Volcanic ash detection and cloud top height estimates from the GOES-12 imager: Coping without a 12 μm infrared band

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[1] The Geostationary Operational Environmental Satellite (GOES)-12 Imager, which was activated 1 April 2003, has been re-configured with the addition of a 13.3 μm Infrared (IR) spectral band, in place of the "split window" 12.0 μm band. Since the latter channel had been successfully used for volcanic ash detection from GOES for nearly ten years, there is some concern about the impact of this change on short term warnings and forecasts for aviation operations over North and South America. The first significant volcanic eruptions observed by the new GOES-12 satellite occurred during 12–15 July 2003 at the Soufriere Hills Volcano, Montserrat. GOES-12 was able to observe the eruption clouds adequately during this period using multi-spectral techniques. Based on comparisons with multi-spectral images from the GOES Sounder, GOES-12 ash detection capability for this event was equal in quality to what would have been available from prior GOES with a 12.0 μm band. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 8409 Volcanology: Atmospheric effects (0370); 8419 Volcanology: Eruption monitoring (7280); 8494 Volcanology: Instruments and techniques. **Citation:** Ellrod, G. P., and A. J. Schreiner (2004), Volcanic ash detection and cloud top height estimates from the GOES-12 imager: Coping without a 12 μm infrared band, *Geophys. Res. Lett.*, *31*, L15110, doi:10.1029/2004GL020395.

1. Introduction

[2] On 1 April 2003, Geostationary Operational Environmental Satellite (GOES)-12 became the primary spacecraft to monitor weather and environmental hazards over North and South America. *Hillger et al.* [2003] (see http://www.cira.colostate.edu/ramm/goesm/GOES-12_Science_Test_Report.htm) describe the GOES-12 data and products and assess their quality. An important modification to the GOES-12 Imager was the replacement of a 4 km resolution 12 μm Infrared (IR) band with a lower resolution (8 km) IR band centered near 13.3 μm (see Table 1). The 12 μm band will not be restored until about 2013 when the GOES-R spacecraft becomes operational. There has been a concern that the loss of the 12 μm band will negatively affect volcanic ash detection and aviation safety, since that channel has been effectively used in a two-band "split window" technique [*Prata*, 1989] for over a decade. An impact study has indicated that some degradation of remote sensing of volcanic ash is likely, leading to both under-detection of thin ash, and an increase in the area of "false" ash, resulting in possible over-warning for aviation advisories [*Ellrod*, 2004].

[3] The first significant opportunity to evaluate GOES-12 volcanic ash detection capabilities occurred with several moderate eruptions of Soufriere Hills Volcano on the island of Montserrat in the Eastern Caribbean from 12–15 July 2003. The eruptions were triggered by a major lava dome collapse, followed by pyroclastic flows (Montserrat Volcano Observatory, unpublished data, 2003) (see http://www.mvo.ms). Ash was dispersed throughout the troposphere across the region, with maximum ash top heights estimated to range from 8–16 km (Washington Volcanic Ash Advisory Center, unpublished data, 2003) (see http://www.ssd.noaa.gov/VAAC/ARCH03/archive.html) (W-VAAC). The VAACs were established during the 1990's as part of the International Airways Volcano Watch (IAVW) to provide current advisories on existing volcanic ash clouds. Regional Meteorological Watch Offices then issue warnings (known as SIGMETs) to en route aircraft based on the VAAC advisories. The W-VAAC has responsibility for the Caribbean region, as well as large portions of North and South America, and the Central and Western Pacific [*International Civil Aviation Organization*, 2000].

2. Volcanic Ash Detection Methods

[4] Traditional methods for detection of volcanic ash often employ a bi-spectral technique based on the brightness temperature difference (BTD) of two Infrared (IR) bands centered near 11.0 and 12.0 μm [*Prata*, 1989; *Holasek and Rose*, 1991]. These two IR bands have been available at 1 km resolution from the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting National Oceanic and Atmospheric Administration (NOAA) satellite series since the early 1980's. By the mid-1990s, similar spectral bands also became available on the GOES. Although the spatial resolution of GOES IR sensors is only 4 km, their advantage is frequent coverage (nominally 30 min) over most volcanically active regions of North and South America, as opposed to four times daily from the AVHRR.

[5] There are some situations where the two-band difference method (hereafter referred to as the Two-Band Split Window (TBSW)) fares poorly however, due to: (1) the excessive thickness of the eruption cloud (which often contains copious water and large ejected particles) within a few hours after the eruption, (2) a lack of temperature contrast between the airborne ash and underlying surface, and (3) ambient atmospheric moisture that can mask low

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Table 1. Summary of GOES Imager Spectral Bands Showing Changes in the New Series (M-P) in Bold, Compared With Previous Spacecraft (GOES 8-11)[a]

	GOES 8-11		GOES M-P	
Band	Wave-length (μm)	Res. (km)	Wave-length (μm)	Res. (km)
1	0.6	1	0.6	1
2	3.9	4	3.9	4
3	6.7	8	**6.5**	**4**
4	10.7	4	10.7	4
5	12.0	4	-	-
6	-	-	**13.3**	**8**

[a]Band 6 will improve to 4 km resolution beginning with GOES-O (circa 2007).

level ash clouds [e.g., *Simpson et al.*, 2000]. Despite these shortcomings, the TBSW technique has become an international benchmark for volcanic ash detection. The loss of this channel on GOES-12 created the urgent need for a different approach.

[6] The altitude of the ash cloud is also important to aviation, and estimates of the top of the ash layer are provided in the VAAC messages. At the W-VAAC, the ash cloud heights are determined by matching the trajectory of different portions of the ash cloud with upper level wind profiles obtained from adjacent radiosondes or numerical prediction models. In this paper, we will describe new techniques for detecting volcanic ash clouds and estimating their maximum heights using the new spectral band combination available from the GOES-12 Imager.

3. GOES-12 Imager Ash Detection Algorithm

[7] A new algorithm has been developed to detect ash from GOES-12 Imager Infrared (IR) brightness temperature (BT) data, using an arithmetic combination of Bands 2 (3.9 μm), 4 (11 μm) and 6 (13.3 μm). Bands 6 and 4 have shown the ability to discriminate volcanic ash from ice-laden cirrus cloud layers due to emissivity differences at those wavelengths [*Ellrod*, 2004]. Thermal differences between Bands 2 and 4 have been used in a three-band method [*Ellrod et al.*, 2003] which exploits reflectivity and absorption effects near 3.9 μm. The GOES-12 algorithm was empirically determined by experimentation with NASA MODerate resolution Imaging Spectroradiometer (MODIS) data [*Ellrod and Im*, 2003] and GOES Sounder data. The new algorithm is:

$$B = 5(DT) - 230 \tag{1}$$

[8] Where B is output brightness count, DT = ($T_2 - 1.5T_4 + 1.5T_6$), T_2 is BT observed in Band 2 (3.9 μm), T_4 is BT in Band 4 (10.7 μm) and T_6 in BT in Band 6 (13.3 μm). DT values between 230 and 300 are scaled to output brightness counts between 0 and 255. Values of B that are large relative to surrounding clouds and terrain represent volcanic ash. Thresholds for volcanic ash detection using this new approach have not yet been established due to the diurnal variation of T_2. Even in bright daytime scenes, the ash clouds stand out against the background if they are sufficiently dense. The plot in Figure 1 shows brightness count (B) from equation (1) obtained on 14 July 2003 at 0915 UTC (0515 Caribbean Standard Time (CST)) for several different types of features. The volcanic ash is clearly distinguishable from the cirrus, mid-level clouds, and ocean at this time. Note that if only thermal IR data are used, the ash would be virtually indistinguishable from other cloud types in the region due to similar brightness temperatures.

[9] The three-band technique was evaluated for three of the four Soufriere Hills eruptions. For validation and comparison, graphical ash analyses from W-VAAC were available, as well as imagery and derived products from the GOES Sounder. The Sounder is an independent instrument that employs a different scanning strategy, with the goal of producing temperature and humidity profiles (retrievals), as well as image products such as cloud top pressures (CTP), total precipitable water (TPW), and Lifted Index [*Menzel et al.*, 1998]. The GOES Sounder has nineteen spectral bands, with a resolution of 10 km at nadir compared with 4–8 km for the Imager. For the Eastern Caribbean, Sounder scans were only available at 0120 UTC, 0720 UTC, 1320 UTC and 1920 UTC.

4. Case I: 12–13 July 2003 Event

[10] Triggered by a major collapse of the Soufriere Hills lava dome, first eruption occurred late on the evening of 12 July 2003 (around 0230 UTC, 13 July 2003). The resulting ash cloud reached 15.7 km based on an IR estimate by the Washington VAAC. The development, expansion, and northeastward drift of cold cloud tops associated with the eruption column could easily be seen in GOES-12 Band 4 thermal IR images. However, the three-band IR product described in Section 2 was not effective, probably due to extensive water in the eruption cloud, and because high level non-volcanic clouds in the area obscured most of the dissipating ash. Although this is a common weakness of IR detection techniques (see Section 2), minimum cloud top temperatures were around 200 K for several hours following the eruption. The estimated extent of the eruption cloud at 0645 UTC (circled) is shown in Figure 2. Later confirmation

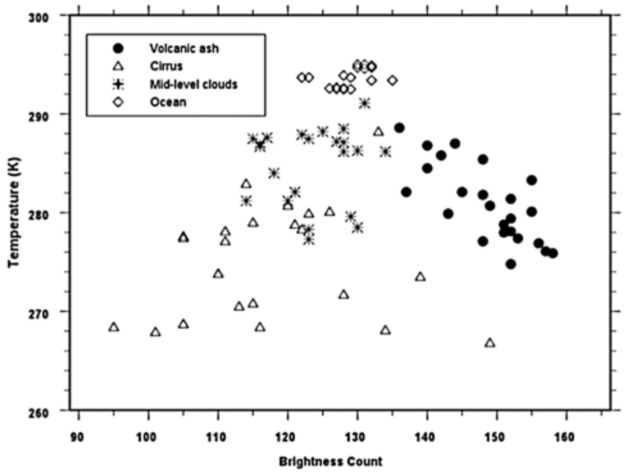

Figure 1. Scatter plot of brightness count from equation (1) versus IR band 4 temperature (K) from GOES-12 on 14 July 2003 at 0915 UTC (see Figure 3) for volcanic ash, ocean surface, cirrus clouds, and mid-level clouds.

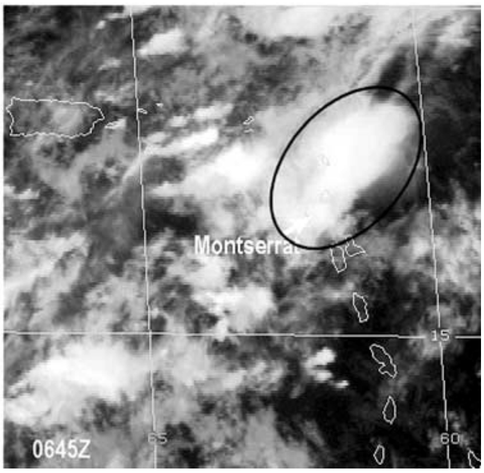

Figure 2. GOES-12 IR Band 4 (10.7 μm) at 0645 UTC, 13 July 2003 showing estimated extent of eruption cloud (brighter cloud tops within ellipse) from Soufriere Hills volcano, Montserrat.

that this was likely volcanic ash came from the Total Ozone Mapping Spectrometer (TOMS) at around 1530 UTC that day (not shown), which indicated that there were large concentrations of high altitude SO_2 gas to the northeast of the Leeward Islands (image available from the NASA TOMS archive: http://toms.umbc.edu.

5. Case II: 14 July 2003 Event

[11] Shortly after Midnight on 14 July 2003, another release of ash occurred, with maximum cloud top heights estimated by the VAAC to be 11.3 km. Minimum T_4 cloud top temperatures for this event were about 238 K at 0615 UTC, but quickly became warmer as the cloud thinned out. For this case, there was less cloud cover in the region, allowing an evaluation of multi-spectral ash detection techniques. An hourly sequence of the three-band IR images depicted the mid-upper level ash cloud as it drifted toward the west and northwest. Lower level ash was more difficult to distinguish against the ocean background. A comparison of the three-band IR product from both Imager (A) and Sounder (B) is shown in Figure 3, along with a TBSW image, also from the Sounder (C). Valid times for the Imager and Sounder scans were 0715 UTC and 0720 UTC, respectively. The Imager product depicts the boundaries of the ash cloud (lighter gray shades) much more clearly than the Sounder, which is smeared considerably due to its lower resolution. The TBSW image is similar in quality to the three-band product from the Sounder. The dark, embedded pixels are believed to be caused by cirrus clouds or perhaps mid level water clouds, as would be expected from Figure 1.

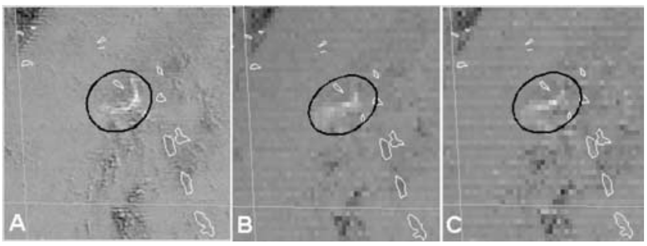

Figure 3. Comparison of GOES-12 three-band IR image from Imager at 0715 UTC on 14 July 2003 (A) with the same image product from the Sounder valid at 0720 UTC (B). Panel C is a Two-Band Split Window image based on 11 μm and 12 μm channels, also from the Sounder at 0720 UTC. Ash is shown by lighter gray shades within encircled areas.

6. Case III: 15 July 2003 Event

[12] On 15 July 2003 at approximately 0530 UTC, the fourth eruption in this series sent ash to as high as 14.7 km (47,000 ft) as reported by the Washington VAAC. The minimum cloud top temperature (T_4) was 224 K at 0645 UTC. Figure 4 provides a two-hour interval sequence of three-band IR images showing the spread of the eruption clouds from 0745 UTC to 1345 UTC. The ash cloud, the background ocean, and meteorological clouds all brighten around 1145 UTC due to solar reflectance in the 3.9 μm IR band.

7. Cloud Top Height Estimation

[13] The availability of the 13.3 μm IR band from the Imager on GOES-12 and its successors provides an opportunity to test a CO_2 Absorption Technique (COAT) [*Schreiner and Schmit*, 2001; *Schreiner et al.*, 2002] in the estimation of volcanic ash cloud top heights on a frequent basis. The COAT is a physical relationship based on a special version of the Radiative Transfer Equation. The main assumptions are (1) cloud is opaque but infinitesimally thin (thus allowing application for semi-transparent clouds), and (2) emissivity is the same in both spectral ranges. The latter assumption, when applied to the 13.3 μm and 10.7 μm bands, is only valid when a volcanic cloud is partially composed of ice.

[14] A comparison of a GOES cloud height analysis from 14 July 2003 at 0545 UTC with the VAAC graphical height analysis is shown in Figure 5. Based on subjective, textural

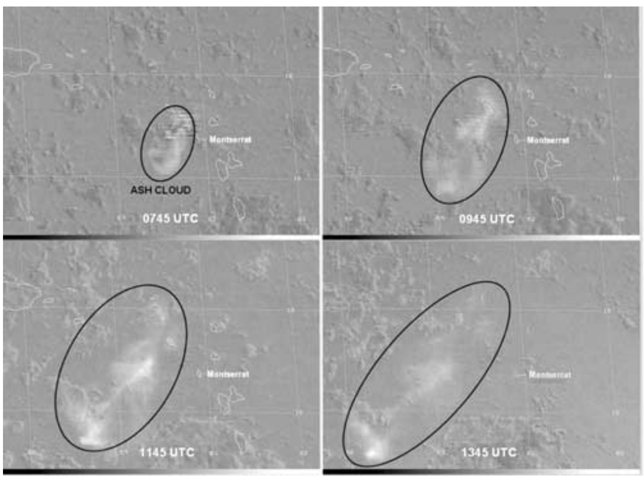

Figure 4. Two-hourly interval GOES-12 three-band IR images showing evolution of ash on 15 July 2003 from 0745 UTC to 1345 UTC.

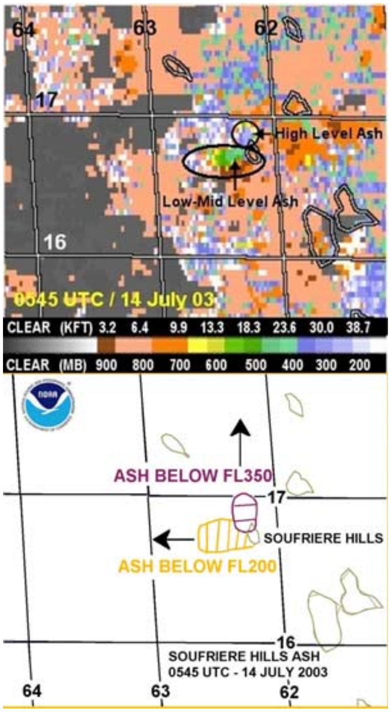

Figure 5. Cloud top height product based on the GOES-12 Imager CO_2 Analysis Technique (COAT) (top) compared with the VAAC analysis both valid 0545 UTC, 14 July 2003.

evaluation of IR data, the high level ash was nearly opaque, while the low-mid level ash was semi-transparent. Cloud top heights from the GOES-12 product ranged from 7.6 km (24,000 ft) for the mid-level ash, to about 11.1 km (35,000 ft) for the high level ash, in good agreement with the VAAC analysis (based on an independent technique described in section 2).

8. Summary and Conclusions

[15] The first significant volcanic eruptions observed by the new GOES-12 satellite occurred from 12–15 July 2003 following a lava dome collapse at the Soufriere Hills Volcano, Montserrat. A new IR technique that used the 3.9, 10.7 and 13.3 μm channels (Bands 2, 4, and 6) was able to observe the ash clouds effectively for two of the events during the period, while the strongest event could be monitored by a sequence of Band 4 IR images. Ash cloud heights based on the CO2 Absorption Technique for the 14 July 2003 case were consistent with those from the VAAC analysis, which employs an independent wind trajectory matching technique. The uniformly warm ocean background, which provided excellent thermal contrast with the airborne ash clouds, was an advantage for observing these events which will not be present for Continental volcanoes. The presumption that there would be under-detection and increased false alarms for ash detection using GOES-12 was not observed for this particular event. While the loss of the 12 μm IR band is likely to degrade the overall volcanic ash detection capability somewhat, this episode shows that imagery from GOES-12 and its successors will prove to be an effective means of warning pilots of hazardous ash clouds in many situations.

References

Ellrod, G. P. (2004), Loss of the 12 μm "Split Window" Band on GOES-M: Impacts on volcanic ash detection, *J. Volcanol. Geotherm. Res.*, *135*, 91–103.

Ellrod, G. P., and J.-S. Im (2003), Development of volcanic ash image products using MODIS multi-spectral data, paper presented at the 12th Conference on Satellite Meteorology and Oceanography, Am. Meteorol. Soc., Long Beach, Calif., 9–13 Feb.

Ellrod, G. P., B. H. Connell, and D. W. Hillger (2003), Improved detection of airborne volcanic ash using multispectral infrared satellite data, *J. Geophys. Res.*, *108*(D12), 4356, doi:10.1029/2002JD002802.

Hillger, D. W., T. S. Schmit, and J. Daniels (2003), Imager and sounder radiance and product validations for the GOES-12 science test, *NOAA Tech. Rep. 115*, U.S. Dept. of Commerce, Washington, D. C.

Holasek, R. E., and W. I. Rose (1991), Anatomy of 1986 Augustine eruptions as revealed by digital AVHRR satellite imagery, *Bull. Volcanol.*, *53*, 420–435.

International Civil Aviation Organization (ICAO) (2000), *Handbook on the International Airways Volcano Watch (IAVW): Operational Procedures and Contacts List*, 1st ed., *ICAO Doc. 9766-AN/968*, Montreal, Canada.

Menzel, W. P., F. Holt, T. Schmit et al. (1998), Application of GOES-8/9 soundings to weather forecasting and nowcasting, *Bull. Am. Meteorol. Soc.*, *79*(10), 2059–2077.

Prata, A. J. (1989), Observations of volcanic ash clouds in the 10–12 micrometer window using AVHRR/2 data, *Int. J. Remote Sens.*, *10*, 751–761.

Schreiner, A. J., and T. J. Schmit (2001), Derived cloud products from the GOES-M imager, paper presented at the 11th Conference on Satellite Meteorology and Oceanography, Am. Meteorol. Soc., Madison, Wis.

Schreiner, A. J., T. J. Schmit, and R. M. Aune (2002), Maritime inversions and the GOES Sounder cloud product, *Natl. Weather Dig.*, *26*, 27–38.

Simpson, J. J., G. Hufford, D. Pieri, and J. Berg (2000), Failures in detecting volcanic ash from a satellite-based technique, *Remote Sens. Environ.*, *72*, 191–217.

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