Using GPS Signal Strength Data to Detect Volcanic Plumes

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Introduction

GPS is a L-band navigation system. GPS satellites are operated by the U.S. Department of Defense, and jointly managed with the U.S Department of Transportation. They transmit coded signals at two primary frequencies: 1.5575 GHz (L1) and 1.2276 GHz (L2). As part of a modernization program, a third frequency (L5) was recently added, but this signal can only be tracked with newer instrumentation. GPS has been used by geoscientists for decades to measure crustal deformation. It is also routinely used to monitor water vapor in the atmosphere and timing. GPS units of this type cost from $5,000-$10,000, depending on one's access to volume purchase prices.

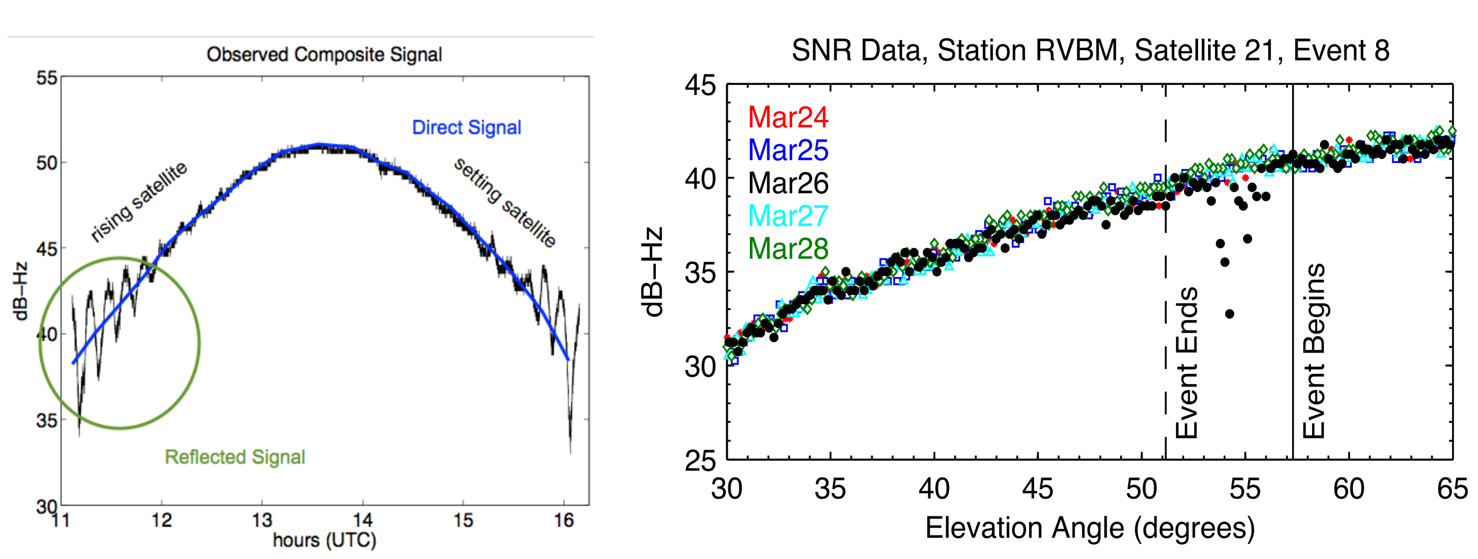
GPS has been used to monitor volcanoes for over twenty five years. Generally geodetic-quality GPS units are deployed on the volcano, recording dual-frequency ranging observations at sampling rates of 30 seconds. Fundamentally, GPS receivers measure the one-way travel time (ranges) between multiple satellites and a single GPS antenna. Modeling of satellite orbits, satellite and receiver clocks, relativistic effects and atmospheric delays allows geodesists to estimate position (latitude, longitude, and height) with least squares techniques. With appropriate software, mm-cm level measurements of ground displacements can be easily measured.

About 10 years ago, volcano geodesists began to evaluate the effects on volcanic plumes on GPS signals (Houlie et al., 2005a,b). As with most geodetic studies, these focused on using the measured ranges (the distances between the satellites and the GPS antenna) because ranging measurements are longer if there is water vapor in it. More recently volcanic plumes in Alaska, New Zealand, Japan, and Italy have been studied with GPS ranging measurements (Grapenthin et al., 2013; Ohta et al., 2015; Aranzulla et al., 2013; Fournier and Jolly, 2014). Typically the volcanic plume is detected by evaluating least squares residuals used when estimating positions. This has the unfortunate effect of combining the volcanic plume effect (which generally only affects a single satellite) with all the satellites that were in view at the same time. Larson (2013) showed that GPS signal strength data (SNR) could also be used to sense plumes. Currently many groups of volcano geodesists are looking closely at detecting plumes with GPS, which build on these common principles:

1. GPS is a L-band, global, all-weather system. From 6-12 satellites are visible at any time.
2. GPS ranging data are significantly affected by water vapor and precipitation.
3. GPS signal strength data are not affected by water vapor or precipitation, but correlate well with other plume observations of ash.
4. The GPS constellation consists of 30+ satellites operating in 6 orbital planes at an inclination of 55 degrees with respect to the equator. The GPS orbital period is nearly half a sidereal day, and thus the satellites are in the same place in the sky ~4 minutes earlier each day (Agnew and Larson, 2007).
5. Transmission power of the GPS signals is tightly controlled, and thus signal strength levels (and SNR) are very repeatable from day to day.
6. In principle any GPS-like signal (GLONASS, GALILEO, and BEIDOU) could be used for volcanic plume sensing; all navigation constellations operate in the L-band.
7. Because of the satellite inclination, different geometries will be observable at different latitudes. For example, in most of the northern hemisphere, there are no useable satellites at northern azimuths (-30 to 30 degrees). This means that GPS receivers should not be placed to the south of a volcano if desiring to observe a plume.

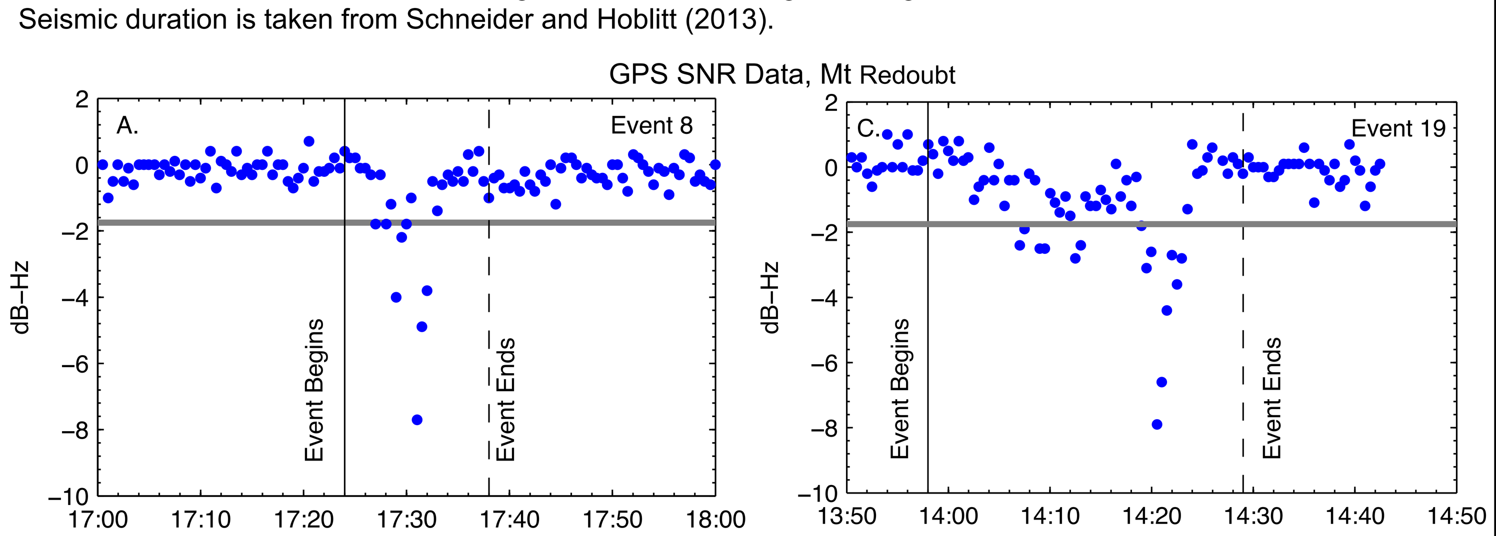
GPS Signal Strength Data (SNR)

Although ranging measurements are the primary observables produced by a GPS instrument, all receivers will calculate an engineering measurement (C/No) which is a proxy for signal strength. These data are frequently called the GPS SNR (signal to noise ratio) data. The figure below on the left shows a typical SNR dataset. The direct signal – the one that travels along the straight line between the satellite and the antenna – has a very simple SNR profile which can be approximated by a polynomial. The lower SNR values as the satellite rises and sets is primarily due to the gain pattern of the antenna. The oscillations seen at low elevation angles in this figure (circled in green) are due to signals reflected from the ground. The amplitude, frequency, and phase of these oscillations can be used to measure vegetation water content, snow depth, and soil moisture (Small et al., 2010; Larson et al., 2009; Larson et al., 2008).



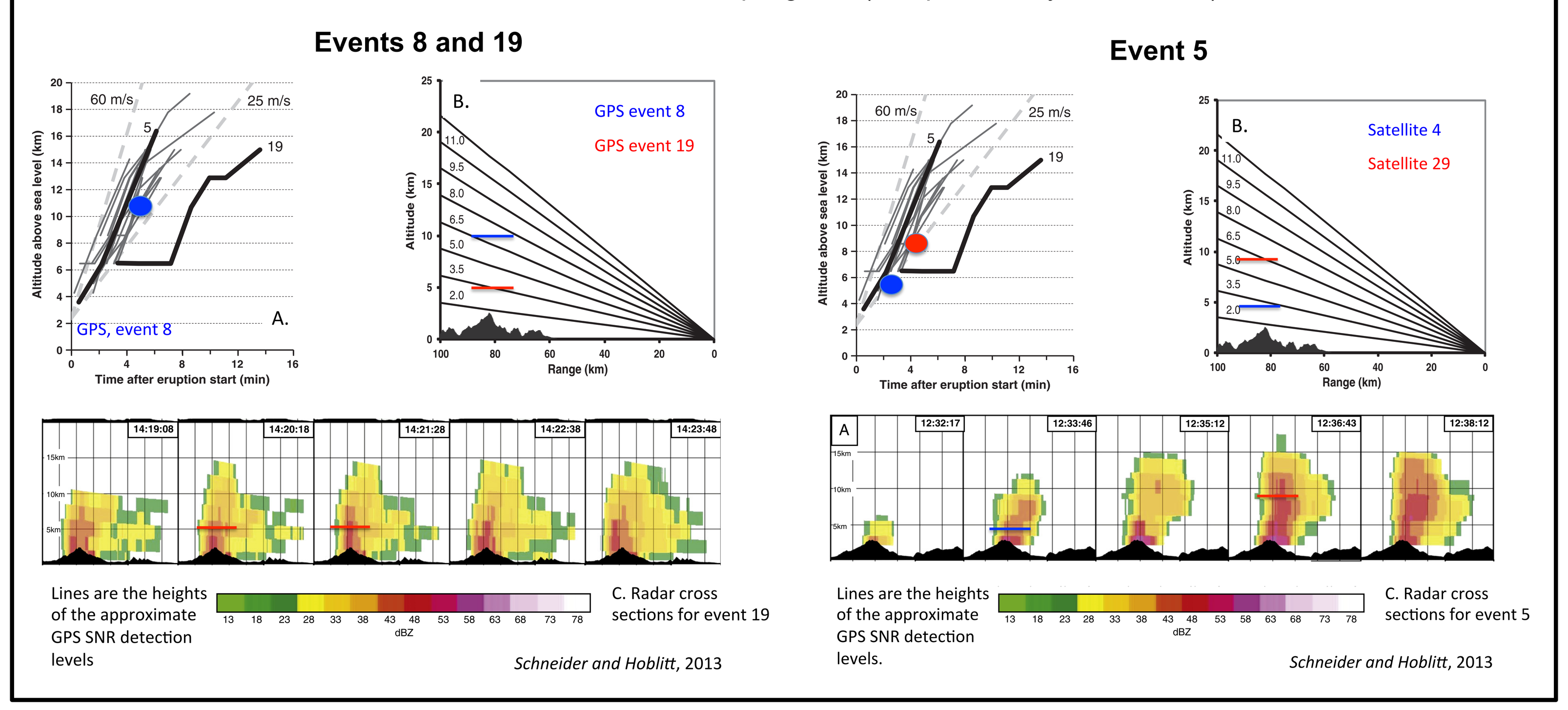
Left: raw SNR data for a single satellite pass for a typical geodetic GPS site, plotted as a function of time; right: SNR data collected for five consecutive days near Mt. Redoubt, Alaska, plotted as a function of elevation angle. The day of the eruption is plotted in black. Elevation angle is the angle from the GPS antenna to the satellite with respect to the horizon.

Larson (2013) first detected the presence of a volcanic plume using SNR data. Shown above are SNR data collected by a geodetic-quality GPS receiver operated near Mt. Redoubt at the time of eruption 8 (Fee et al., 2013; McNutt et al., 2013; Schneider and Hoblitt, 2013). This instrument was deployed for the purpose of measuring ground deformation, and thus sampling was set to 30 seconds (Grapenthin et al., 2013). The particular station shown is located ~5 km to the west of the main vent of Mt. Redoubt. A total of five days of SNR data are shown – demonstrating that SNR behaves similarly each day except during event 8. The repeatability of the SNR levels are used to model the "direct signal." The remaining SNR signal is shown below for events 8 and 19. Seismic duration is taken from Schneider and Hoblitt (2013).



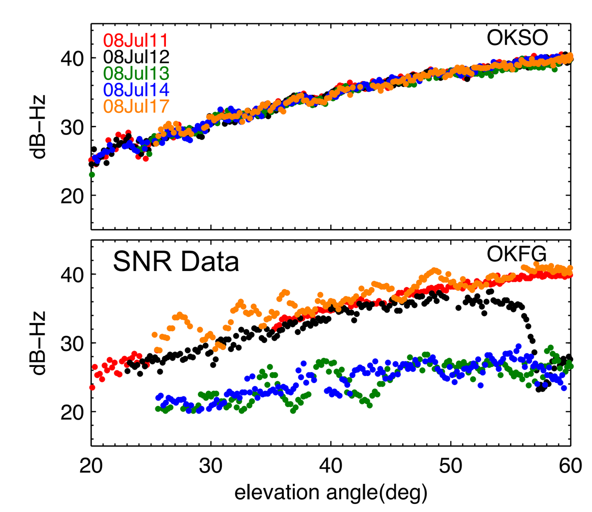
Mt. Redoubt: Comparisons with Radar

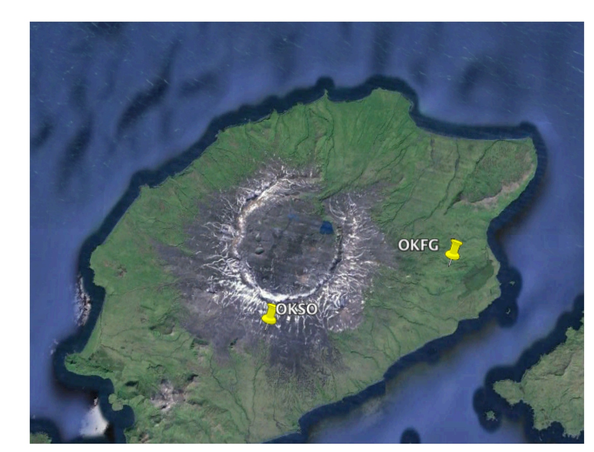
Shown below are comparisons between GPS SNR detections of plumes and radar observations for Mt Redoubt Events 5, 8, and 19. Note that each detection is based on a satellite that is at a different elevation angle, and thus a different plume height. For event 5, detections for two satellites are available; both are consistent with a velocity of ~25 m/s. More precise detections are somewhat limited because of the GPS sampling rate (one point every 30 seconds).



Okmok

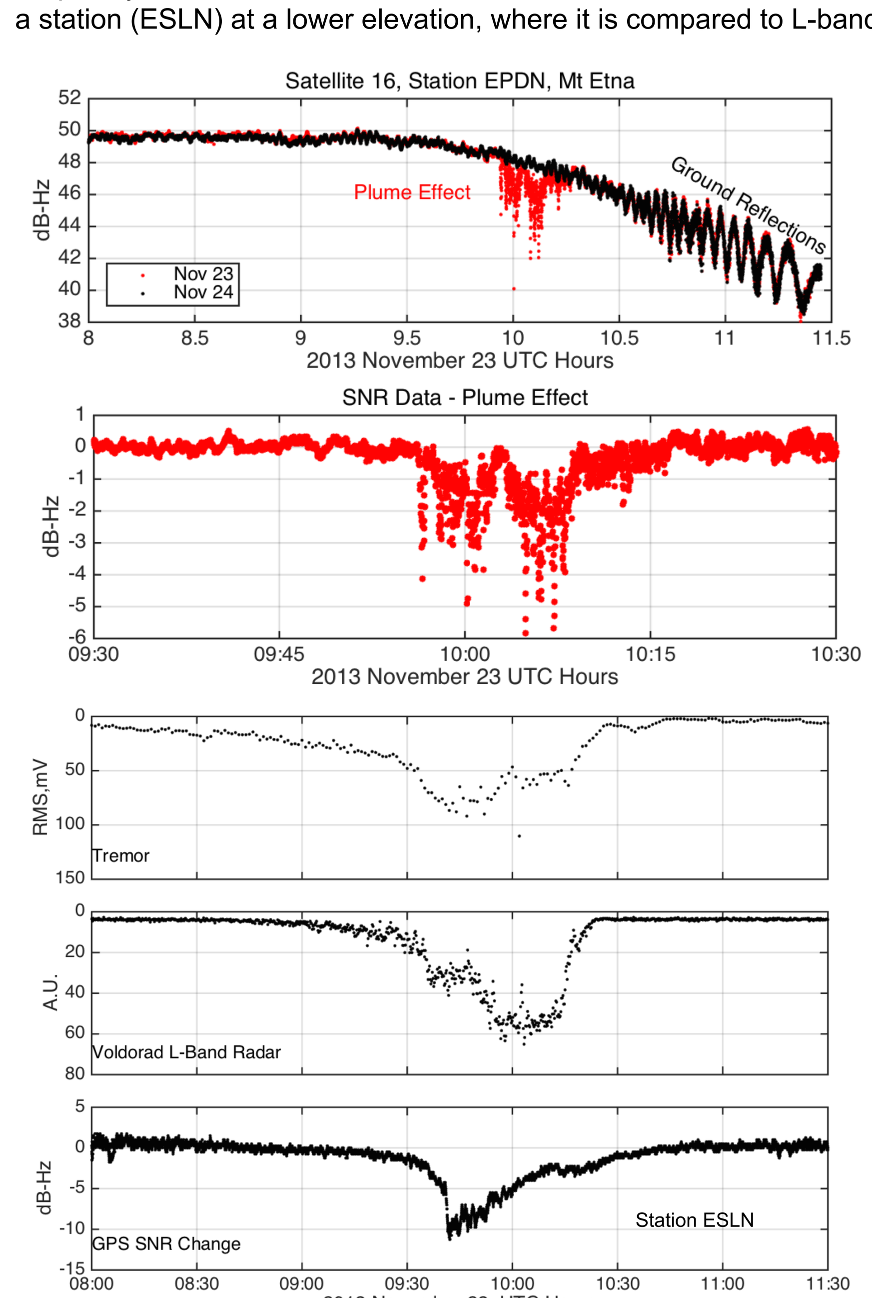
An eruption began at Okmok Volcano on July 12, 2008. The University of Alaska, Fairbanks and the Alaska Volcano Observatory were operating two GPS receivers near the summit. The GPS receiver OKSO, directly to the south, was not observing any satellites that crossed the plume. The GPS receiver at OKFG, to the east, did not observe the eruption either, but ~hour later, a large disruption in SNR was observed (see below). SNR values remained low until July 17. We hypothesize that the flat GPS antenna was covered by ash, attenuating the signal. This ash was not removed until a rain storm on July 16. One can see in the orange trace (for July 17) that oscillations are now clearly present, indicating a planar reflecting surface below the antenna. These reflections were not observable before the eruption, presumably because the ground was not as smooth as it was after ash was deposited. The USGS reports ~10 cm of ash fell near OFKG.

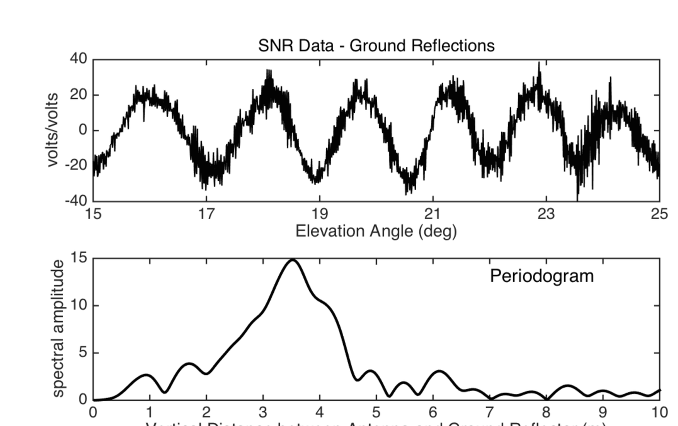




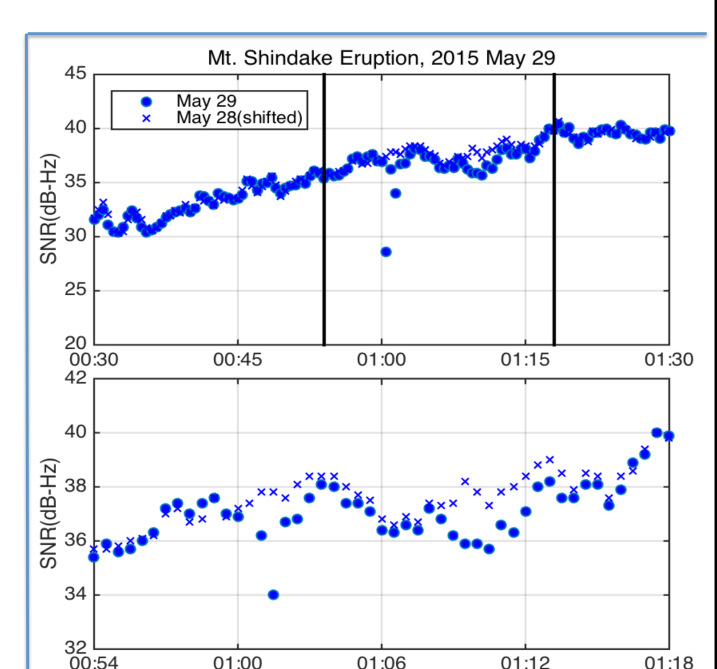
GPS Plume Detections in Italy and Japan

Below we show GPS detections of volcanic plumes from Mt. Etna and Mt. Shindake. On the left we show a detection for a summit site in Mt. Etna. There is clear attenuation in SNR (shown in red) when compared to SNR data from the previous day (shown in black). We also point out the oscillations in the SNR data that are representative of ground reflections. The frequency of these oscillations can be used to determine variations in snow depth (right). Plume effects can also be seen at a station (ESLN) at a lower elevation, where it is compared to L-band radar and seismic tremor data.





Top panel: SNR data for station EPDN; bottom panel: a periodogram of the SNR data. The frequency of the SNR data is converted to meters, the distance between the antenna and the dominant reflector. In principle this method can be used to measure ash deposits on the ground.



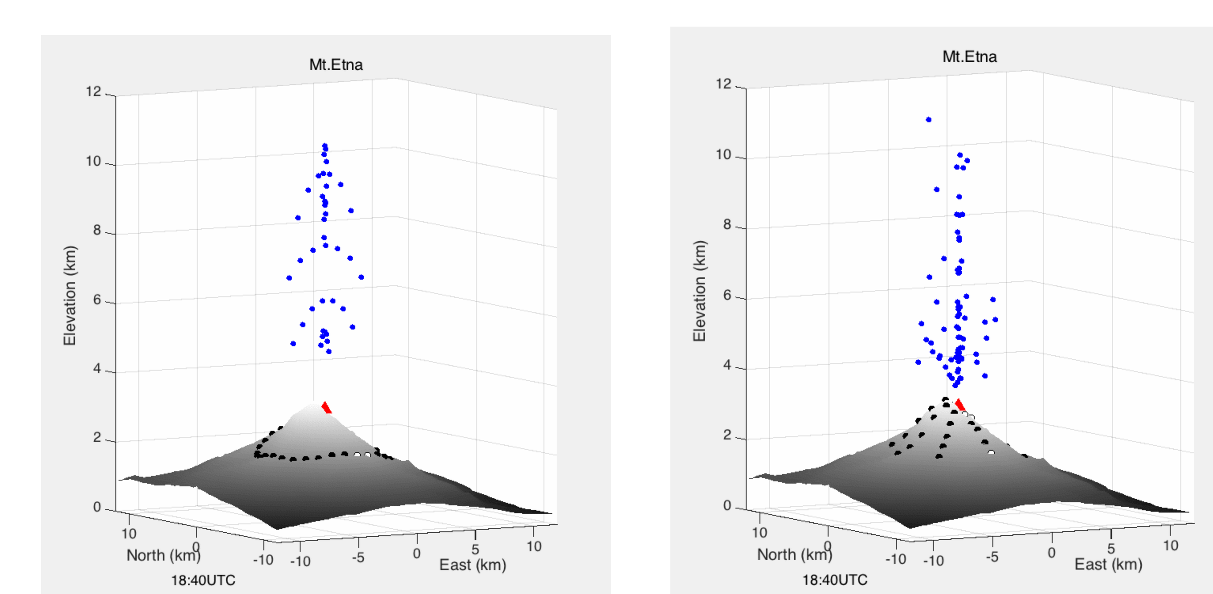
Ongoing Work

1. Working with geodetic colleagues around the world, we are compiling datasets of GPS SNR detections of volcanic plumes. These data will allow us to characterize the performance of the method and provide insight as to the physical mechanisms in play.
2. With radar remote sensing colleagues, we are developing a forward model for SNR changes due to constituents of volcanic plumes.
3. Where available (e.g. Mt. Redoubt), we are comparing GPS SNR detections with radar backscatter observations.

For past volcanic eruptions, our datasets come from geodetic deployments of GPS instruments. These are generally not placed in a way that provides optimal resolution of the plume, nor do they record data at high sampling rates. In many cases, as with Mt. Shindake, only a single GPS satellite can see the plume. This significantly limits the value of the observations. In order to improve the temporal and spatial sampling of this method, we need to increase the number of satellites viewed and the number of receivers in the field. Geodetic receivers are expensive, and they are not typically deployed to provide viewing of the plume.

NASA has funded our group to explore ways to use inexpensive GNSS instrumentation for plume sensing. At a cost of ~$50/unit, it becomes feasible to deploy a large number of receivers at high sampling rates in an optimal geometry. We should be able to track both GPS and GLONASS using this receiver/antenna system, providing a total of 55 satellite sources. When the European and Chinese constellations are completed, 110 satellites will be available. We are currently collaborating with the Istituto Nazionale di Geofisica e Vulcanologia and the Mt Etna Volcano Observatory to develop and deploy this low-cost GNSS plume sensor array.

At the University of Colorado we are developing the software and hardware needed for this low-cost sensor array. Instead of using existing geodetic GPS sites, we will evaluate via simulation which receiver deployments optimize the greatest number of plume detections at multiple heights. We will test both GPS and GPS+GLONASS scenarios. Two notional low-cost GPS arrays for Mt. Etna are shown below. In the network on the left, the receivers are set at a given distance from the center of the volcano, whereas in the right, the receivers are set along spokes. The simulation here was set to have a plume of radius 3 km, centered on the red triangle. Detections are shown as blue circles, which represents the midpoint of the GPS signal intersection with the cylindrical "plume." In this scenario, the array on the right finds more plume detections than on the left. The GPS units are being built to include telemetry so that individual sites can transmit their data to nearby sites, ending at two hubs, where a detection algorithm will operate in a PC. We are testing the equipment in Boulder this winter, and hope to deploy 3-4 sites in Italy next summer, with a full deployment the following year. In parallel we are working to improve our models.



Conclusions

We have shown that there are strong correlations GPS signal power (also called SNR data) and volcanic plumes. SNR data are insensitive to water/water vapor, and thus have potential to contribute to ash detection activities at volcano observatories. SNR data are computed by a GPS receiver to evaluate the health of its tracking algorithms, and thus are readily available. We are evaluating both the precision and accuracy of SNR data so that we can place uncertainty bounds on our plume detections. We are also working to develop forward models for ash and other plume constituents so that we can convert SNR detections into parameters that would be of more value to this community.

We encourage any country that operates a GPS network with **open data policies** to contact us if they are interested in testing their datasets, as we would be happy to share software with you.

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