Automated, high temporal resolution, thermal analysis of Kilauea volcano, Hawai'i, using GOES satellite data

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Abstract. Thermal data are directly available from the Geostationary Operational Environmental Satellites (GOES) every 15 minutes at existing or inexpensively installed receiving stations. This data stream is ideal for monitoring high temperature features such as active lava flows and fires. To provide a near-real-time hot spot monitoring tool, we have developed, tested and installed software to analyse GOES data on-reception and then make results available in a timely fashion via the web. Our software automatically: (1) produces hot spot images and movies; (2) uses a thresholding procedure to generate a hot spot map; (3) updates hot spot radiance and cloud index time series; and (4) issues a threshold-based e-mail alert. Results are added to <http://volcano1.pgd.hawaii.edu/goes/> within ~12 minutes of image acquisition and are updated every 15 minutes.

Analysis of GOES data acquired for effusive activity at Kilauea volcano (Hawai'i) during 1997–98 show that short (<1 hour long) events producing 100 m long (10^7 to 10^8 m²) lava flows are detectable. This means that time constraints can be placed on sudden, rapidly evolving effusive events with an accuracy of ± 7.5 minutes. Changes in activity style and extent can also be documented using hot spot size, intensity and shape. From radiance time series we distinguish (1) tube-fed activity (low radiance, $<10 \text{ MW m}^{-2} \text{ m}^{-1}$); (2) activity pauses (no radiance); (3) lava lake activity (low radiance, $<5 \text{ MW m}^{-2} \text{ m}^{-1}$); (4) short (<3 km long) flow extension (moderate radiance, $10\text{--}20 \text{ MW m}^{-2} \text{ m}^{-1}$); and (5) 12 km long flow extension (high radiance, $15\text{--}30 \text{ MW m}^{-2} \text{ m}^{-1}$).

The ability of GOES to detect short-lived effusive events, coupled with the speed with which GOES-based hot spot information can be processed and disseminated, means that GOES offers a valuable additional volcano monitoring tool.

1. Introduction

Data from the Geostationary Operational Environmental Satellites (GOES) offer great potential for low-cost, high temporal resolution, near-real-time remote

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monitoring of hazardous, mutable high temperature phenomena, such as active lava flows and wild-fires. Thermal data are available every 15 minutes which, although having a nominal spatial resolution of ~ 4 km, are capable of detecting and monitoring rapidly developing hot spots associated with effusive volcanic eruptions (Harris *et al.* 1997a). Lava flows may be emplaced over a period of minutes to hours, and timely provision of details regarding event occurrence and development are essential for hazard assessment and mitigation. For this reason the direct availability and frequency of GOES data are attractive features for volcano hot spot detection and monitoring. Previously GOES data have been utilised to detect, track and analyse rapidly developing volcanic features such as dispersing volcanic ash plumes (Sawada 1987, Glaze *et al.* 1989, Holasek and Self 1995), and to detect and monitor biomass burning (Menzel *et al.* 1991, Prins and Menzel 1992). Until Harris *et al.* (1997a) showed how GOES data could be used to produce a detailed chronology of an effusive eruption, however, the potential of GOES for volcanic hot spot monitoring remained unexplored in the published literature.

GOES Imager data are available in five wavebands: (a) 0.52 to 0.72 μm (channel 1: visible band), (b) 3.78 to 4.03 μm (channel 2: mid-infrared band), (c) 6.47 to 7.02 μm (channel 3: water vapour band), (d) 10.2 to 11.2 μm (channel 4: far-infrared band), and (e) 11.5 to 12.5 μm (channel 5: far-infrared band). Although channel 1 has a nominal spatial resolution of 1 km at nadir, channels 2, 4 and 5 have a resolution of 4 km and channel 3 has 8 km resolution. In routine mode, images covering the United States are collected every 15 minutes, with one full Earth disk image being acquired every 3 hours. However, this latter image requires a longer scanning time of 28 minutes. In warning mode GOES is capable of collecting eight images of the United States every hour (Menzel and Purdom, 1994). GOES West is geostationary above 135°W and provides images which cover an area extending, at the equator, from $\sim 170^\circ\text{E}$ to 80°W . GOES East is geostationary above 75°W and provides images covering an area extending, at the equator, from $\sim 130^\circ\text{W}$ to 20°W (Cracknell and Hayes 1991). This coverage includes all of the active volcanoes in Hawai'i, the Caribbean, and North, Central and South America. However, since the geostationary view of the Earth's disc becomes increasingly glancing with increasing latitude, low-distortion coverage only extends to $\sim 55^\circ$ from nadir, precluding adequate hot spot coverage of the Kamchatkan, Aleutian and Alaskan volcanoes. Free, direct reception of these data for volcano monitoring purposes can be attained if, as here, access to an existing receiving station is possible or if a dedicated receiving system is purchased and installed. Such equipment typically costs US\$ 2700 to 62 000 depending on sophistication (Harris 1996).

GOES data are available at 3.78–4.03 and 10.2–12.5 μm , wavebands which have proved valuable in detecting and monitoring volcanic hot spots (Weisnet and D'Aguanno 1982, Mougini-Mark *et al.* 1994, Harris *et al.* 1995a,b, 1997b; Higgins and Harris 1997). GOES, unlike polar orbiting spacecraft, also provides data from a consistent position in space. This greatly reduces the processing time and complications which result from the variable viewing geometry of, for example, AVHRR data (Mougini-Mark *et al.* 1994, Harris *et al.* 1997b).

To examine and utilise these potential benefits for volcano monitoring, we have developed and tested a number of tools designed to allow hot spot monitoring using GOES data. To be of value for monitoring at a volcano observatory, data and results must be processed and made available in almost real-time. Thus our aim has been to fully automate our techniques so that processed hot spot information can be

made available in a timely fashion via the World Wide Web. One of the most useful monitoring roles that GOES can offer is the provision of regular (once every 15 minutes) assessments of whether activity is occurring. Our aim has thus not been to produce quantitative algorithms for accurate measurement of parameters such as land surface temperature, but instead to provide a simple, but effective, qualitative means for near-real-time event detection.

Here we first demonstrate the high-temporal resolution detection ability of GOES for effusive eruptions and the volcano monitoring role that such a capability can contribute. We then describe our algorithms and resultant near-real-time, web-based monitoring tool which we have developed to utilise this ability, the end product being a hot spot monitoring tool which is up-dated every 15 minutes with information typically ~ 12 minutes old (<http://volcano1.pgd.hawaii.edu/goes/>). Although, as we discuss, the tool has been applied to numerous volcanoes around the Pacific rim, in this paper we illustrate the capabilities using data acquired during the current eruption of Kilauea volcano (Hawai'i, figure 1), an eruption which has been in progress since January 1983. Specifically our study focuses on the period between January 1997 and March 1998.

2. GOES hot spot images: preprocessing, hot spot detection and anomaly types

Our GOES data are received at the Naval Research Laboratory (NRL) in Monterey (California, USA). Here the data are calibrated, i.e. the pixel digital numbers in channels 1 to 5 are converted to percentage albedo or brightness temperature. Two sub-scenes are then extracted from the full scene: (1) an 800×500 , 1 km pixel sub-scene covering the Hawaiian Island chain, and (2) a 220×220 1 km pixel sub-scene of the Island of Hawai'i (figure 1). Sub-scene data are then sent to the University of Hawai'i via File Transfer Protocol (FTP). The typical delay between the satellite acquisition and our receipt of the data in Hawai'i is 5 to 15 minutes.

Because each raw image only uses a limited portion of the full (8-bit) dynamic range, raw images are lacking in contrast. These images also suffer from geometric distortion. Therefore, to ease visual interpretation, our software automatically contrast enhances the images and corrects for geometric distortion by reprojecting the data to a mercator projection (figure 2). At the same time the 4 km channel 2, 4 and 5 pixels are subsampled to 1 km (resulting in 4×4 pixel blocks of identical pixels in these channels). This allows compositing and spatial comparison with 1 km resolution channel 1 data.

2.1. Hot spot detection

Following Harris *et al.* (1995b) and Higgins and Harris (1997) we base our hot spot detection algorithms on a band subtraction technique. This approach subtracts the brightness temperatures obtained in the far-infrared band (channel 4, T_4) from those obtained in the mid-infrared (channel 2, T_2) to give a brightness temperature difference image ($\Delta T = T_2 - T_4$). For a pixel entirely filled with surfaces at ambient temperatures, T_2 and T_4 should be roughly equal so that ΔT approximates zero. However, if we place a sub-pixel hot spot within a GOES thermal pixel (for example, a 2500 m^2 lava lake with a mean surface temperature of 800°C against an ambient background at 25°C), then the differing sensitivities of channels 2 and 4 to this sub-resolution hot spot result in T_2 and T_4 of 45.6 and 25.4°C , respectively, yielding ΔT of 20.2°C . Hence ΔT will be highly elevated over high temperature sub-pixel features (e.g. active lavas and fires) but not over solar heated anomalies.

Figure 1. Map of the flow fields emplaced during the 1983–1998 Pu'u 'O'o–Kupaianaha eruption (Kilauea, Hawai'i) with the approximate location of the August 1997 to March 1998 tube system and locations where lava was entering the ocean (ocean entries) at this time (Kamokuna and Waha'ula). Maps of the Hawaiian Island chain and the Island of Hawai'i are given as inset showing the location of Kilauea (K), Mauna Loa (ML), Hualalai (H) and Mauna Kea (MK) volcanoes. While Kilauea is currently erupting, Mauna Loa and Hualalai last erupted in 1984 and 1800–01 respectively, and Mauna Kea has not erupted for ~4000 years (Wolfe and Morris 1996). The two inset maps cover the same areas as the GOES Island chain and Island of Hawai'i sub-images that we process and display on our hot spot monitoring web site.

On the channel 2 image given in figure 3(a) the hot spot due to active lava flows at Kilauea is difficult to distinguish from solar heating of barren, but inactive, lava flows to the west. The ΔT image (figure 3(b)), however, highlights the active lava hot spot and suppresses the solar heating, where hot spots due to active lava and fires are distinguished as anomalously bright (high ΔT) pixels. This ΔT image also confirms a hot spot on Maui, this being due to a fire. Because of the incidence of sugar cane burning in Maui, such ephemeral (typically <1 hour long) fire-related hot spots are common here.

There are a number of complicating factors when using ΔT to distinguish hot

Figure 2. (a) Raw GOES channel 1 image of the Island of Hawai'i (lighter tones=higher reflectances) showing poor contrast and geometric distortion, with (b) the digital number (DN) frequency histogram for this raw image. (c) The same image after automatic contrast enhancement and geometric correction with (d) the DN frequency histogram for this enhanced image showing how the DNs have been automatically remapped (table 1) to improve contrast. Note the white plumes due to gas and steam emitted by active lava at the Pu'u 'O'u vent (PO) and where lava enters the ocean (OE) respectively (see figure 1 for location).

spots. Notably, as discussed by Higgins and Harris (1997), elevated ΔT will not only result from sub-pixel hot spots, but also from: (1) differential emissivity and atmospheric effects between the two wavebands, and (2) the contribution of reflected radiation to the mid-infrared signal. This latter problem will only apply to daytime images. On GOES scenes of Hawai'i, by day the reflected contribution to channel 2 raises T_2 such that ΔT are typically 0 to 2°C and 2 to 6°C over ocean and land, respectively. Over cloud, higher reflection results in ΔT of 2 to 40°C. By night we obtain ΔT of 0 to 2, -2 to 2, and -5 to 15°C over ocean, land and cloud, respectively. The absence of a night-time reflected contribution means that these differentials are entirely due to atmospheric and emissivity effects, and are in agreement with the analysis of differential emissivity and atmosphere/reflection effects on ΔT by Higgins and Harris (1997). For a range of barren and vegetated surfaces Higgins and Harris (1997) obtain ΔT of -3 to 6 and -2 to 2°C due to the two effects, respectively, with a maximum predicted ΔT due to the combination of the

Figure 3. (a) GOES channel 2, and (b) ΔT images acquired at 07:45 HST on 10 August 1997, with (c) channel 2, and (d) ΔT images for 09:30 HST on the same day. Each sub-scene covers the State of Hawai'i area given as inset in figure 1, where the Maui and Hawai'i portions of the sub-scene are located using white boxes. On each image higher temperatures or ΔT give lighter tones. On (a) and (b) hot spots are evident as anomalously bright/white pixels within the Maui and Hawai'i boxes.

two effects of $\sim 8^{\circ}\text{C}$. This compares with ΔT over active lavas of $\gg 10^{\circ}\text{C}$ (see above and also Harris *et al.* (1995b)).

The effects discussed above can be seen on figure 3(c–d). On the T_2 image (figure 3(c)) areas of elevated surface temperature (bright areas) are apparent across

both Maui and Hawai'i. Because T_2 – T_4 over solar heated surfaces, the ΔT image shows that most of these hot areas are due to solar heating, evident from low ΔT and hence dark tones (figure 3(d)). Areas of cloud, however, appear bright in the ΔT image, their reflected contribution to the channel 2 signal resulting in $T_2 > T_4$ and thus high ΔT . Although complicated by the areas of bright cloud, pixels containing active lava flows are still apparent from anomalously high (bright) ΔT in the SE sector of the Hawai'i box (figure 3(d)). Using the ΔT image, several apparent hot spots on the T_2 image can be rejected as solar heating. For example, the persistent T_2 anomaly coincident with the summit of Haleakala volcano (Maui) is confirmed as a solar heating by virtue of its low ΔT (figure 3). This $\sim 12 \text{ km} \times 4 \text{ km}$ area is surfaced by barren ash and lava prone to solar heating.

Following our analysis of ΔT values on GOES images of Hawai'i, we suggest that by night an active-lava-induced hot spot must attain $\Delta T > 5^\circ\text{C}$ to be distinguishable from the normal ambient background. By day, due to the reflected solar component in the mid-infrared, ΔT of 10 – 15°C must be attained. The size and temperature that an active lava must achieve to exceed such limits are given in figure 4, where most active lavas which attain areas greater than 10^2 to 10^3 m^2 should be detected.

2.2. Anomaly types

From our 15 month long analysis of GOES ΔT images of Kilauea we define four types of thermal anomaly typical of this period (figure 5). Each of these can be associated with a specific style of effusive activity and thus allow these to be distinguished.

Type 1 anomalies developed when activity was confined to the vent area (Pu'u 'O'o, figure 1). Such activity was characterised by lava lake activity on the floor of the Pu'u 'O'o crater and eruption of short ($< 1 \text{ km}$ long) lava flows. This caused localised, moderate-sized (4–8 pixel), intense (saturated) anomalies (figure 5(a)).

Type 2 anomalies evolved during surges in effusion at the vent. These often followed brief pauses in the eruption and fed longer (6–7 km long) surface flows which rapidly extended from the vent towards the coast. The increased area of active lava resulted in large (> 8 pixel), intense (saturated) anomalies (figures 5(b–d)), where anomaly elongation would correspond to the direction of flow extension.

Type 3 anomalies developed when surface flows began to roof over to form tubes. In such instances, development of the tube roof effectively shielded the lava's radiance from the satellite view. Young (1–7 day old) tubes resulted in small (< 8 pixel), narrow (1–2 pixels wide), intense anomalies, elongated in the flow direction (figure 5(e)). Intense radiance along the length of the anomaly was due to numerous holes (skylights) in the young tube roof and/or active surface flows (breakouts) from the tube system. Intense hot spots at either end of the anomaly could be related to lava lake and surface flow activity at the proximal and distal ends of the tube system, respectively.

Type 4 anomalies developed as the tube matured. Mature, stable tubes have few skylights and, often, no breakouts along their length. Such tubes, extending $\sim 12 \text{ km}$ to the coast (figure 1), resulted in a dual point source anomaly, with two hot spots separated by a cooler (tubed) zone (figure 5(f)). The two hot spots were due to lava lake and surface flow activity at the proximal and distal ends of the tube system, respectively. During periods of no or reduced lava lake activity, the contrast between the proximal anomaly and its background became exceedingly low (figures 5(g–h)).

Figure 4. The size and temperature that a hot spot must achieve in order to attain ΔT of (a) 5 °C , (b) 10 °C , and (c) 15 °C given ambient background temperatures (T_b) of 0, 25 and 50 °C .

Similarly the spot spot at the distal end would wane once the tube reached the coast. During such times lava entered the ocean within a few tens of metres of exiting the tube, thus reducing the area of active surface flow visible to the satellite and hence the hot spot intensity. If breakouts occurred, however, Type 3 anomalies would evolve and persist for the breakout duration.

3. Temporal observations

Given the frequency with which GOES data are available, they are ideally suited for detecting phenomena which (1) have a sudden onset, and (2) evolve over a period of hours. Next we show how GOES can be used to track effusive events which evolve over times scales of hours, days and months.

Figure 5. Typical ΔT anomaly types encountered in Kilauea during effusive activity between 1997 and 1998. (a) Type 1: localised, moderate sized, intense anomaly. (b–d) Type 2: Extended, large, intense anomaly. (e) Type 3: Extended, small, intense anomaly. (f–h) Type 4: Dual point source anomaly. Locations of Pu'u 'O'o and the ocean entry hot spots are marked PO and OE, respectively. Lighter tones relate to higher ΔT .

3.1. Techniques

To track the onset and evolution of effusive activity we use two change detection techniques: (1) movie loops of sequential images and (2) radiance time series.

We build 3–5 day long movie sequences using all (177 to 295) ΔT images acquired during that period. Analysis of such loops allows the arrival of new hot spots, and shifts in location and variation in radiant intensity of existing hot spots to be monitored. As we describe below, observed variations can be related to eruptive activity, and permit time constraints to be placed on the onset and duration of different phases of activity.

Radiance time series derived from anomalous ΔT pixels containing active lava offers a second means of building effusive event chronologies. Following the technique of Harris *et al.* (1997a, 1997b) and Harris and Thornber (1999) we use volcanic radiance ($R_{2\text{volc}}$), this being the channel 2 radiance of an anomalous pixel minus that of its immediate, non-anomalous background. Following Harris and Thornber (1999) we then sum $R_{2\text{volc}}$ for all anomalous pixels to give $\Sigma R_{2\text{volc}}$. Peaks and troughs in such time series have been shown to correlate with observed effusive events and permit event timings to be constrained with an accuracy of 15 minutes (Harris *et al.* 1997, Harris and Thornber 1999). Because different styles of activity cause hot spots of differing size and intensity, different styles of effusive activity also give characteristic levels of $\Sigma R_{2\text{volc}}$.

3.2. Monitoring short (<1 day long) duration events

We use two events to illustrate how GOES can track events of sudden onset and which develop over a period of a few hours. The first occurred during 14 January 1998. Between 18:20 and 20:30 (all times are Hawaiian Standard Time) magma moving into the summit reservoir caused the summit of Kilauea to inflate. Summit deflation followed as magma moved down the conduit which links the Pu'u 'O'o vent to the summit reservoir. The subsequent surge in supply to Pu'u 'O'o caused an increase in effusive activity from Pu'u 'O'o and skylights in the tube system (GVN

1997a). The second event occurred on 24 February 1997 when, following a 14 day long pause in activity, a helicopter pilot reported fresh lava at the Pu'u 'O'o vent (GVN 1997b).

The first event was clearly detectable in movie loops and $\Sigma R_{2\text{volc}}$ times series (figures 6 and 7(a)). Prior to 19:15 on 14 January 1998 a Type 4 anomaly, due to lava lake activity at Pu'u 'O'o and tube-fed surface flows at the coast, was apparent (figures 6(a–e)). Between 19:15 and 20:00, however, the Pu'u 'O'o hot spot increased in size and intensity to give a Type 1 anomaly (figures 6(e–i)). Over the following hours a Type 2 anomaly developed and extended south-east (figures 6(j–l)), elongation resulting from extension of surge-fed flows seawards over Pulama pali (figure 1). The $\Sigma R_{2\text{volc}}$ time series showed increasing $\Sigma R_{2\text{volc}}$, and therefore probable onset of increased effusion at Pu'u 'O'o, beginning between 19:15 and 19:30 (figure 7(a)). The second event was similarly detectable, where reappearance of lava at Pu'u 'O'o was marked by a thermal anomaly on the 07:00 GOES image of 24 February 1997 (figure 7(b)). Because no thermal anomaly was apparent prior to 07:00, and a persistent one was evident thereafter, GOES observations gave a time on the reappearance of lava at Pu'u 'O'o of between 06:45 and 07:00, at least 40 minutes earlier than the first field report (Harris *et al.* 1997a).

3.3. Monitoring medium (week to month long) duration events

We use data processed between 1 January and 10 May 1997 to illustrate the ability of GOES to track events which develop over the course of several weeks. This period began with lava flow in a stable tube system which extended from Pu'u 'O'o to the ocean (figure 1). This style of activity ended on 30 January when a 22 hour long, intermittently active, fissure eruption occurred in Napau Crater (GVN 1997c, Harris *et al.* 1997a, Thornber *et al.* 1997, figure 1). Thereafter supply to Pu'u 'O'o and the tube system ceased (GVN 1997c) with no active lava reported until 24 February. Activity then remained confined to the Pu'u 'O'o crater until 28 March when lava began to extend beyond Pu'u 'O'o to reoccupy old tubes and feed surface flows in the vicinity of Pu'u 'O'o (GVN 1997d).

Each of these activity types were apparent from variations in the thermal anomaly form and $\Sigma R_{2\text{volc}}$ level. The tube-fed activity of 1–30 January resulted in Type 4 anomalies and low $\Sigma R_{2\text{volc}}$ (figure 8(a)). Two short duration (1–24 hour long) surface flows (tube breakouts) on 14 and 24 January, however, caused $\Sigma R_{2\text{volc}}$ peaks coincident with these events. The eruption at Napau was marked by Type 1 anomalies and a $\Sigma R_{2\text{volc}}$ peak (figure 8(a)). As described by Harris *et al.* (1997a), $\Sigma R_{2\text{volc}}$ variations during this event could be used to time the opening and shut down of eruptive fissures. During the following pause no hot spots were observed until, as already discussed, a weak thermal anomaly developed with the reappearance of lava at Pu'u 'O'o. While lava remained confined to Pu'u 'O'o $\Sigma R_{2\text{volc}}$ remained low (figure 8(b)), a result of the small lava area and sluggish lake activity (GVN 1997d). When flows extended beyond Pu'u 'O'o, however, the increased lava area resulted in small (= 4 pixel) Type 1 anomalies and an immediate rise in $\Sigma R_{2\text{volc}}$ (figure 8(b)). Lava typically did not extend more than 2 km from Pu'u 'O'o, except on 17 April when a flow extended 3 km (GVN 1997e) causing a $\Sigma R_{2\text{volc}}$ peak on this date (figure 8(b)).

3.4. Monitoring long (= 1 year long) duration events

Considering $\Sigma R_{2\text{volc}}$ for the whole of 1997 (figure 9) shows that six different levels of $\Sigma R_{2\text{volc}}$ can be related to changes in the style of activity between tube-fed flow

Figure 6. Selected scenes from a GOES colour image movie generated during a surge in activity at Pu'u 'O'o during 14–15 January 1998. The colour image gives channel 2 in red, channel 4 (inverted) in green and channel 1 in blue. The full Island of Hawai'i sub-image is given in the first window (a). An enlargement of Kilauea (white box defined on (a)) is given in subsequent windows. Hot pixels located by our hot spot detection algorithm are displayed in bright yellow if they are located and saturated or dull yellow if they were located but not saturated (table 1). In this combination, by day (08:00–17:00) cloud, land and ocean appear as light blue, green-brown and dark blue, respectively. By night, both cloud and land appear dark blue, and ocean is brown.

Figure 7. ΣR_{2volc} calculated for hot spot pixels at Kilauea on (a) 14 January 1998 and (b) 24 February 1997. Grey zones indicate periods of cloud cover.

(periods 1 and 6), no activity (period 2), lava lake activity (period 3), localised flows (period 4) and widespread flows (period 5). Initial low ΣR_{2volc} levels resulted from lava flow in tubes. Because most of the radiance was shielded from the satellite view by the tube roof, low ΣR_{2volc} resulted. As already discussed the pause of 31 January to 14 February, followed by lava lake and then <3 km long lava flow activity resulted in zero, low and moderate ΣR_{2volc} , respectively. On 10–11 July, however, a flow reached the foot of Pulama pali (figure 1) and extended across the coastal flats to reach the ocean during the night of 12 July. Surface and tube fed flows occurred between Pu'u 'O'o and the ocean throughout the rest of July and early August (GVN 1997f), where the ΣR_{2volc} variations for this period of effusive activity are described, and related to ground-based observations, in Harris and Thornber (1999). Widespread surface flows during this period resulted in the highest levels of ΣR_{2volc} recorded during 1997 (figure 9). During mid-August a tube system extending from Pu'u 'O'o to the ocean began to establish (figure 1) with the tube becoming stable

Figure 8. ΣR_{2volc} between (a) 1 January and 19 February, and (b) 19 February and 30 May 1997. Anomalously high ΣR_{2volc} due to (1) tube-system break-outs and longer flows, and (2) a fissure-fed eruption at Napau crater (located on figure 1) are given by white and grey squares, respectively.

during September so that lava flowed 10 km in tubes to the ocean for the rest of the year (GVN 1997g, 1997h). This resulted in low ΣR_{2volc} until the end of the year. Surface flows from a breakout in the tube system on 30 December (GVN 1997a), however, caused an isolated ΣR_{2volc} peak at the year end (figure 9). These flows extended no more than 100 m (GVN 1997a) showing, in agreement with the modelled-based predictions of figure 4, that events covering areas of 10^2 to 10^3 m^2 are resolvable.

4. Cloud effects

During cloudy periods, cloud will mask radiance emitted by the target or, if radiance passes through thin cloud or between broken clouds, cause cloud-induced reductions in ΣR_{2volc} . To determine whether peaks and troughs in ΣR_{2volc} time series are due to eruptive events or clouds, we therefore derive a cloud index.

Figure 9. ΣR_{2volc} during 1997, with the six periods of distinct ΣR_{2volc} which can be related to different styles of activity marked. GOES data gaps are given by the grey boxes.

We use a channel 1 threshold to obtain a simple measure of cloud cover. Our analysis of channel 1 reflectance (R_1) data for Hawai'i shows that cloud and land surfaces (typically barren lava flows or vegetation) are characterised by reflectances of $>5\%$ and $<5\%$, respectively. Thus we apply a R_1 threshold of 5% to generate a simple cloud mask, where pixels with $R_1 > 5\%$ are flagged as cloud contaminated. A cloud index (CI) is then calculated using a 41×41 1 km pixel box centred on the active vent, where $CI = n_{cloud}/n_{total}$, in which n_{cloud} and n_{total} are the number of cloudy pixels and total number of pixels (1681) in the box, respectively.

Examining CI and ΣR_{2volc} together allows variations in ΣR_{2volc} to be assessed in terms of cloud cover, where increases in CI typically result in decreases in ΣR_{2volc} . We suggest that ΣR_{2volc} obtained coincident with low (<0.25) CI or ΣR_{2volc} variations which are independent of variations in CI are trustworthy. Considering the period 10–20 January 1998 (figure 10), low ΣR_{2volc} during 10–14 January are consistent with tube-fed activity, where a trough between 11–12 January was due to extensive cloud cover ($CI > 0.5$) rather than a pause in activity. Following the 14 January surge event (discussed in §3.2) an apparent ΣR_{2volc} trough just before 12:00 on 15 January is cloud-induced. Low ΣR_{2volc} coincident with low CI (<0.25) on 15 January (13:15–14:30) and 16 January (12:00–20:00), however, indicated diminished activity and was coincident with an observed pause in activity. Low CI during a ΣR_{2volc} peak beginning on 16 January (after 20:00) suggests resumption of activity at this time, whereas low ΣR_{2volc} at the end of the period given in figure 10 are due to extremely high levels of cloud cover as revealed by the CI.

5. Web-based, automated, near-real-time hot spot monitoring using GOES

Because GOES data are available in near-real-time once every 15 minutes, we have automated the analysis procedures described and demonstrated in the case studies above so that data can be processed on reception and hot spot information made available as they are produced. Our hot spot monitoring software (figure 11 and table 1) examines the GOES archive every 2 minutes to check whether a new image has arrived. If a new image is identified then it is processed and the derived

Figure 10. ΣR_{2volc} (in black) and cloud index (CI—in grey) for 10–20 January 1998. Note that the cloud index drops to zero at night because it relies on a reflection/albedo threshold applied to channel 1 data.

results are added to <http://volcano1.pgd.hawaii.edu/goes/>. Four main products are automatically generated: (1) hot spot images and movies for qualitative, visual interpretation, (2) a hot spot map, (3) ΣR_{2volc} and CI graphs, and (4) threshold-based e-mail alerts. The lag between satellite acquisition and information being posted on the web site is typically ~ 12 minutes, with updates occurring every 15 minutes.

5.1. Hot spot image and movie generation

Three main images are generated: a black and white ΔT hot spot image, a colour image which combines the T_2 , T_4 and R_1 images, and a channel 1 cloud image. Each image is automatically contrast enhanced to highlight hot spots and clouds (table 1), facilitating visual hot spot searches and assessments. The current image only is displayed on the web site, and is refreshed as soon as a new image is processed. Older images are placed in a temporary archive which holds the most recent (3 to 6 days worth) of data. Each processed image is used to update movie loops of ΔT , colour and channel 2 images. During each update, the latest image is added to the end of the movie sequence and the oldest image is dropped from the beginning. In this way an up-to-date movie sequence, with a 15 minute resolution, is maintained, covering a 3–5 day moving window.

5.2. Hot spot search and ΣR_{2volc} graph generation

To alert to new or increased effusive activity our software includes an automated hot spot thresholding (detection) algorithm. This routine (detailed in table 1) scans 41×41 km pixel target areas, centred on predefined volcano coordinates, searching for anomalous ΔT . Because cloud can result in highly elevated ΔT during the day, we implement a cloud mask to reduce cloud-induced false alarms (table 1). Any pixel which is located by the algorithm is displayed on the colour image in bright yellow, if the pixel is located and saturated, or dull yellow, if the pixel is located but not

Figure 11. Flow diagram summarising our automated processing of GOES data to provide a web-based hot spot monitoring tool (see table 1 for detail). Time taken for data to flow through these processes is ~ 12 minutes.

saturated (e.g. figure 6). Detected hot spots are also projected onto a topographic map. This is also displayed on the web site to show the location of flagged hot spots in relation to roads, towns and other geographic features. ΣR_{2volc} and CI are then calculated using each located hot and cloud pixel, respectively. As each new image is processed, so the ΣR_{2volc} and CI time series is updated, where data covering ~ 1 month long periods are displayed graphically.

5.3. E-mail alert

If the Table 1-defined threshold is exceeded, and ΣR_{2volc} exceeds the maximum ΣR_{2volc} obtained during the previous 24 hours, then an e-mail is automatically sent to a distribution list (table 1). This gives the details of the image on which the alert was triggered and, by giving a link to the relevant web-based images, allows immediate data inspection. This feature means that: (1) users do not need to constantly check the web site for new events, instead they are automatically alerted if a thermally interesting event occurs, and (2) potential activity is brought to the users attention

Table 1. Detail of automated processing steps summarised in figure 11.

Step	Processing
1	<p><i>Initialisation</i></p> <p>Real channel 1 albedo (R_1), and channel 2 & 4 brightness temperature (T_2 & T_4) images</p> <p>Create ΔT image ($= T_2 - T_4$)</p> <p>Determine image date and time from file name</p> <p>Sub-sample to 1 km pixel resolution and apply geometric rectification</p>
2	<p><i>Depending on time of day, set data offsets to improve contrast enhancement</i></p> <p>IF Time < 6 Time > 19 THEN set offsets of Min $T_2 = 10$, Max $T_2 = 20$</p> <p>IF Time > 8 && Time < 17 THEN set offsets of Min $T_2 = 8$, Max $T_2 = 17$</p> <p>IF Time ≥ 6 && Time ≤ 8 THEN set offsets of Min $T_2 = 10 + 15(\text{Time} - 6)/2$, Max $T_2 = 20 + 15(\text{Time} - 6)/2$</p> <p>IF Time ≥ 17 && Time ≤ 19 THEN set offsets of Min $T_2 = 25 - 15(\text{Time} - 17)/2$, Max $T_2 = 35 + 15(\text{Time} - 17)/2$</p>
3	<p><i>Creation of working images (convert 10-bit raw data to 8-bit working data and apply offsets)</i></p> <p>8bit$R_1 = 1 - \exp(-0.1 \times 10\text{bit}R_1)$</p> <p>8bit$T_2 = 255(10\text{bit}T_2 - \text{Min}T_2)/25$</p> <p>8bit$T_4 = 255(\text{Max}T_4 - 10\text{bit}T_4)/25$</p> <p>8bit$\Delta T = 255(10\text{bit}\Delta T + 10)/30$</p>
4	<p><i>Hot spot search and $\Sigma R_{2\text{volc}}$ calculation</i></p> <p>Apply cloud mask, where pixel is masked if $R_1 > 5\%$</p> <p>Define target region (41 × 41 km box centred on the volcano latitude and longitude)</p> <p>Calculate cloud index (= fraction of target region which is cloud masked)</p> <p>Calculate mean and σ in ΔT for a 5 pixel band around the target box</p> <p>Flag all pixels with $T_2 > 50^\circ\text{C}$ (= saturated pixels)</p> <p>Loop, flagging pixels with $\Delta T > 3.3\sigma$ above the mean as hot</p> <p>Recalculate mean and σ excluding found hot pixels until no new hot pixels are flagged</p> <p>Calculate $\Sigma R_{2\text{volc}}$ using all flagged pixels</p> <p>Assign hot pixels as 200, 200, 0 and saturated pixels as 255, 255, 0 in the R_1, T_2 and T_4 images</p> <p>Project flagged, hot pixels onto map of the targeted region</p>
5	<p><i>Outputs</i></p> <p>Write R_1, T_2, ΔT and RGB (where $R = T_2$, $G = \text{inverted} - T_4$, $B = R_1$) images (with time and date stamp), and hot spot map. Display current images and maps on web site</p> <p>Write $\Sigma R_{2\text{volc}}$ and cloud index file, update plots and display $\Sigma R_{2\text{volc}}$ and cloud index plots on web site</p> <p>Build R_1, T_2, ΔT and RGB MPEG movies (add new image to end of sequence, drop oldest from the beginning)</p> <p>Send e-mail with image details to distribution list if a hot spot is flagged and $\Sigma R_{2\text{volc}}$ for the hot spot is hotter than any other $\Sigma R_{2\text{volc}}$ encountered during the previous 24 hours</p>

in a timely manner, the event to which the e-mail relates having occurred minutes before e-mail receipt, e.g. GVN (2000).

5.4. Threshold reliability

Figure 12 summarises the performance of the hot spot thresholding algorithm from an assessment of all GOES images acquired during the first 50 days of 1998

Figure 12. Analysis of the performance of our hot spot detection routine as run on GOES data for Kilauea received and processed during the first 50 days of 1998. This assessment considers results from running the algorithm on a total of 3742 images.

(3742 images). This period covered a range of activity and a variety of cloud conditions. The algorithm ran successfully (i.e. it located a hot spot if one was apparent or located no hot spot if the hot spot was cloud covered or not present) on 90% of the images. On the remaining 10% of the images, the hot spot was either missed or non-hot spot pixels were located (false alerts).

Non-detection occurred on 6% of the images (figure 12). This occurred when stable tube systems developed feeding narrow (tens of metres wide) zones of surface

flow where the tube entered the ocean. During such activity subtle anomalies, with ΔT elevated by 1 or 2°C above the background, resulted. These small area ($<10^2$ to 10^2 m^2) flows thus caused ΔT to fall below our detection limits (figure 4). Even so, hot spots were still occasionally located (once or twice an hour). During intensified activity, for example surges in supply to Pu'u 'O'o, rapidly increasing flow area generated ΔT of sufficient intensity ($>15^\circ\text{C}$) to always be detected. We are therefore confident that new or intensified activity (e.g. fissure and lava fountain-fed flows at the beginning of an eruption) will trigger the alert.

False alerts occurred on 4% of the images (figure 12). These were due to cloud, where high cloud reflectances caused high ΔT . By night the absence of reflection in channel 2 meant that false alarm rates dropped to 0% (figure 12). If reflection is taken into account by setting daytime thresholds higher than night-time thresholds, ΔT can be used to detect hot spots by day in spite of the reflected component in channel 2. We achieve this by calculating thresholds on an image-by-image basis using data taken from pixels immediately surrounding the interrogated area (table 1). This takes local ΔT variations due to differential atmospheric, reflection and emissivity effects into account. The low occurrence of false alerts when applying this algorithm to daytime data (figure 12) indicates that the approach is robust. Successful results have also been obtained using similar automated, image specific, ΔT thresholding algorithms and daytime data for lava flows and fires (Harris *et al.* 1995b, Harris 1996, Higgins and Harris 1997).

6. Use of the GOES hot spot monitoring tool at the HVO

Our automated processing and resultant web-based hot spot monitoring tool enables routine hot spot detection and analysis. This near-real-time nature of the tool and frequent up-dates, coupled with the e-mail alert, enables image inspection as, or shortly after, the event occurs.

These web-based monitoring tools have been a useful addition to the tool set used for eruption monitoring at the Hawaiian Volcano Observatory (HVO). Prior to availability of the GOES images, HVO relied heavily on a network of seismometers and electronic tiltmeters for real-time volcano monitoring (Heliker *et al.* 1986). Monitoring of surface flows and vent activity was carried out by human observers in aircraft or on the ground. While the GOES images do not preclude the need for human observers, the images do offer an almost 24 hour overhead presence for the detection of new heat sources on the volcano's surface. On several occasions during the current life time of the operational web site (June 1997–May 1998), HVO scientists have been able to use the GOES-derived information to verify that surface activity has increased or decreased in response to a seismic or tilt event before leaving the office to see what kind of surface activity is occurring. There are many instances where we have been able to identify an event as having been localised at the vent or coast even though the crude resolution (4 km pixel representations of a 12 km by 4 km flow field) would seem to preclude confident location.

The GOES tool offers several new opportunities for volcano monitoring to an organisation such as HVO. In the aftermath of an event the images can be used to place time constraints on effusive events (with a 15 minute accuracy) than can complement observations by field crews (Harris *et al.* 1997a). During periods of continuous vent activity, a times series of radiance values centred on the vent can show variations in the intensity of the activity that HVO has only recently been able to monitor otherwise using telemetred video images (Thorner 1997). Finally, the

GOES images offer a quick and inexpensive way to rule out surface activity as a result of unexplained seismic alarms, electronic tilt alarms, or observations by the public on areas of Hawaiian volcanoes other than at the current eruption site on Kilauea. In particular, alarms and observations of a possible eruption on Mauna Loa (figure 1) must be taken seriously and are often difficult to resolve as false without effort and the expense of getting an aircraft in the air to see whether surface activity has begun. A quick scan of the GOES web site has been enough to allay concerns about a possible Mauna Loa eruption at least twice.

7. Use of GOES within the MODIS thermal alert system

The Moderate Resolution Imaging Spectrometer (MODIS), scheduled for launch as part of the Earth Observing System (EOS AM-1, now Terra), will offer 36 spectral channels between 0.4 and 14.4 μm at varying spatial resolutions (2 channels at 250 m pixel^{-1} , 5 channels at 500 m pixel^{-1} , and the remainder at 1000 m pixel^{-1}). MODIS has a swath width of 2330 km, and hence will sample the entire globe once every 1 to 2 days. We have developed a thermal alert algorithm which will automatically search the entire MODIS night-time data stream for hot spots. The detection algorithm uses a combination of radiance thresholds and differences from the 3.959 μm (Channels 21 and 22) and the 11.020 μm (Channel 31) or the 12.010 μm (Channel 32) channels to generate thermal alerts. Each alert file will contain geographical information (pixel latitude and longitude, sensor/solar zenith and azimuth angles) as well as five detailed radiance measurements from the 3.959, 8.55 (Channel 29), 11.020, and 12.010 μm channels.

We envision that the two (GOES and MODIS) thermal alert systems will not only provide a means of cross-verification of events that occur within the GOES location masks, but will also be corner stones of a web-based thermal monitoring system. The MODIS alert will offer the strategic overview necessary to answer questions such as how many volcanic or fire-related events happen per day, what regions of the Earth are prone to large fires or eruptions, how frequently do they occur, and roughly, how long do they last. GOES will offer an important tactical perspective in that we will be able to assess how many events actually occur in a given region and how many MODIS will be able to detect. Using GOES we will also be able to track the progress of brief, extremely mutable events, such as surges in magma supply to the Pu'u 'O'o vent and extrusion of lava flows. Without the very high temporal resolution of GOES, such detailed analyses would not be possible. The exciting synergy of the two systems can be easily imagined. Eruptions in the Americas initially spotted with MODIS may then be targeted for temporally detailed monitoring using GOES.

Also, with the launch of Landsat 7, the ETM+ instrument now provides high spatial resolution (15 m panchromatic, 30 m shortwave infrared, 60 m infrared) images of global targets. Both the Landsat 7 and ASTER Long-Term Acquisition Plans (LTAP) include collecting volcano data on a regular basis. The automated GOES tools described here will be used to monitor and assess volcanic eruptions and for generating emergency targeting requests to the Landsat 7 and ASTER teams.

8. Conclusions: application to other volcanoes and fires

GOES can be used to detect and track hot spots to provide a valuable, regular, timely and trustworthy hot spot monitoring capability. Variations in hot spot size,

shape and radiance, along with information on cloud cover, provide reliable information as to whether activity has commenced or stopped, is waxing or waning. Using automated web updates and e-mail alerts, events can be detected within 12 minutes of event occurrence and monitored every 15 minutes, where even small ($\sim 10^2 \text{ m}^2$) active lava bodies can be tracked.

We have therefore extended our monitoring to other volcanoes covered by GOES-W and -E. As shown in Harris *et al.* (2000), by setting offsets and thresholds on an image by image basis using statistics calculated from pixels in the vicinity of a specified target, our software has proved flexible and universally applicable. Additional volcano targets currently include: (1) Popocatépetl and Colima (Mexico), (2) Santa Maria, Fuego and Pacaya (Guatemala), (3) Cerro Negro and Masaya (Nicaragua), (4) Soufriere Hills (Montserrat), (5) Cotopaxi and Guagua Pinchincha (Ecuador), (6) Lascar, Planchon-Peteroa, Lonquimay, Llaima and Villarrica (Chile), (7) Fernandina and Cerro Azul (Galapagos Islands), and (8) White Island (North Island, New Zealand) (Harris *et al.* 2000; <http://volcano1.pgd.hawaii.edu/goes/>). Each of these volcanoes are currently in eruption or are frequently active, and present targets where hot spots and/or ash clouds due to volcanic activity should be detectable by GOES. In the case of volcanoes such as Lascar, satellite images may provide the only observations for periods of months to years (Oppenheimer *et al.* 1993, Wooster and Rothery 1997). For all volcanoes targeted to date our experiences have been similar to those with the Kilauea data set presented here, where the capabilities and monitoring uses to which the tool has been put at many of the volcanoes listed above are described in Harris *et al.* (2000).

Development of the GOES thermal alert algorithm is part of our ongoing research in which the software is continuously improved through evaluation of the algorithm and results. As a consequence, the results given in this paper are valid, but have not been calculated using the latest versions of the algorithms. A more recent version was installed in mid-1998 which, as described above, is now run on a number of volcanic targets. This includes more sophisticated hot spot thresholding and (day and night-time, multi-channel) cloud screening algorithms, as well as an increased range of hot spot image tools (see Harris *et al.* 2000 and <http://volcano1.pgd.hawaii.edu/goes/>).

Being non-site specific, our automated processing software can be used to target any high temperature feature. In the course of our analysis of volcanic targets the software has also detected many fire events, and we anticipate that our software will also be a valuable fire monitoring tool. To this end we are examining data for zones in which agricultural/forest clearance fires and wild fires frequently occur, such as the Amazon (<http://volcano1.pgd.hawaii.edu/goes/amazon/>), and plan to adapt the software to provide a monitoring tool for such targets.

We look forward to the launch of future geostationary satellite offering a 15 minute, $3.9 \mu\text{m}$ capability (e.g. MSG and MTSAT). With the launch of these satellites, GOES-type coverage will be extended over the Atlantic and Indian Oceans, Africa, Europe, Asia and Australia. Applying software adapted from the early version described here to these data will allow near-global, near-real-time hot spot searches every 15 minutes.

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