Iezzi *et al. Journal of Applied Volcanology (2024) 13:8*
https://doi.org/10.1186/s13617-024-00146-9

Journal of Applied Volcanology

METHODOLOGY **Open Access**

Debris-flow monitoring on volcanoes via a novel usage of a laser rangefinder

Alexandra M. Iezzi[1*], Emily Bryant[1], Weston A. Thelen[1], Craig Gabrielson[1,2], Seth C. Moran[1], Matthew R. Patrick[3], E. Frank Younger[3] and Maciej K. Obryk[1]

Abstract
Mount Rainier has had at least 11 large lahars over the last 6,000 years, including one occurring without evidence of eruptive activity. This prompted the creation of a lahar detection system that uses a combination of seismic, infrasound, and tripwires. We test a laser rangefinder placed on a river channel bank for detecting and confirming mass movements flowing past a station as an alternative to the physical tripwires. After testing the device at an experimental debris-flow flume, the laser rangefinder successfully captured a small debris flow on Mount Rainier in 2023, confirming its effectiveness as a lahar detection and monitoring tool. Over the 2-month deployment at Mount Rainier, we find that spurious recordings in the laser rangefinder data (noise) tend to correlate with high humidity, and that periods of noise do not correlate with increased co-located seismic amplitude. Therefore, the impact of the noise on future alarms can be mitigated by coupling a laser rangefinder alarm with that of independent datasets.

Keywords Debris flow monitoring, Lahar detection, Laser rangefinder, Volcano monitoring

Introduction

Surficial mass movements such as debris flows and lahars can occur at volcanoes with or without associated unrest and have the potential to impact life and infrastructure for tens of kilometers downstream with little warning (Pierson et al. 2014; Vallance 2024). Small debris flows and lahars can occur at volcanoes due to heavy rainfall or snow- and ice-melt in the summer, combined with unconsolidated sediment on the volcano. These flows can be detected by a variety of instruments (Hürlimann et al. 2019), including seismic and infrasound sensors that record vibrations from the flow (Allstadt et al. 2018; Marchetti and Johnson 2023; Kogelnig et al. 2014; Johnson and Palma 2015; Belli et al. 2022; Coviello et al. 2019; Bosa et al. 2021; Johnson et al. 2023). These instruments also show promise for use in real-time debris-flow monitoring systems (e.g., Marchetti et al. 2019; Lai et al. 2018; Badoux et al. 2009). Many flows have low-amplitude emergent onsets in seismic and infrasound data, making initial detection difficult. An additional complicating factor is that surficial mass movements have time-varying source locations, making characterization challenging. To mitigate these issues, complementary multidisciplinary data, such as cameras, tripwires, and post-flow deposit analysis, can be used to help instill confidence in a detection (e.g., Lavigne et al. 2003). Such observations can also provide constraints on timing and flow properties such as inundation depth, which in turn can help constrain volume estimates, which is difficult with indirect methods such as seismic and infrasound alone, but critical to understanding the impacts of the flow.

Mount Rainier (Washington, USA) is an active volcano that has produced at least 11 large lahars over

---

*Correspondence:
Alexandra M. Iezzi
aiezzi@usgs.gov
[1] U.S. Geological Survey, Volcano Science Center, Cascades Volcano Observatory, 1300 SE Cardinal Ct, Vancouver, WA 98683, USA
[2] Geology Department, Western Washington University, Bellingham, WA, USA
[3] U.S. Geological Survey, Volcano Science Center, Hawaiian Volcano Observatory, Hilo, HI, USA

the last 6,000 years that have reached the Puget Lowland (Vallance and Sisson 2022; J. Vallance, USGS, oral personal communication, 2023) as well as numerous debris flows. Diefenbach et al. (2015) estimated that over 90,000 people live in Mount Rainier lahar hazard zones, a number that is likely higher today. All of these large lahars were associated with eruptive activity, with the possible exception of the ~1507 C.E. landslide-initiated Electron Mudflow (~260 million cubic meters, Crandell 1971; Scott et al. 1995), for which no evidence of an associated eruption has yet been found (Vallance and Sisson 2022; Sisson and Vallance 2009). While rare, the Electron Mudflow deposits showed that the flow inundated valleys 40 to 50 km NW from the summit of Mount Rainier (Crandell 1971; Sisson and Vallance 2009). Recent studies show that the western flank of Mount Rainier contains hydrothermally altered rock that could produce future non-eruptive landslides and associated large lahars down the Puyallup River and/or Tahoma Creek drainages (Finn et al. 2001; Reid et al. 2001). Recent modeling indicates that a lahar equivalent in size to the ~1507 Electron Mudflow could reach nearby small towns within 10-20 minutes (~25 km downstream) and larger communities within 50-60 minutes (~50 km downstream, George et al. 2022). We note that local communities and emergency management agencies have adopted a communication strategy whereby smaller flows that stay within the National Park limits be referred to as “debris flows” and that the term “lahar” be used only for larger flows extending outside the Park. For consistency, we continue with that practice in this paper.

There are few well-recorded examples of lahars in the seismic and infrasound literature, and none that we are aware of on the scale of the Electron Mudflow. However, example flow signals are needed to develop and test novel monitoring techniques as well as assess, tune, and optimize detection and characterization algorithms in the absence of larger, less frequent lahars. Smaller debris flows are common within the drainages surrounding Mount Rainier, including over 60 debris flows and outburst floods that have occurred between 1926 and 2019 due to high-intensity precipitation storms in the fall and melting of glacial ice and snow in the summer months (Beason et al. 2021). At least 33 debris flows occurred in Tahoma Creek between 1967 and 2019, including one that closed the once popular Westside Road at milepost 3 and associated hiking trail in 1988 due to lateral migration of the channel as a result of debris flows (Beason et al. 2021). One of our objectives has been to record one or more of these debris flows in order to generate data that can be used to test various lahar detection algorithms.

In 1998, the U.S. Geological Survey (USGS) Cascades Volcano Observatory (CVO), in partnership with state and local agencies, installed a lahar detection system (heretofore called the Rainier Lahar Detection System, RLDS) as one means for mitigating the risk posed by large lahars from Mount Rainier. The 1998 system was installed along two drainages (the Puyallup and Carbon Rivers) and featured multiple sites with acoustic flow monitors (short period seismometers, Hadley and LaHusen 1995) and tripwires. Data from these sites were transmitted every several minutes to base stations located at 24/7 Emergency Operations Centers (EOCs) operated by the Washington State Division of Emergency Management (WA EMD) and the Pierce County Department of Emergency Management (PCDEM). Automated detection software running on both base stations was configured to alert EOC staff via sirens and flashing lights, after which EOC staff were to follow standard operating procedures for sending alarms to communities at risk. Having a robust lahar detection system that will detect every large lahar without false alarms is essential to maintaining public trust.

In 2016, CVO began a years-long process to upgrade and expand the capabilities of the RLDS (the reader is referred to Kramer et al. 2024 for details). Upgrades included replacing acoustic flow monitors with broadband seismometers, updating tripwire systems, adding infrasound and cameras to a number of stations, and installing new stations to improve detection capabilities. Of these sensor types, tripwires have proved the most problematic to install and maintain. Tripwires serve the purpose of confirming that a flow is physically moving down the river channel, which can sometimes be ambiguous using seismic or infrasound data alone. However, they have a number of challenges, including: they are prone to being tripped by wildlife; they can only be installed at sites with adequate solar, adequate real-time telemetry, and with steep banks that are close to the channel; they provide no state-of-health information (they’re either “tripped” or they’re not); and once they have been “tripped” they are unusable for detecting subsequent lahars.

In an effort to find an alternative for tripwires, CVO began testing the capabilities of laser rangefinders in 2023. Laser rangefinders are instruments that can be used to record a single point distance between the instrument and a given target. They typically are used to determine distances to solid surfaces, but may also be appropriate for debris-ladden flows. Handheld laser rangefinders have been used by the USGS Hawaiian Volcano Observatory (HVO) for measuring crater floor and lava lake elevations (Patrick et al. 2019a). HVO installed a permanent laser rangefinder at the summit of Kīlauea in 2018 for continuous 1 Hz measurements of the lava-lake level (Patrick et al. 2019b, 2022). While only being used for monitoring at volcanoes in a limited way, laser rangefinding devices have been used to observe natural (e.g., Hürlimann et al. 2019; Tang et al. 2019; Kean et al. 2011; McCoy et al. 2010) and experimental (e.g., Chen et al. 2015) debris flows when suspended directly over the thalweg of the channel to determine flow depth, as well as using a laser profile scanner to observe superelevation of the flow surface (e.g., Takahashi et al. 2019). However, to our knowledge, a single point distance laser rangefinder has not been used in a natural setting placed discreetly on the bank at an oblique angle to the channel perpendicular to the flow for monitoring. Laser rangefinders have several benefits, including low power requirements, low telemetry bandwidth, ability to be placed at longer ranges out of the lahar hazard zone, state-of-health information, relatively small installation footprints, and ability to be used for subsequent flows, that make them particularly attractive as candidates for tripwire replacements in the RLDS. They are also potentially more feasible for use in areas with difficult logistics and/or land-use restrictions, which make other approaches for debris-flow monitoring, such as check dams with force plates (e.g., Illgraben, Switzerland, Mount Yakedake, Japan, and Gadria, Italy) and channel spanning bridges/suspension systems to hang flow stage sensors above the flow (e.g., Illgraben, Switzerland, Chalk Cliffs, U.S.A.; Hürlimann et al. 2019; Badoux et al. 2009), problematic.

In this study, we present results of a test of a continuous laser rangefinder as a "virtual tripwire" placed on the channel bank perpendicular to the flow that can confirm a flow is moving past the station without some of the drawbacks of the physical tripwire currently used by the RLDS. This is the first such usage that we are aware of for monitoring mass movements at volcanoes. We describe an initial test of the instrument at the USGS experimental debris-flow flume, a successful recording of a natural debris flow at Mount Rainier along the Tahoma Creek drainage in August 2023, and its potential integration into real-time lahar monitoring systems.

Equipment & testing at the USGS debris-flow flume

We used a LaserTech TruSense S200 laser rangefinder (Fig. 1b) that has an accuracy of up to ±4 cm with a range of up to 750 m. According to the specifications, range can be extended up to 2,900 m with accuracy of up to ±15 cm based on measurement mode and surface reflectivity. The laser rangefinder records the distance from the instrument, and the change in distance (Δd) can easily be converted to the change in height (Δh) above the target location using the angle from horizontal that the laser rangefinder is pointing (θ, Fig. 1a, Eqs. 1 and 2). For plotting, we set the Δh to be zero prior to an event.

$$sin(\theta) = \frac{\Delta h}{\Delta d} \tag{1}$$

$$\Delta h = sin(\theta) * \Delta d \tag{2}$$

We first tested the laser rangefinder at the USGS debris-flow flume with three simulated flows, one of which we describe here (May 16, 2023, local, May 17, 2023, UTC). The flume is located near Blue River, Oregon, and consists of a reinforced concrete channel that is 95 m long and 2 m wide at a 31° slope (Iverson et al. 1992, 2010; Logan et al. 2018). The laser rangefinder was located on a platform ~75 m from the top of the flume near the break in slope and was pointed near the center of the channel at an angle of 61° from horizontal, perpendicular to the channel (Fig. 1a). Data were recorded at ~3 Hz directly onto a laptop for this initial test. The laser rangefinder clearly observed the flow front arrival and subsequent deposition of material via the recording of distance from the laser rangefinder (Fig. 1c) and converted change in height from the flume bed (Fig. 1d).

Application to a debris flow at Mount Rainier

The laser rangefinder was deployed at Mount Rainier from July 11th to September 14th, 2023 (~2 months), and co-located with the permanent station TABR (Fig. 2a, b, c) operated by CVO (Cascades Volcano Observatory/USGS 2001). The permanent CVO station TABR includes a 3-component Trillium Compact Posthole seismometer and Chaparral 64VX infrasound sensor digitized on a Nanometrics Centaur. Although TABR data are telemetered at 50 Hz (BHZ and BDF channels), we locally logged and retrieved data for this event at 250 Hz for infrasound (CDF) and 500 Hz for seismic (CHZ) that we use for analysis here. TABR is situated adjacent to Tahoma Creek (Fig. 2a) as part of the RLDS within Mount Rainier National Park. The laser rangefinder was positioned at an angle of 29° from horizontal with a slant distance of ~65 m to the center of the active channel in Tahoma Creek. Vertical component seismic and infrasound data at TABR are bandpass filtered between 1 and 124 Hz. Laser rangefinder data were recorded locally at 1 Hz using a Campbell Scientific CR6 digitizer with timing antenna, and the closest weather station is at Paradise (~9 km from TABR, Fig. 2a) with average values recorded every 60 minutes (temperature, relative humidity, and rainfall used in this study).

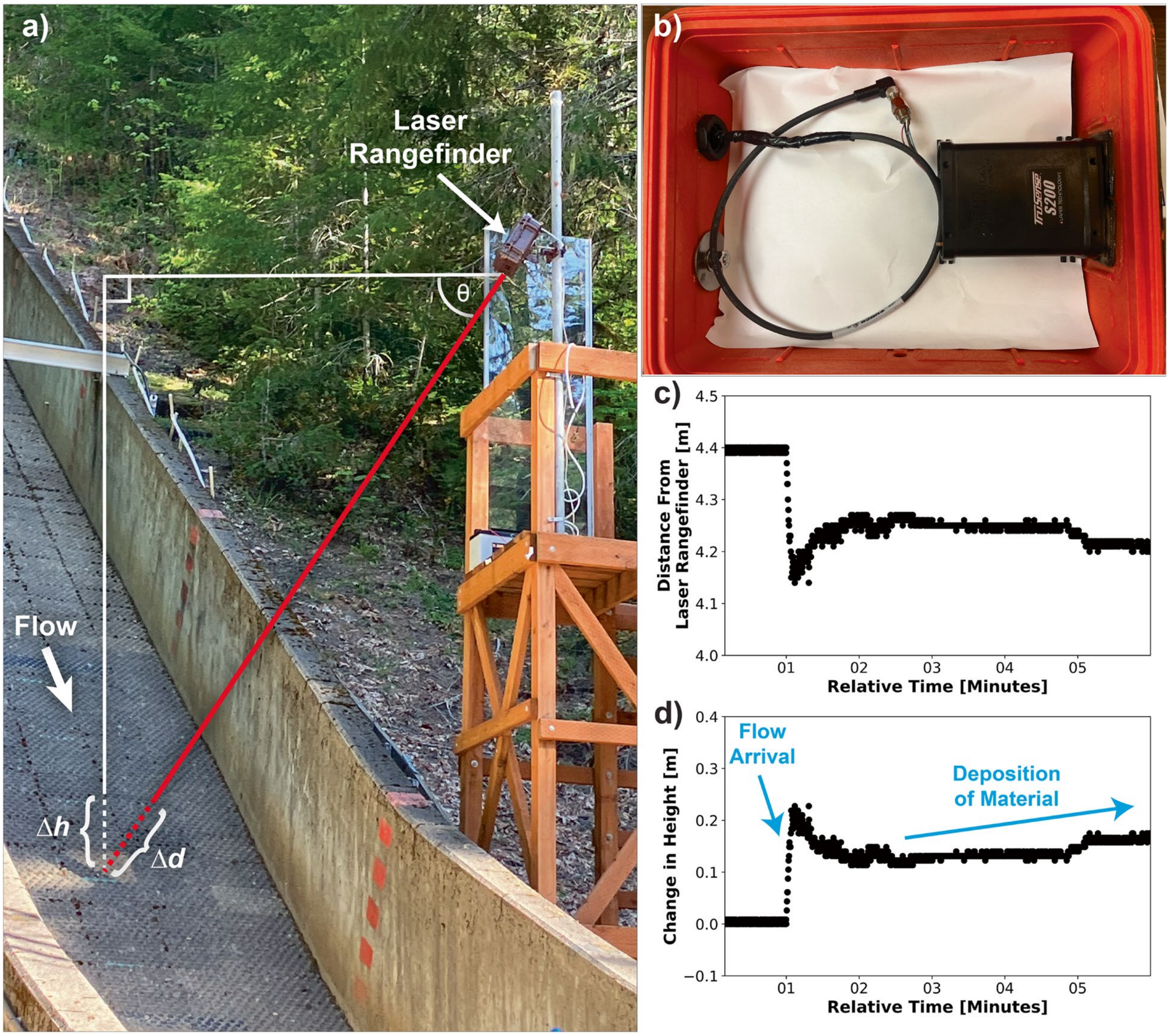

Fig. 1 Deployment at the USGS debris-flow flume in May 2023. **a** Photo of the laser rangefinder fixed to the pole on a nearby platform pointing at the channel with sketch and conversion from change in distance (Δ*d*) to change in height (Δ*h*) overlain. **b** Photo of the laser rangefinder. **c** Distance recorded by the laser rangefinder, and **d** converted change in height showing the flow front arrival at the sensor and subsequent deposition of material

A small debris flow occurred on Tahoma Creek on August 15th, 2023, at approximately 23:24 UTC (16:24 local), as estimated based on the onset of the seismic and infrasound signals higher up in the drainage. The debris flow was caused by a glacial outburst flood from the South Tahoma Glacier, occurring late in the afternoon on a hot summer day (high of 28.6°C, Paradise weather station). It was recorded on 10 broadband seismometers, 4 infrasound arrays, and 1 single infrasound sensor as part of the newly upgraded permanent monitoring network for the RLDS (Kramer et al. 2024). The debris flow moved down the channel and passed directly by TABR, as shown by the laser rangefinder (Fig. 2d), seismic (Fig. 2e), and infrasound (Fig. 2f) data. The laser rangefinder successfully recorded the debris flow (Fig. 2d), and the seismic data show that the main pulse of the flow lasted less than ten minutes (Fig. 2e). Increased sediment concentrations and/or flow volume likely occurred for hours, as evidenced by the elevated seismic and infrasound amplitudes in the longer time series.

We calculate the envelope of the seismic and infrasound traces using a Hilbert transform that is convolved with a Hanning window of 5 minute duration and compare these envelopes with the laser rangefinder data for a 15 minute window surrounding the flow (Fig. 2g). The smoothing filter is used just for visualization purposes

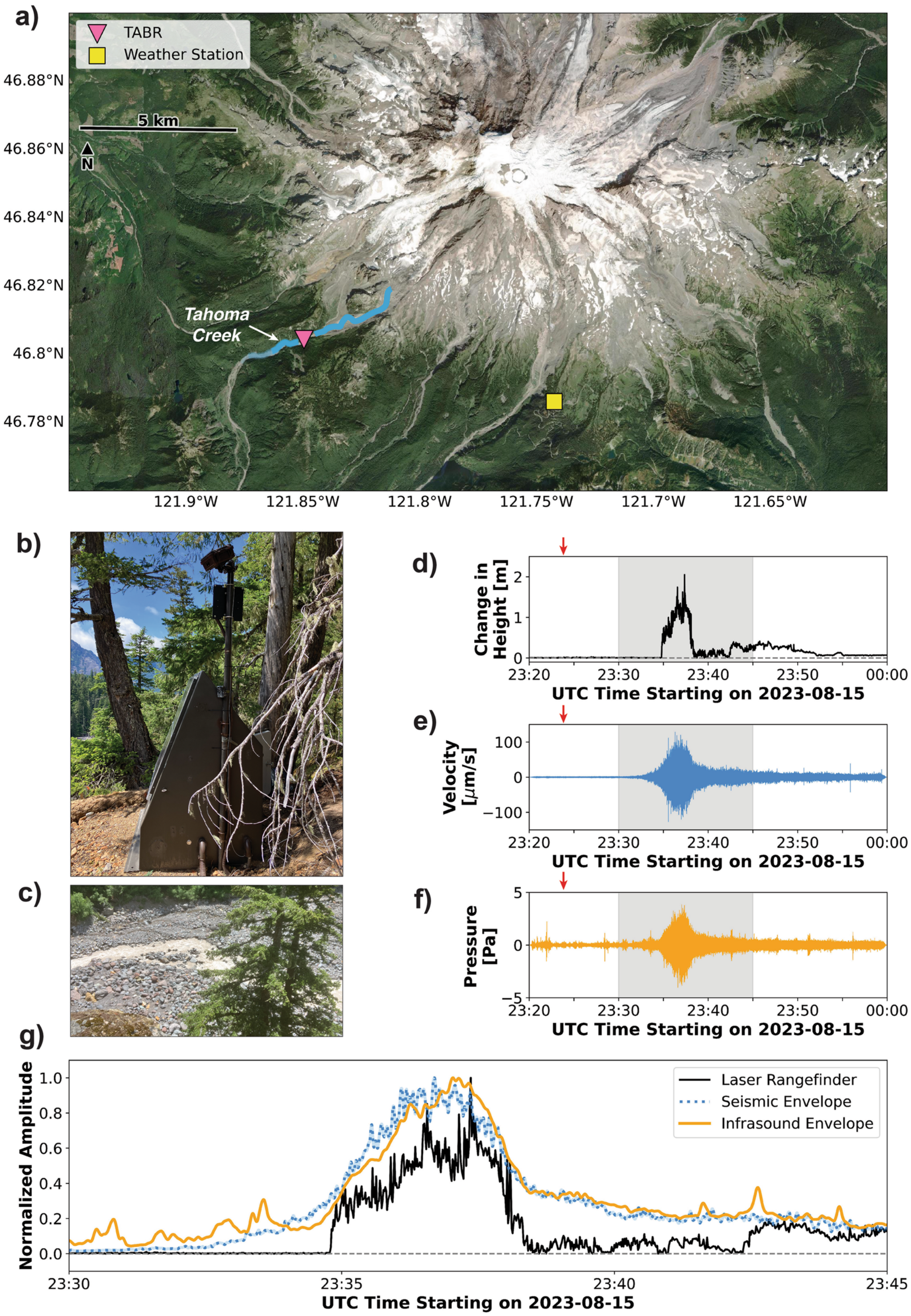

Fig. 2 Deployment at Tahoma Creek. **a** Map of Mount Rainier showing station TABR (pink inverted triangle), weather station at Paradise (yellow square), and the estimated debris-flow path that fades downstream as the downstream extent is not well-constrained (blue line). Photos of the deployment are shown in **b** the laser rangefinder affixed to station TABR and **c** the view from the laser rangefinder at the active Tahoma Creek channel (taken on July 11th, 2023 during installation). Data recorded for the 40 minutes surrounding the event are shown for the **d** change in height calculated from the laser rangefinder recording, **e** vertical component seismic, and **f** infrasound, both bandpass filtered between 1-124 Hz. **g** Zoomed-in time period (gray boxes in **d**, **e**, **f**) for the laser rangefinder (black), seismic envelope (blue dotted), and infrasound envelope (orange). The red vertical arrows in **d**, **e**, **f** denote the initiation time of the August 15th debris flow

to easily compare the three data types, and trends discussed are still apparent in the non-smoothed envelopes. The emergent onset of the seismic signal appears a few minutes prior to the arrival of the flow on the laser rangefinder, consistent with the flow starting higher in the drainage and increasing in seismic amplitude as the flow moved closer to this station (Fig. 2g). The laser rangefinder signal onset at 23:34:48 UTC (~ 11 minutes after the flow initiation) corresponds with the onset of the high amplitude seismic and infrasound signals (Fig. 2g). The laser rangefinder onset is clear, precise, and occurs approximately 2 minutes before the peak of the seismic amplitude, thus allowing for improved arrival time and tracking information as the flow moves down the drainage. We also note that the peak of the seismic amplitude occurs about a minute before the peak in laser rangefinder data, which may be attributed to the energetic flow front moving past the station and farther away while water level/sediment load still increased at the station as recorded by the laser rangefinder. The time differences both of the signal onset and of the peak amplitude between the seismic, infrasound, and laser rangefinder datasets may be important considerations for monitoring purposes.

Discussion

The laser rangefinder successfully recorded debris flows both at the USGS debris-flow flume and a natural event at Mount Rainier. However, we aim to better understand the entirety of the data that are being recorded before this technique can confidently be used as an operational monitoring tool. We investigated the full 2-month long dataset and compare the laser rangefinder results with seismic and weather data. We calculated the 1-minute real-time seismic amplitude measurement (RSAM, Endo and Murray 1991) for the co-located vertical seismic channel at TABR, a metric and window length that CVO uses for monitoring alarms (Fig. 3a). We also examined the air temperature (Fig. 3d), relative humidity (Fig. 3e), and rainfall (Fig. 3f) from the local weather station at Paradise. The August 15th debris flow occured coincident with the highest RSAM level (by far) for the 2-month deployment (Fig. 3a), after a days-long increase in temperature and near the peak temperature of the day (Fig. 3d), low relative humidity (Fig. 3e), and no rainfall (Fig. 3f).

Similar to most geophysical signals, the raw laser rangefinder data have spurious recordings that are not the water surface (which we refer to in this study as noise, Fig. 3b) that should be analyzed further. With the distance from the laser rangefinder to the channel being ~65 m, we find that 1.05% of the data over the entire deployment are less than 61 m from the sensor and thus considered anomalous (Fig. 3b). The noise in the raw laser rangefinder data (Fig. 3b) generally corresponds to high humidity (Fig. 3e) and, to some extent, rainfall (Fig. 3f). This can be seen more clearly in Fig. 4a-f, where we highlight two 10-day windows that had the highest levels of noise (blue and gray boxes in Fig. 3), especially with returns closer to the channel. Returns that are clearly not accurate (e.g., <40 m from the sensor) can easily be filtered out of the data within the monitoring algorithms. We note that the spurious detections do not occur coincident with high seismic RSAM (Fig. 3a), so we envision being able to couple a laser rangefinder alarm with seismic RSAM or some other dataset to mitigate false positives just like the current RLDS tripwire alarm, as well as incorporating post-processing filters into the laser rangefinder dataset.

The laser rangefinder recorded the diurnal streamflow variations of Tahoma Creek throughout the deployment (Fig. 3c), with variations smaller in amplitude for the first few weeks, muted for two weeks, then larger in amplitude the last week of the deployment. The diurnal variations increased in amplitude for the few days leading up to the debris flow, coincident with an increase in temperature (Figs. 3 c-d and 4 g). Peaks in the laser rangefinder data are temporally consistent with changes in air temperature (Fig. 4g), likely a result of the laser rangefinder being located high in the drainage, therefore recording increased flow as soon as warming occurs each day. This relationship is in contrast to the stream gage data on the Nisqually River near National (US Geological Survey 2024), where peaks are delayed from the peaks in laser rangefinder and temperature, consistent with its position ~25 km downstream of TABR so it takes awhile for increases in flow from Tahoma Creek and other glacially fed creeks to reach the gage. The diurnal peaks recorded by the rangefinder are indicative of water surface detection, though we note that deploying a laser rangefinder close to a stream gage can confirm this in the future.

Another feature that is evident in the laser rangefinder plots are two notable offsets with respect to the initial baseline stream height in the data directly after the August 15th flow and on August 28th after rainfall (Fig. 3c). There are two plausible scenarios that may have caused these: 1) limitations in the accuracy of the laser rangefinder or 2) changes in the channel morphology. The details we observe in the laser rangefinder data show that the instrument is sensitive and precise. However, there is a possibility that the instrument is not as accurate and that large changes in the recording may not result in the distance observed by the laser rangefinder going back to the same exact baseline as before. The second scenario is that there were changes in channel morphology as a result of the two periods of higher flow; therefore, the laser rangefinder that is only a point measurement

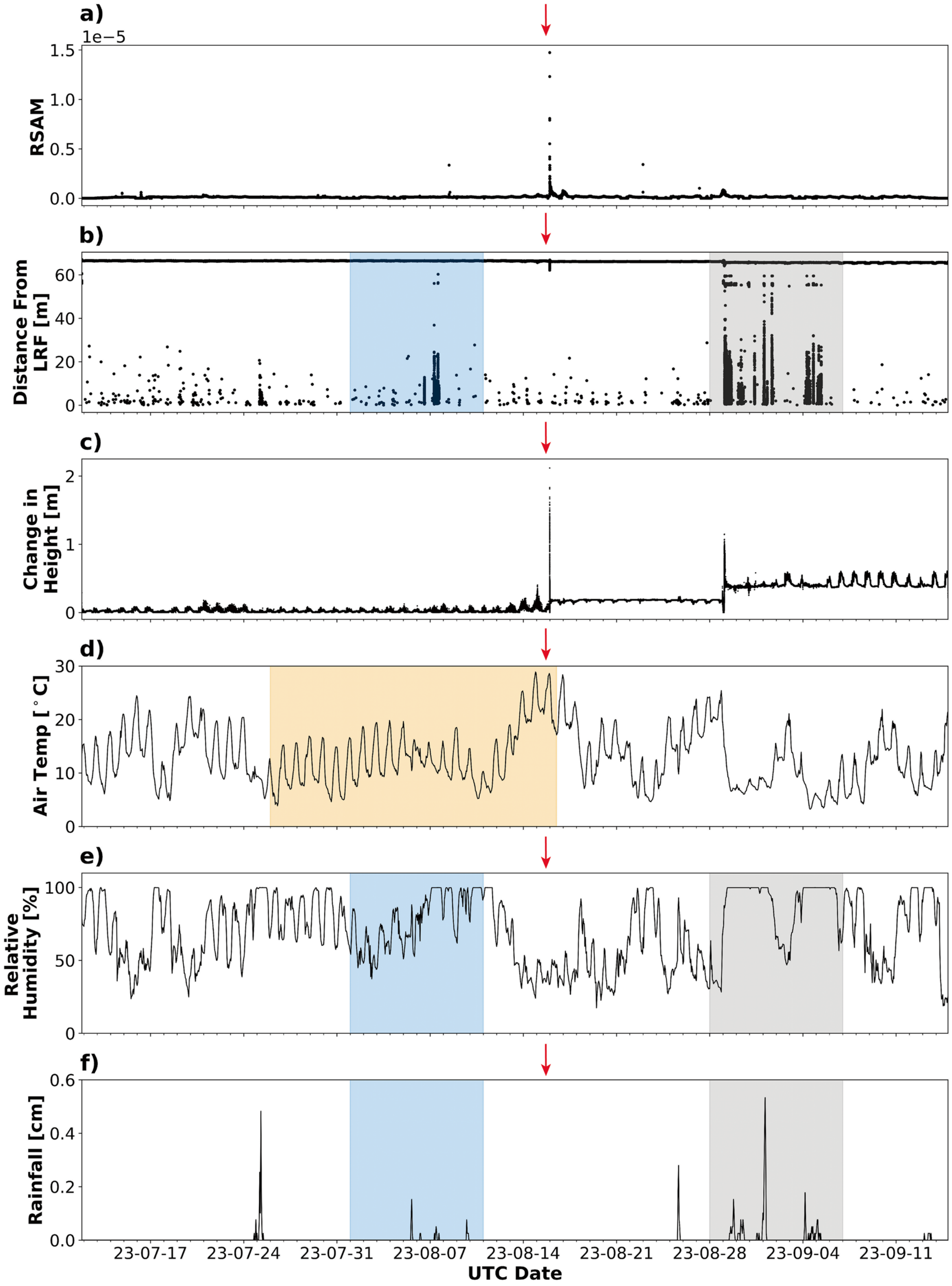

Fig. 3 Entire 2-month deployment at Tahoma Creek along with weather data. **a** 1-minute RSAM for station TABR (vertical component). **b** Distance and **c** converted change in height recorded by the laser rangefinder. **d** Air temperature, **e** relative humidity, and **f** rainfall recorded by the weather station at Paradise. The blue and gray shaded regions in **b**, **e**, **f** correspond to Fig. 4 panels **a**, **c**, **e** and **b**, **d**, **f**, respectively. The orange shaded region in **d** corresponds to Fig. 4**g**. The red vertical arrows denote the August 15th debris flow

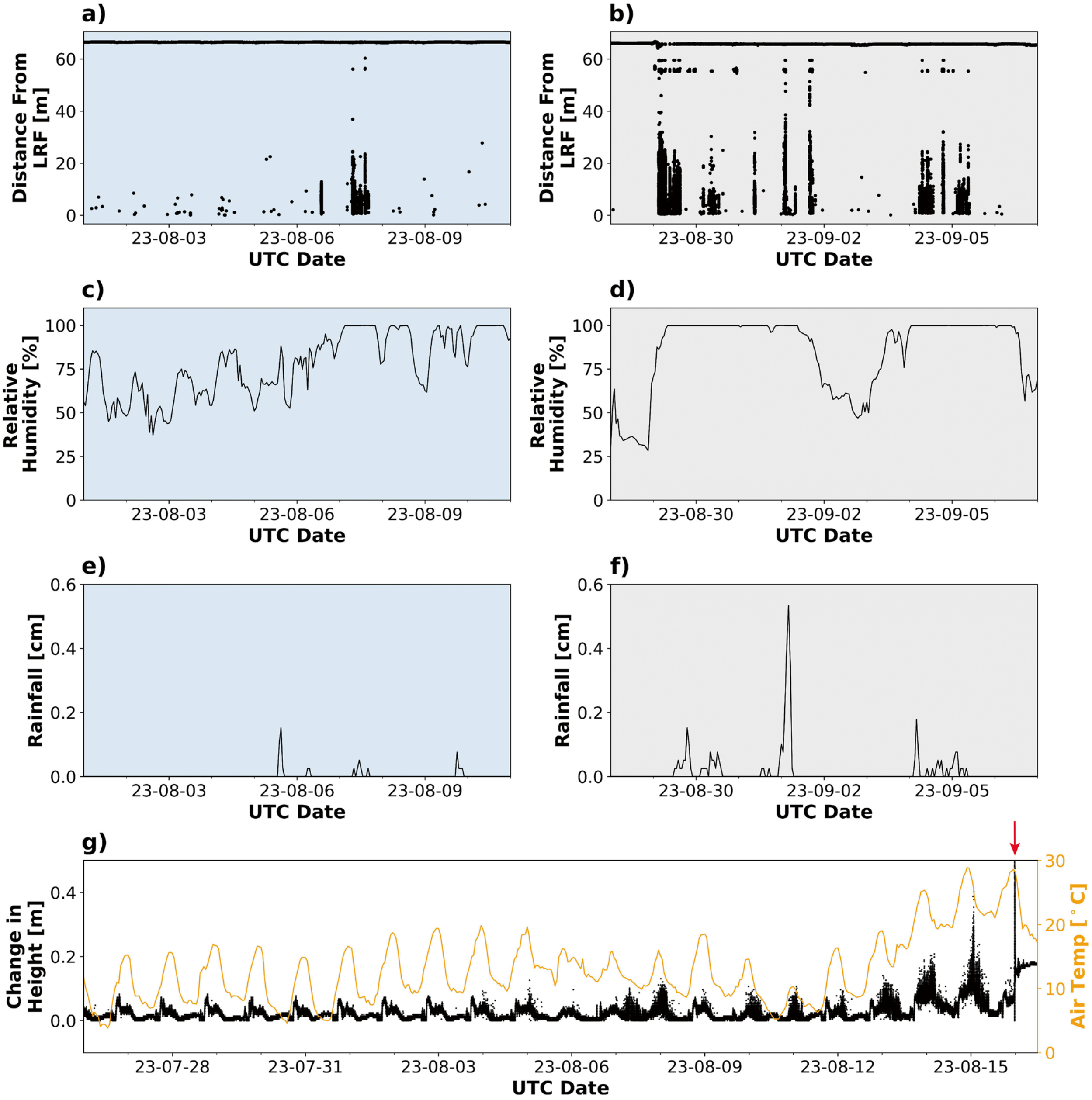

Fig. 4 Zoomed in time periods during the 2-month deployment at Tahoma Creek along with weather data. **a**, **b** Distance recorded by the laser rangefinder, **c, d** relative humidity, and **e**, **f** rainfall from **a**, **c**, **e** August 1-10, 2023 (blue shaded region in Fig. 3), and **b**, **d**, **f** August 28 - September 6, 2023 (gray shaded region in Fig. 3). **g** Converted change in height recorded by the laser rangefinder (black) with air temperature at the Paradise weather station (orange) between July 26 and August 16, 2023 (orange shaded region in Fig. 3). The red vertical arrow denotes the August 15th debris flow. Note that the y-axis in **g** was intentionally truncated to highlight the diurnal patterns leading up to the debris flow

may not have been recording the exact same portion of the flow after each event. This a likely scenario for the Tahoma Creek, and the significant diminishment of the diurnal peak observations between August 15 - 28th may support this reason as we may not have been recording the most active portion of the creek for that time period. Satellite imagery from before and after the flow support changes in channel morphology as the cause in these step increases, as well as reports noting that changes in stream morphology are common on the Tahoma Creek occurring consistently anytime there is increased flow. Future deployments could include time-lapse cameras to help investigate any changes in channel morphology and its impact on the laser rangefinder data.

Conclusions & future work

A laser rangefinder clearly and successfully recorded debris flows at both the USGS debris-flow flume and the Tahoma Creek at Mount Rainier. Over the 2-month deployment at Mount Rainier, we find that the spurious recordings (noise) tend to correlate with high humidity (likely fog), and that periods of noise do not correlate with increased seismic amplitude (RSAM), so the impact of the noise can be mitigated by coupling a laser rangefinder alarm with an independent dataset, such as RSAM. There are settings on the laser rangefinder itself that can also decrease the spurious recordings, such as a range gate filter or the strength of the recorded return, which should be tested. We note that the testing only occurred over the summer, so future work should test its capabilities over winter months through various weather conditions. Future deployments of the laser rangefinder would ideally include a well-configured camera to record flow dynamics and changes in channel morphology pre- and post-flow to help interpret features of the data, and could be deployed near a stream gage to ground truth the changes in height that are being recorded. We also suggest a co-located weather station to better understand the impacts of humidity and rain, metrics that may be used as an arrester for future alarms. Finally, we suggest that installing a second laser rangefinder at the same site may aid in the calculation of flow velocity and volume as well as decrease the false detection rate. The laser rangefinder we tested did not have an optical pointer to aim the sensor, so there are some uncertainties on the exact location within the channel that is being recorded. Therefore, improvements to the aiming of the laser should be explored. We also note that the model tested here does not have the range for some of our tripwire sites on the Puyallup River drainage, so we plan to test a laser rangefinder with longer range capabilities (few kilometers), which has a different wavelength so we have to test it for use on debris flows since they are designed for solid targets, which would have a stronger return surface. Finally, we are actively working on telemetering the laser rangefinder data so we can see these features in real-time and start testing their potential incorporation into alarm systems.

Over 90,000 people live in Mount Rainier lahar hazard zones (Diefenbach et al. 2015), with recent modeling indicating that a lahar equivalent in size to the ∼ 1507 Electron Mudflow could reach nearby small towns within 10-20 minutes (∼25 km downstream) and larger communities within 50-60 minutes (∼50 km downstream, George et al. 2022). Therefore, it is imperative to have an alarm system with no failed detections so that emergency managers can issue evacuation warnings as well as no false detections to mitigate unnecessary evacuation complexities and costs. The laser rangefinder proved to be a viable alternative to current RLDS tripwires; however, year-round testing across all weather conditions is necessary before full scale implementation. The Tahoma Creek debris flow serves as an ideal way to test and calibrate the RLDS algorithms and alarms using the newly upgraded network. The RLDS alarm has zero tolerance for both missed detections of a lahar and false detections when no lahar is present. However, all geophysical datasets are prone to noise, so a multidisciplinary approach to our alarm system is key. In its current form, the RLDS alarm is based on both a tripwire and RSAM exceeding a given threshold to mitigate false alarms. We envision that the laser rangefinder would benefit from a similar multidisciplinary approach, mitigating the spurious noise recordings of the laser rangefinder data and requiring less maintenance than the current tripwire systems.

Acknowledgements

We would like to acknowledge our USGS Volcano and Landslides Hazards Program colleagues for help with the deployments at the USGS debris-flow flume and at Mount Rainier, the field and engineering team at CVO for installing and maintaining the permanent monitoring network at Mount Rainier, and Mount Rainier National Park geologists Scott Beason and Taylor Kenyon for help with permitting. We would also like to thank Elaine Collins for help with satellite imagery of the channel, Kurt Spicer for discussion on hydrology/river mechanics, and Peter Kelly for letting us borrow the Campbell digitizer for the Mount Rainier deployment. We thank reviewers Lucia Capra, Jeff Johnson, and Dennis Staley as well as editor Amiel Nieto-Torres for their comments that improved this manuscript. Seismic and infrasound data processing were performed using ObsPy (Beyreuther et al. 2010). Any use of trade, product, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Authors' contributions

A.I. wrote the manuscript text and prepared the figures. A.I., E.B., W.A., C.G., S.C., M.P., and F.Y. conceptualized the methodology, and A.I., E.B., W.A., C.G., and M.O. performed the engineering and fieldwork for data collection. All authors reviewed, edited, and approved the manuscript.

Funding

Not applicable.

Availability of data and materials

The laser rangefinder data are released via ScienceBase and can be accessed at https://doi.org/10.5066/P1ZDFGIJ (Iezzi et al. 2024). Seismic (channel CHZ) and infrasound (channel CDF) data for station TABR are available on EarthScope via network code "CC" (Cascades Volcano Observatory/USGS 2001). Weather station data from Paradise is available by the Northwest Weather and Avalanche Center and can be accessed at https://nwac.us/data-portal/location/mt-rainier/.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 14 May 2024 Accepted: 26 August 2024

References

Allstadt KE, Matoza RS, Lockhart AB, Moran SC, Caplan-Auerbach J, Haney MM, Thelen WA, Malone SD (2018). Seismic and acoustic signatures of surficial mass movements at volcanoes. J. Volcanol. Geotherm. 364:76–106. https://doi.org/10.1016/j.jvolgeores.2018.09.007

Badoux A, Graf C, Rhyner J, Kuntner R, McArdell BW (2009) A debris-flow alarm system for the alpine Illgraben catchment: design and performance. Nat Hazards 49:517–539. https://doi.org/10.1007/s11069-008-9303-x

Beason SR, Legg NT, Kenyon TR, Jost RP (2021) Forecasting and seismic detection of proglacial debris flows at Mount Rainier National Park, Washington, USA. Environ Eng Geosci 27:57–72. https://doi.org/10.2113/EEG-D-20-00014

Belli G, Walter F, McArdell B, Gheri D, Marchetti E (2022) Infrasonic and seismic analysis of debris-flow events at Illgraben (Switzerland): Relating signal features to flow parameters and to the seismo-acoustic source mechanism. J Geophys Res Earth Surf 127. https://doi.org/10.1029/2021JF006576

Beyreuther M, Barsch R, Krischer L, Megies T, Behr Y, Wassermann J (2010) Obspy: A python toolbox for seismology. Seismol Res Lett 81:530–533. https://doi.org/10.1785/gssrl.81.3.530

Bosa A, Johnson JB, De Angelis S, Lyons J, Roca A, Anderson J, Pineda A (2021) Tracking secondary lahar flow paths and characterizing pulses and surges using infrasound array networks at Volcán de Fuego, Guatemala. Volcanica 4:239–256. https://doi.org/10.30909/vol.04.02.239256

Cascades Volcano Observatory/USGS (2001) Cascade chain volcano monitoring [Data set]. International Federation of Digital Seismograph Networks. https://doi.org/10.7914/SN/CC

Chen J, Chen X, Li Y, Wang F (2015) An experimental study of dilute debris flow characteristics in a drainage channel with an energy dissipation structure. Eng Geol 193:224–230. https://doi.org/10.1016/j.enggeo.2015.05.004

Coviello V, Arattano M, Comiti F, Macconi P, Marchi L (2019) Seismic characterization of debris flows: Insights into energy radiation and implications for warning. J Geophys Res Earth Surf 124:1440–1463. https://doi.org/10.1029/2018JF004683

Crandell DR (1971) Postglacial lahars from Mount Rainier volcano. Washington. Geol Surv Prof Pap 677. https://doi.org/10.3133/pp677

Diefenbach AK, Wood NJ, Ewert JW (2015) Variations in community exposure to lahar hazards from multiple volcanoes in Washington State (USA). J Appl Volcanol 4. https://doi.org/10.1186/s13617-015-0024-z

Endo ET, Murray T (1991) Real-time seismic amplitude measurement (RSAM): a volcano monitoring and prediction tool. Bull Volcanol 53:533–545

Finn CA, Sisson TW, Deszcz-Pan M (2001) Aerogeophysical measurements reveal collapse prone hydrothermally altered zones at Mount Rainier volcano, Washington. 14th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems. https://doi.org/10.3997/2214-4609-pdb.192.AIR_6

George D, Iverson R, Cannon C (2022) Modeling the dynamics of lahars that originate as landslides on the west side of Mount Rainier, Washington. US Geological Survey Open-File Report 2021–1118. https://doi.org/10.3133/ofr20211118

Hadley KC, LaHusen R (1995) Technical manual for the experimental acoustic flow monitor. US Geological Survey Open-file Report 95-114. https://doi.org/10.3133/ofr95114

Hürlimann M, Coviello V, Bel C, Guo X, Berti M, Graf C, Hübl J, Miyata S, Smith JB, Yin HY (2019) Debris-flow monitoring and warning: Review and examples. Earth-Sci Rev 199:102981. https://doi.org/10.1016/j.earscirev.2019.102981

Iezzi AM, Bryant E, Thelen WA, Gabrielson C (2024) Laser rangefinder data for surficial mass movements in the Cascades. US Geological Survey data release. https://doi.org/10.5066/P1ZDFGIJ

Iverson RM, Costa J, LaHusen R (1992) Debris-flow flume at H.J. Andrews Experimental Forest, Oregon. US Geological Survey, Water Fact Sheet, Open-file Report 92-483. https://doi.org/10.3133/ofr92483

Iverson RM, Logan M, LaHusen RG, Berti M (2010) The perfect debris flow? Aggregated results from 28 large-scale experiments. J Geophys Res Earth Surf 115. https://doi.org/10.1029/2009JF001514

Johnson JB, Palma JL (2015) Lahar infrasound associated with Volcán Villarrica's 3 March 2015 eruption. Geophys Res Lett 42:6324–6331. https://doi.org/10.1002/2015GL065024

Johnson JB, Roca A, Pineda A, Mérida R, Escobar-Wolf R, Anderson JF, Mock J, Bosa A, Bejar G, Waite GP (2023) Infrasound detection of approaching lahars. Sci Rep 13. https://doi.org/10.1038/s41598-023-32109-2

Kean JW, Staley DM, Cannon SH (2011) In situ measurements of post-fire debris flows in southern California: Comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions. J Geophys Res 116(F04):019. https://doi.org/10.1029/2011JF002005

Kogelnig A, Hübl J, Suriñach E, Vilajosana I, McArdell BW (2014) Infrasound produced by debris flow: Propagation and frequency content evolution. Nat Hazards 70:1713–1733. https://doi.org/10.1007/s11069-011-9741-8

Kramer RL, Thelen WA, Iezzi AM, Moran SC, Pauk BA (2024) Recent expansion of the Cascades Volcano Observatory geophysical network at Mount Rainier for improved volcano and lahar monitoring. Seismol Res Lett. https://doi.org/10.1785/0220240112

Lai VH, Tsai VC, Lamb MP, Ulizio TP, Beer AR (2018) The seismic signature of debris flows: Flow mechanics and early warning at Montecito, California. Geophys Res Lett 45:5528–5535. https://doi.org/10.1029/2018GL077683

Lavigne F, Tirel A, Floch DL, Veyrat-Charvillon S (2003) A real-time assessment of lahar dynamics and sediment load based on video-camera recording at Semeru volcano, Indonesia. Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Millpress, Rotterdam, pp 871–882. https://www.researchgate.net/publication/236341493

Logan M, Iverson R, Obryk M (2018) Video documentation of experiments at the USGS debris-flow flume 1992–2017. US Geological Survey Open-File Report 2007–1315. https://doi.org/10.3133/ofr20071315

Marchetti E, Johnson J (2023) Infrasound array analysis of rapid mass movements in mountain regions. Adv Geophys 64:1–57. https://doi.org/10.1016/bs.agph.2023.06.001

Marchetti E, Walter F, Barfucci G, Genco R, Wenner M, Ripepe M, McArdell B, Price C (2019) Infrasound array analysis of debris flow activity and implication for early warning. J Geophys Res Earth Surf 124:567–587. https://doi.org/10.1029/2018JF004785

McCoy SW, Kean JW, Coe JA, Staley DM, Wasklewicz TA, Tucker GE (2010) Evolution of a natural debris flow: In situ measurements of flow dynamics, video imagery, and terrestrial laser scanning. Geology 38:735–738. https://doi.org/10.1130/G30928.1

Patrick MR, Swanson D, Orr T (2019a) A review of controls on lava lake level: insights from Halema'uma'u crater. Kīlauea volcano. Bull Volcanol 81:13. https://doi.org/10.1007/s00445-019-1268-y

Patrick MR, Younger EF, William DT (2019b) Lava level and crater geometry data during the 2018 lava lake draining at Kīlauea volcano, Hawaii. US Geological Survey data release. https://doi.org/10.5066/P9MJY24N

Patrick MR, Swanson D, Orr T, Younger F, Tollett W (2022) Elevation of the lava lake in Halema'uma'u crater, Kīlauea volcano, from 2009 to 2018. US Geological Survey data release. https://doi.org/10.5066/P9ULRPMM

Pierson TC, Wood NJ, Driedger CL (2014) Reducing risk from lahar hazards: Concepts, case studies, and roles for scientists. J Appl Volcanol 3. https://doi.org/10.1186/s13617-014-0016-4

Reid ME, Sisson TW, Brien DL (2001) Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington. Geology 29:779–782. https://doi.org/10.1130/0091-7613(2001)0292.0.CO;2

Scott K, Vallance J, Pringle P (1995) Sedimentology, behavior, and hazards of debris flows at Mount Rainier. Washington. US Geological Survey Professional Paper 1547. https://doi.org/10.3133/pp1547

Sisson TW, Vallance JW (2009) Frequent eruptions of Mount Rainier over the last 2600 years. Bull Volcanol 71:595–618. https://doi.org/10.1007/s00445-008-0245-7

Takahashi Y, Fujimura N, Akita H, Mizuno M (2019) Dynamic characteristics of extreme superelevation of debris flows observed by laser profile scanners in Sakura-jima volcano, Japan. 7th International Conference on Debris-Flow Hazards Mitigation. https://doi.org/10.25676/11124/173217

Tang H, McGuire LA, Rengers FK, Kean JW, Staley DM, Smith JB (2019) Evolution of debris-flow initiation mechanisms and sediment sources during a sequence of postwildfire rainstorms. J Geophys Res Earth Surf 124:1572–1595. https://doi.org/10.1029/2018JF004837

US Geological Survey (2024) USGS 12082500 Nisqually River near National, WA, in USGS water data for the nation: U.S. Geological Survey national water information system database. https://doi.org/10.5066/F7P55KJN

Vallance JW (2024) Lahars: Origins, Behavior and Hazards, Springer International Publishing, Cham, pp 347–382. https://doi.org/10.1007/978-3-031-48691-3_12

Vallance J, Sisson T (2022) Geologic field-trip guide to volcanism and its interaction with snow and ice at Mount Rainier, Washington. US Geological Survey Scientific Investigations Report 2017-5022-A. https://doi.org/10.3133/sir20175022A

Publisher's Note