Performance analysis of mineral mapping method to delineate mineralization zones under tropical region

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Abstract. Geothermal explorations and productions are currently being intensively conducted at certain areas in Indonesia such as Wayang Windu Geothermal Field (WWGF) in West Java, Indonesia. The WWGF is located at wide area covering about 40 km². An accurate method to map the distribution of heterogeneity minerals is necessary for wide areas such as WWGF. Mineral mapping is an important method in geothermal explorations to determine the distribution of minerals which indicate the surface manifestations of geothermal system. This study is aimed to determine the most precise and accurate methods for minerals mapping at geothermal field. Field measurements were performed to assess the accuracy of three proposed methods: 1) Minimum Noise Fraction (MNF), utilizing the linear transformation method to eliminate the correlation among the spectra bands and to reduce the noise in the data, 2) Pixel Purity Index (PPI), a designed method to find the most extreme spectrum pixels and their characteristics due to end-members mixing, 3) Spectral Angle Mapper (SAM), an image classification technique by measuring the spectral similarity between an unknown object with spectral reference in n-dimension. The output of those methods were mineral distribution occurrence. The performance of each mapping method was analyzed based on the ground truth data. Among the three proposed method, the SAM classification method is the most appropriate and accurate for mineral mapping related to spatial distribution of alteration minerals.

Keywords: mineral mapping, geothermal manifestations, Minimum Noise Fraction, Pixel Purity Index, Spectral Angle Mapper.

1. Introduction
The remote sensing technology is an effective and efficient tools to identify physical properties of rocks at surface such as alteration [1, 2], moisture and texture [3], and roughness [4],[5]. The main advantage to use the remotely sensed data is to reduce the field investigation time or to define the prospect for geophysical surveys at wide coverage area [6].

Mineral mapping method is useful in geothermal potential expansion to determine the alteration mineral spatially. We selected the Wayang Windu Geothermal Field (WWGF) because the area is composed by various surface manifestations with heterogeneity of mineral compositions covering wide areas.
Therefore, precise and accurate mapping method is necessary to determine the distribution of these minerals. This study is aimed to determine the most precise and accurate methods for mineral mapping under tropical conditions for geothermal exploration purposes.

We used Hyperion data in this study. Hyperion is a hyperspectral sensor covering the 0.4 to 2.5 µm spectral range with 242 spectral bands at approximately 10 nm spectral resolution and 30 m spatial resolution from a 705 km orbit [7]. Hyperion is a pushbroom instrument, capturing 256 spectra each with 242 spectral bands over a 7.5 km-wide swath perpendicular to the satellite motion with 160 km path length [8]. The system was utilized by two spectrometers; a visible/near infrared (VNIR) spectrometer (approximately 0.4 – 1.0 µm) and a short-wave infrared (SWIR) spectrometer (approximately 0.9 – 2.5 µm).

2. Study Area

The WWGF is composed by the two small lava domes without eruption history [9]. The field is located at Pengalengan, approximately 35 km to the south of Bandung, the capital of West Java, Indonesia (see Figure 1). The elevation lies between 1500 – 2100 m above sea mean level [10]. The geothermal systems of WWGF are associated with the dominance of steam fluid caps southern part of Mt. Malabar, a large stratovolcano composed of lava, breccia, lava and dacitic tuffs, and andesite.

There are about 9 thermal manifestations including fumaroles, hot springs, mud pools and altered ground situated along the southern slopes of the Mt. Malabar. Fumaroles are located between Mt. Wayang and Mt. Windu with temperatures between 93°C to 96°C and indicated slightly superheated compared to the normal water boiling point at altitudes 2000 m. Hot springs located in altitudes between 1495 m and 1985 m with temperatures from 41°C to 88°C. Water discharge as hot springs are bicarbonate type, except for hot springs located near the fumaroles as acid sulphate water [11].

The lithology at WWGF consists of four main units, from the young to old units: Malabar-Bedil andesite, Kancana lavas, Malabar-Tilu volcanic, and the younger Wayang volcanic units (see Figure 2). The geothermal system at WWGF is classified as transition between vapor and liquid dominated systems [13].

![Figure 1. Study area at WWGF, West Java presented by red rectangular overlaid on Landsat -8 imagery.](image-url)
3. Methods

There are three methods of mineral mapping that will be compared to the ground truth (field survey) data: Minimum Noise Fraction (MNF), Pixel Purity Index (PPI), and Spectral Angle Mapper (SAM).

3.1. Minimum Noise Fraction (MNF)

The MNF transformation is a linear transformation related to principal components that orders the data according to signal-to-noise-ratio [15]. The MNF transformation is used to separate the data space into two parts: one associated with large eigenvalues and coherent eigenimages, and a second with near-unity eigenvalues and noise-dominated images [16]. In general, the higher numbered MNF bands contain progressively lower signal-to-noise. MNF is also a linear transformation method for eliminating the correlation between bands and for reducing the noise in the data [17].

3.2. Pixel Purity Index (PPI)

Based on MNF results, the lower order MNF bands are usually excluded and the higher order bands are selected for further processing. For the Pixel Purity Index (PPI), processing is designed to locate the most spectrally extreme (unique or different or “pure”) pixels [18]. The most spectrally pure pixels typically correspond to mixing endmembers. The PPI is computed by repeatedly projecting n-dimensional scatterplots onto a random unit vector.

The extreme pixels in each projection are recorded and the total number of times each pixel is marked. A PPI image is created in which the digital number of each pixel corresponds to the number of times that pixel was recorded as extreme. A threshold is interactively selected using the histogram and used to select only the purest pixels in order to keep the number of pixels to be analyzed to a minimum. These pixels are used as input to an interactive visualization procedure for separation of specific endmembers.

Figure 2. Geological map of Wayang Windu Geothermal Field [14].
3.3. Spectral Angle Mapper (SAM)

SAM is a supervised classification algorithm, which utilizes spectral angular information for the classification of hyper-spectral data [19]. It treats each pixel in a hyper-spectral image as an n-dimensional vector, where n equals the number of spectral bands. The algorithm measures similarity of a target to a reference spectrum by calculating spectral angles between them (see Figure 3). A smaller angle represents a closer match to the reference spectrum. The angle between a target spectrum vector $a$, reference spectrum vector $b$, can be calculated by:

$$\alpha = \cos^{-1}\left(\frac{a \cdot b}{\|a\| \cdot \|b\|}\right) \quad (1)$$

where $\|\|$ is a norm function [20], Eq. (1) can also be written as:

$$\alpha = \cos^{-1}\left(\frac{\sum_{i=1}^{n} a_i \cdot b_i}{\left[\sum_{i=1}^{n} a_i^2\right]^{1/2} \left[\sum_{i=1}^{n} b_i^2\right]^{1/2}}\right), \quad (2)$$

where $n$ is the number of spectral bands, $a_i$ denotes value of the target spectrum at $i^{th}$ band and $b_i$ denotes value of the reference spectrum at $i^{th}$ band.

This measure of similarity is insensitive to gain factors because the angle between two vectors is invariant with respect to the lengths of the vectors. As a result, laboratory spectra can be directly compared to remotely sensed apparent reflectance spectra, which inherently have an unknown gain factor related to topographic illumination effects.

**Figure 3.** Plot of a reference spectrum and test spectrum for a two-band image. The same materials with varying illumination are represented by the vectors connecting the origin (no illumination) and projected through the points representing the actual spectra [19].

4. Result and Discussion

The results of each method are compared with the existing ground truth in order to determine which method is the most precise and accurate for mapping minerals (alterations). The table below is the result of ground truth:

| Observation Points | Lithology          |
|--------------------|--------------------|
| A1-2               | Altered rock       |
| A1-9D              | Altered andesite   |
| A4-1               |                    |
| A4-9               |                    |
| A5-10              |                    |
| A9-5               |                    |
| A17-3              |                    |
| A17-1              |                    |
| PA5-1A             |                    |
| WA1-12             |                    |

There are 19 observation points, and 10 point that showed the presence of geothermal manifestations which characterized by lithology in the form altered rock and altered andesite, that points: (A1-2), (A1-9D), (A4-1), (A4-9), (A5-10), (A9-5), (A17-3), (A17-1), (PA5-1A), and (WA1-12).
Table 1. The result of ground truth data and the point of observation and lithology.

| No. | Waypoint | Lithology                  |
|-----|----------|-----------------------------|
| 1   | DR10-2   | Andesite porphyri           |
| 2   | A1-2     | Altered rock                |
| 3   | A1-9D    | Altered rock                |
| 4   | A4-1     | Altered rock                |
| 5   | A4-9     | Altered andesite            |
| 6   | A5-10    | Altered rock                |
| 7   | A7-5     | Volcanic breccia            |
| 8   | A9-5     | Altered andesite            |
| 9   | A14-2    | Pyroclastic breccia         |
| 10  | A17-3    | Altered rock                |
| 11  | PA1-4    | Andesite                    |
| 12  | PA2-7    | Brecciated andesite lava    |
| 13  | PA3-7    | Volcanic breccia            |
| 14  | PA5-1A   | Altered rock                |
| 15  | WA1-12   | Altered rock                |
| 16  | WA3-1    | Travertin                   |
| 17  | A17-1    | Altered rock                |
| 18  | A7-3     | Volcanic breccia            |
| 19  | WA1-10B  | Andesite                    |

4.1. MNF Result

The parameters used in analyzing the MNF Transform are input image, output noise statistics, and output MNF stats. If these parameters have been met, then eigenvalues can be obtained. Eigenvalues are values of the transformation shown the dimensional distinctions based on testing of digital values. Eigenvalue is the discriminant level of the band. The greater eigenvalue means the greater of the difference level, or the noise is getting smaller. Figure 4 shows that there are 147 bands with respective eigenvalues, where the results of MNF shows that the initial bands has large eigenvalues.

Figure 4. MNF plot with the total eigenvalue of each band.
MNF analysis is applied by selecting three bands with the highest eigenvalue (MNF-1, 2, 3). To analyze it, the plot surface manifestation of the composite MNF, and observe the hue and toned appearance. Based on the results of existing ground truth, the location of alteration zones was indicated by altered rocks at (A1-2), (A1-9D), (A4-1), (A4-9), (A5-10), (A9-5), (A17-3), (A17-1), (PA5-1A), and (WA1-12).

An subset image in Figure 5 shows that the altered rock samples are located at a relatively bright hues and greenish color. The appearance of the brightness and color was identified as an anomaly originated from alteration zones.

4.2. PPI Result

Pixel purity index (pixel Purity Index) is used to find the purity of a pixel on multispectral and hyperspectral imagery. Pure pixel is a pixel that is truly representative of the object to be homogeneous. Mixed pixel is a pixel representing several objects at once.

There are two parameters in pixel purity index plot, ie parameter y are number of pixels, and the parameters x are number of iterations. The number of iterations of itself means the ability an image to read a number of pixel values at once. From PPI curve can be seen that the value of iterations performed 10,000 times. It is seen that the more iterations performed, the index value is also higher purity (see Figure 6).
Figure 6. PPI iteration vs. total cumulative pixel

Figure 7 shows the result of the mapping based on the brightness of the pixel (PPI output), where the bright pixels represent spectral extremes (pure) and dark pixels represent the spectral less pure. The points that indicate geothermal manifestations were located on the pixel with a relatively dark (black).

Figure 7. The PPI image indicating bright and dark pixels represent more and less spectrally extreme (pure), respectively. The red arrows are a manifestation points.

4.3. SAM Result

SAM process dividing the objects in the image into 48 classes or 48 different spectra. The points manifestations (10 points) was then plotted into the SAM map and can be seen that: three points are in class 46 that point are: (A1-9D, A1-2, A4-1), three point were in class 29: (PA5-1A, A9-5, A5-10 ), two points are in class 35 that are: (A17-3, A4-9), one point is in class 27, that is point (A17-1) and one point is in class 23, that is point (WA1-12).
Figure 8. Plot spectrum target with (a). Spectrum class 46; (b). Spectrum class 29; (c). Spectrum class 35; (d). Spectrum class 27; and (e). Spectrum class 23.

All spectra class above (see Figure 8) will be matched with the reference spectra of clay minerals from spectra library ENVI and USGS (Illit, kaolinite and montmorillonite) to determine the minerals contained in the class.

Figure 9. Matching process between target spectrum to reference spectra
Figure 9 shows that the spectrum of the target (class 46, 29 and 35) has a relatively similar pattern, so we interpreted that the three spectra is same object or target. After matching process, we obtained that the spectra originated from illite mineral. Pattern of the spectrum in class 27 also resemble the pattern of minerals montmorillonite and class 23 is kaolinite. Figure 10 shows that the light blue, brown, and pink were identified as illite, the green is montmorillonite mineral, and dark blue is kaolinite mineral.

Conclusion
The MNF and PPI methods showed that the appearance of the target at the ground surfaces was presented by color and gray. The MNF method showed that all altered rock samples were located at bright hues and greenish color. For PPI method, the samples were located at dark pixel. According to the SAM method, there were eight out from ten rock samples were identified by illite mineral, and the other two samples were montmorillonite and kaolinite minerals. The SAM method could identify the minerals at low vegetation covers. Therefore, among the three methods, the SAM method is the most suitable for altered minerals mapping. The similarity spectra from reference and spectra was used as basis of mineral identification spatially.

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