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Temperature estimates using the Grey-body Emissivity Method at Lascar Volcano (Chile)

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Abstract. Volcanoes are associated with the movement of heat from the Earth's mantle to the surface. The ability to measure the temperature of volcanic targets from space would provide a particularly useful tool in furthering the understanding of volcanic systems. However this goal has remained difficult to obtain because of the heterogeneous nature of volcanoes and their ability to saturate sensor channels, especially those spanning through the infrared wavelengths that are sensitive to magmatic temperatures. We propose a new approach based on the Grey-body Emissivity Method and the similar atmospheric transmissivity of wavelengths within the thermal infrared (TIR) region at around 10-12 μm. This has allowed approximate temperature estimates of Lascar volcano to be made using ASTER bands 13 and 14. We find that eruptive events are generally associated with increases in temperature, which have been attributed to degassing events. The youngest temperature estimates show the summit crater has ceased to display elevated temperatures, this has followed the longest and warmest eruptive period. Thermal maps, created over Lascar's edifice, provide constraints on the spatial extent of the heat source. Future amendments to the model, so that atmospheric effects are quantitatively incorporated, are likely to allow the additional detection of temperatures at low altitudes as well.

Key words: remote sensing, ASTER, grey-body emissivity, temperature, volcano, Lascar

1. Introduction

1.1. Volcano monitoring

The monitoring of volcanoes is important because of their hazardous nature. This nature can obviously affect people or property situated within the vicinity of a volcano that may, for example, be at risk from pyroclastic flows, lava flows and lahars. Furthermore, explosive eruptions are capable of producing ash plumes that create a significant hazard to areas that are not necessarily close to the source volcano (e.g. the 1993 eruption of Lascar volcano [Chile] deposited ash in Buenos Aires [Argentina] some 1500 km away). Volcanic ash can cause respiratory problems, roof collapse and mechanical failure. The later point is of particular interest to the aviation industry due to the density of air-traffic over volcanically active regions. These among other hazards provide the motivation behind the monitoring of volcanic processes in the hope of obtaining an ever increasing understanding of their behaviour.

1.2. Remote Sensing of Volcanoes

It would seem that remote sensing is a particularly apt method of volcano monitoring.

People tend to avoid living in hazardous areas and subsequently many volcanoes are left being somewhat isolated. Furthermore, it is clearly dangerous to collect samples and observations in the field, especially on a routine basis.

To date, however, there has been no satellite purpose built for the study of volcanoes. Although the retrieval of volcanic observations has been as far as included within a broad list of mission objectives for NASA's 'Mission to Earth', the design of satellites remains predominantly geared towards meteorological, agricultural and resource exploration applications.

Despite this the use of satellite data to monitor volcanic activity has become increasingly popular over the last thirty years. Significant reasons for this success can be attributed to the facts that satellites provide a synoptic coverage of the Earth's surface, and a typically more continuous source of volcano monitoring data than relatively expensive, ground-based observations can acquire.

1.3. Volcanic Temperature Estimates from Space

We aim to produce a model that can reliably retrieve temperature estimates of volcanic phenomenon. This would clearly provide a useful constraint on the physical processes that govern their behaviour. However, calculating temperatures over volcanic regions is not trivial, not least of which because bands that are sensitive to bodies at magmatic temperatures (i.e. those monitoring the short- and mid-wave infrared wavelengths) are prone to saturation over such targets.

The goal of deriving volcanic temperatures using satellite images is further complicated by the heterogeneous nature of the target, whose components vary significantly through both space and time. This restricts the use of absolute emissivity estimates to reliably derive temperature and so requires some model assumptions. These may, for example, involve estimates on the spatial extent and temperature of thermal components, as used within the dual-band approach (Dozier 1981). We shall outline a method that relies on relative emissivity assumptions of the target at two different wavelengths. It should be noted that all temperature estimates derived from model assumptions are only as reliable as the assumptions themselves.

1.4. Lascar Volcano

Lascar volcano in Northern Chile (23º37'S, 67º76'W) has a well established remote sensing history (e.g. Francis & McAllister 1986, Oppenheimer et al. 1993, Wooster & Rothery 1997, Flynn et al. 2001, Pavez et al. 2006). It was characterised by cyclic variations in radiance between 1984 and 1996, where decreases in radiance were followed by explosive events, as observed by Oppenheimer et al. (1993) using Landsat Thematic Mapper (TM) and by Wooster and Rothery (1997) using the Along Track Scanning Radiometer (ATSR) sensor. These variations have been associated with cycles of dome extrusion followed by dome subsidence and substantial degassing and then terminating in an explosion (Matthews et al. 1997).

The volcano has experienced a new phase of eruptive activity between July 2000 and April 2006 (Smithsonian Institute), in which an approximate periodicity to the events appears to be displayed. Six events occurred within this period, their average repose (i.e. length of time from one eruption to the next) was 1.15 (+/- 0.27) years, with error given as one standard deviation. Minor activity was reported to have continued until July 2007 (Smithsonian Institute).

The climate at Lascar provides an excellent environment for remote sensing, with dry stable atmospheric conditions during most of the year. As a result the area tends to display particularly low levels of cloud cover as well as a lack of glacial cover. The high altitude of the volcano (5592 m) significantly reduces atmospheric affects and also acts towards improving the local image quality by restricting the growth of vegetation.

2. Methodology

Temperature estimates of Lascar volcano shall be calculated using Thermal infrared (TIR) data taken by Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) during the 2000-2008 period. We have chosen to adopt the Grey-body Emissivity Model (GEM) to retrieve temperatures. The model and its assumptions are outlined below.

2.1. Temperature and Emissivity 'Separation'

Calculating temperatures from satellite imagery is well known to be complicated by the fact that spectral radiance, of a given wavelength, is dependent on both the temperature and the emissivity of the radiating body, as described by the Planck function [1]. Essentially this creates an 'ill-posed' problem or, in other words, more unknown parameters than equations. To solve this equation assumptions have to be made about either temperature or emissivity.

$$L_{(\lambda,T)} = \varepsilon_\lambda c_1 \lambda^{-5} / [\exp(c_2/\lambda T) - 1] \qquad [1]$$

where $L_{(\lambda,T)}$ is the spectral radiance as a function of wavelength (λ) and kinetic temperature (T), ε_λ is the emissivity of a radiating body for a given wavelength, c_1 and c_2 are constants.

2.1.1. Grey-Body Emissivity

Barducci and Pippi (1996) reported that laboratory derived emissivity spectra for various rocks, minerals and sediments showed a general 'flattening off' in the TIR (8 – 12 μm), especially for wavelengths greater than 10 μm. This would correspond to ASTER TIR bands 13 (10.25-10.95 μm) and 14 (10.95-11.65 μm). Therefore they proposed that changes in emissivity with wavelength could be modelled as negligible, see equation [2], as long as relative changes in blackbody radiance were high enough. There are various ways of manipulating this assumption. Essentially it allows one to constrain emissivity and find a solution for temperature. As the model is based on the assumption that emissivity spectra *do not change* with wavelength, at least for certain wavelength ranges, the authors named it the Grey-body Emissivity Method.

$$\frac{\delta \varepsilon}{\delta \lambda} = 0 \qquad [2]$$

We propose a new method for using this assumption and allowing temperature estimates to be calculated. A ratio of Planck functions describing the radiance of a grey-body at two different wavelengths, will result in the equal emissivity values cancelling out. Thus one can solve for temperature. This requires an iterative solver unless the Wien approximation is used, in which case a temperature estimate can be calculated as follows:

$$T = \frac{c_2\left(\frac{1}{\lambda_j} - \frac{1}{\lambda_i}\right)}{\ln\left[\frac{L_i}{L_j}\left(\frac{\lambda_i}{\lambda_j}\right)^5\right]} \qquad [3]$$

where *i* and *j* represent the effective-wavelengths of two separate sensor channels. We have assumed that the effective-wavelengths of ASTER bands 13 and 14 are equivalent to their mid-range values.

A benefit of this method is that temperature estimates can be calculated directly from spectral radiance values, therefore allowing them to be computed by standard GIS programs capable of executing 'band arithmetic', which would subsequently allow, albeit approximate, thermal maps of target areas to be produced fairly easily.

2.2. Atmospheric Correction

In reality the effects of the atmosphere should be accounted for. To do this formerly would require the spectral radiance ratio part of equation [3] to be substituted as follows:

$$\frac{L_i}{L_j} = \frac{[(R_i - P_i/\tau_i) - (1-\varepsilon_i)S_i]/\varepsilon_i}{[(R_j - P_j/\tau_j) - (1-\varepsilon_j)S_j]/\varepsilon_j} \quad [4]$$

where R_i is the measured radiance, P_i the path radiance and S_i the sky irradiance for the i^{th} channel of a given sensor. Similarly, the subscript j represents the same parameters for the j^{th} channel.

This would be simplified for the case in which i) $(R_i - P_i/\tau_i) >> (1-\varepsilon_i)S_i$ and ii) $R_i >> P_i$ hold true for both wavelengths. That is to say that i) target surface radiance is much larger than reflected sky irradiance, and ii) measured radiance is much larger than path radiance. As both the atmospheric terms could then be modelled as negligible. Consequently, the ratio of radiance values measured by the sensor would reflect the actual radiance ratio, in the case where both emissivity terms are the same (i.e. $\varepsilon_i/\varepsilon_j = 1$) and both transmissivity terms are the same (i.e. $\tau_i/\tau_j = 1$). The equal emissivity assumption is the basis of the Grey-body Emissivity Method (GEM) and the equal transmissivity assumption has also been adopted.

We suggest that this equal atmospheric transmissivity assumption is, in general, fairly reasonable for the TIR range incorporated by ASTER bands 13 and 14 (10.25-11.65 um). Previous atmospheric modelling at Lascar in particular (Wooster and Rothery 1997) has reported transmissivities as showing minimal variation locally (0.965 +/- 0.005). Notably this 'equal transmissivity' assumption relies on the properties of these wavelengths in Earth's atmosphere and not on the properties of the radiating body.

In reality the path radiance is unlikely to be negligible as the Earth radiates abundantly at these wavelengths, thus any one pixel is likely to have significant amounts of contamination. On the other hand, the reflected sky irradiance may be somewhat negligible as these wavelengths show low scattering in the atmosphere and relatively little contamination from space, due to the scarcity of bodies close to the Earth radiating in the thermal infrared. Furthermore, many terrestrial materials have strong absorption features at these wavelengths and therefore low reflectivities (Hapke 1993).

In order to ensure that atmospheric effects are as negligible as possible our time series is composed of peak radiance values. These are defined as the brightest pixel within an image of Lascar's summit craters throughout the 2000-2008 period. These are implicitly assumed to represent maximum temperature values. A further benefit of using 'peak pixel' values is that this parameter is easy to constrain and yet still tells us something about the physics of the system.

Improvements to the model by quantitatively accounting for atmospheric effects are included within our short-term aims. However, these preliminary results show temperature estimates are passively 'corrected' for atmosphere effects by the nature of the model utilizing the similar behaviour of TIR in the atmosphere, as well as the fact that Lascar is a high altitude volcano whose summit therefore lies well above the bulk of the Earth's atmospheric water vapour, thus above the main region of infrared absorption (Wooster and Rothery 1997).

2.3. Wien Approximation

In a hypothetical world, where there is no atmosphere and spectral radiance is described perfectly by the Wien approximation, kinetic temperature estimates of grey-bodies can be derived from satellite data using equation [3]. In such a world the ratio of spectral radiances could be denoted as (L_w/L_w).

However, as appears to be the case in reality, spectral radiance follows Planck's law. A ratio of real spectral radiance values (L_p/L_p) used inside equation [3] would produce increasingly large underestimates of temperature as the actual kinetic temperature of the radiating body increases (Fig 1a).

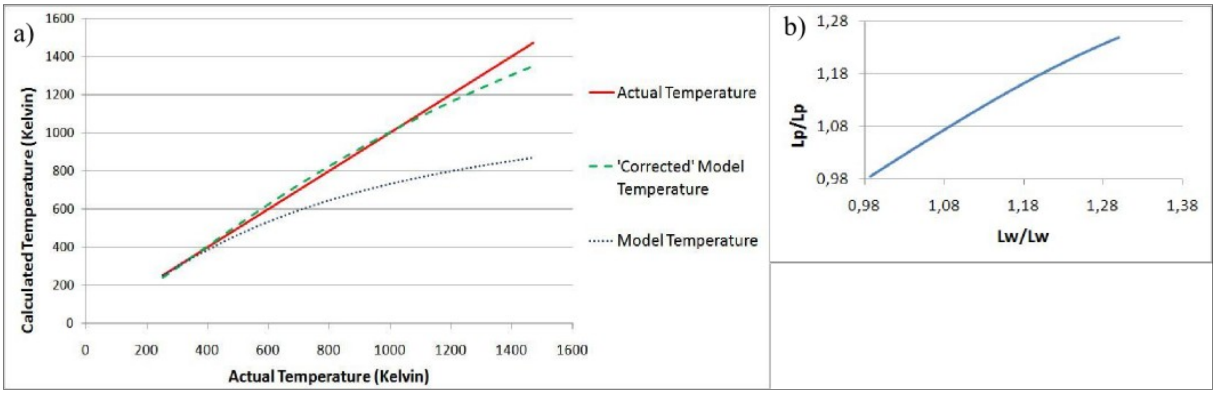

Figure 1. a) The relationship between actual temperature, model temperature [i.e. equation [3]) and 'corrected' model temperature, which is based on b) the linear relationship between Planck spectral ratios (Lp/Lp) and Wien spectral ratios (Lw/Lw) for a temperature range of -20 to 1200ºC (see text).

A solution to this problem can be found by accounting for the change of L_p/L_p from L_w/L_w as a function of temperature. Modelling this directly is complicated by the fact that it is difficult to linearise the Planck function due to the '-1' term in the denominator restricting natural logarithms from being taken. However, if we plot the change of L_p/L_p from L_w/L_w over a temperature range we might reasonably expect for volcanoes (-20 to 1200ºC) it can be seen (Fig 1b) that their relationship is approximately linear. This can be used to modify measured radiance values (L_p/L_p) into 'hypothetical radiance values' that would be produced in the world were the Wien approximation holds true. These 'corrected' radiance values would therefore produce more reliable model temperature estimates as the model (i.e. equation [3]) was itself based on the Wien approximation.

Alternatively, as in the original paper (Barducci and Pippi 1996), it would be possible to use an iterative solver to derive grey-body temperatures directly from measured spectral radiance values. However the approach is inherently cumbersome and cannot be directly applied in the contemporary standard GIS programs.

The most effective way of correcting L_p/L_p to L_w/L_w, in terms of accuracy and computational efficiency, would be to create a series of look-up tables (LUTs), in which individual LUTs are called up depending on user defined values of path radiance and sky irradiance. This would allow the rapid calculation of temperature estimates for 'grey-bodies' anywhere on the Earth's surface. The development of such an image processing tool is under way at the time of writing.

3. Results

Figure 2. displays temperature estimates (blue dots) for the period during 2000-2008, derived using ASTER bands 13 and 14 and our 'corrected' grey-body emissivity model. They represent the single most radiant pixel on Lascar's edifice for each image used in this study.

We interpret them as equating to the single hottest pixel. Within this period six eruptions were reported to have occurred (vertical bars), for which five show discernible increases in temperature. The apparent lack of a temperature increase associated with the 2001 eruption maybe a result of the paucity of data available during this time period.

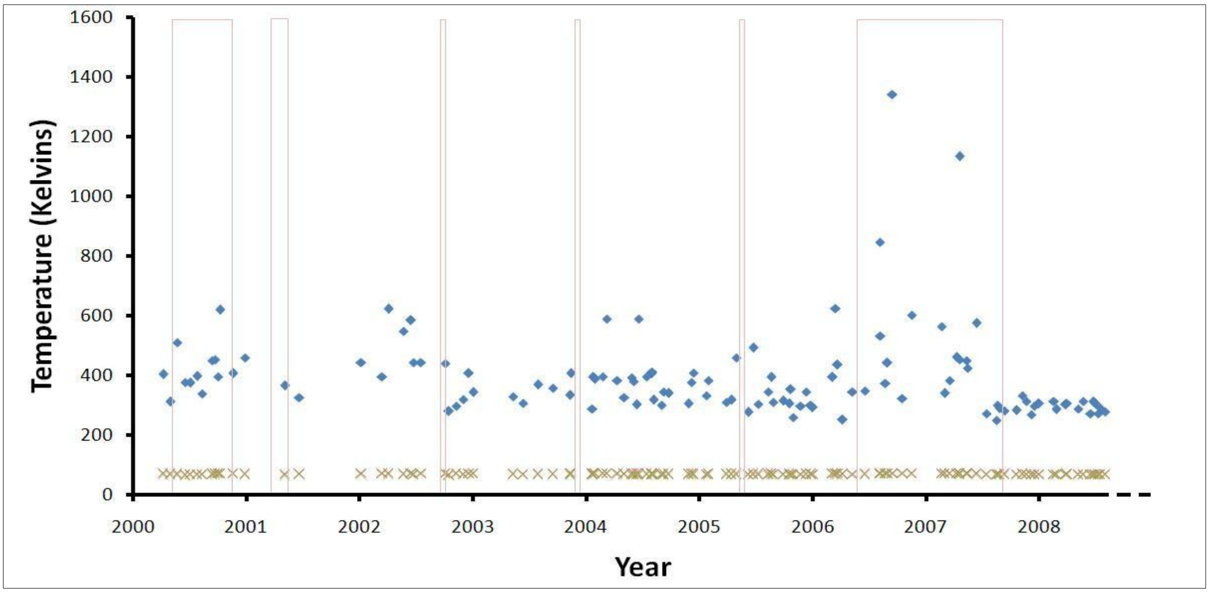

Figure 2. Temperature Estimates of Lascar volcano using the Grey-body Emissivity Method (GEM) for the 2000-2008 period. The dots are GEM temperatures, the vertical bars indicate the duration and occurance of the six reported eruptions (Smithsonian Institute). For comparison the brightness temperatures of ASTER bands 13 and 14 are shown respectively as red and green cross-marks.

Most thermal peaks occur during or after an eruptive event. This may reflect a style of activity previously modelled for Lascar volcano (Matthews et al. 1997). They suggested explosive eruptions are followed by periods of degassing. This fumerolic activity diminishes through time as the dome subsides and magma porosity simultaneously decreases, which maybe further expedited by deposition of hydrothermal minerals within pore spaces.

As they are often used to infer some physical significance from remote sensing data, we have included brightness temperatures from the same TIR channels (i.e. ASTER bands 13 and 14). It can be seen that they show very limited variation around temperatures that are far too cold for the surface of the Earth (~70K). This implies that atmospheric effects and absolute emissivities have a significant impact on brightness temperatures, as discussed later. Consequently, they are poor indicators of actual temperatures.

The largest thermal anomaly is associated with the latest and longest eruptive period, in which pixel averaged temperature estimates reached as high as 1341K (i.e. 1069ºC) This hot, prolonged activity may represent a significant loss of energy from the system and therefore go towards explaining the subsequent 'cold' period which began in July 2007 and continued until the last processed image of August 2008.

The eruption that began on the 9th October 2002 (Smithsonian Institute) was clearly preceded by a thermally anomalous period. This can be seen within the greyscale images (ASTER band 13) and corresponding GEM temperature estimates of Lascar, taken on 23rd May 2002 (Fig 3a.) and 13th June 2002 (Fig 3b.) They appear to show that temperatures are relatively homogeneous for the majority of the image, compared to the particularly hot feature within Lascar's active summit crater. Within the context of Lascar volcano these 'hot spots', clearly restricted to the summit crater, are probably due to either fumaroles or active dome growth. This activity maybe associated with an undocumented eruption or, perhaps, signify a thermal precursor for the eruptive activity to follow. A snapshot of the October 2002 eruption was taken by ASTER on the 15th (Fig 3c), six days after the activity was reported to have begun. The greyscale image displays a fairly disperse ash plume being emitting from Lascar.

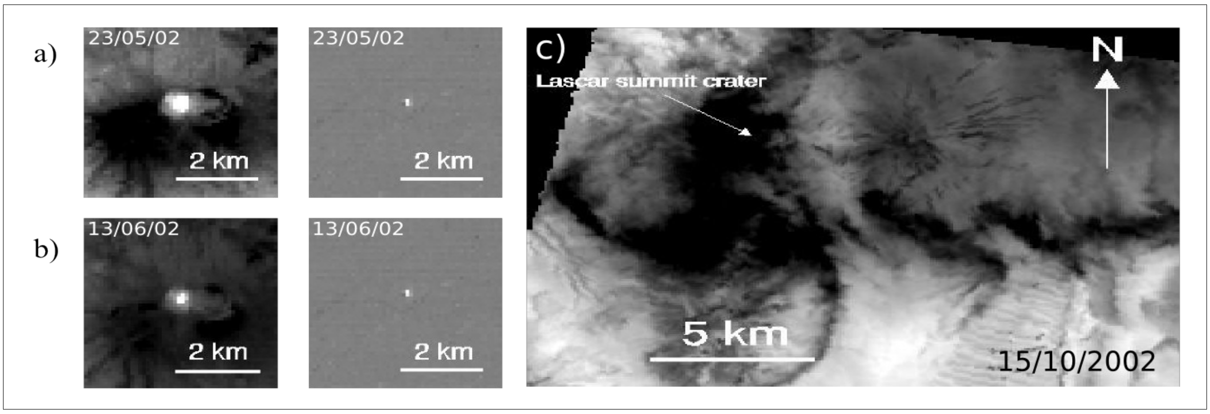

Figure 3. ASTER band 13 images of Lascar volcano taken during a) 23 May 2002 and b) 13 June 2002, with corresponding Grey-body Emissivity Method (GEM) temperature estimates. c) An ash plume originating from Lascar's summit crater taken on 15th October 2002, six days after the start of the eruptive period.

For all peak radiance values measured during 2000-2008, the coldest corresponding temperature estimate was 250.7K (-21.4ºC), taken during August 2007. There were, however, occasions were anomalously cold temperatures estimates, as low as 210K (-60ºC), were observed for other pixels on the volcanic edifice. These coincide with unusual pixels in which band 13 was found to be smaller than band 14. This could be due to the presence of small ash plumes, preferentially absorbing wavelengths monitored by band 13 and thus nullifying the 'equal transmissivity' assumption.

4. Discussion

Brightness temperatures (BT) are anomalously small because the measured spectral radiance is used as a direct substitute for actual radiance values (equation [5]). Therefore atmospheric effects are not mitigated and this discrepancy is subsequently multiplied by wavelength to the power five (λ^5), which exasperates the problem enormously.

$$BT = \frac{C_2}{\lambda \ln[(c_1/L_\lambda \lambda^5) + 1]} \qquad [5]$$

On the other hand the model we have proposed mitigates atmospheric effects for each band simultaneously. This is because i) the wavelengths used within the spectral ratio have similar atmospheric interactions and ii) this spectral ratio is then multiplied by a λ^5 ratio instead of a single λ^5 value.

Another advantage of the GEM is that it accounts for changes in reflectivity/emissivity of a surface with the viewing angle of the sensor, whilst other approaches, such as the reference channel approach or normalized emissivity method, do not (Barducci and Pippi 1996).

5. Conclusions

The Grey-body Emissivity Method (GEM) offers a way of retrieving temperature estimates for dynamic systems such as volcanoes. This can be principally attributed to the fact that the method avoids making absolute emissivity estimates. This may be especially appropriate for volcanic targets as the selection of components that contribute to measured radiance values may vary through time, and often in ways that are difficult to determine form satellite images alone (e.g. variations in the rate of gas flux).

ASTER bands 13 and 14 potentially provide a very useful pair of TIR channels for estimating temperature due to the fact that they tend to show similar emissivity and transmissivity values. In general the thermal infrared would appear to have advantages over shorter wavelengths (e.g. SWIR) because it undergoes relatively less refraction in the atmosphere and is less likely to saturate over volcanic targets.

The atmospheric assumptions used here will only be reliable for other high altitude volcanoes, such as those along the Andean volcanic chain. However, improvements to this method can be achieved by: 1) quantitatively accounting for the atmosphere, thus allowing low terrain estimates of temperature, and 2) selecting narrower band widths, as will presumably become a feasible reality with the advent of hyperspectral data.

6. References

Barducci, A.; Pippi, I. Temperature and Emissivity Retrieval from Remotely Sensed Images Using the “Grey Body Emissivity” Method. **IEEE Transactions on Geoscience and Remote Sensing**. v. 34, n. 3, p. 681-695, 1996.

Dozier, J.; A method for satellite identification of surface temperature fields of subpixel resolution. **Remote Sensing of Environment**. v. 11, p. 221-229, 1981.

Flynn, L. P.; Harris, A. J. L.; Wright, R. Improved identification of volcanic features using Landsat 7 ETM+. **Remote Sensing of Environment.** v. 78, p. 180–193, 2001.

Francis, P. W.; McAllister, R. Volcanology from space; using Landsat Thematic Mapper data in the Central Andes. **EOS Transactions, American Geophysical Union.** v. 67, p. 170–171, 1986.

Hapke, B. **Theory of reflectance and emittance spectroscopy**. Cambridge University Press, 1993.

Matthews, S. J.; Gardeweg, M. C.; Sparks, R.S.J. The 1984 to 1996 cyclic activity of Lascar volcano, northern Chile: cycles of dome growth, dome subsidence, degassing, and explosive eruptions. **Bulletin of Volcanology**. v. 59, p. 72– 82, 1997.

Oppenheimer, C.; Francis, P. W.; Rothery, D. A.; Carlton, R. W. T.; Glaze, L. S. Infrared image analysis of volcanic thermal features: Lascar volcano, Chile, 1984– 1992. **Journal of Geophysical Research**. v. 98, p. 4269–4286, 1993.

Pavez, A.; Remy, D.; Bonvalot, S.; Diament, M.; Gabalda, G.; Froger, J. L.; Julien, P.; Legrand, D.; Moisset, D. Insight into ground deformations at Lascar volcano (Chile) from SAR interferometry, photogrammetry and GPS data: Implications on volcano dynamics and future space monitoring. **Remote Sensing of Environment.** v. 100, p. 307–320, 2006.

Smithsonian Institute, Lascar. **Bulletin of the Global Volcanism Network**. Available at: <http://www.volcano.si.edu/>.

Wooster, M. J.; Rothery, D. A. Thermal monitoring of Lascar volcano, Chile, using infrared data from the along-track scanning radiometer: a 1992– 1995 time series. **Bulletin of Volcanology**. v. 58, p. 566–579, 1997.