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A new way to detect volcanic plumes

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[1] Detection of volcanic plumes, especially ash-laden ones, is important both for public health and aircraft safety. A variety of geophysical tools and satellite data are used to monitor volcanic eruptions and to predict the movement of ash. However, satellite-based methods are restricted by time of day and weather, while radars are often unavailable because of cost/portability. Here a method is proposed to detect volcanic plumes using GPS signal strength data. The strengths and limitations of the method are assessed using GPS data collected during the 2008 and 2009 eruptions of the Okmok and Mt. Redoubt volcanoes. Plume detections using this GPS technique are consistent with independently collected seismic and radar data. **Citation:** Larson, K. M. (2013), A new way to detect volcanic plumes, *Geophys. Res. Lett.*, *40*, 2657–2660, doi:10.1002/grl.50556.

1. Introduction

[2] Global Positioning System (GPS) instrumentation is now routinely used to measure ground deformation near volcanoes. In doing so, it plays a critical role in assessing volcanic hazards. During an eruption these measurements are used to constrain changes in the magma system. However, GPS instruments are rarely used to detect effects of the eruption above ground. *Houlie et al.* [2005a, 2005b] first showed how GPS data could be used to model volcanic plumes. *Grapenthin et al.* [2013] extended the technique to include detection. Both groups used standard geodetic processing techniques for position and treated the plume signal as an atypical atmospheric effect. These methods require analysis of thousands of GPS carrier phase ranges and estimation of the effects of station coordinates, orbits, relativity, clocks, atmospheric delays, and phase ambiguities. This kind of geodetic approach is technically challenging because both the plume and the receiver's positions are time-varying phenomena. Because least squares estimation is used for geodetic solutions, any mismodeling is distributed to other estimated parameters and satellite observations that do not cross the plume. In this study, a new method is proposed for detecting volcanic plumes. Instead of the GPS carrier phase data, GPS signal strength (signal-to-noise ratio, SNR) data are used. SNR data are very sensitive to large ash particles and can be modeled without estimating position, thus providing a clearer picture of a volcanic plume.

2. GPS Signal Strength

[3] GPS receivers routinely record SNR data. These data correspond to carrier-to-noise-density ratio (C/N$_0$), the ratio of signal power to the noise power spectral density. SNR is related to C/N$_0$ through the noise bandwidth (B) as in SNR = (C/N$_0$)/B [*Joseph*, 2010], thus having units of decibels. GPS receiver manufacturers primarily report this quantity assuming a 1 Hz bandwidth, or dB-Hz. SNR data provide no information about the distance between the satellite transmitting the signal and the receiver, and thus make no direct contribution to positioning solutions. For this reason, SNR data are generally ignored by geophysicists and geodesists. However, SNR data have value because they can directly measure signal blockages. If, for example, an ash-laden volcanic plume crosses a GPS signal, parts of that signal are attenuated and scattered. This means that the signal that does arrive at the GPS receiver has less power than it would ordinarily. In contrast, water in the atmosphere does not significantly reduce GPS signal power. This lack of sensitivity to water is the same reason that L-band radars are being developed to observe ash clouds [e.g., *Donnadieu*, 2012]. Previous GPS plume studies used carrier phase data, which are sensitive to both water vapor and ash.

[4] A full description of the GPS signal structure and how a receiver generates observables is beyond the scope of this paper [see, e.g., *Misra and Enge*, 2006], but it is useful to review here some of the general characteristics of GPS SNR data. In Figure 1 the top panel highlights two satellite tracks for L1 (1.5754 GHz) SNR using the public C/A code. The bottom panel shows L2 (1.2276 GHz) SNR data using two different codes, L2C (which is also public) and the encrypted L2P code. All show SNR values slowly increasing as the satellite rises from 5 to 65° in elevation angle. This is known as the direct signal effect. The slow increase in SNR is primarily due to the antenna gain pattern. The L1 SNR data above 25° have high-frequency noise that is both systematic and random. In contrast, the high-elevation L2 SNR data have much smaller levels of high-frequency noise. This difference is due to the fact that the C/A code is much shorter than L2P or L2C and thus suffers from cross-channel interference. However, L2P has much lower SNR values than C/A or L2C because the receiver cannot use the encrypted code in its retrieval. As a final comment, L2C is only available on satellites launched after 2005. Furthermore, it is often not tracked unless the user requests it.

[5] The oscillations you see in SNR data at elevation angles <25° are caused by ground reflections. A reflected signal travels a longer distance than the direct signal and interferes with the direct signal; this causes the observed modulations. The frequencies in the SNR data below 25° can be related to soil moisture content, snow depth, and sea level height [*Larson et al.*, 2008; 2009; 2013]. Here only the higher elevation angle SNR data—of interest for plume sensing—will be

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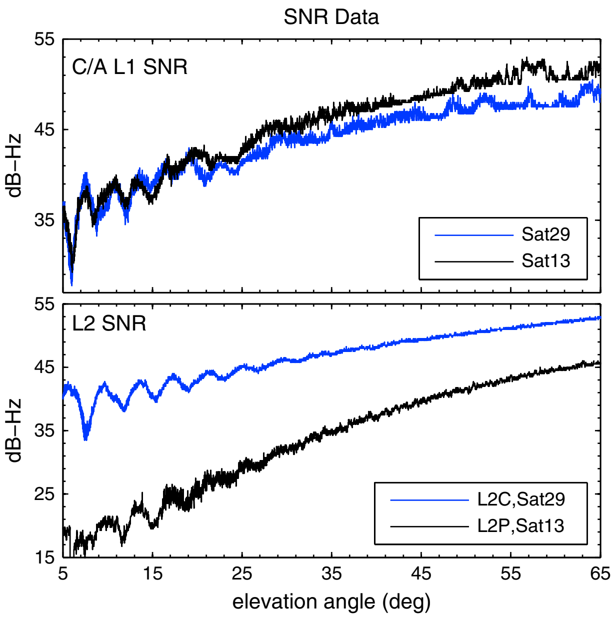

Figure 1. (top) L1 SNR data derived from the C/A code (I inadvertently left out the word data). Satellite 29 is offset by 2 dB-Hz to highlight the data for large elevation angles. (bottom) L2 SNR data using L2C (satellite 29) and L2P (satellite 13).

used. Because it has better precision at higher elevation angles, the L2P SNR data are used to isolate the effect of plumes. Figure 2 shows representative L2 SNR data for an eruptive sequence at Mt. Redoubt, Alaska for a 5 day period (L1 data are given in Figure S1 in the supporting information). As expected, the SNR data vary smoothly by ~20 dB-Hz over the satellite arc. To isolate the plume signal, the following algorithm is used. No data below elevation angles of 20° are used, as these data are both less precise and more likely to be impacted by ground reflections. Data on the 2 days before and after the eruptive event are shifted by 4 min/d to account for the repeating satellite geometry, then averaged and smoothed over 10 points. While more precise orbit repeat times are available [*Agnew and Larson*, 2007], the 30 s sampling rate used at the sites in this study precludes a need to use them. The smoothed SNR model—which represents the expected values for a given station and satellite at a given time—is then subtracted from the SNR data collected on the day of the eruption. This SNR change is what is used to detect the presence of plumes. The standard deviation of the SNR data for the 30 min before each eruption is calculated to provide a quality-control measure, and detections are required to be 2.5 times this standard deviation. If no SNR data are available before the eruption, the satellite track is discarded. Finally, no detection is reported (regardless of its standard deviation), unless its value exceeds 1.75 dB-Hz, in order to avoid reporting false detections.

3. Results

3.1. Mt. Redoubt

[6] The algorithm described in section 2 was used to detect plumes for the four largest explosive events from the 2009 Mt. Redoubt eruption sequence [*Bull* et al., 2012]. Here summaries are provided for two of these events: event 8 (26 March 2009) and event 19 (4 April 2009) (Figures 3a and 3c). These events sent ash to heights of ~19 and 15 km, respectively. Timing of the eruptions is defined by nearby seismic instruments [*Fee et al.*, 2013; *McNutt et al.*, 2013]. For each event, data from four GPS receivers (AC17, RBED, RVBM, and DUMM) were analyzed (Figures 3b and 3d). Neither event was detected at stations AC17 and RBED. Station AC17 is >30 km from Mt. Redoubt, precluding detection using our data set because the elevation angles needed to see the plume would be too small. In contrast, RBED is ~5 km due south of Mt. Redoubt. However, there are no northern satellite tracks in Alaska above an elevation angle of 20°. Even so, the data from AC17 and RBED are important. Ionospheric scintillation can also produce significant changes in SNR data [*Kinter et al.*, 2007]. The fact that AC17 and RBED do not see any changes means that the detections at RVBM and DUMM cannot have been caused by ionospheric scintillation.

[7] A large plume detection at an azimuth of 90° for station RVBM can be observed for event 8 (Figure 3b). Smaller detections are seen for satellite tracks to the north-northwest of the caldera. Because the ray path from satellite 21 to RVBM passes directly over the caldera, the data can be used to estimate how fast the plume rose (Figure 4). Using the first SNR detection (180 s after the event start time), the plume rose at a rate of 32–40 m/s; the uncertainty is based on the 30 s GPS sampling rate. Tighter error bounds on determining the plume velocity would require higher-sample rate GPS data. The GPS plume velocity agrees well with *Schneider and Hoblitt* [2013], a C-band radar study that found plume velocities of 25–60 m/s for the Mt. Redoubt eruptive sequences.

[8] In contrast to event 8, event 19 is only reliably detected at station RVBM by one satellite track (Figures 3c and 3d). This satellite is at a lower elevation angle, which means the SNR data are noisier and sense a lower altitude (4–6 km) than event 8. The data again qualitatively agree with the seismic sensors. In particular, the GPS data show that event 19 was much longer than event 8. This is also consistent with the findings of *Schneider and Hoblitt* [2013], which found that the plume rose slowly in the first 7 min and then rapidly increased its ascent rate. As a final comment, the SNR data are measuring an integrated path effect. The volume being sensed changes as the plume rises and moves laterally. Comparisons should be made between the radar scans and the SNR data to determine the method's constraints in terms of ash particle size and density.

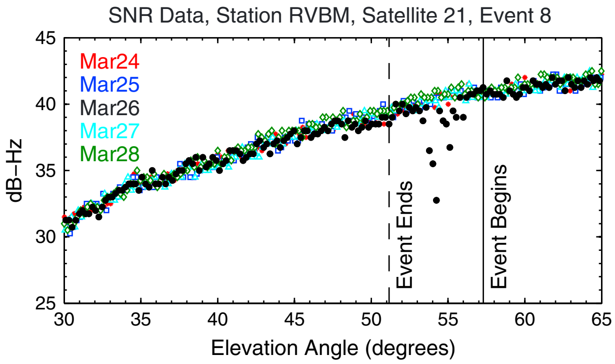

Figure 2. L2 SNR data for 2 days before and after Mt. Redoubt eruptive event 8 (26 March 2009). Event times determined by seismology are noted. A time span of ~3 h is shown.

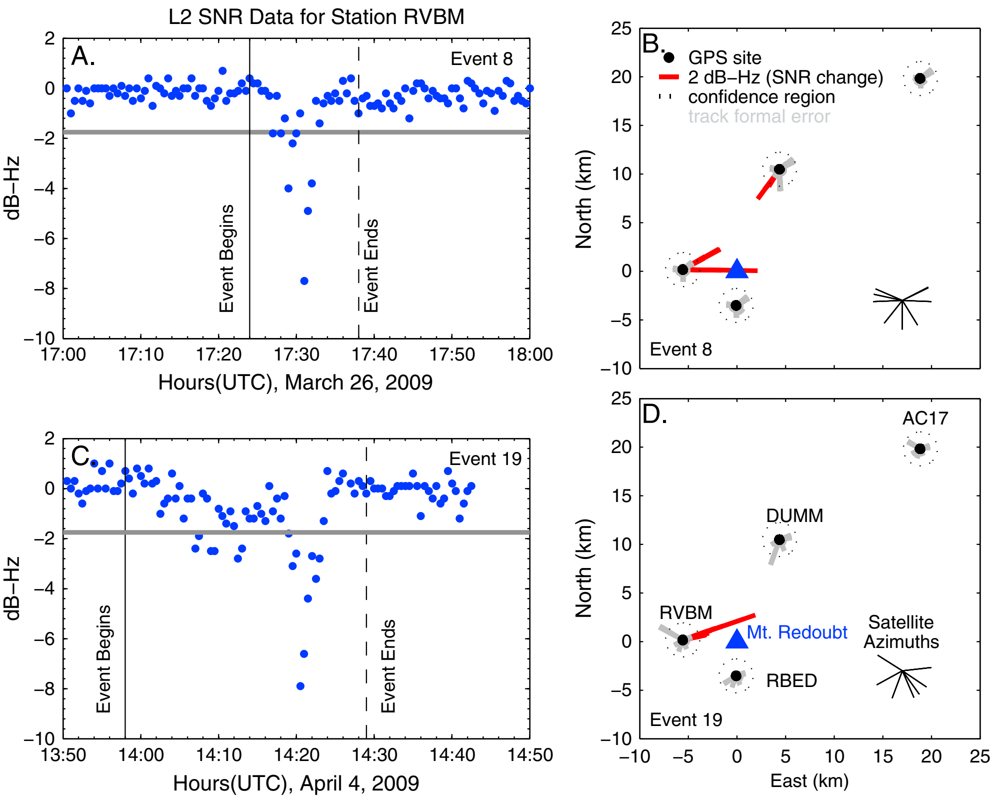

Figure 3. (a and c) SNR data for GPS station RVBM and events 8 and 19. Eruption times are determined with seismic sensors [*Bull et al.*, 2012]. Nominal detection level is shown as the horizontal gray line. (b and d) Summary mapview representation of plume detections. Gray lines at four stations (black circles) indicate nondetections for satellites transmitting from those azimuths. Red lines indicate significant plume detections (scale given).

3.2. Okmok Volcano

[9] GPS data from the primary Okmok eruption (12 July 2008) were also analyzed to see if a plume could be detected [*Freymueller and Kaufman*, 2010; *Grapenthin*, 2012]. Okmok Volcano is located on Umnak Island, Alaska. Two GPS receivers were operating on the island at the time of the first seismic activity. The GPS sites OKSO and OKFG are located within 15 km of the caldera. At Mt. Redoubt, drops in SNR caused by volcanic plumes were followed within 30 min by a recovery to its expected value. At Okmok, the temporal behavior of the SNR data is quite different (Figure 5). At OKFG, there is a dramatic 15 dB-Hz

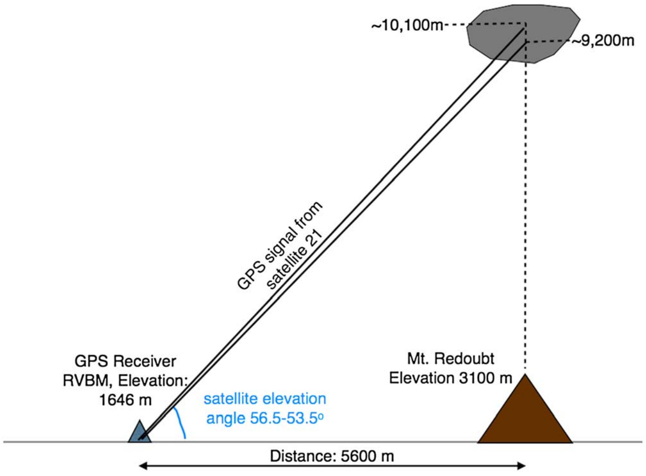

Figure 4. Cartoon of plume geometry for GPS station RVBM, satellite 21, and event 8 (26 March 2009). Elevations of the caldera, GPS site, and plume detection heights (for the eruption start and stop times) are also noted.

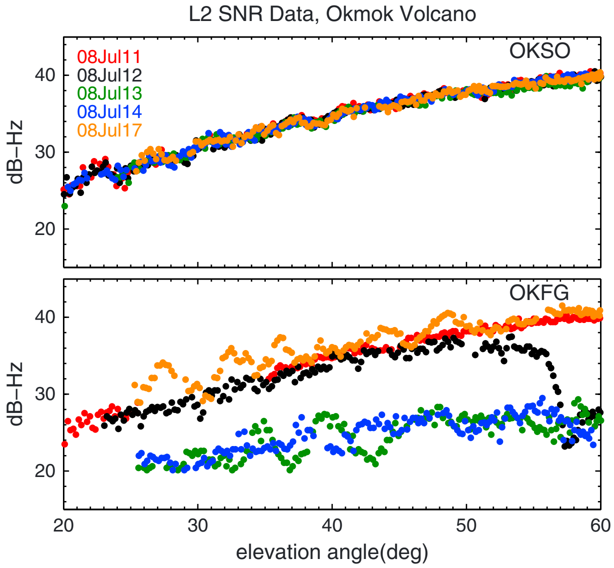

Figure 5. SNR data for two Okmok Volcano GPS sites, OKFG and OKSO. A rising arc for satellite 10 is shown for the hours 20:00–22:30 UTC on 12 July 2008. *Fee et al.* [2010] found that the eruption began at 19:43 UTC, i.e., ~15 min before the data shown here.

drop in SNR, but it is 1.5 h after seismic activity began [*Fee et al*., 2010]. SNR values then remained low for the next 2 days, suggesting that the ash effects being observed in this example were not in a plume, but sitting on the GPS antenna. The USGS confirmed that significant ash fall (10 cm) was reported near OKFG (P. Cervelli, personal communication, 2013). Given that the GPS antenna used at this site is a flat disk, this is the simplest explanation for the drop in GPS signal strength.

[10] Rainfall and heavy winds on Umnak Island were reported on 15–16 July. By 17 July, the OKFG SNR data have returned to their pre-event levels, with one interesting change. Previously, there were no oscillations in the low elevation angle data, which is consistent with the antenna being surrounded by rough ground surfaces. After the ashfall, oscillatory behavior can now be observed, which is consistent with reflections from a smoother ground surface [*Larson et al*., 2008]. The SNR records for the southern site, OKSO (Figure 5), are consistent for all days, indicating both that the satellite track shown for this site failed to observe the plume and that the antenna was not as impacted by ashfall.

4. Discussion

[11] There are several advantages to using GPS SNR data for volcanic plume detection. GPS receivers are frequently deployed near volcanoes to monitor ground deformation; as shown here, these same data can be used for plume detection without any modifications to the equipment. Second, SNR data are not very sensitive to water vapor, and thus provide a better detector for ash than GPS carrier phase data. Finally, SNR data do not depend in a complicated way on station position, clocks, and satellite orbits. Simple models can be used to fit the data, which means an SNR-based algorithm could be more easily used in real-time. As shown for the Okmok event, SNR data can also be used to warn geodesists that the integrity of their positioning solutions is at risk. Easy ways to improve the results from the SNR method would be to (1) increase receiver sampling rates, (2) track the new L2C signal when available, and (3) insist that receiver manufacturers record SNR data with subinteger precision. The receiver used in this GPS reports precision of 0.25 dB-Hz, but other receiver manufacturers only report 1.0 dB-Hz.

[12] Global positioning system SNR data also have disadvantages. Unlike radar, GPS has no scanning capability and can only use the GPS frequencies. It is always possible that there will be no satellite tracks that cross the plume during the eruption. However, four Global Navigation Satellite System constellations are expected to be fully operational in the next decade. This would yield signals from 100+ satellites. This would substantially increase the likelihood of plume detections. Given the simplicity of SNR data, it would also be straightforward to combine the SNR data from the different constellations. Finally, the cost of a geodetic-quality GPS receiver is significantly less than a radar, and considerably more portable. Large deployments of GPS receivers could be installed around volcanoes before eruptions, providing the potential for plume tomography. Finally, the plume detections shown here are given in SNR units of dB-Hz, analogous to radar retrievals of reflectance. Additional research would be needed to convert these integrated path effects into an ash density value.

5. Conclusions

[13] I have demonstrated that SNR data collected by GPS receivers can be used to detect volcanic plumes. Unlike geodetic positioning, only simple models are needed to analyze GPS SNR data, and these plume detections are not impacted by ground motion. This suggests that with simple modifications (higher sampling rates, tracking all signals, and using all Global Navigation Satellite System (GNSS) constellations), GPS can play an important role in helping detect ash-laden, volcanic plumes in real-time.

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