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► **To cite this version:**

N. Houlié, Pierre Briole, A. Nercessian, M. Murakami. Volcanic plume above Mount St. Helens detected with GPS. *Eos, Transactions American Geophysical Union*, 2005, 86 (30), pp.277-281. 10.1029/2005eo300001 . hal-04270647

**HAL Id: hal-04270647**

**<https://hal.science/hal-04270647v1>**

Submitted on 6 Jun 2024

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# EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 86 NUMBER 30

26 JULY 2005

PAGES 277–284

## Volcanic Plume Above Mount St. Helens Detected With GPS

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Eruptions can produce not only flows of incandescent material along the slopes of a volcano but also ash plumes in the troposphere [Sparks *et al.*, 1997] that can threaten aircraft flying in the vicinity [Fisher *et al.*, 1997]. To protect aircraft, passengers, and crews, the International Civil Aviation Organization and the World Meteorological Organization created eight Volcanic Ash Advisory Centers (VAAC, <http://www.ssd.noaa.gov/VAAC/vaac.html>) around the globe with the goal of tracking volcanic plumes and releasing eruption alerts to airports, pilots, and companies. Currently, the VAAC monitoring system is based mostly on the monitoring systems of any local volcano observatories and on real-time monitoring of data acquired by meteorological satellites.

In the case of the 18 August 2000 eruption of the Miyakejima volcano in Japan, Houlié *et al.* [2005] showed that the Global Positioning System (GPS) might be used as an additional tool for monitoring volcanic plumes. The present article indicates that the 9 March 2005 eruption of Mount St. Helens, Washington, also produced detectable anomalies in GPS data.

Since September 2004, the Cascades Volcano Observatory of the U.S. Geological Survey (CVO/USGS, <http://vulcan.wr.usgs.gov/>) has registered a period of activity at Mount St. Helens (46.2N, 122.2W), with two phreatic eruptions on 16 January and 9 March of 2005 (Figure 1) [Major *et al.*, 2005]. The CVO research team has monitored several parameters (including deformations, gas samplings, and seismicity) in order to understand the volcanic process and alert the local population of a possible risk [Dzurisin *et al.*, 2005]. Pilots of commercial aircraft reported that on 9 March 2005, an atmospheric plume propagated upward and reached an elevation of about 13 km above sea level (a.s.l.) [Major *et al.*, 2005]. The VAAC Office of Vancouver (Washington) tracked the volcanic plume over the United States in the hours that followed.

The data used in this study were acquired at seven permanent GPS stations deployed in

the vicinity of the Mount St. Helens lava dome by the U.S. National Science Foundation's EarthScope Plate Boundary Observatory (PBO, <http://www.earthscope.org/>) since the volcano's September 2004 reawakening after 15 years of rest. Figure 2 shows the locations of the seven stations (P690, P693, P695, P696, P697, P698, P699). The data were processed daily using GAMIT (GPS Analysis MIT) software [King and Bock, 1999], assuming the troposphere is fully modeled by a standard meteorological model with a troposphere parameter estimated every four hours.

The hypothesis, successfully validated in the case of the 18 August 2000 Miyakejima eruption, is that the single- or double-difference phase residuals were containing a clear signature of the presence of the plume, and that this signature was relatively easy to extract and model and interpret quantitatively. (The single-difference phase is the difference of phase emitted by one satellite and received at two different sites; the double-difference phase is the difference

of the phases emitted by two satellites and received by two receivers.)

Figure 3 shows the six residuals of the LC frequency (LC is a linear combination of the two carriers emitted by the GPS satellites L1 and L2;  $LC = 2.545 L1 + 1.545 L2$ ) computed using each satellite seen by each receiver with respect to the satellite PRN22 and the site P690.

The amplitude of the typically observed noise is about 0.15 cycles on LC frequency (or 7 cm of anomalous pseudorange; the pseudorange is the distance between the satellite and the GPS receivers), and the anomalies observed during the eruption are about twice this value (0.3 cycles). The error on the location of a given site perturbed by a plume is about 14 cm (Figure 2). The event is visible for 20 min on the GPS residuals of satellites PRN18 and PRN22. However, the residuals presented here are less than for the Miyakejima eruption in 2000, and this made them less obvious to locate in the data.

Anomalous signals were observed only for satellites PRN18 and PRN22. These two satellites were located between the azimuth N0 and N90 during the eruption with elevation angles equal to 27° for PRN18 at 1.35 (UT) and 59° for PRN22 at the same time. The spatial location of the plume anomaly retrieved by GPS is compatible with the lateral drift of

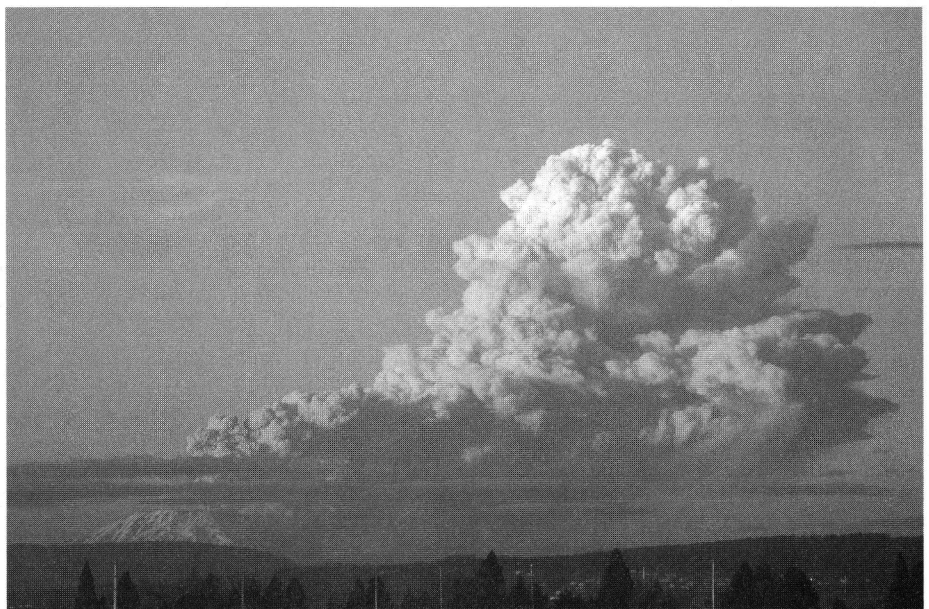


Fig. 1. Photo of the 9 March 2005 Mount St. Helens eruption. The plume reached 11.2 km above sea level. Image credit: U.S. Geological Survey. Original color image appears at the back of this volume.

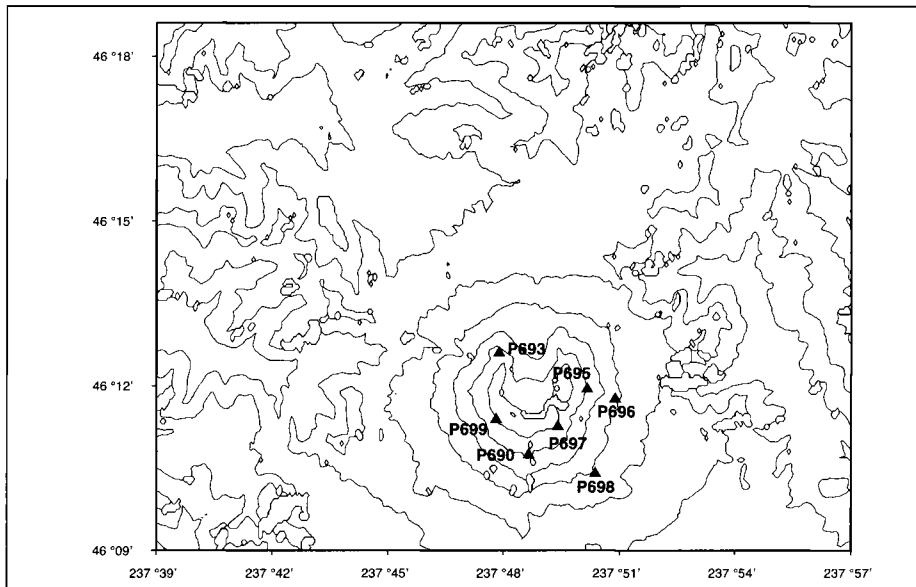


Fig. 2. Map of the Plate Boundary Observatory network around Mount St. Helens.

the volcanic plume pushed to the east by the wind, as reported by direct observations from ground and air during the event (see Figure 1 and Major et al. [2005]).

This new, successful retrieval of a subtle but clear anomaly in residuals of GPS phase delay modeling, corresponding to 5 to 10 cm of equivalent pseudorange delay, confirms that GPS data can be used for detecting and quantifying volcano plumes. In the case of Mount St. Helens, the PBO system already allows data to be released on an hourly basis on the Internet, and the processing of the data and extraction of the residuals can easily be automated. The next step of this research, also relatively easy to implement, will be the real-time analysis of the data and extraction of residuals.

The softwares modeling the troposphere several times per day using meteorological models [Saastamoinen, 1972; Niell, 1996] are particularly dedicated to the study of volcanic plumes. Indeed, the processing of an entire day of data will allow the determination of average troposphere delay that precedes the analysis of the residuals using a rowing window. (A rowing window is a strategy to smooth the data. At every sampling time, the mean value of the  $n$  value constituting the rowing window is being computed.)

The GPS networks that are efficient for detecting volcanic plumes are networks of very limited spatial extent (typically 10 km). Thus, the problem of assessing for short sessions various standard parameters [Saastamoinen, 1972] such as the average troposphere is not critical.

Furthermore, in some cases a larger number of single-frequency instruments would probably be even more appropriate than fewer double-frequency units. This is because analysis of the L1 frequency instead of LC would result in less noisy data and therefore in lower thresholds for the detection of anomalies.

### Acknowledgments

We thank the Plate Boundary Observatory (PBO) project and the Scripps Orbit and Permanent Array Center (SOPAC) team for providing the data. We are grateful to Jon Clark for his help.

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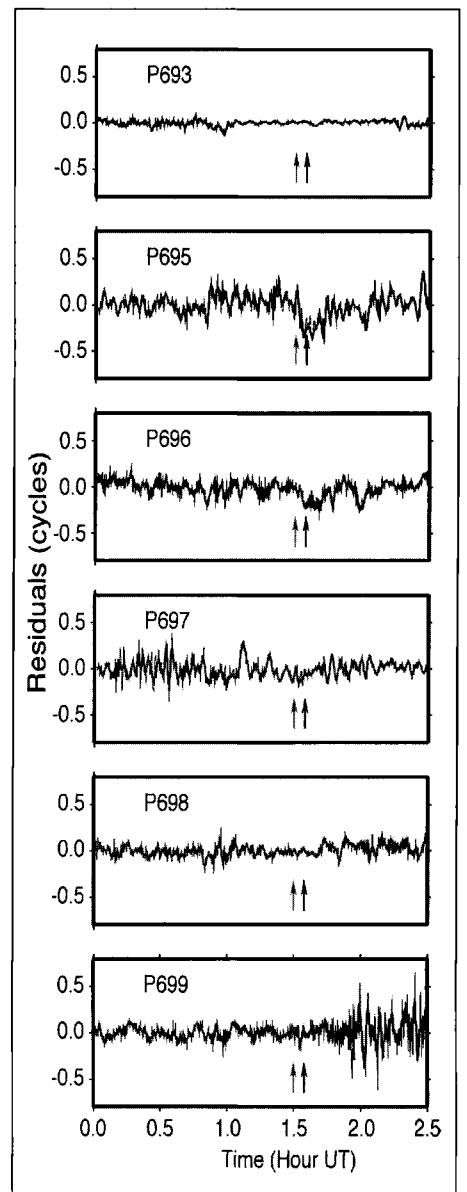


Fig. 3. Anomalous residuals for satellite PRN22 during the event. The plume is clearly visible on the residuals of the sites of P695 and P696. The solid arrow signals the official time of the occurrence of the 9 March event. A shaded arrow signals the most probable time. The differences between the observed residuals are due to the specific pattern of the plume. The moving mean ( $n = 6$ ) is drawn by a red line. Original color image appears at the back of this volume.



Fig. 1. Photo of the 9 March 2005 Mount St. Helens eruption. The plume reached 11.2 km above sea level. Image credit: U.S. Geological Survey.



Fig. 1. M/V Western Legend (left), soon to be converted as R/V Marcus G. Langseth, will replace the Maurice Ewing (right) as the primary U.S. seismic research vessel.

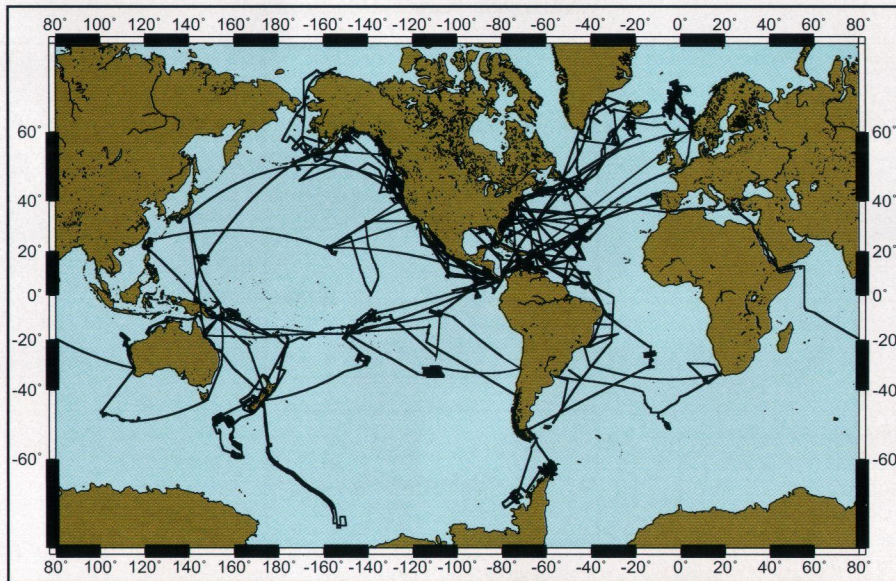


Fig. 2. In nearly 15 years of operation, R/V Ewing carried out 118 science "legs," or individual nontransit cruises.

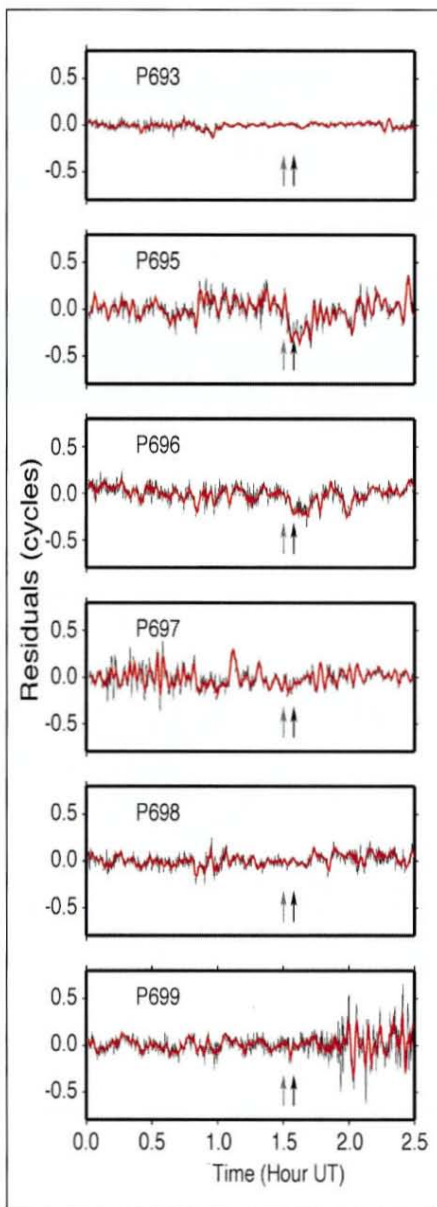


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