A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006
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Chapter 16

Instrumentation in Remote and Dangerous Settings; Examples Using Data from GPS "Spider" Deployments During the 2004–2005 Eruption of Mount St. Helens, Washington

By Richard G. LaHusen[1], Kelly J. Swinford[1], Matthew Logan[1], and Michael Lisowski[1]

Abstract

Self-contained, single-frequency GPS instruments fitted on lightweight stations suitable for helicopter-sling payloads became a critical part of volcano monitoring during the September 2004 unrest and subsequent eruption of Mount St. Helens. Known as "spiders" because of their spindly frames, the stations were slung into the crater 29 times from September 2004 to December 2005 when conditions at the volcano were too dangerous for crews to install conventional equipment. Data were transmitted in near-real time to the Cascades Volcano Observatory in Vancouver, Washington. Each fully equipped unit cost about $2,500 in materials and, if not destroyed by natural events, was retrieved and redeployed as needed. The GPS spiders have been used to track the growth and decay of extruding dacite lava (meters per day), thickening and accelerated flow of Crater Glacier (meters per month), and movement of the 1980–86 dome from pressure and relaxation of the newly extruding lava dome (centimeters per day).

Introduction

Typically, volcano monitoring and associated eruption forecasting relies on several disciplines of volcanology, principally seismology, gas geochemistry, and geodesy (Dzurisin, 2006). No single tool or technique can adequately monitor or predict the range of volcanic behaviors—from aseismic deformation to relatively benign dome building to major explosive eruptions. Accordingly, volcanologists rely on an assortment of instruments and techniques to monitor volcanic unrest. Sensors and related instrumentation have been developed in attempts to accommodate the needs of each particular discipline. However, even when an instrument is available that is capable of making a desired measurement, use of the instrument may be limited by expense or by an inability to deploy it in dangerous or inaccessible sites close to volcanic vents. New techniques and instruments are notable to volcanologists when they are affordable and minimize exposure of personnel to hazards. This paper describes the rapid development and application of a self-contained instrument package that was used successfully to monitor deformation close to the vent during the renewed eruption of Mount St. Helens in 2004–2005.

Prior Near-Vent Geodesy at Mount St. Helens

Pioneering geodetic work done during the 1980–86 eruptions of Mount St. Helens demonstrated that some eruptions could be predicted by monitoring accelerating deformation on localized parts of the dome (fig. 1; Swanson and others, 1983; Dzurisin and others, 1983). The 1980s geodetic work demonstrated that substantial preeruptive dome deformation typically was limited to areas near the active vent. The geodetic-deformation measurements commonly required the repeated and prolonged presence of personnel working close to the vent to bury electronic tiltmeters or to measure distances between fixed monuments by using electronic distance meters. Fortunately, with the subsequent availability of commercial GPS instruments, it is now possible to make repeated high-precision geodetic measurements on the volcano without exposing personnel to prolonged periods of work in hazardous areas.

Prototype GPS Instrument

For 4 years prior to the September 2004 seismic unrest at Mount St. Helens, an automated L1 GPS system was intermittently operated as a prototype monitoring tool. The system was

[1] U.S. Geological Survey, 1300 SE Cardinal Court, Vancouver, WA 98683

being developed by the U.S. Geological Survey's Cascades Volcano Observatory (CVO) as an inexpensive, near-real-time, ground-deformation monitoring tool with design emphasis on low cost, power conservation, and telemetered data integrity (LaHusen and Reid, 2000). Station DOM1 was installed on the 1980–86 dome within the crater of Mount St. Helens, and stations SFT2 and POA3 were installed outside the crater about 4 km to the west and east of DOM1, respectively. Each station was powered by a 20-W solar panel and a rechargeable lead-acid battery. Within each was a USGS microcontroller controlled remotely from a desktop computer at CVO using a 100-km multi-hop 900-MHz radio link. The operational scheme conserves power at the remote stations by alternately powering the GPS receivers and radio-telemetry components. During data-acquisition cycles, a CMC Allstar model L1 GPS receiver coupled with a Micropulse model 1372 survey-grade GPS antenna is powered for 20 minutes while raw GPS data at 10-s epochs are logged to the microcontroller. At the end of each data-logging session, the GPS receiver is switched off to conserve power, and the radio is switched on to relay data packets to CVO. Each data-transmission session lasts several minutes and includes error checking and retransmission to achieve error-free blocks of raw GPS data. The operational duty cycle is adjustable to balance power conservation, frequency of measurement, and station longevity.

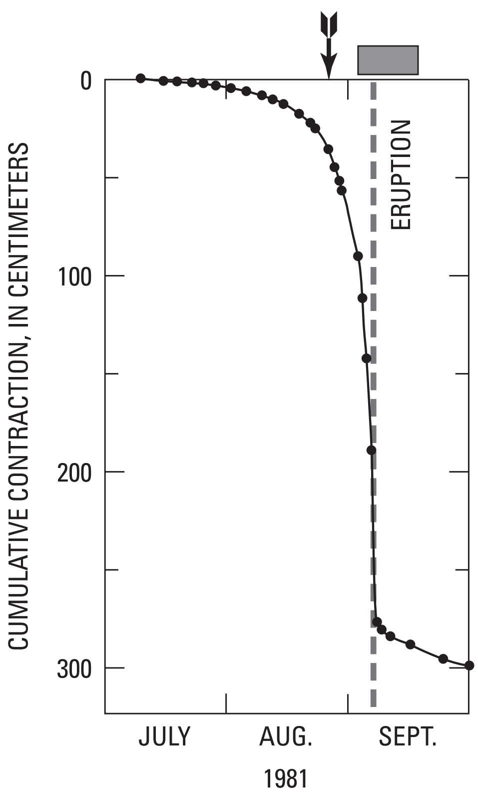

Figure 1. Movement of monument on lava dome in 1981 as determined by sequential EDM measurements, Mount St. Helens, Washington. Arrow indicates issuance of eruption prediction for time window shown by rectangular bar. Vertical dashed line shows time that dome eruption began (from Swanson and others, 1983).

Fixed, static, double-differential solutions between stations were calculated automatically using USGS control and scheduling software that applied a commercial software module, Waypoint Precise DLL. An independent position solution was calculated for every 20-minute data-acquisition period. Although GPS data acquisition within the crater posed substantial challenges owing to obscured views of the sky, mantling by rime ice, and noise from multipath reflections, this monitoring scheme typically transferred data reliably and repeatedly. The accuracy of each single solution was 1 cm plus 1 ppm of the differential baseline length (4 km), or 1.4 cm for the horizontal components. Vertical accuracy was found to be about double the horizontal value. This noise, inherent to single-frequency GPS solutions, was reduced greatly by applying a moving median filter that allowed discrimination of more subtle motions of less than a centimeter over longer time periods. Between 2002 and February 2004, the system measured dome subsidence that possibly reflected contractive cooling of the dome interior. The subsidence was at an annual rate of about 8 cm/yr downward and 2 cm/yr eastward, toward the center of the dome (fig. 2). Batteries at DOM1 failed in February 2004 and were not replaced until September.

When the GPS system was reactivated on September 27, 2004, following initiation of seismicity at Mount St. Helens, station DOM1 was in a location significantly different from what would have been predicted based on the subsidence trend of the preceding years. It was about 20 cm north and 12 cm higher than the predicted location (fig. 2). These location changes occurred between February 2004 and September 27, 2004, but we cannot further constrain the rate and timing of this deformation. Automated measurements on September 27 showed that DOM1 was moving northward at 2 cm per day. This station and a companion seismometer, the only stations on the old dome, were destroyed 4 days later, on October 1, by ballistic fragments ejected during the first phreatic explosion of the 2004 eruption (fig. 3).

GPS Spider Deployments

Loss of the only GPS station in the crater presented a dilemma because near-vent deformation could no longer be monitored. The time-consuming task of reinstalling a solar-powered GPS station onsite was considered unsafe because of the risk of additional, unpredictable phreatic explosions. Other challenges for deformation monitoring in the crater included the likelihood of additional ashfall from explosions and the impending onset of winter snowfall.

As an alternative to installing a permanent, monumented station, we assembled three GPS stations electronically similar in design to the original DOM1. However, unlike DOM1, which

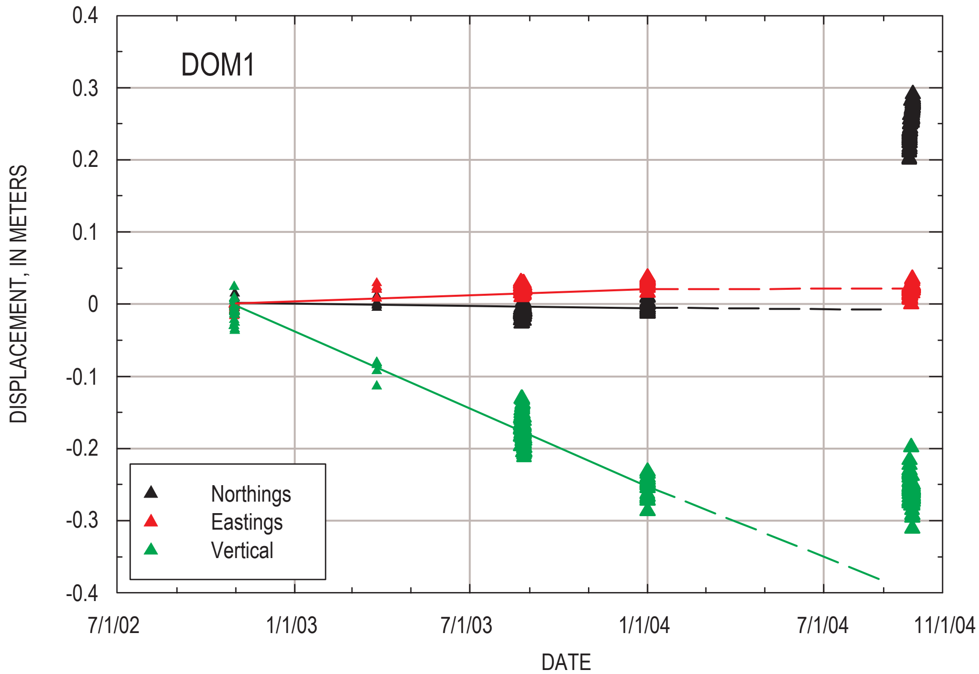

Figure 2. Time series of preeruptive deformation at GPS station DOM1, Mount St. Helens, Washington. Prior to February 2004, the 1980–86 dome was subsiding, possibly due to contraction of cooling interior. When DOM1 was reactivated on September 27, 2004, it was 20 cm north and 12 cm above its predicted location based on its previous trend (dashed lines).

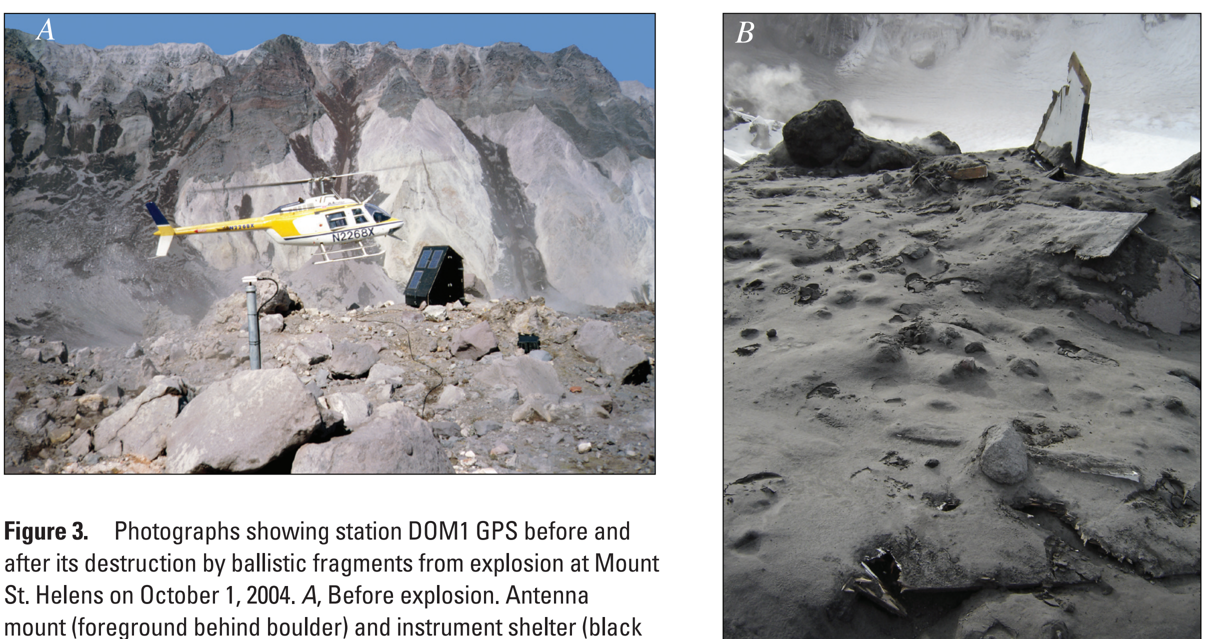

Figure 3. Photographs showing station DOM1 GPS before and after its destruction by ballistic fragments from explosion at Mount St. Helens on October 1, 2004. *A*, Before explosion. Antenna mount (foreground behind boulder) and instrument shelter (black box), with helicopter hovering just beyond. USGS photo by R.G. LaHusen. *B*, After explosion, from slightly closer viewpoint. White jagged sheet of plywood is the only side of instrument box still erect. USGS photo by S.C. Moran, November 5, 2004.

was pieced together on site, these new stations were constructed as self-contained portable units. Each unit consisted of an aluminum case that housed a 1,200-Ah supply of nonrechargeable air-alkaline batteries and a weatherproof ABS plastic case enclosing the electronic components. A GPS antenna was attached to a 1.5-m-long steel pipe mast on one end of the aluminum case, and a similar mast on the other end supported a radio antenna. A rope sling with a swivel eye was bolted to the outer metal case for attachment to a helicopter sling-cable remote-release hook. Each of these three stations weighed approximately 70 kg, and parts for each unit cost about $2,500, making it practical to deploy several stations and constituting an acceptable loss if a station were destroyed. With this design, stations could be set in the crater near the source of the recent explosion, and personnel would be exposed only briefly to potential hazards. Initial results from these portable installations were promising, demonstrating that GPS stations could be installed quickly to provide repeatable results at centimeter accuracy in near-real time. One unit toppled shortly after deployment, so we redesigned the frame with three widely spaced legs for better stability on rocky, uneven terrain.

Spider Frame Design

Field tests of several frame prototypes helped to determine design requirements and constraints. These included the need for a frame that was: (1) strong and rigid for its weight, (2) corrosion resistant, (3) relatively inexpensive and simple to build, (4) capable of accommodating various onboard electronic instruments and antennas, (5) capable of being slung safely beneath a helicopter, (6) capable of deployment by helicopter sling cable onto uneven and rocky terrain, (7) stable when placed on uneven and rocky terrain, and (8) capable of being retrieved by grappling hook from a helicopter for redeployment to another site or transport to a safe location to replace batteries.

Using these design considerations, we constructed 18 frames at CVO (fig. 4). The frames were built of type 6061 stainless steel square tubing with 1.6-mm-thick walls and a 38×38-mm cross section. The tubing was cut with a horizontal band saw and welded using stainless steel welding wire.

The large leg span (1.4 m) of the three-legged frames and the low center of gravity of the welded aluminum battery and electronics box (0.34 m above ground surface) provided a stable platform for the onboard batteries and electronics. The GPS antenna was mounted to one of the three framing legs that extended higher than the other two, 1.7 m from the ground. A short leg served as a mount for a 1-m-long omnidirectional antenna for the data transceiver.

A pyramidal stainless steel tripod canopy of the same tubular material was welded to the legs, culminating 1.8 m above the ground where a lifting eye, cable, and swivel were attached. In addition to strengthening the frame, this canopy provided a centered attachment point for airborne transport and presented a large, open target for helicopter retrieval using a grappling hook. With the addition of the spindly-legged framework, these self-contained stations took on the appearance and nickname of “spiders.”

The spider is stable when in flight beneath a helicopter, and the low center of gravity and wide leg span make the station resistant to tipping during deployment and retrieval, as well as resistant to toppling by high winds after deployment. Over the first 18 months of use, the stainless steel frames did not deteriorate in the harsh volcanic environment except for damage from direct ballistic impact. During 2004–5, we experimented with additional instruments on board some spiders including tiltmeters, cameras, gas sensors, and seismic accelerometers (McChesney and others, this volume, chap. 7).

Examples of GPS Spiders at Mount St. Helens, 2004–2005

GPS Spiders on the 1980–86 Dome

Remotely placed GPS spiders have occupied five sites on the 1980–86 dome. These sites were about 400–500 m from

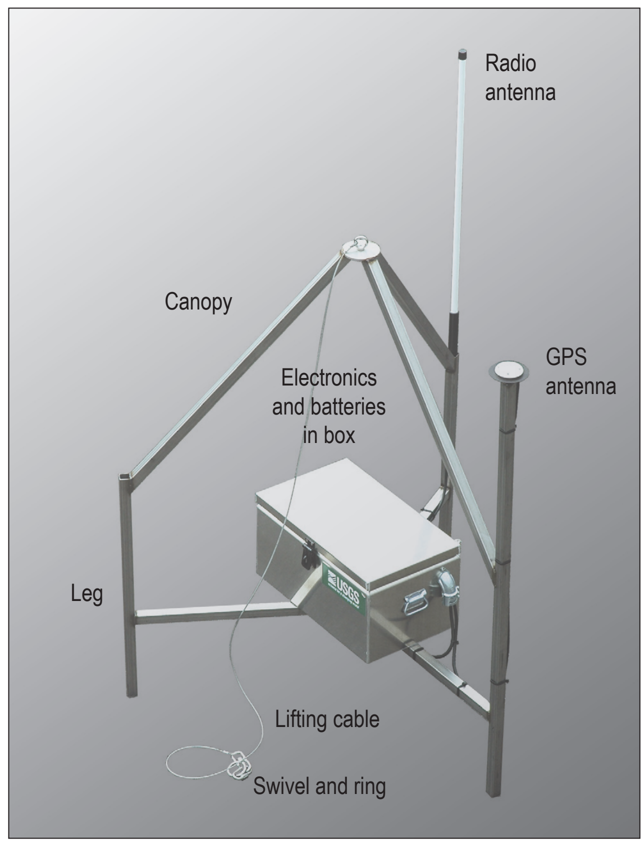

Figure 4. Photograph of GPS spider with stainless steel leg and canopy framework (leg span, 1.4 m) and aluminum box housing the unit’s electronics and batteries. GPS antenna is located on extended leg in right foreground, and data radio antenna is attached to right rear leg. Stainless steel lifting cable with swivel and ring is attached to top of canopy. USGS photo by M. Logan.

Table 1. History of GPS spider deployments in the crater of Mount St. Helens, Washington, 2004–2005.

Station	Start date	End date	Displace-ment (m)	Fate
1980–86 dome				
DOM1.0 [1]	9/27/04	10/1/04	--	Explosion October 1, 2004
NDM5	10/3/04	1/2/05	0.15	Toppled, recovered
NRM6	10/4/04	11/20/04	--	Toppled, recovered
TOP7	10/4/04	3/8/05	--	Explosion March 8, 2005
DOM1.1	11/6/04	3/8/05	0.4	Explosion March 8, 2005
NEDB	11/20/04	3/8/05	0.16	Explosion March 8, 2005
DOM1.2	3/10/05	8/5/05	0.1	Moved
NEDB.1	4/6/05	3/2/06	0.1	Batteries expired
DOM1.3	8/5/05	12/25/05	0.05	Batteries expired
HIE5.2	9/21/05	12/31/05+	0.05	Continued operating into 2006
Middle zone				
MID9.0	10/27/04	2/3/05	1.4	Explosion damage Jan. 16, 2005
MIDE.0	2/11/05	3/8/05	0.22	Explosion March 8, 2005
MID9.1	4/6/05	6/29/05	2.3	Removed
MID9.2	11/17/05	12/16/05	0.17	Buried by talus
New dome				
CLF4	10/27/04	1/21/05	48	Rockfall
ELEA.0	11/20/04	11/27/04	67	Rockfall
HNY0	1/3/05	1/29/05	78	Rockfall
CDAN	1/15/05	1/16/05	8	Explosion Jan. 16, 2005
AHAD	2/8/05	2/16/05	41	Removed
ELE4.0	4/19/05	4/21/05	2	Moved
SEV7	5/24/05	3/24/06	10	Batteries expired
East Crater Glacier				
ICY4	2/16/05	4/8/05	22	Lost in crevasse
ICY5.0	2/16/05	3/8/05	28	Explosion March 8, 2005
ELE4.1	4/21/05	6/30/05	26	Moved
ELE4.2	6/30/05	7/28/05	6.7	Moved
HIE5.0	7/18/05	8/19/05	8.5	Moved
ELE4.3	7/28/05	8/19/05	7.8	Moved
West Crater Glacier				
WES6	7/14/05	9/14/05	70	Removed
ELE4.4	8/19/05	11/9/05	122	Batteries expired
HIE5.1	8/19/05	9/14/05	24	Moved

[1] Permanent monumented station; restarted Sept. 27, 2004.

the center of September 2004 deformation, ensuing phreatic explosions, and lava-spine extrusion. The history of emplacement and subsequent life is summarized in table 1; distribution and mapped progression is shown in figure 5.

The first three portable GPS stations were set on the north, east, and approximate center of the 1980–86 dome on October 3 and 4, 2004; station designations were NDM5, NRM6, and TOP7, respectively. Results from these installations showed that (1) motion of the three stations was similar, indicating the relative stability of the remotely deployed packages, and (2) the northward movement of the 1980–86 dome was continuing and was not restricted to the area of DOM1 on the west side of the dome. The 1980–86 dome lay north of the vent, so these spiders typically moved slightly northward. It appeared that the entire 1980–86 dome was moving to the north, away from the vent area, as if it were being shouldered aside in response to the growing mass beneath its south flank. Consequently, the northing component of the GPS solution best depicts the predominant motion. Magnitude of total motion during this period was less than 1 m (fig. 6). Rates were as much as 2 cm per day northward. Vertical displacement was typically within the noise of the analysis.

The 1980–86 dome appeared to behave as a semicoherent block so that, with few exceptions, spiders at different sites responded similarly (fig. 6). The rate of displacement varied with time. The limited evidence suggests that the rate of old-dome movement varied directly with the linear extrusion rate of the new dome, as shown by the coincidence of highest 1980–86 dome displacement rates with the greatest velocity for spiders riding on the extruding spine (fig. 6). We were

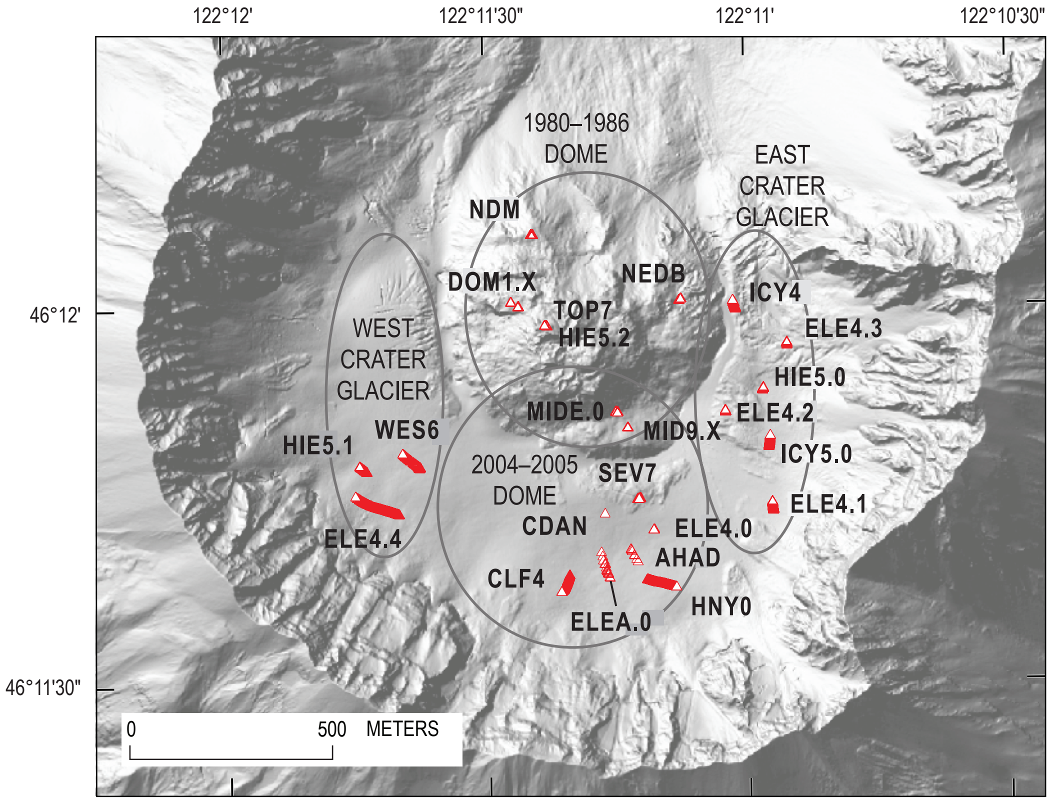

Figure 5. Shaded-relief digital elevation model (2003) showing GPS spider deployments (red triangles) in crater of Mount St. Helens, Washington. Tracks of triangles indicate total movement of stations (table 1).

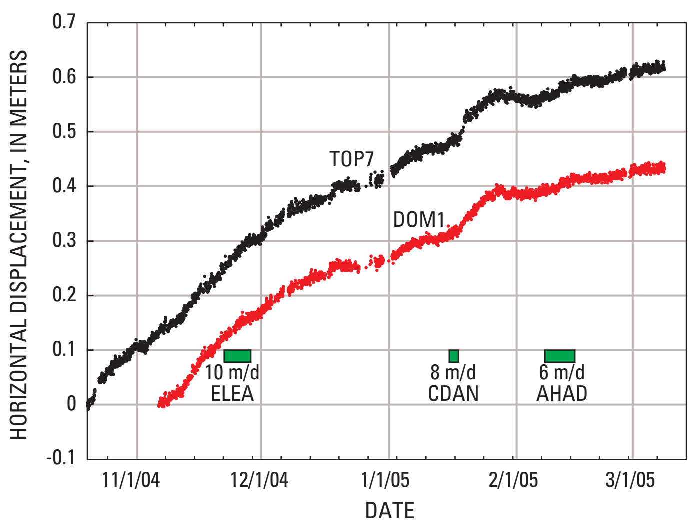

Figure 6. Graph showing movement of two GPS spiders on 1980–86 dome (DOM1, TOP7) and three GPS spiders on 2004–5 dome (ELEA, CDAN, and AHAD) during first 5 months of eruption. Location of stations shown in figure 5. The green boxes show duration of new-dome spiders, each labeled with elapsed horizontal velocity, which was nearly halved from November 2004 to March 2005. These three spiders had substantial displacements (as much as 67 m over a 7-day period for ELEA), which makes it difficult to portray their data in a manner comparable to the old-dome spiders TOP7 and DOM1.

unable to maintain a spider on the extruding spine long enough to demonstrate this relation more convincingly.

Intermittently, velocity of GPS spiders on the old dome increased as the rate of seismicity increased, as measured by real-time seismic amplitude measurements, or RSAM (Endo and Murray, 1991; Moran and others, this volume, chap. 2). One example of this correlation occurred on January 15, 2005, when TOP7 and other near-vent stations accelerated away from the vent as RSAM values started to increase (fig. 7). An explosion the following day destroyed several spiders (table 1).

GPS Spiders on the New Dome

Measurements of extrusive rates are the most effective way to monitor the progress of effusive eruptions. The best day-to-day proxy for extrusive rate at Mount St. Helens was the linear rate at which lava emerged from the vent; thus, we first targeted sites on and immediately adjacent to the actively extruding dome. Prior to new lava appearing at the surface on October 11, 2004, intense surface deformation created an uplift of part of the 1980–86 dome, deformed glacier ice, and crater-floor debris, or the "welt," through which the first lava spines emerged (Vallance and others, this volume, chap. 9). Sites on the welt had the advantage of longevity compared to placement directly on the active lava spines and were used first in October 2004. Although not directly on the extruding lava, these spiders were useful as proxies of eruption vigor because they were being actively pushed away from the vent. By late November 2004, we began placing spiders directly astride the actively extruding lava spine.

The first spider was set on the welt adjacent to the northeast side of the new dome on October 12, 2004, but its GPS antenna was damaged on deployment, rendering it geodetically useless. The spider also had seismic instrumentation on board that continued to function (McChesney and others, this volume, chap. 7). The next GPS spider, station CLF4, was installed on October 27, adjacent to the south flank of newly emergent spine 3, on uplifted crater-floor debris of the welt (fig. 5; table 1). Station CLF4 moved downward and to the south, traveling 10 m in the first three days as spine 3 plowed across the crater floor. Station CLF4 was pushed away from the growing spine as if riding the bow wave of a ship. It operated for 85 days, outliving the growth period of spine 3 and persisting into the first third of spine 4's life before succumbing to rockfall.

Some of the most interesting correlations between eruptive phenomena and movement of GPS spiders came from site MID9, which was on the saddle midway between the new and old domes (figs. 5, 8). On November 12, November 22, and December 8, 2004, MID9.0, the first of the MID9 spiders (table 1), accelerated away from the vent (fig. 9) coincident with increased RSAM counts. These velocity changes appeared as surge-pause-surge phases that lasted several days. The correlation with RSAM was masked for some other events that occurred in stormy weather, owing to heightened seismic noise that accompanied high wind.

On December 21, MID9.0 stalled and slowly reversed direction, heading back toward the vent and downward (figs. 9, 10). This change may have been in response to depressurization within the conduit and relaxation at the surface. Other crater GPS stations also slowed or stopped moving away from the vent. This event coincided with a change in seismicity, during which several large earthquakes had downward first motions as opposed to the typical pattern of upward first motions (S. Malone, written commun., 2004). But station MID9.0 continued its southward and down motion into 2005 while extrusion continued, so a more likely explanation for the ventward motion is that vent-adjacent bedrock was shifting in response to some other factor. Because this area between the

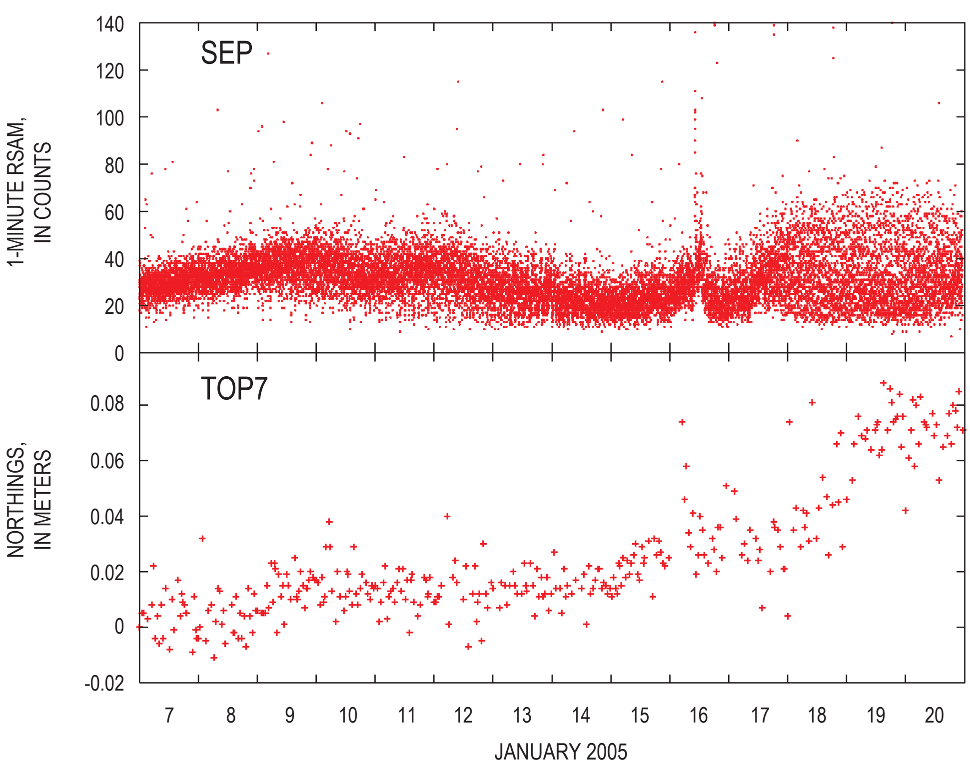

Figure 7. Graphs showing relation between increases in real-time seismic amplitude (RSAM) and northward motion of station TOP7 in mid-January 2005. Seismic station SEP is located 100 m northwest of TOP7, on the September lobe of the 1980–86 dome.

domes was so responsive to changes in eruption dynamics, we tried to keep a functioning GPS spider near the original MID9.0 location. Accordingly, after MID9.0 suffered antenna damage in an explosion on January 16, it was replaced by MIDE.0 followed by MID9.1 and MID9.2 (table 1).

On November 20, spider ELEA.0 was placed on the highest point of spine 3 (fig. 5). Its initial motion was an astonishing 10 m per day. Before it was destroyed by a rockfall 6 days later, ELEA.0 had moved 67 m south-southeastward and 8 m up.

The remarkable record of ELEA.0 reinforced our decision to keep a GPS spider on the actively growing spine of the new dome. A GPS spider, especially one carrying an accelerometer (seismometer), could add substantially to the amount of data available for evaluating steady-state extrusion models and for locating seismic sources more precisely. The task of slinging spiders onto hot lava spines proved more difficult than expected, owing to turbulence and decreased lift in heated air. Thermal surveys showed surface temperatures of spines away from the vent typically were less than 50°C, but cracks exposed interior lava as hot as 700°C (Vallance and others, chap. 9; Schneider and others, this volume, chap. 17) and created strong hot updrafts. A successful installation on January 3, 2005, deployed spider HNY0 (Happy New Year) on a large block near the south end of spine 4 (fig. 5). For more than 3 weeks, spider HNY0 moved 2–2.5 m/day east-southeastward, consistent with eastward spreading as the south end of the spine broke apart.

Figure 8. January 2005 photograph of station MID9 site (red box) between 1980–86 dome on the right and snow-free spine 4 on the left. Vent is marked by smooth emergent lava spine. Ground on which MID spiders were deployed was warm and was chosen to reduce burial by snow. USGS photo by D. Dzurisin, January 3, 2005.

Because spine 4's surface rose steeply from the vent, we built a spider with legs of differing length, cut appropriately to match the spine's 32° slope. This spider, CDAN, held fast in the soft fault gouge that mantled the spine (fig. 11). However, station CDAN was toppled and buried in talus during an explosion on the day after its installation, but not before it had moved about 8 m southward and upward (table 1).

Spiders were sited on the active spine sporadically into 2006 (table 1). Spines 5–7 grew more vertically than their recumbent predecessors and became increasingly mantled by talus, preventing us from finding sites suitable for setting a spider. Sites in talus were notably perilous, owing not only to instability of blocks on which spiders could be placed, but also to destruction by rockfalls from upslope debris. Summits of spines were free of risk from rockfall, but unlike the earlier recumbent spines that extended hundreds of meters from the vent—the site of greatest heat discharge—spines 5–7 grew more steeply, formed smooth surfaces for relatively short distances, and produced mostly rubble and large flanking talus aprons. Consequently, the summits of spines 5–7 were too hot and the air there too turbulent to safely deploy the instruments.

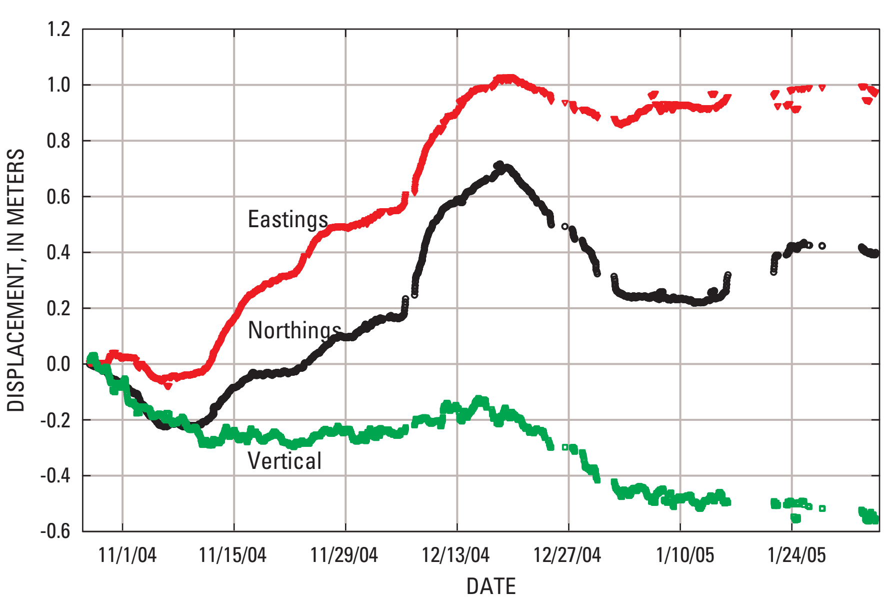

Figure 9. Graph of displacement of MID9.0 GPS spider, indicating accelerations, decelerations, and reversals as this near-vent station responded to subtle changes in eruption dynamics.

Spiders on Crater Glacier

Throughout the 2004–5 eruption, lava-dome growth through formerly horseshoe-shaped Crater Glacier has caused dramatic disruption and deformation (Walder and others, this volume, chap. 13). This remarkable process was documented with intermittent aerial photographs and creation of digital elevation models (Schilling and others, this volume, chap. 8), albeit with some difficulty owing to the lack of persistently identifiable features on the glacier surface. Those GPS spiders placed on the glacier provided a more continuous record of glacial deformation that allowed detailed examination of glacier compression, thickening, and increased rate of flow. Initially, growth of the welt and lava extrusions affected the southeastern part of the crater, cleaving Crater Glacier into east and west arms and compressing the east arm against the crater wall. Visual observations of this process indicated that the east arm was being greatly thickened. In response, the flow rate appeared to accelerate as a bulging lobe advanced northward toward the glacier's terminus east of the old lava dome. This deformation was accompanied by pervasive fracturing of the glacier with the formation of deep crevasses and, ultimately, extensive fields of seracs. In order to quantify these phenomena, several spiders were deployed temporarily on the glacier in nine locations between February and August 2005 (table 1).

Spiders ICY4 and ICY5.0 were installed on the east arm of Crater Glacier on February 16, 2005. Spider ICY5.0 was placed on the thickened and bulging part of the glacier, and ICY4 was placed on the relatively undisrupted part downslope of the bulge. Resultant velocity measurements from ICY4 showed the upper part of the glacier was moving 1.4 m/d and the lower undisturbed part was moving only 0.4 m/d. Of particular interest was the lack of diurnal velocity changes that typify temperate glaciers, indicating that Crater Glacier has a permeable bed that precludes basal slip resulting from meltwater accumulation (Walder and others, this volume, chap. 13). Additional spiders placed on the east and west arms confirmed these observations (table 1).

When dome growth shifted westward in midsummer 2005, the west arm of Crater Glacier started to show signs of bulging and crevassing, so in July and August 2005 a series of spider deployments was begun in order to collect data necessary to track changes. Stations WES6, ELE4.4 and HIE5.1 showed velocities of 1 m/d or more (fig. 12). Of particular interest was the stations' utility as an indirect confirmation of continuing lava extrusion because their instruments indicated continued upward motion as the advancing lava compressed the glacier against the crater wall. In times of limited visibility when remote cameras were ineffective, these spiders were our only means of confirming continuing dome growth. Their utility was limited by the occasional need to move them away from widening crevasses in the summer and by their inability to function under accumulation of several meters of snow during winter months.

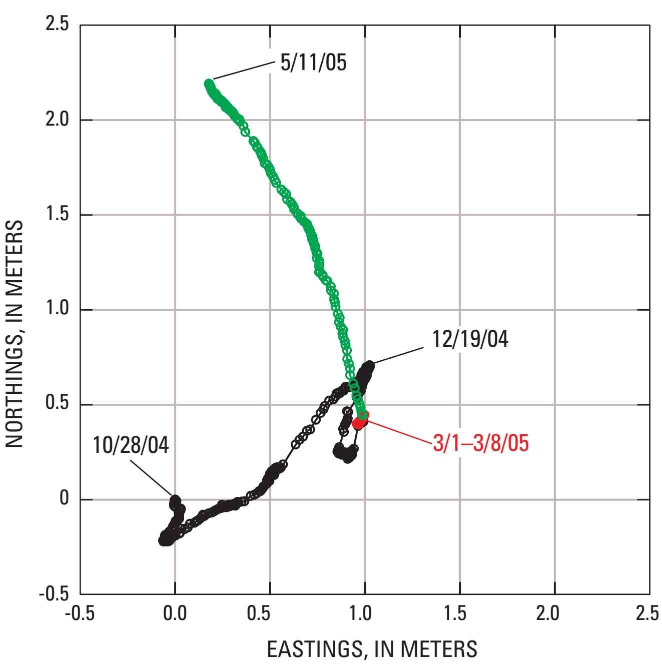

Figure 10. Schematic map showing horizontal path of three sequentially placed GPS spiders as they moved from the initial MID site. Site was alternately pushed away or relaxed toward the vent area during the course of deployment. Vent lay about 200 m southwest of MID. Change of symbol colors is solely to clarify the trace of displacement path.

Conclusions

During the 2004–5 eruption of Mount St. Helens, portable GPS stations, nicknamed spiders, installed by helicopter-sling operations proved to be an invaluable volcano-monitoring tool at sites in hazardous settings or where landing a helicopter was not possible. With real-time telemetry of data, spiders transmitted day and night. Cloudy weather that obscured camera images had no effect on the monitoring capability of GPS spiders. Although seismicity has become the most widely used real-time tool to detect explosive eruptions, real-time deformation monitoring may be equally or

Figure 11. Mid-January 2005 photograph of station CDAN GPS spider on extruding spine 4. Legs of differing lengths permitted level deployment on 32° slope. Legs are embedded several centimeters into soft gouge that mantles spine. USGS photo by J.S. Pallister, January 14, 2005.

more valuable to track dome-building eruptions. At present, nothing demonstrates ongoing extrusion of lava as directly as a GPS receiver riding on an active spine. Costing about $2,500 each in materials, spiders can be built relatively quickly and deployed in numbers needed to obtain data that provide a detailed record of near-vent deformation, lava extrusion, and effects on adjacent glaciers.

Acknowledgments

Our success with spiders stems in part from highly skilled helicopter pilots. In particular Jeff Linscott of JL Aviation and Morgan Kozloski of Hillsboro Aviation have carried greatest responsibility for installing and retrieving equipment. We gratefully acknowledge manuscript reviews by Tom Murray and Mark Reid.

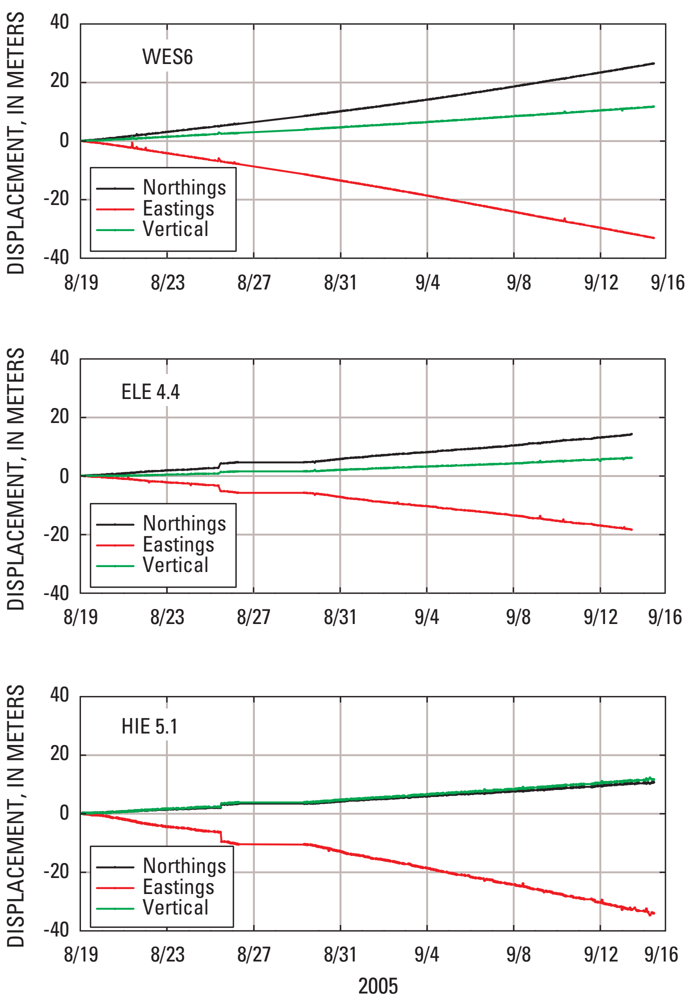

Figure 12. Plot of three GPS spiders on west arm of Crater Glacier during summer 2005, showing similar uplift and motion away from the advancing lava dome as the glacier was compressed against crater wall. Site locations shown in figure 5.

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