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# Volcano Surveillance by ACR Silver Fox

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**Recent growth in the business of unmanned air vehicles (UAVs) both in the US and abroad has improved their overall capability, resulting in a reduction in cost, greater reliability and adoption into areas where they had previously not been considered. Uses in coastal and border patrol, forestry and agriculture have recently been evaluated in an effort to expand the observed area and reduce surveillance and reconnaissance costs for information gathering. The scientific community has both contributed and benefited greatly in this development. A larger suite of light-weight miniaturized sensors now exists for a range of applications which in turn has led to an increase in the gathering of information from these autonomous vehicles.**

**In October 2004 the first eruption of Mount St Helens since 1986 caused tremendous interest among people worldwide. Volcanologists at the U.S. Geological Survey rapidly ramped up the level of monitoring using a variety of ground-based sensors deployed in the crater and on the flanks of the volcano using manned helicopters. In order to develop additional unmanned sensing methods that can be used in potentially hazardous and low visibility conditions, a UAV experiment was conducted during the ongoing eruption early in November. The *Silver Fox* UAV was flown over and inside the crater to perform routine observation and data gathering, thereby demonstrating a technology that could reduce physical risk to scientists and other field operatives. It was demonstrated that UAVs can be flown autonomously at an active volcano and can deliver real time data to a remote location.**

**Although still relatively limited in extent, these initial flights provided information on volcanic activity and thermal conditions within the crater and at the new (2004) lava dome. The flights demonstrated that readily available visual and infrared video sensors mounted in a small and relatively low-cost aerial platform can provide useful data on volcanic phenomena. This was made possible by utilizing GPS and computer-controlled flight direction and stabilization to acquire and track target areas within the Mount St. Helens crater. It was also determined that additional light-weight sensor development will be needed to enable autonomous measurements of volcanic gasses and imaging in poor-weather conditions.**

## I. Introduction

The development of autonomous vehicles has allowed scientists to explore un-chartered anomalies and to consider alternative approaches to existing methods of data collection with a significant reduction in the risk to human life. One area that promises to benefit from the development of UAVs is the study of volcanoes. In late September, 2004, Mount St. Helens began its first sustained eruption since 1986, and for the first time UAVs were sent into an erupting volcano. This was made possible when Advanced Ceramics Research (ACR) volunteered to work with the United States Geological Survey (USGS) and provided the Silver Fox UAV to collect visual and IR data at the volcano, and to explore additional sensor technology that could be used to monitor volcanoes.

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### A. Threat from Erupting US Volcanoes

The United States is among the most volcano-rich nations on Earth, with 45 eruptions and 15 cases of notable unrest at 33 volcanoes since 1980[1]. Some of these mountains are fairly well monitored but several potentially hazardous volcanoes are located beyond everyday reach. According to the first comprehensive assessment of U.S. volcano risks[2], this potentially represents a significant threat to thousands of people. One of the major dangers posed by volcanoes worldwide is their ability to inject large quantities of volcanic ash into the air in a relatively short period of time; constituting a significant threat to commercial airliners. It can take only 5 minutes for an ash plume to rise to a height of 30,000 feet, and ash clouds can drift for thousands of miles downwind. Ash particles are composed of volcanic glass and mineral grains – they are abrasive and they can melt at temperatures within jet engines, clogging turbines and causing engines to flame out; and have caused hundreds of millions of dollars in damage to aircraft. They abrade aircraft windshields to the point that they can leave pilots blinded. Their static charges can wipe out navigation systems. Since the eruption of Mount St. Helens in 1980, nearly 100 commercial jets worldwide are known to have inadvertently flown into volcanic ash, at altitudes as high as 37,000 feet, including eight incidents in which one or more engines shut down. In three of these recorded incidents, commercial airliners lost power in all four engines and experienced frightening losses in altitude before engines were able to be restarted and recoveries were made[2].

Instrumental monitoring of volcanoes provides a means to detect impending eruptions, provide early warnings, and reduce risk to people and property. Volcanologists gather as much information as possible about volcanic processes, but information of three main types is generally most useful to issue warnings of impending eruptions.

- Monitoring of ground deformation (swelling or subsidence) is detected and measured using ground-based and satellite systems.
- Seismic measurements detect rock breakage and vibrations caused by underground movement of magma.
- Gas analysis from volcanic plumes provides information on the ascent and degassing of magma as it approaches the Earth's surface.

Additional information, such as the amount of eruptible magma, its composition, gas content, temperature, and rate of ascent are also needed to understand of the workings of the volcano. In addition, information on the size and potential explosivity of eruptions, extent of hazardous areas, and ash content and distribution of eruptive plumes are needed to evaluate and mitigate risks. Volcanoes are broadly predictable in terms of the types of eruptive behavior they exhibit, and the areas at risk. They also generally give seismic, gas and deformation signals that an eruption is brewing. Consequently, with adequate monitoring data, eruptions can be forecast. However, because these are complex natural systems, the exact timing and size of an impending eruption cannot be predicted in advance. Therefore, volcanologists monitor unrest and issue warnings when the probability of an eruption is increased. Where there has been adequate monitoring and effective communication, these warnings have been effective in saving lives and property. However, data collection can be hazardous, and it can be difficult and expensive to acquire aerial observations, especially at remote localities.

In 1991 at Mount Pinatubo, in the Philippines, volcanologists were able to forecast the second largest eruption of the 20$^{th}$ century, leading to the evacuation of 58,000 people and resulted in the saving of several thousands of lives[3]. However, at Pinatubo, as at other volcanoes world-wide, volcanologists take calculated risks to make aerial observations of volcanoes from manned aircraft and to deploy monitoring instruments – both activities that are required to acquire the data needed to forecast eruptions and issue warnings.

Aircraft and rotorcraft are used extensively to deliver scientists and remote sensing equipment into volcanic craters where they can collect information on the status of unrest at the volcano. The use of these manned aircraft is however, dependent on both weather conditions and the extent of hazards within the crater. In addition, there are only a few pilots with experience flying near active volcanoes. Therefore it can be difficult to ensure that the data is collected when it's needed. An effective strategy is to deploy continuous recording and telemetered ground-based seismic, deformation (GPS-based), and video systems. However; there are times when other data, such as visual observations and plume-gas measurements are critical, but they cannot be obtained because it is too dangerous to approach the volcano, or because adverse weather prevents manned flights, or simply because of a lack of availability of manned aircraft. A specific task that would benefit volcanologists would be to collect visual, infrared, radar, gas and other remotely sensed data on a more regular schedule and at close range, irrespective of time of day, weather, or hazardous conditions. The use of autonomous vehicles to collect these data has long been discussed as a means of limiting the risk to human life and, to a lesser extent, reducing the overall associated costs. Consequently, when Mount St. Helens began erupting in 2004 and the Federal Aviation Administration created a Temporary Restricted Area in the airspace surrounding the volcano, an unusual opportunity emerged to conduct a real-world experiment to determine the practicality of using relatively low-cost UAV's to monitor the eruption.

### B. The Recent Eruption of Mount St.Helens

The 2004 and ongoing eruptions, refreshed memories about the tragedy of May 18, 1980, in which 57 people lost their lives in the largest landslide in recorded history and ensuing eruption. Following several steam and ash explosions in early October, parts of the Mount St. Helens National Monument were evacuated and the public was not allowed within 15 miles (24km) of the volcano. The FAA created a Temporary Restricted Area in the airspace extending 5 nautical miles from the center of the volcano and to an altitude of 13,500 feet. The initial steam and ash explosions were centered inside the crater to the south of the old lava dome – a vent area where a spine of lava emerged on 11 October. Continued lava extrusion has produced a large new lava dome (>50 million cubic meters) which is currently still being extruded (July, 2005). The ongoing eruption is monitored closely by the USGS, who had a helicopter over the volcano shooting digital photographs, video and Forward-Looking Infrared (FLIR) imagery during the initial steam and ash explosion, as shown in Figure 1.

**Figure 1**. The first eruptions of Mount St.Helens taken on October 1st 2004 by John Pallister (USGS). The first explosive event (left) grew into the larger phreatic eruption (right) in only a few minutes.

The crater covers an area approximately 1 mile (1.6km) east to west by approximately 1.5 miles (2.4km) north to south. The crater floor is approximately 6,000 feet (1,832m) and the crater rim approximately 8,400 feet (2565m) above sea level. In mid-March the volume of the new lava dome was 45 million cubic meters. The highest point on the new dome was about 7675 feet (2,344m), more than 500 feet above the elevation of the old lava dome as is evident in Figure 2. Since then, the dome has gone through a period of disintegration and spreading as it continues to increase in volume.

### C. Conventional Data Collection at MSH

There is a network of about 15 seismometers and 20 GPS instruments on the volcano, which transmit their results in real-time to the USGS Cascades Volcano Observatory (CVO) in Vancouver, WA. In addition, gas composition, temperature and mineralogical data are collected intermittently by manned aircraft when conditions permit. Occasionally, a helicopter is used to collect rock samples through a bucket/scoop arrangement. $SO_2$, $H_2S$ and $CO_2$ concentrations of the gas plume reveal information on how gas-rich and consequently explosive the magma is, and provide information about the depth and degree of magmatic degassing. $SO_2$ concentrations (usually measured in a few ppm/m) are typically measured using an upward looking spectrometer using scattered UV light from the sun. The absorption due to $SO_2$ in the plume can be measured as the spectrometer is moved under the plume. Accuracy is increased through the use of an internal standard. Additional concentrations of $H_2S$, $SO_2$ and $CO_2$ in the plume are made by direct measurement techniques.

The temperature and thermal flux from the lava dome can be estimated from a series of calibrated infrared images, which when combined with accurate growth rates of the lava dome volume can be used to determine the total thermal flux. The rate of growth of the lava dome has been estimated from Digital Elevation Models, constructed from aerial photographs taken every two to three weeks. From these measurements it is possible to estimate the lava dome growth rate in $m^3/s$ (growth rates have ranged from >8 $m^3/s$ to <2 $m^3/s$).

At Mount St.Helens data collection is significantly hampered by weather conditions, particularly during winter months, which makes regular collection of airborne observational and gas data difficult.


**Figure 2.** New lava dome to the south of the old lava dome (just out of view on the right). *Courtesy of USGS May 10th 2005*

### D. The Silver Fox - Unmanned Air Vehicle

The Silver Fox is one of several UAVs designed and manufactured by ACR in Tucson, AZ. The Silver Fox weighs approximately 20 lbs and is able to carry sensor payloads of up to 8 lbs in weight[4]. Typical missions are flown between 500 feet and 1,200 feet above ground level although the UAV can operate up to a service ceiling of approximately 16,000 feet. It has an 8 foot wingspan and flight duration of 10 to 20 hours with a speed between 35 and 60 knots. The UAV is made from an all-composite construction, is fully autonomous and can be operated with either gasoline or heavy fuels. Data and image transmission is through a radio modem, which can operate via line-of-sight up to approximately 18 to 20 miles (29 to 32 km).

The Silver Fox is light enough to allow it to be hand launched, although a pneumatic catapult is typically used as shown in Figure 3. The plane is designed to be landed on it's belly and can be recovered from small patches of grass, dirt roads, or, in the case of Mount St. Helens, from the parking lot at the Johnson Ridge Observatory (JRO).

**Figure 3.** Silver Fox mounted on the pneumatic catapult in the parking lot where it was launched and recovered

## II. Silver Fox UAV Operations at Mount St.Helens

In early Oct 2004, shortly after the onset of the recent eruption of Mount St.Helens, ACR began a collaborative agreement with the USGS to investigate the possible use of UAVs for image and data gathering. A flight base was established at the evacuated JRO approximately 5 miles (8km) from the volcano and a Certificate of Authorization (COA) was applied for and granted by the Federal Aviation Administration (FAA) to permit operations within the Temporary Flight Restriction (TFR) surrounding the volcano. Although there were several less-accessible areas from which the Silver Fox could have been launched within the TFR, the possible threat of a larger eruption meant that road access was necessary in case of an emergency evacuation. JRO is also equipped with a basement bunker for protection from volcanic blasts and it has line-of-sight visibility to the volcano, required for the initial Visual Flight Rules (VFR) tests of the UAV. The TFR area over the volcano extended 5 nautical miles (8km) out, which excluded all but official aircraft from entering this airspace. Several shakedown flight test were made early in October but were limited by the FAA to VFR flight. FAA later granted authority to operate in less than VFR conditions, although flight in these conditions was not conducted. In late October and early November the weather at Mount St.Helens was too poor to fly under VFR, it was not until November 4 when the weather cleared and the Silver Fox was able to fly it's first mission to the volcano.

During these flight tests the Silver Fox was equipped with visible electro-optical (EO) and infrared (IR) video cameras and data were transmitted continuously to the ground station via a video link. Topographic data from NASA satellite imaging and USGS maps were used to establish the initial GPS way-points over the volcano and the flights were performed slightly above the crater rim altitude to allow for any discrepancies which might have arisen from registration of these data. On the 4th and 5th of November similar flights were made with Silver Fox flying slightly inside the crater rim and both EO/IR video cameras pointing directly downwards. The flight time for each flight was approximately 2 hours in duration and the UAV remained in contact with the ground station at JRO continuously. On the initial flight, video contact was lost for a short time when the UAV circled behind the lava dome. Repositioning of the communications antenna at the ground station appeared to solve this problem on subsequent flights. For each flight the altitude remained fairly constant at around 8548 feet (2610m) and the speed at around 50 knots. The wind inside the crater varied greatly and close to the crater wall the aircraft was subjected to significant turbulence. Wind circulation inside the crater periodically exceeded the speed of the aircraft, resulting in the aircraft moving backwards with respect to the ground. During these first flights a rock fall was observed on the inside of the west crater rim wall and a small explosive eruption was observed on video as shown in Figure 4. Because the Silver Fox was not visible from the ground station, autonomous flight control was used and as video images of interest were observed the flight speed was varied to further investigate these regions.


**Figure 4**. EO video stills collected inside the crater on 5th November 2004. The left image is taken of a rock fall on the west side of the rim taken from a camera inclined at 20° below the horizontal. The right image shows a small explosive eruption from the vent area of the new lava dome, visible in the top right of the picture just above the old lava dome, - camera at 90° to the horizontal.

A series of electrochemical gas sensors weighing approximately 2 lbs. were mounted onto the Silver Fox UAV to monitor 7 gases. However, on further discussions with representatives from the USGS it was determined that the sensitivity of these sensors (nominally 1 – 100ppm) was outside the concentration range of gases expected in the gas plume Additionally, the electrochemical sensors have a response period that ranges between 30 and 60 seconds before the maximum concentration is measured. During this time it was thought that the UAV may well have entered and exited the region of interest, thereby generating false concentration values. Consequently, the sensor suite was not flown. Additional development is needed to improve resolution and response time of light-weight sensors for use in volcanic gas monitoring using the Silver Fox-class UAV.

On November 6, the weather once again turned bad and it was not until December 15, that additional flights were made. These flights ranged in duration from 1 to 2 hours. The payload for these flights was an IR video camera. Interest in the formation of the new lava dome, which was growing rapidly, directed these flights to collect thermal data around the lava dome. Figure 5 shows images taken of the new lava dome on December 15. The left image is a color enhanced IR image which shows the topography on the new lava dome pushing up out of the snow covered floor of the crater. The image on the right shows an inverted IR image (dark represents hot).

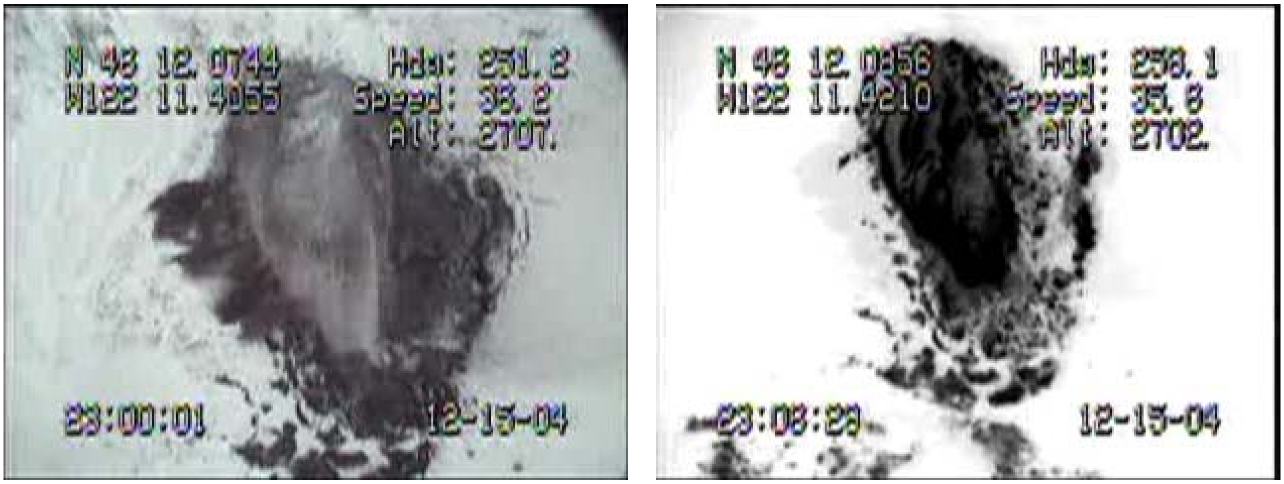


**Figure 5.** Still images taken from IR video of the new lava dome approximately 900 feet in length. The left image shows a color enhanced image which brings out the topography. The right image is an inverted IR image.

Following analysis by USGS it was determined that thermal emissions had increased along a northerly trending zone that extended from the new dome across the older (1980-1986) dome, and consistent with FLIR observations.

## III. Discussions

The opportunity to fly the Silver Fox UAV at Mount St. Helens was a challenging one requiring a combination of legal, political, logistical and technical capabilities. One issue which severely hampered data collection was the need to do initial flight testing during intermittent periods of good weather. During our operation windows outside those discussed in this paper there were a number of other clear-weather periods, but they were short in duration and did not always coincide with times that our flight crew was present at JRO. The FAA was extremely cooperative and timely in issuing the clearance for flight in "less than VFR". However, we were unable to conduct UAV flights in less-than VFR conditions because upon completion of VFR tests, ACR commitments to other programs meant that a workable window of time could not be found.

On the technical side of the expedition, ACR was not familiar with existing data collection techniques and the gas concentration levels that could be expected for the types of missions flown. With additional work and collaboration with USGS and the volcanology community, and with additional sensor development, we anticipate that multi-species gas plume monitoring could be conducted on a more regular basis than has been possible in the past, especially at volcanoes where logistical constraints or funding has prevented routine measurements.

Many challenges exist ahead for the use of UAVs in the data collection and observation of volcanoes. Gas and particle sampling of the ash plume is usually performed from manned flights. Unmanned air vehicles equipped with the necessary sensor packages could readily augment the collection of data from manned flights allowing more frequent data collection, potentially at a lower cost. Flights inside plumes could accurately determine gas flow rates and allow particulate density mapping thereby providing additional data to aid in warning aircraft of hazardous ash-rich clouds and to support ash deposit predictions. Much of the equipment presently used by volcanologists requires further miniaturization to make it compatible with the small low-cost UAVs being considered for volcano operations. Once these small sensor packages become available, it is essential for UAV operators to work closely with volcanologists to make sure that data collection, interpretation, and hazard analysis is accurate and representative. Reliable operation within acid and ash-bearing volcanic plumes will benefit from improvements in both the UAV engines and airframes. While the testing of ceramic, erosion resistant engines[5] has been demonstrated previously with heavy fuels, these advancements still need to be evaluated in realistic volcanic plume environments to determine whether or not they offer sufficient advantages and reliability.

The use of UAVs for volcanic exploration and assessment not only reduces the potential risk to human life but may offer a considerable cost advantage over existing data collection approaches from manned aircraft. The work described in this paper was supported at no-cost to USGS. While baseline costs for ground station and UAV platforms may approach $75,000 the range of sensors required may greatly affect the overall cost of the systems. Once a system has been installed however, it can be operated by a single user and offers the ability to collect data irrespective of factors which would otherwise hinder data collection from manned vehicles. Additionally, the UAV and associated ground station are very portable and can be readily transported to remote locations. Projected operational costs once developed could be considerably less than $100/hour but would greatly depend upon location and the required maintenance resulting from the severity of the operation environment. It is therefore projected that these UAVs would be used more regularly than manned airborne systems.

Following the use of the Silver Fox UAV at Mount St. Helens, it is clear that the UAV technology could be a significant benefit to the volcano monitoring community as a whole and that we will observe a growing use of UAVs for these activities in the future.

## IV. References

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