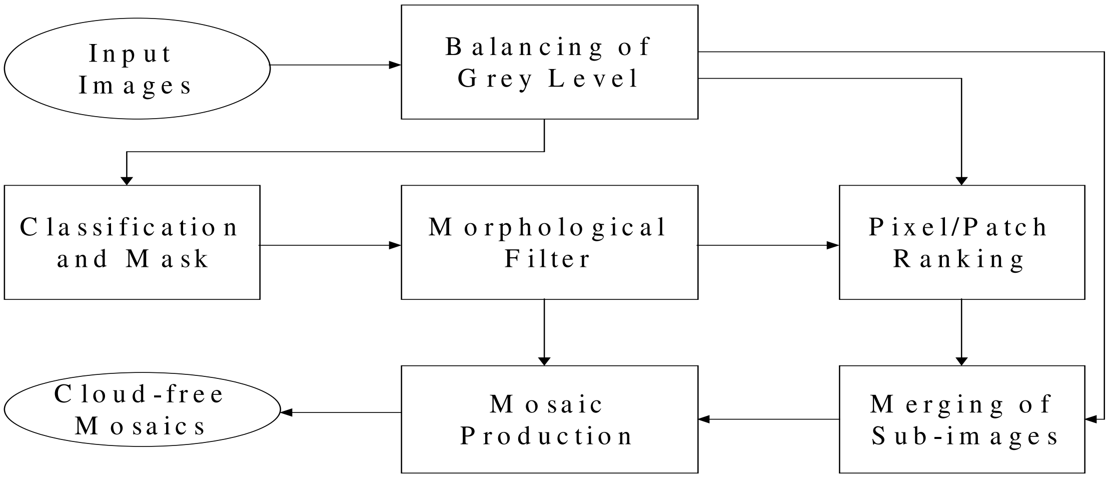

Figure 1. A schematic diagram of the cloud-free and cloud shadow-free mosaic generating system

The initial cloud mask produced using a fixed intensity threshold usually excludes the thin clouds at cloud edges. To solve this problem, a morphological filter is applied to dilate the initial cloud mask patch so that the thin clouds at cloud edges are included in the cloud mask.

2.4 Pixel/Patch Ranking

In the masking process, some bright patches on bare soil can still be mistaken as cloud patches due to the similar intensity level and colour. These patches can be unfilled because no good data patches in the set of co-registered cloudy images can be used to mosaic the composite image. We therefore introduce a pixel/patch ranking procedure that employs the pixel/patch intensity and some suitably chosen band ratios to rank the pixels/patches in the order of “cloudness” and “shadowiness” according to some predefined ranking criteria described below. In this procedure, a shadow intensity threshold T_s, a vegetation intensity threshold T_v, a cloud threshold T_c are determined from the intensity histogram. The pixel/patch ranking procedure uses these shadow and cloud thresholds to rank the pixels/patches in order of “cloudiness” and “shadowness”. Each of the non-cloud and non-shadow pixels/patches in the images is classified into one of three broad classes based on the band ratios: vegetation, open land and others.

For each image n from the set of N acquired images, each pixel/patch at a location (i, j) is assigned a rank $r_n(i, j)$ based on the pixel/patch intensity $Y_n(i, j)$ according to the following rules:

1) For $T_s \le (Y_m, Y_n) \le T_v$, if $Y_m < Y_n$ and class = "vegetation", then $r_m < r_n$;
2) For $T_v \le (Y_m, Y_n) \le T_c$, if $Y_m < Y_n$ and class = "open land", then $r_m < r_n$;
3) If $Y_m < T_s$ and $Y_n > T_c$, then $r_m < r_n$;
4) For $Y_m, Y_n < T_s$, if $Y_m > Y_n$, then $r_m < r_n$;
5) For $Y_m, Y_n > T_c$, if $Y_m < Y_n$, then $r_m < r_n$;

In this scheme, pixels/patches with lower rank values of r_n are more superior and are more likely to be selected. Pixels/patches with intensities falling between the shadow and cloud thresholds are the most superior, and are regarded as the "good pixels/patches". The “good pixels/patches” are further classified into “vegetation pixels/patches” or “open land pixels/patches” depending on whether the pixel/patches intensity is below or above the vegetation threshold. As rule of thumb, the darker “good pixels/patches” are preferred over the brighter “good pixels/patches” because the brighter “good pixels/patches” may be contaminated by thin clouds. Where no good pixels/patches are available, the "shadow pixels/patches" are preferred over the "cloud pixels/patches". Where all pixels/patches at a given location are "shadow pixels/patches", the brightest shadow pixels/patches will be chosen. In locations where all pixels/patches have been classified as "cloud pixels/patches", the darkest cloud pixels/patches will be selected. After ranking the pixels/patches, the rank-r index map $n_r(i, j)$ representing the index n of the image with rank r at the pixel/patch location (i, j) can be generated. It is preferred that only the rank-1 and rank-2 index maps are generated and kept for use in generating the cloud-free and cloud-shadow free mosaics.

2.5 Merging of Sub-images

The rank-1 and rank-2 index maps generated from the pixel/patch ranking procedure are used to merge the input multi-scenes that have been processed by the grey-level balance. If the pixel at a given location has been classified as “vegetation pixel”, the pixels from the rank-1 image and the rank-2 image at that location may be averaged together in order to avoid sudden spatial discontinuities in the final mosaic image. Otherwise, the pixels from the rank-1 image are used.

2.6 Mosaic Production

The basic idea of the cloud-free and cloud shadow-free mosaic algorithm is to mask the clouds, cloud-shadows and select good image data from the different scenes in a selected set of co-registered cloudy images, and to mosaic “clean” data together. If the clean data pixels from different scenes are simply consolidated without additional processing, the final image will be very “speckled” and appear discontinuous. Therefore, a patch of pixels rather than the individual pixels is chosen to form the final mosaic.

The final mosaic is composed from the images with cloud, cloud-shadow masks and the merged image generated from the merging of sub-images procedure. To suppress the visibility of the seam line between adjacent patches, the residual intensity differences between the patches are balanced using the intensity histograms of local patches. Secondly, the patches are made to overlap at their boundaries and the system will blend the image intensity from one patch to another in these overlapping regions. Finally, the images resulting from the mosaic process are geo-referenced to a map. The mosaic production procedure will put the image from the mosaic process into the map.

3. RESULTS AND CONCLUSIONS

An example of applying the cloud-free mosaicking algorithm the six cloudy SPOT panchromatic images is shown in Figure 2. Figure 3-(a) shows a mosaic of cloudy SPOT multispectral images over Singapore and the southern part of the Peninsular Malaysia. The resulting cloud-free and cloud shadow-free mosaic is shown in Figure 3-(b). The mosaicking algorithm has also been tested on 1-m resolution IKONOS colour images.

In this paper, we have presented the method for producing cloud-free and cloud shadow-free multi-scene mosaics from cloudy SPOT and IKONOS images. The system has been implemented successfully over a large area covered by about 50 SPOT scenes. The success of the cloud-free and cloud shadow-free mosaic depends on the choice of the shadow, vegetation and cloud intensity thresholds. Confusions arise when high-albedo open land surfaces or buildings are encountered. Such confusions can be resolved by making use of size and colour information to classify the pixels /patches into a few broad land cover classes. In many cases the clouds that need to be masked out are much large than the individual building, an automatic method is developed to calculate the size of the bright patches in order to eliminate improper masking of these buildings. As a result, this procedure allows a few small cloud patches to remain in the mosaic. A large, very bright and white patch of open land surface will be considered as cloud. When the bright and white patch of open land does not contain cloud-shadow, it is still possible for this patch of open land surface to be selected and used in forming the final mosaic. The approximate location of cloud shadow can be predicted based on the knowledge of solar illumination direction, sensor viewing direction and cloud height.

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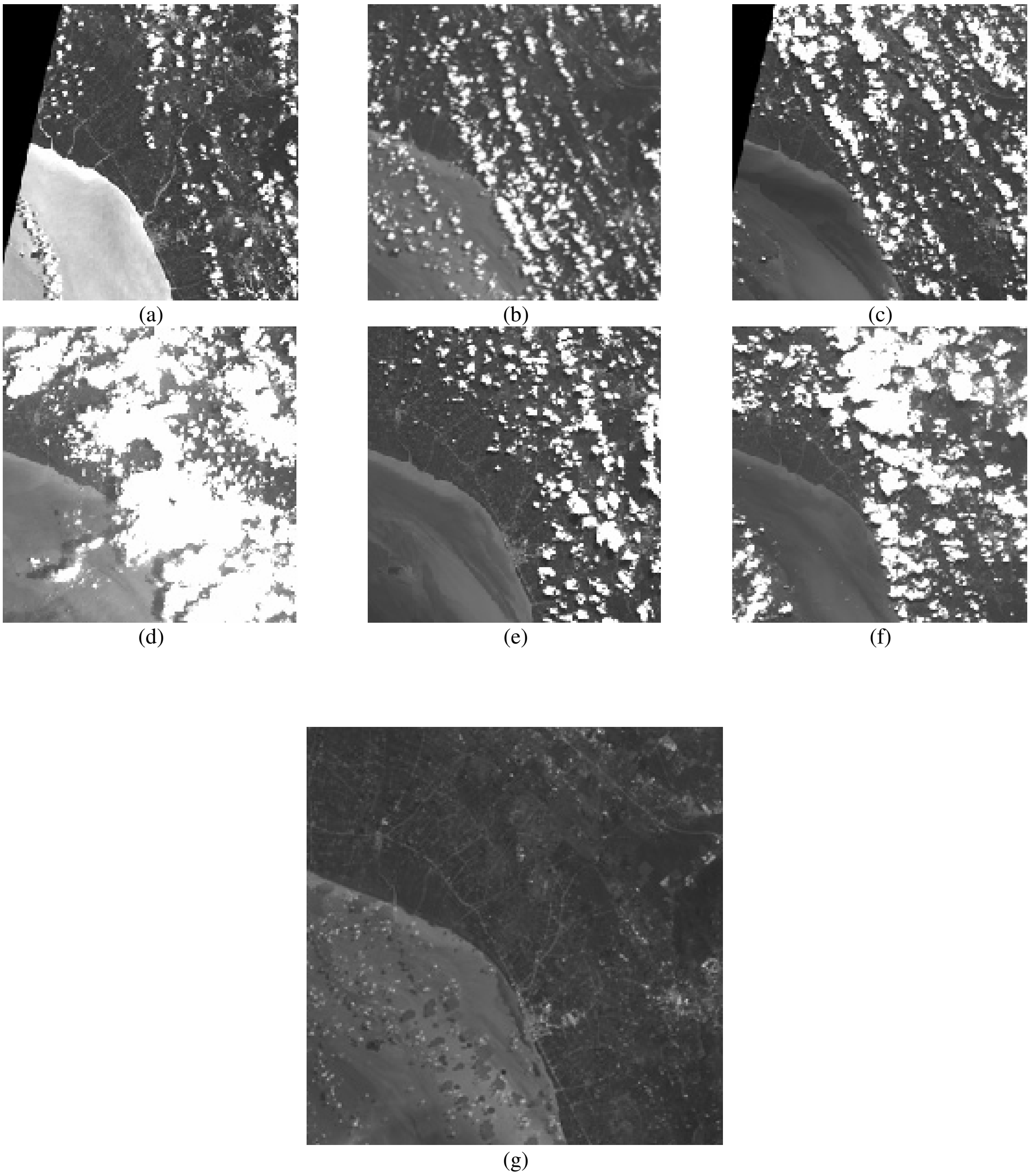

Figure 2. An example of applying the cloud-free, cloud shadow-free mosaicking algorithm to six cloudy SPOT panchromatic images (a – f) and the cloud-free, cloud shadow-free composite (g) of the same area

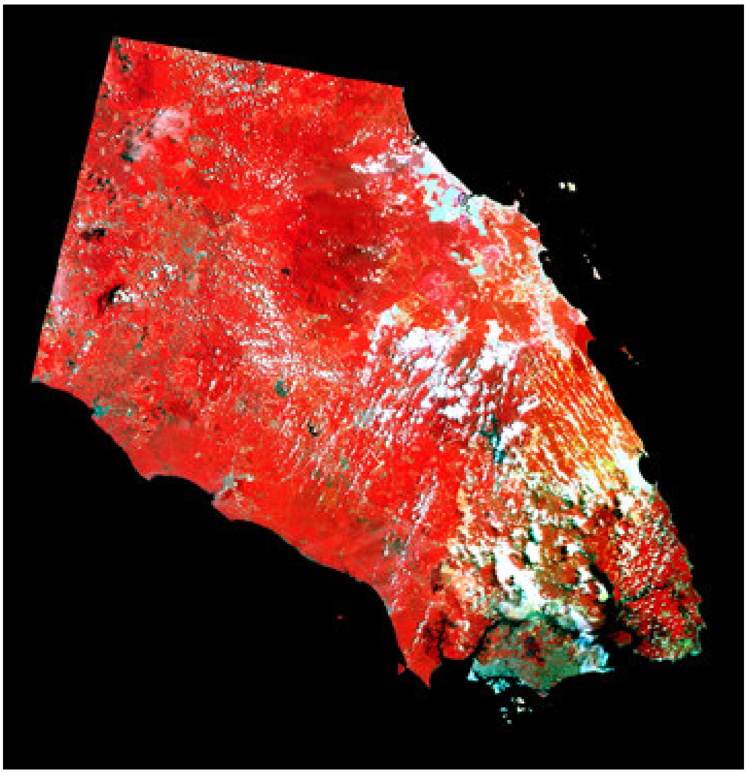

Figure 3-(a). Mosaic of cloudy SPOT multispectral images of Singapore and Southern Peninsular Malaysia Images with the lowest cloud coverage have been chosen to generate this mosaic.
(SPOT images © CNES, acquired and processed by CRISP, reproduced under licence from SPOT IMAGE)

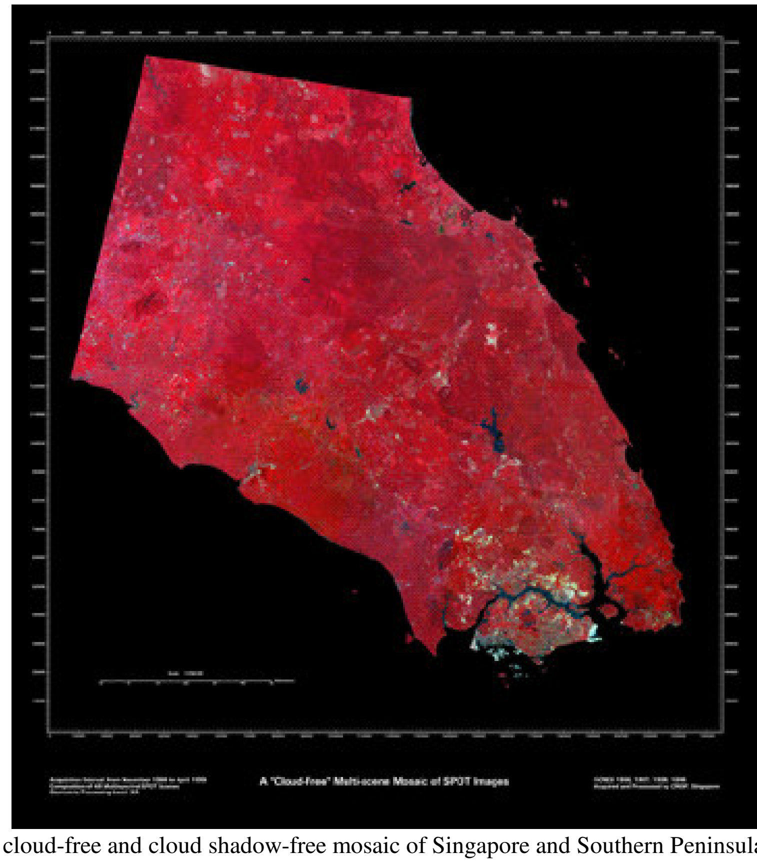

Figure 3-(b). Multi-scene cloud-free and cloud shadow-free mosaic of Singapore and Southern Peninsular Malaysia generated using 48 SPOT multispectral scenes.
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