Methodology for calculating volcano vent temperature using optical remote sensing data*

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Conventional methods to estimate volcano vent temperature using ground-based methods are hazardous, and there is need to explore alternate methods like those involving the utilization of remote sensing data. A volcano eruption took place recently in Barren Island of Andaman and Nicobar group of islands. Unusual event of this nature generated a lot of interest. A methodology of temperature estimation of volcano vent using optical remote sensing data of Landsat Thematic Mapper (TM) is presented. The dynamic range of thermal infrared band gets saturated as it has been designed for normal terrestrial temperatures. The sensitivity of various spectral bands is discussed and the utility of near IR band data for the measurement of vent temperature is emphasized. The effect of sub-pixel size vent in the estimation of pixel-integrated temperature is estimated by assigning weighted radiation value to the non-vent component of the pixel using values of surrounding background pixels. It is inferred that if the volcanic vent occupies 21% area of the pixel, the computed pixel-integrated temperature of the vent is within 1% error. Even if the vent occupies 10% of pixel area, the error in volcano vent temperature estimate would be around 3%. This is due to the exponential nature of Plank's black body function.

1 Introduction

A volcanic eruption took place in Barren Island of Andaman and Nicobar group of islands during April 1991. Monitoring of volcanoes is essential to predict eruptions and related hazards. Remote sensing data available from satellites are mostly from visible and near IR region of electromagnetic radiation and the sensor having thermal IR band gets saturated for volcanic vent temperatures. This emphasizes the need to look for a methodology to estimate volcanic vent temperatures which are of the order of 1000°C using optical remote sensing data. This paper presents the methodology for estimating vent temperature over Barren Island volcano using Landsat Thematic Mapper (TM) data and discusses the accuracy of the estimates from geometric considerations. Due to narrow swath width of ~180 km needed to provide high spatial resolution data sets within the given data rate and with minimum distortions due to the earth's curvature effect, the Indian Remote Sensing Satellite (IRS), SPOT, and Landsat view the same geographical area once in 22, 26 and 16 days (revisit cycles) respectively. The optical band data of IRS and SPOT satellites could also be used. The availability of cloud-free and smoke-free conditions over the vent and its coincidence with the date and time of viewing by TM resulted in the use of Landsat TM data.

2 Theoretical Basis

Landsat Thematic Mapper (TM) provides 30 m spatial resolution data in six spectral bands in 0.45-2.35 μm region and 120 m spatial resolution data in 10.4-12.5 μm thermal IR band. Table 1

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength range (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45-0.52</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75</td>
</tr>
<tr>
<td>6</td>
<td>10.4-12.5*</td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35</td>
</tr>
</tbody>
</table>

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* Spatial resolution, 120 m
Fig. 1—Electromagnetic radiation emitted by familiar objects at various temperatures; ambient refers to normal earth features.

Gives the spectral characteristics of TM. The volcanic vent would witness temperature around 1000°C and would have an emissivity in the range 0.6-0.8. Field studies have indicated the emissivity value around 0.8 in the near IR region. The thermal IR band of TM saturates at temperature around 100°C and is thus not useful in estimating volcano vent temperature.

Figure 1 depicts the electromagnetic radiation emitted by familiar objects at various temperatures. It can be inferred from the figure that volcano vent region will have maximum energy emitted in near IR region. Figure 2 depicts the wavelength dependence of emitted radiance as given by Planck's law for the temperature range of -50 to 1000°C with an emissivity value of 0.8. Here, the spectral regions of different TM bands together with their sensitivity limits have also been marked. The TM band 7 (2.08-2.35 μm) and band 5 (1.55-1.75 μm) have capability to measure temperatures, integrated over the pixel, in 160-420°C range (Fig. 2). Pixel-integrated temperature in the range 420-600°C falls in the region between the saturation limits of TM band 5 (1.55-1.75 μm) and lower edge sensitivity limit of TM band 4 (0.76-0.90 μm). The band 4 of TM (0.76-
LANDSAT TM TEMPERATURE SENSITIVITIES
(EMISSIVITY = 0.8)

\[
\begin{array}{cccc}
\text{WAVELENGTH (µm)} & 0.5 & 1.0 & 1.5 & 2.0 & 2.5 & 3.0 \\
\hline
\text{RADIANCE (mW cm}^{-2} \text{s}^{-1} \text{sr}^{-1}) & 0.1 & 1.0 & 10 & 100 & 1000 & 10000 \\
\end{array}
\]

Fig. 2—Response characteristics of Landsat TM bands with reference to emitted energy at various temperatures (emissivity = 0.8).

0.90 µm) could measure temperatures, integrated over the pixel, in 700-1000°C range. Thus, this near IR band of electromagnetic spectrum is useful in the spacecraft-based measurements of high temperatures encountered during volcanic eruption.

3 Methodology and results
Satellite-based sensors convert the incoming energy into the digital number (DN) which gets recorded for each spectral band of the sensor. The digitization on-board for Landsat TM covers a 8-bit scale which provides 0-255 dynamic range for the DN. The DN can be converted into spectral radiance (W m\(^{-2}\) µm\(^{-1}\) sr\(^{-1}\)) using the calibration data. The cloud-free data sets around the volcanic eruption zone were selected from Landsat TM data set of 6 May 1991 (Fig. 3). The assigning of red, green and blue (RGB) to TM bands 7, 4 and 5 images respectively enabled clear identification of vent area which was seen in bluish-yellow colour. Here, the saturated DN value of 255 for bands 7 and 5 which were superimposed in red and blue colours dominated the DN value of 35 in band 4 which was given the green colour. This gave the bluish-yellow look to vent in this false colour composite (FCC) shown.

Fig. 3—False colour composite (FCC) of Landsat TM data in bands 7 (Red), 4 (Green) and 5 (Blue) for 6 May 1991 depicting the volcano vent in bluish-yellow colour.
The pixel-integrated temperature estimated from this method for the observed DN value of 35 in band 4 of 6 May 1991 Landsat TM data set is 1084 K. The observed DN value of 35 in band 4 TM data of 6 May 1991 can have DN value of $35 \pm 0.5$ according to the resolution of the system. The pixel-integrated temperature estimated from this method of the DN value $35 \pm 0.5$ is $1084 \pm 1$ K. To provide for first order correction in Fig. 3. The DN dump depicted value of 255 over the vent and the surrounding plume covered region in bands 7 and 5.

The calibration coefficients for Landsat TM as given by Price$^2$ were used and emitted radiance $(R_\lambda)$ in TM band 4 was computed using equation

$$R_\lambda = \alpha \times \text{DN} + \beta \quad \text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1} \ldots (1)$$

where $\alpha = 0.815$, $\beta = -1.5$. The 0.76-0.90 $\mu\text{m}$ band of Landsat TM gave a DN value of 35 for the pixel containing the volcano vent. The pixel-integrated temperature $(T)$ for the volcanic vent pixel was computed using inverse Planck's function given by

$$T = C_2 / \lambda \ln[(e C_1 \lambda^{-5}/\pi R_\lambda) + 1] \ldots (2)$$

where

- $C_1 = (2 \pi h c^2) = 3.742 \times 10^{-16} \text{Wm}^2$
- $C_2 = (hc/k) = 0.0144 \text{mK}$
- $\lambda$ is the central wavelength for the band ($\mu\text{m}$)
- $h$ is Planck's constant
- $k$ is Boltzmann's constant
- $c$ is Speed of light
- $\varepsilon$ is Emissivity of the radiating surface taken as 0.8

The pixel-integrated temperature estimated from this method for the observed DN value of 35 in band 4 of 6 May 1991 Landsat TM data set is 1084 K. The observed DN value of 35 in band 4 TM data of 6 May 1991 can have DN value of $35 \pm 0.5$ according to the resolution of the system. The pixel-integrated temperature estimated from this method of the DN value $35 \pm 0.5$ is $1084 \pm 1$ K. To provide for first order correction for reflectance factor to the temperature estimate over the volcanic vent region, the pre-eruption count value of 22 as seen in 3 Mar. 1991 image was subtracted from the Landsat TM data of 6 May 1991. The vent temperature estimated from this method using Eq. (2) comes to be around 1015 K. The field observations reported by GSI$^3$ confirmed that rigorous eruption took place around first week of May 1991 as observed in Fig. 3. The band 5 and band 7 values of TM data of 6 May 1991 are saturated at 255 over the vent region which corresponds to temperature of 696 K in band 5 and 555 K in band 7 and are in confirmity with Fig. 2.

The nominal pixel size of Landsat TM is 30 m x 30 m square. The area of terrain over which the radiance is collected to produce each image pixel is actually somewhat larger because of optical characteristics of the system. It is reasonable to assume that the area sampled by TM sensor would be more than 30 m and this has to be considered while deriving information about hot volcanic features.

The TM pixel of the volcanic vent is a mixed signature of the background and vent area$^4$. Normally, the vent area will be less than one pixel area and the derived pixel-integrated temperature accuracy can be estimated from the following geometric considerations.

The total spectral radiance recorded at satellite $(R_\lambda)$ is a combination of area-weighted average of the vent spectral radiance $(R_{\lambda,v})$ and the background spectral radiance $(R_{\lambda,b})$ given by

$$R_\lambda = (A_v/A) R_{\lambda,v} + (A_b/A) R_{\lambda,b} \ldots (3)$$

Fig. 4—Variation of volcano vent temperature as a function of vent area for 0.76-0.90 $\mu\text{m}$ Landsat TM data on 6 May 1991.
where \( A, A_v \), and \( A_b \) denote the total pixel, vent, and background areas respectively. From Eq. (3), \( R_{\lambda,v} \) can be obtained by

\[
R_{\lambda,v} = A/A_v \left[ R_{\lambda} - (A_b/A) R_{\lambda,b} \right]
\]  \( \ldots (4) \)

The background contribution to the vent pixel was separated by averaging the three nearest background pixels. The results of this method are depicted in Fig. 4. It can be inferred from Fig. 4 that if the volcanic vent occupies 21% area of the pixel, the computed pixel-integrated temperature is within 1% of the vent temperature. Even if the vent occupies 10% of the pixel area, the percentage difference between the vent temperature and pixel-integrated temperature is around 3%.

4 Conclusions

The earth resources satellite data in 0.76-0.90 \( \mu \text{m} \) spectral region, with the existing saturation levels optimized for the best dynamic range to observe normal terrestrial phenomena, can be used effectively for estimating volcanic vent temperature. The deviation of vent temperature from computed pixel-integrated temperature is marginal for vents occupying less than 20% of the pixel area. The methodology adopted will be helpful in monitoring singular high temperature phenomena like volcanic eruptions using optical data available from satellite platforms.

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References