APPENDIX C. IMPLEMENTATION OF REAL-TIME SURFACE MONITORING FOR ACTIVE LANDSLIDES

Note that this appendix contains the Project 2020 STIC & SPR807 Supplement Memorandum Submitted by Andrew Senogles, Michael J. Olsen, and Ben A. Leshchinsky in August 2021 to ODOT and the FHWA. Minor updates have been made.

1.1 ABSTRACT

The sudden, rapid, and overwhelming movement of landslides can result in significant consequences to highways. On-site instrumentation is essential to understand and quantify the kinematics of landslides and to predict movement that can disrupt the highway system. However, the standard methodology for instrumentation to understand kinematics requires costly drilling beneath the earth's surface—which is neither safe nor possible in an active landslide. This project showcased the implementation of low-cost, innovative surface monitoring efforts. Specifically, this surface monitoring used surface geospatial monitoring technologies (Real Time Kinematic Global Navigation Satellite System, RTK-GNSS) to monitor landslide movement. Using this methodology, several sensors for remote monitoring were located throughout the slide surface, which can then be monitored remotely. Implementation of RTK-GNSS monitoring at an active landslide for analysis of landslide behavior can inform statewide application for monitoring active slides that impact infrastructure where drilling is unsafe, impracticable, or even impossible.

1.2 INTRODUCTION

1.2.1 Problem Statement

The sudden, rapid, and overwhelming movement of the Hooskanaden landslide greatly disrupted traffic along US 101 in Curry County during Spring of 2019. Alarmingly, numerous, very large landslides similar to Hooskanaden exist throughout the State that can result in similar consequences resulting from yearly rainfall or coastal erosion, such as the Arizona Inn landslide. On-site instrumentation is essential to understand and quantify the kinematics of landslides and to predict movement that can disrupt the highway system. However, the standard methodology for instrumentation to understand kinematics requires costly drilling beneath the earth's surface—which is neither safe nor possible in an active landslide. This project showcased the implementation of low-cost, innovative surface monitoring efforts. Specifically, this surface monitoring used surface geospatial monitoring technologies (Real Time Kinematic Global Navigation Satellite System, RTK-GNSS) to monitor landslide movement. Using this methodology, several sensors for remote monitoring were located throughout the slide surface, which can then be monitored remotely. Implementation of RTK-GNSS monitoring at an active landslide for analysis of landslide behavior will inform statewide application for monitoring active slides that impact ODOT infrastructure where drilling is unsafe, impracticable, or even impossible.

1.2.2 Objectives of the Study

Currently, long-term geotechnical monitoring of active landslides is not cost-effective. However, by using a rapidly deployable system of RTK GNSS units, we may leverage real-time data to monitor slide movements without the concern of losing instrumentation under significant ground distress. Such a system would enable high temporal resolution for landslide velocities with increased spatial resolution by deploying several nodes throughout the landslide mass. Supplemented with change detection using high-resolution lidar and photogrammetric techniques, which are already ongoing as a part of ODOT Research Project SPR807, we can quantify change at high spatial resolution. Thus, we may corroborate slide movement vectors between GNSS units, which can better quantify the movement in both horizontal and vertical directions. Tasks include: 1) deploy RTK-GNSS units across an active coastal landslide; 2) use current and past monitoring by ODOT to estimate slope failures and erosion, and include acquisition of a second round of drone lidar to assist in validation (terrestrial acquisition of coastal bluff is no longer safe); 3) create framework and guidance for determining slide dynamics; and 4) based on landslide RTK-GNSS testing and validation, provide recommended guidance.

1.2.3 Scope of Work

For this effort, the research team completed the following tasks:

1. Plan instrumentation coverage in consultation with ODOT,
2. Acquire, assemble, and install instrumentation at Arizona Inn. (Note that additional sensors were installed at Hooskanaden through a supplement to SPR 807),
3. Analyze the data acquired from the sensors in conjunction with other data collected for SPR807 including terrestrial laser scanning, drone lidar, etc.,
4. Present a framework for using RTK-GNSS to capture slide dynamics, and
5. Provide recommended guidance for deployment and provide demo of results to ODOT personnel.

1.2.4 Background

Monitoring plays an essential role in understanding and mitigating active landslides. Prior to performing any mitigation efforts on an active landslide, it is important to develop an understanding of the characteristics of failure and movement. This often involves the drilling of boreholes and installation of inclinometers and piezometers. This can provide useful information about the landslide including the rate of movement, depth of the shear plane, and groundwater table. However, the benefits gained from drilled instrumentation come with several drawbacks. For one, drilling boreholes can be prohibitively expensive, with mobilization costs in the $1000's, drilling costs of range of $50-100 per foot, and instrumentation costs. Further, drilling can take several days to complete a single hole and is often not feasible while moving significantly. Lastly, the instrumentation installed can often shear after only several centimeters of movement, precluding further subsurface monitoring and recovery of expensive instrumentation.

These limitations support the use of supplementary surface monitoring in addition to drilling to characterize subsurface landslide conditions. Further, surface monitoring techniques may also provide insight into relative landslide movement, thus serving as a method of prioritization between different sites for further investigation, a means of monitoring surficial movement at relatively fast-moving landslides where the shear depth is already known from previous exploration, understanding landslide movement at higher temporal resolution, and as an early warning system for a site adjacent to valuable infrastructure.

Other methods of tracking landslide surficial movement without drilling can be split into surveying methods and instrumentation methods. Survey methods include those that require an expert surveying practitioner as well as specialized equipment to be on the site, these include, but are not limited to: Terrestrial laser scanning (TLS) surveys, Survey monument monitoring (Total station or GNSS), UAS (Unmanned aircraft systems) based surveys (photogrammetric or lidar). The use of these methods for monitoring both landslides and coastal erosion is studied in more detail as part of the SPR807 research project and the reader is referred to the interim report (and future final report) for further reading. In general, survey methods allow for very high-resolution geospatial monitoring of landslides; however, they are limited in terms of temporal resolution since they require an expert survey practitioner to physically visit the site to perform the survey.

Instrumentation methods include permanently installed instrumentation that can be used to monitor a landslide without the need for drilling a borehole. These include, but are not limited to: GNSS observations on monuments, Robotic Total station monuments, extensometers, terrestrial radar, and RTK-GNSS systems, which is the subject of this memorandum.

GNSS observations on monuments can be used to monitor surface displacement by making frequent satellite observations. These data can then be transferred to an external online machine and processed using a variety of GNSS processing techniques including DGNSS (differential GNSS), and PPP (Precise point positioning). These systems can enable near continuous tracking of landslide displacement; however, the actual measurement frequency depends on personnel, power, and data transfer constraints. Because they require an online connection to transmit data, somewhat high data transfer rates, and complex post processing are necessary in order to create useable displacement data.

Robotic total stations can be used to monitor displacement of prisms setup throughout the area of interest. This allows for precise measurements to be repeated throughout the day in order to accurately track deformation. Robotic total stations have previously been used to monitor foundation deformation (source), bridge deformation. Tradeoffs of robotic total stations are that the total station is required to be setup on a stable area (or setup of additional prisms on stable area), the total station must maintain complete line of sight with each prism, prisms must stay clean to prevent measurement error, and lastly power consumption is high requiring a large power source.

Extensometers are a practical, common surface monitoring technology; however, they must be placed both on and off the active landslide, which may not always be evident. Further, standard extensometers do not provide a vectorized direction of movement, but rather a total displacement without knowledge of direction.

RTK-GNSS systems can also be used to monitor landslide surface displacement by using online DGNSS techniques with a local base station. This system has the advantage of allowing for continuous monitoring data, while not requiring line of sight to the base station, or a high-power consumption. With the advent of low cost multi constellation and multi frequency band GNSS receivers this has become significantly more affordable in recent years and as a result has become an increasingly popular method to monitor landslides (Šegina et al, 2020; Hamza et al, 2021).

1.3 SYSTEM OVERVIEW

The low cost RTK-GNSS solutions assessed in this project is a custom-built system consisting of installing a base station and multiple rovers at each of the landslide sites. These devices used a local RTK network to compute the position of each of the rovers relative to the base (referred to as a baseline vector). For a comprehensive overview of how RTK GNSS works, the reader is referred to key textbooks and other resources on the topic: e.g., Hofmann-Wellenhof et al, 2007; Van Sickle, 2015; or Teunissen & Montenbruck, 2017. Only a brief summary is provided below.

An RTK-GNSS network can be used to compute the relative position of a rover GNSS receiver to a base GNSS receiver in real time achieving accuracies typically in the range of a few centimeters (Allahyari, et al. 2018; Jamieson, 2019). The GNSS base receiver logs pseudoranges (i.e., approximate distances) it receives from each visible satellite and uses those to estimate its position. It then compares this estimated position to its "known" coordinates and computes a correction for each epoch of time (typically at 1 Hz). These correctors are then broadcast to the GNSS rover receiver to adjust its position relative to the base. The primary error source present in the pseudoranges originates from variations in travel times due to changes in velocity as waves travel through the ionosphere which has highly variable activity. However, there are also other systematic errors such as satellite clock bias, orbital error, etc. If the assumption is made that the base and rover are sufficiently close (within 10's of kilometers), then these errors in the rover position will be nearly identical to the errors in the base receiver given their proximity and similar satellite constellation. As a result, the GNSS rover receiver can utilize differential processing to cancel out relative errors in the measurements and therefore precisely derive its relative position to the GNSS base receiver.

There are several steps in this processing in order to arrive at precise coordinates. One step is to derive the carrier phase ambiguity, which can be thought of as the integer number of cycles of the carrier wave between the satellite and the receiver. Using this method, errors derived from the satellite clock bias, satellite orbital error, and both ionospheric and tropospheric delay can be accounted for; however, it is important to note, that while these error sources can be assumed to be identical for both the GNSS base and rover receivers, in actuality, they degrade as the distance between the base and rover increases. While RTK-GNSS can be used to correct for the aforementioned errors, it cannot be used to correct for error sources that are not the same at both the rover and the base. Such error sources may include multipath from objects blocking satellite visibility, and antenna/receiver noise, etc. Once the position of the GNSS rover receiver relative to the GNSS base receiver, or baseline, is known, the coordinate of the rover in a global coordinate system can be calculated by adding the baseline coordinates to the known coordinates of the base receiver within the global coordinate system while accounting for relevant geodetic or map projection principles.

In the low cost RTK-GNSS solution assessed in this project, the base station broadcasts RTK correctional messages to the rovers every 30 minutes for a defined period of time. Each of the rovers then use these messages to compute their average relative position to the base for each 30-minute interval. A standard deviation is also computed as a measure of precision to help determine the quality of the coordinates. The position of each rover is then transferred back to the base via a radio link and uploaded to cloud storage via a cellular modem at the base station. This system allows for precise and relatively high frequency monitoring of a landslide at a relatively low cost. Since the system is not in the ground, it is also robust to high rates of displacement unlike more traditional in ground measurement systems such as inclinometers. Hence, it is ideal for long term monitoring of fast-moving landslides.

1.3.1 Hardware Overview

GNSS-RTK monitoring solutions usually consist of the following main components:

1. GNSS Receiver
2. GNSS Antenna
3. Radio/ other telemetry
4. Computer
5. Power source
6. Data Transfer/Storage

The following sections provide a brief explanation of each of these main units, considerations in selecting components, and a discussion of how they interlink.

1.3.1.1 GNSS Receiver

The GNSS receiver is one of the most important (and expensive) components in any RTK-GNSS system. The GNSS receiver decodes the GNSS signals that the GNSS antenna receives from each of the satellites and generating observational messages for each of the satellites/frequencies. In some cases, the GNSS receiver also resolves the rover locations using RTK techniques, as described above.

When selecting a GNSS receiver to use it is important to consider features such as: the constellations it can receive (e.g., GPS-US, Glonass-Russia, Galileio-European Union, BeiDou-China, etc.), the signal bands it can receive (e.g., L1, L2, L5, etc.), noise filtering present, and much more. In recent years there has been a drastic reduction in cost of high quality GNSS receivers; as a result, many dual frequency, multi constellation receivers are now available within the price range of hundreds of dollars.

1.3.1.2 GNSS Antenna

The GNSS Antenna receives the signals broadcast from each of the GNSS satellites, performs some basic noise filtering, and passes this signal to the GNSS receiver. When selecting a GNSS Antenna, similar features to the receiver should be considered and matched with the receiver to maximize performance such as the number of constellations/signal bands it can receive. Many antennas are designed to reduce multipath by adding features such as choke rings or ground planes, which if properly implemented can increase performance. In addition to using a high quality GNSS Antenna, a high-quality coaxial cable that is as short as possible with the correct impedance should be used to connect the GNSS Antenna to the receiver in order to minimize noise.

1.3.1.3 Radio / other telemetry

Telemetry between the base station and rovers is required in order for devices to be able to communicate including broadcasting the correctional RTK messages. This can be achieved by using a local radio network. In the US this can be broadcast on either the 900MHz or 2.4GHz unlicensed frequency bands. As a rule of thumb, lower frequency bands generally provide a greater broadcast range with the tradeoff of lower bandwidth.

The radio system should comprise of a matching radio antenna and radio receiver, which perform much in the same way as the GNSS antenna / receiver described above. The antenna should match the receiver both in impedance and frequency. The distance/line of sight (LoS) between the base station and rovers determines the power/frequency of the radio required.

1.3.1.4 Computer

RTK-GNSS systems require a computer on which to perform any mathematical operations, timings/synchronization, and organization of communication/data storage. In general, RTK – GNSS sensors do not require high performance computer by today's standards; therefore, a standard microcontroller/microprocessor should provide adequate performance.

When selecting a computer for a RTK-GNSS system, numeric precision for computation, serial communication protocols, peripherals, and hardware timing are all factors that should be considered.

1.3.1.5 Power Supply

RTK-GNSS systems require a constant low noise input power source in order to achieve best performance. Since landslides are predominantly situated in rugged remote terrain this can be non-trivial. As a result, in-place RTK-GNSS power supplies usually consist of a battery to store energy, and an energy harvesting device such as a solar panel to generate power.

When designing a power supply system, the system should be designed for the worst conditions likely to be experienced. For example, a solar panel capable of providing enough energy during the lowest light winter months (late December in the northern hemisphere) should be selected. Solar panels should also be orientated to maximize energy harvesting during this time. Care should also be taken to select a suitable battery chemistry for the expected temperature range of the system to prevent poor battery performance or battery failures.

1.3.1.6 Data Transfer/Storage

In order to access and use data collected by a RTK-GNSS system, a subsystem should be implemented to store/transfer the data for human access. Data can be stored/manually retrieved on an SD card or similar device. Data can also be transferred to an online database via Wi-Fi or cellular network if either are available at the site. Another alternative if no cellular network is available is to use a satellite network such as the iridium network (https://www.iridium.com/); however, this option is significantly more expensive than the other data transfer methods.

1.3.2 Data Access Overview

In order to be able to access and view the data in real time, the RTK-GNSS sensor can be fitted with a cellular or other data transfer modem. The modem allows the base station to upload the data from each of the rovers to an online database. The cloud database can serve as an access point to the data in order to allow for the data to be viewed from any location in the world with an internet connection. In addition, data can be further processed in the cloud utilizing the more powerful compute available compared to directly onboard the RTK-GNSS sensor. This system can be used perform tasks such as coordinate transformations, data filtering, emergency detection/alerts etc.

In 2023, Dr. Andrew Senogles of Espion4D LLC was subcontracted to develop a Microsoft Azure-based system for access to the sensors. The user guide, scripts, and MS-Excel sheet for viewing are provided with this report as a digital appendix. Note that this system will be refined with an improved interface in SPR878.

1.4 INSTALLATION PROCESS

This section contains a brief overview of the planning and installation process for RTK-GNSS sensors including site selection, rover/base location, and installation considerations.

1.4.1 Pre-Installation planning

1.4.1.1 Determining Site Feasibility

The performance of RTK-GNSS sensors will vary substantially depending on the site. For example, landslides covered with dense forest canopy are less suitable compared with landslides with open/grass cover. Before installing these systems at a landslide site, it is important to consider the following factors to determine the feasibility of such a system as well as the optimal potential locations within the landslide to install the systems.

Sky Visibility

For best performance, any system that relies on GNSS measurements should be placed with a clear, unobstructed view of the sky. Installing the systems under dense tree canopy will likely lead to multipath and degradation of the satellite signals that will reduce the accuracy of the GNSS and thus the amount of displacement that can be confidently measured will increase.

In addition, obstructed sky visibility such as dense tree canopy will likely result in casting shadows over the system. If the system is powered via solar energy, this may diminish energy harvesting, especially considering that even partial shade can dramatically reduce power output of a solar panel (Sathyanarayana et al, 2015). This can be offset by installing larger solar panels, or using an alternative energy source, but nonetheless should be considered if installing in a shaded environment.

Base Location considerations

Because this system utilizes a local RTK network, the rovers are fundamentally measuring the baseline (distance) between the base station and rover stations. Therefore, to correctly measure the displacement at each of the rover stations due to landsliding, it is essential that the base station remains stationary with respect to the landslide. Shifts in the position of the base station will introduce bias in the baseline measurements that must be corrected for in order to isolate the displacement due to landsliding at the rover stations. The location of the base station should periodically be checked to verify that no movement has occurred.

It is also important to consider the relative distance between the base station with respect to the rover stations for a couple of reasons. As discussed in Section 1.3, as the baseline distance between the base station and the rover stations increase, error sources such as the tropospheric delay will begin to diverge, reducing measurement accuracy. In addition, when using radio telemetry, it is important to keep the base station in relative LoS (line of sight) with the rover stations in order to maintain a strong connection between the stations. Objects in-between the stations can degrade radio signals resulting in missed data packets, intermittent connections, or complete loss of link. In general, dense objects, such as buildings and terrain will degrade the signal faster than sparse objects (e.g., fences, trees, and other vegetation). To overcome such obstacles, a higher power radio could be used, assuming battery/power source is also sufficiently increased. Lower frequency radios in general have a greater range; however, they also have a smaller bandwidth (amount of data that be transferred per time interval).

Another consideration for choosing the base location is the internet connectivity available at the site. The system used in this project utilized a cellular LTE network to upload data in real time; however, if no such network is available then alternative data transfer methods could be utilized such as satellite telemetry, or even manual data backup from personnel who periodically visit the site.

1.4.2 Installation

1.4.2.1 Base/Rover locations

When selecting a location for the base/rover stations within the landslide body, in addition to determining locations that will captures the landslide kinematics, one should consider several additional factors which may have an impact on the performance/longevity of the RTK-GNSS system. As discussed in Section 1.4.1.1, the sky visibility should be considered if possible when dialing in the specific location for a base / rover station. Accessibility should also be considered, including how personnel will transport the required materials to the site for installation and maintenance. If possible RTK-GNSS systems should be discreet/kept out of view from the public eye in order to reduce the chances of vandalism/theft.

1.4.2.2 Mounting Considerations

RTK-GNSS systems should be mounted in a manner that limits movement of the GNSS antenna with respect to the movement of the landslide. Depending on the surface material present at the specific site location, this can be achieved in many ways. Readers are referred to the guidelines provided by NGS and UNAVCO on setting up GNSS monuments for CORS stations (NGS, 2018; https://www.unavco.org/instrumentation/monumentation/types/types.html; https://kb.unavco.org/kb/article/unavco-resources-gnss-station-monumentation-104.html; Combrinck & Schmidt, 1998).

In ideal scenarios, RTK-GNSS systems would be mounted to bedrock on the surface of the landslide by installing a steel or other rigid post within the rock using concrete or epoxy. Alternatively, a deep anchor post can be used if bedrock is not available. In a less ideal setting, RTK-GNSS systems can be installed via a small footing in unconsolidated material, if this setup is performed, then the user should be aware that movement detected by the RTK-GNSS sensor may include surficial creep in addition to any landslide movement.

Bracing can be used in windy locations to provide additional rigidity although comes with the tradeoff of additional material/labor costs. In all settings, the GNSS Antenna should be mounted sufficiently high to reduce/prevent multipath in order to increase accuracy but also sufficiently low that the antenna does not oscillate from wind on the pole. The radio antenna should also be installed sufficiently high in order to increase antenna performance. Typically 1-2 m is optimal.

If possible, vegetation surrounding the RTK-GNSS sensor should be removed in order to reduce multipath and prevent any shadows being cast on the solar panel (if applicable). Users should consider the construction of fence to mitigate humans or wildlife from disturbing the RTK-GNSS monument, an example fence as setup at the Hooskanaden Landslide is shown in Figure C-1.

In addition, care should be taken during the installation process to ensure adequate weatherproofing to maximize device longevity.

Figure C-1: Photograph of the fence constructed around Rover 3 at the Hooskanaden landslide in order to keep livestock from disturbing the station.

1.5 CASE STUDIES

In order to test the viability of low cost RTK-GNSS systems for monitoring landslide displacement. The above described system was installed at two problematic landslide sites on the southern Oregon coast (Arizona Inn and Hooskanaden landslides). These sites were selected for the following reasons:

1. These sites are known, fast-moving landslides in Oregon that currently cause disruption to HWY 101.
2. These landslides have previously been instrumented with in-ground systems that failed/sheared due to the rapid displacement.
3. These sites are currently monitored as part of the SPR807 project, and thus data from that project can be used to validate data received from the RTK-GNSS systems.

1.5.1 Site Overviews

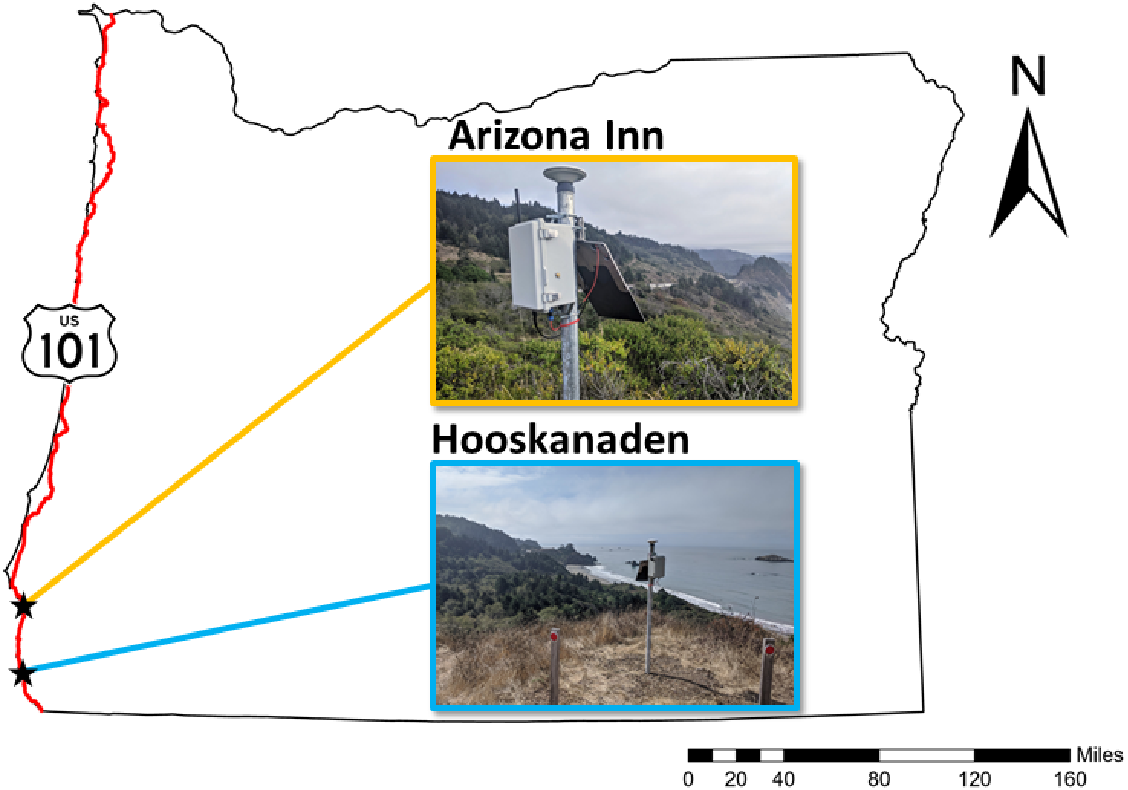

Figure C-2: Overview map showing the location of the two test sites (Arizona Inn & Hooskanaden) within the state of Oregon.

1.5.1.1 Arizona Inn

The Arizona Inn Landslide is located approximately 14.5 miles north of Gold Beach between Hwy 101 Mileposts 315 and 316 (Figure C-2). The landslide area of interest extends south from lookout rock about 650m and extends landward around 350m from Hwy 101. Moving landward, the site extends from a narrow sandy beach to a cobble/boulder beach about 10m wide before reaching a sea cliff around 50m in height. The sea cliff is sparsely vegetated at its base and more heavily vegetated towards the top where Hwy 101 sits. East of Hwy 101, the landslide extends up slope covering a steep grassy slope approximately 120m in height, and 600m wide.

Arizona Inn experienced a major failure event in 1993, closing Hwy 101 for 2 weeks (Squier et al, 1994). Aside from rapid failures, Arizona Inn exhibits creep style mass movement that results in small, but appreciable movement that builds up over time. Larger, more pronounced movements generally correlate with large rainfall events, similar to many landslides throughout western Oregon (Squier et al. 1994).

Arizona Inn's geology consists of approximately 45˚, southwest dipping, Humbug Mountain Conglomerate from the Elk Subterrane of the Western Klamath terrane that was deposited during the Lower Cretaceous (McClaughry et al. 2013). Towards the coast this deposit is overlain by anthropogenic landslide deposits. Below the Humbug Mountain Conglomerate there is Colebrooke Schist from the Pickett Peak terrane from the Upper Jurassic. At this location Elk subterrane has been thrust on top of the Pickett Peak terrane. This is evident from the thrust sheet window present at higher elevations to the east (McClaughry et al, 2013) as well as core logging conducted along the landslide. The south extent of the landslide is bounded by a planar shear surface that forms the north face of a large rock mass that forms the headland in the south, which also bounds the landslide below the ground (Squier et al. 1994).

A total of 1 base station and 4 rovers were installed at the Arizona Inn landslide (Figure C-3**)**. The base station is located on the ridge leading up to lookout rock, approximately 50m west of Hwy 101. This location was selected as it is a stable area thought to be experiencing no ground deformation. This location also has clear sky visibility, allowing for uninterrupted GNSS satellite visibility maximizing the potential accuracy of the system. Lastly, this area is in a relatively high elevation overlooking the rest of the landside body, which allows for uninterrupted broadcast of radio messages for communication with the rovers. A photograph of the Base station and overview of the landslide is shown in Figure C-4.

Below is a description of the four rovers installed at the site:

- **Rover 1** is situated approximately 30m north of the cistern previously installed during the 1990's to collect water from the horizontal drain arrays throughout the upper landslide body. This location was chosen as it is directly above a failing section of the sea cliff and centered within a lower block of the main landslide mass that appears to be the most active region of the landslide. A MEMS in-place inclinometer (consisting of Measurand Shape Accel Array (SAA) systems) and piezometer sensors were previously installed at this location from Feb 2017 to March 2019 and showed a total of 80mm of displacement during that time, approximately half of which occurred during 2019 just prior to the instrument shearing.
- **Rover 2** is situated approximately 110m east/upslope from Rover 1, directly uphill from Hwy 101. This position was chosen as it is approximately located at the head scarp of the previously described lower block. This also coincides with being centered between the two most active crack forming locations on Hwy 101 at this landslide. In combination with Rover 1, this Rover allows for constraining of the landslide movement on this section of Hwy 101 without placing a sensor directly on Hwy 101, which would be infeasible.
- **Rover 3** is situated approximately 220m east/upslope of Rover 2, toward the upper end of the main landslide. This location was chosen in order to monitor any displacement in the upslope portion of the landslide.
- **Rover 4** is situated approximately 450m north of Rover 1, and 70m west of Hwy 101 in the northern portion of the landslide. This location was chosen in order to monitor any erosion driven displacement in the northern portion of the landslide complex.

Figure C-3: Map of the Arizona Inn Landslide showing the location of the RTK-GNSS base and rover stations.

Figure C-4: Photograph of the base RTK-GNSS station at Arizona Inn overlooking the rest of the landside to the south.

1.5.1.2 Hooskanaden

The Hooskanaden landslide is located approximately 13 miles SSE of Gold Beach, just north of milepost 344 on Hwy 101 (Figure C-2). The study area at this location extends from the intersection of Hooskanaden Creek and Hwy 101 NNW around 850m and from Hwy 101 around 450 m E-SE to the coast. Moving landward, the study area extends from a wide pebble/cobble beach to a coastal sea cliff around 10m high in sections. On top of the sea cliff, a heavily vegetated landslide extends landwards around 400 m W-NW horizontally and 60m vertically before running into Hwy 101.

The Hooskanaden landslide has always challenged Hwy 101. Despite poor fill soil availability on the southern Oregon Coast, constructors recognized the site as unstable and built an embankment with a culvert, rather than a bridge, over the adjacent Hooskanaden Creek. While Carpenterville Road, unsigned Oregon Route 255, presents a potential alternate route to Hwy 101 during road closures at the Hooskanaden slide, the road routinely suffers from landslides causing single lane or entire road closures during the winter season. Even during other seasons, the road is steep, narrow, and has sharp curves, meaning that travel is slow and not feasible for some highway traffic (e.g., large trucks, RVs, or small passenger vehicles). Recently, beginning on February 24th, 2019, the Hooskanaden landslide experienced a dramatic surge in movement, with horizontal displacements up to 45m closing Hwy 101 for almost two weeks and reducing it to a single lane for almost 2 months (Alberti et al, 2020), inspiring further monitoring and analysis.

The geology of Hooskanaden is composed of Marine Sedimentary rocks from the Late Cretaceous period. This includes the Cape Sebastian sandstone as well as the Hunter Cove Formation (which includes sandstone, shale and conglomerate) (Ramp et al, 1977). The south side of the landslide is loosely bounded by a SE-NW running fault that cuts along the ridgeline extending NW from the Hooskanaden Creek-Hwy 101 intersection (Ramp et al, 1977). Within the landslide the Marine Sedimentary rocks previously mentioned have been heavily displaced and intermixed from various fault and shear zones existing in the area (Mohney & Raker, 2004).

A total of 1 base and 6 rovers were installed at the Hooskanaden landslide (Figure C-5). The base station is located on a solid ridge on the NW side of the landslide, 75m SW of Hwy 101. This location was chosen, as it is known to be relatively stable from regular TLS surveys performed at the landslide going back to 2016 for SPR807. This location also has excellent sky visibility and overlooks the rest of the landslide body providing excellent LoS to all of the six rover positions (Figure C-6).

Below is a description of each rover:

- **Rover 1** is located approximately 55m SW of HWY 101, on the southern portion of the landslide. This location was chosen as during the February 2019 surge, this location experienced the most displacement (approximately 45m). Even prior to the February 2019 surge, this portion of the landslide experienced relatively rapid displacement. In December 2017, MEMs (consisting of Measurand Shape Accel Array (SAA) systems) and piezometer sensors were installed. These sensors only lasted 42 days before shearing, during which they recorded over 150mm of displacement.
- **Rover 2** is located approximately 230m ESE of Rover 1, and 150m ENE of Hwy 101, on the southern portion of the landslide. This location was chosen to monitor displacement further up slope, in order to help constrain the total displacement above the road.
- **Rover 3** is located approximately 140m NE of Rover 2, further upslope, on the southern portion of the landslide. This location was chosen to monitor displacement on the ablating portion of the landslide.
- **Rover 4** is located approximately 135m NWN of Rover 1, on the northern portion of the landslide. This location was chosen to monitor displacement of the northern portion of the landslide. In the past, the northern portion of the landslide has experienced less overall movement.
- **Rover 5** is located approximately 375m SW of Rover 1, on the southern portion of the landslide, just inland from the beach. During the February 2019 surge event, the beach experienced dramatic uplift of up to 6m. This rover location was selected to monitor any subsequent activity in this area.
- **Rover 6** is located approximately 195m NEN of Rover 4, and 125m NE of Hwy 101, on the northern portion of the landslide. This location was chosen to monitor displacement of the landslide upslope of the highway in the northern portion of the landslide.

Figure C-5: Map of the Hooskanaden Landslide showing the location of the RTK-GNSS base and rover stations and approximate extent of the most active portion of the landslide.

Figure C-6: Photograph of the base RTK-GNSS station at Hooskanaden looking south overlooking the bottom portion of the landside.

1.5.2 Example Results

A network of the RTK GNSS sensors were installed at each of these sites during September of 2020 following the installation process outlined in section 1.4. All of the installed sensors were active during the 2020/2021 winter season (with exception to the outages reported in Section 1.5.3) and are still currently active as of the writing of this report (August 2021). The active sensors reported their positional coordinates relative to the base station at a 30 min interval along with measurement precision, and other relevant metrics. Each coordinate reading was taken from a 3-minute RTK observation period. This data was compiled in an online database as outlined in Section 1.3.2. This data can be used to perform various analyses in order to quantitatively describe the landslide kinematics at a high temporal resolution. A brief analysis of each site is performed in the section below using the data gathered over the “active” winter 2020/2021 period.

1.5.2.1 Arizona Inn

Figure C-7 shows the overall horizontal displacement and Figure C-8 shows the overall vertical displacement of Rovers 1 through 4 at Arizona Inn, from installation September 2020, through to the writing of this report (August 2021). These results show that Rover 1 experienced the most horizontal displacement during the time period with just over 22cm and -7cm of horizontal and vertical displacement, respectively. Rover 2 experienced 15cm horizontal and -15cm vertical displacement, which is the largest vertical displacement observed at the site. Rovers 3 & 4 experienced negligible amounts of displacement. Several data outages were experienced at this site. These outages, including causes and repairs are discussed in Section 1.5.3.

The displacements presented in Figure C-7 & Figure C-8 are calculated by using a weighted moving window average for each 24-hour period, resulting in a single coordinate for each rover for each day. The standard deviation for the observations for each 30-minute coordinate were used for the weights. For the daily coordinates, error bars are shown based on the standard deviations computed for those coordinates from the multiple GPS observations acquired throughout the day. These were typically on the order of 0.5 cm. Using a weighted average increase measurement precision from redundant observations while providing an estimate of measurement uncertainty, resulting in more reliable and readable data for each of the RTK-GNSS stations within the site.

In addition to plotting the displacement of each rover over time, the velocity of each rover can also be observed in order to visualize landslide activity at each of the rovers across time (Figure C-9).

Figure C-9 shows the peak horizontal velocity for Rover 1 was approximately 2.25mm/day during mid-February compared with approximately 1.5mm/day for Rover 2 during the same time. The peak in velocity at Rover 2 appears to have occurred about a week after the peak in velocity at Rover 1, which would indicate retrogressive failure; however, the date outage that occurred before this time period makes this difficult to confirm. Rovers 3 & 4 moved too slowly to confidently register a positive velocity reading. Overall, the propagated measurement standard deviations can be used as uncertainty estimates and show that for this RTK-GNSS system/site a velocity uncertainty of approximately 1mm/day is achievable.

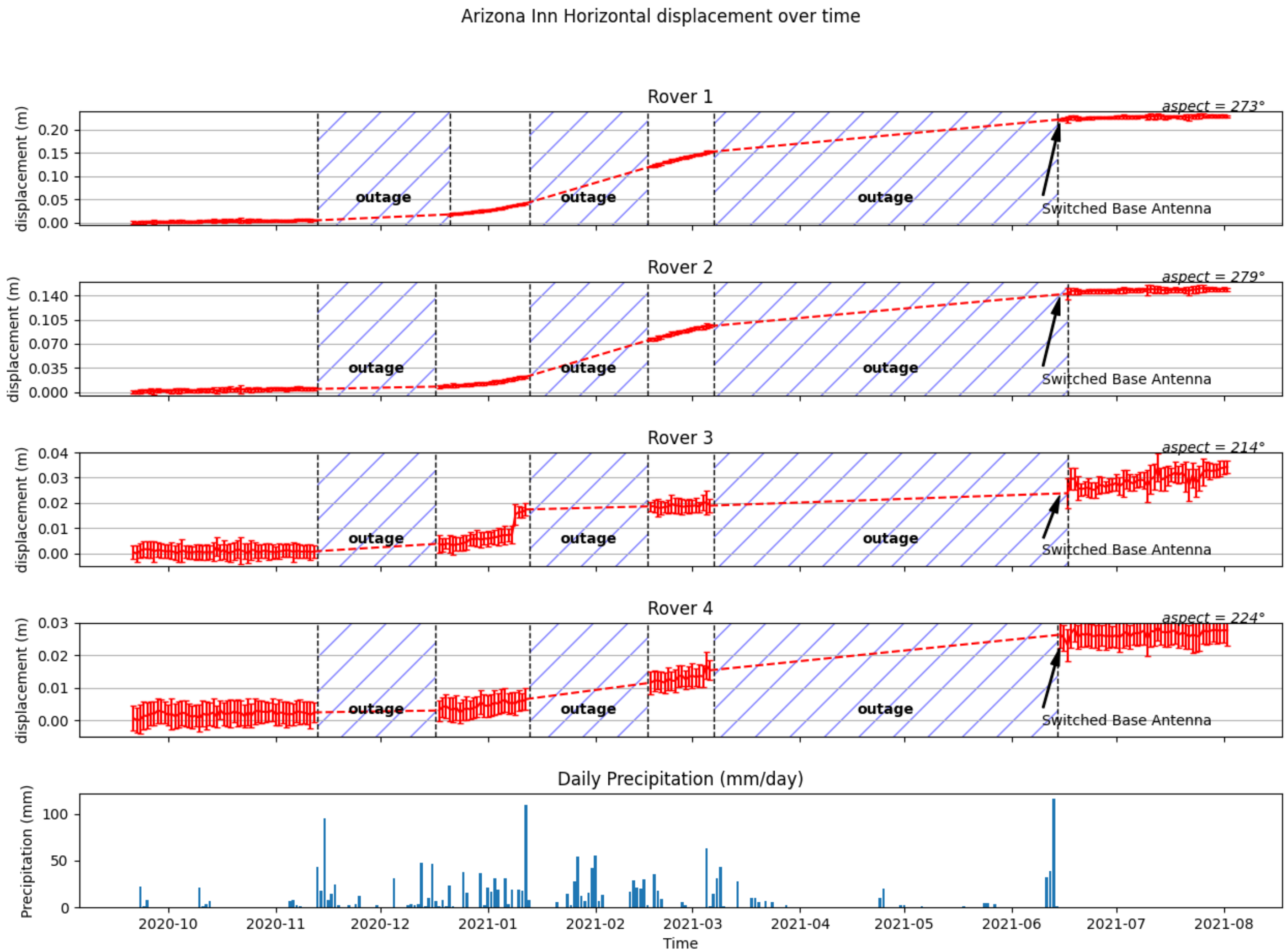

Figure C-7: Graph of daily Horizontal Displacement over time for each rover at the Arizona Inn landslide from September 2020 to the beginning of August 2021. Error bars represent the standard deviation of daily measurements. The bottom graph shows histogram of the daily precipitation in mm during the same time period. Data outages are represented by the hatched area and dashed line.

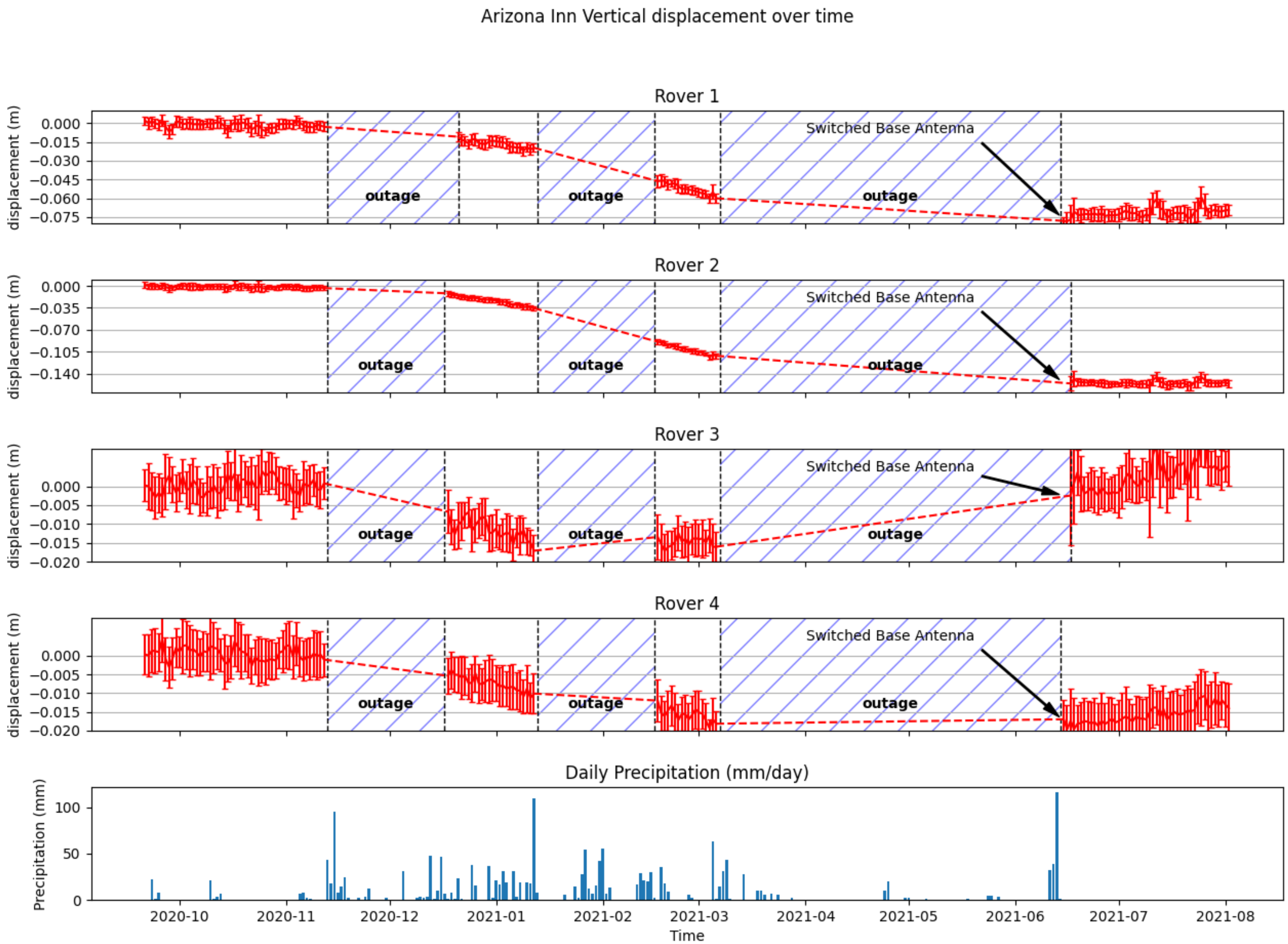

Figure C-8: Graph of daily vertical displacement over time for each rover at the Arizona Inn landslide from September 2020 to the beginning of August 2021. Error bars represent the standard deviation of daily measurements. The bottom graph shows histogram of the daily precipitation in mm during the same time period. Data outages are represented by the hatched area and dashed line.

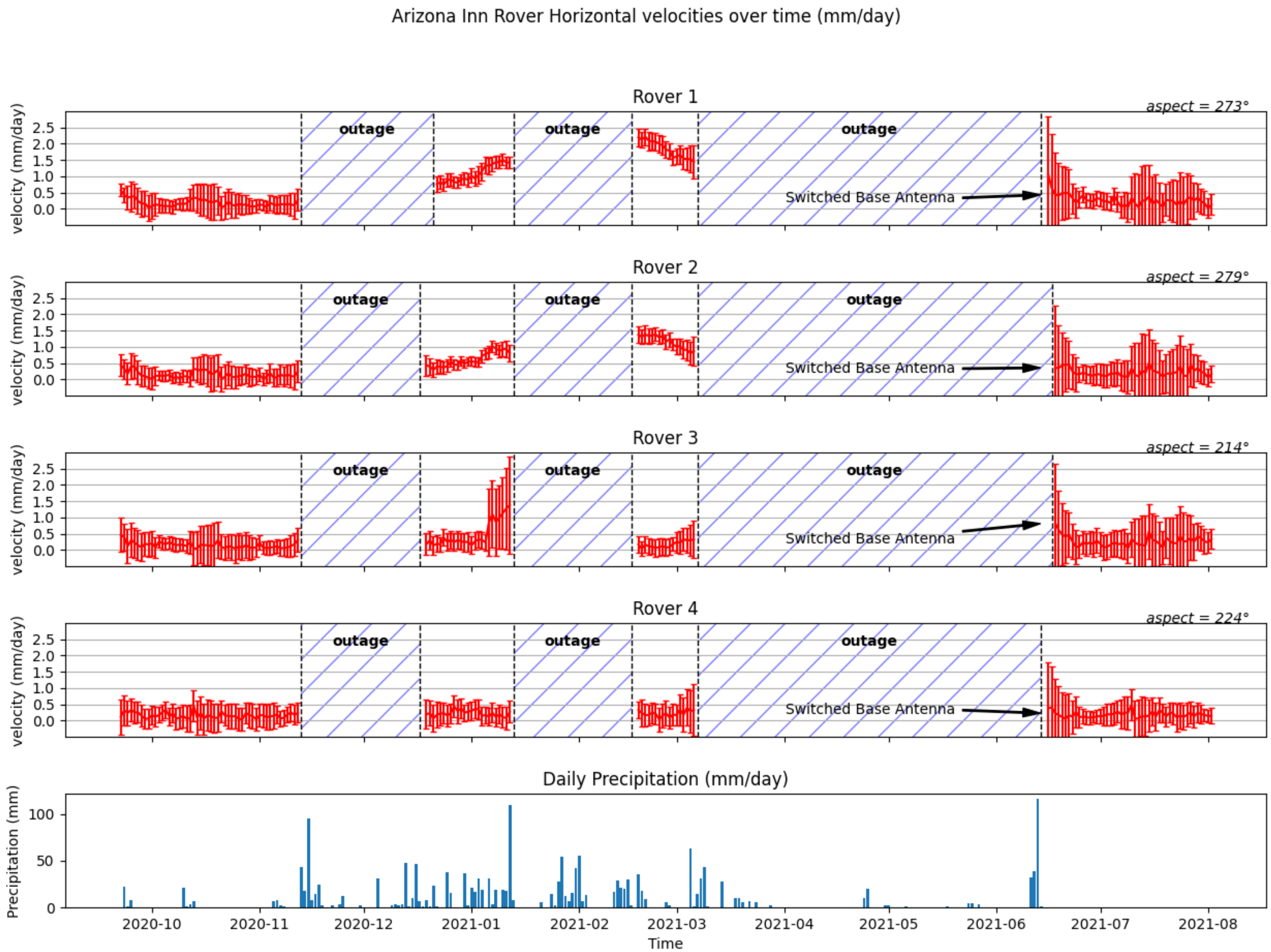

Figure C-9: Graph of Rover Horizontal velocities over time for each rover at the Arizona Inn landslide from September 2020 to the beginning of August 2021. Error bars represent the standard deviation of velocity calculations. Bottom graph shows histogram of the daily precipitation in mm during the same time period. Data outages are represented by hatched area.

1.5.2.2 Hooskanaden

Figure C-11 shows the overall horizontal displacement and Figure C-12 shows the overall vertical displacement of Rovers 1 through 6 at Hooskanaden, from installation in September 2020, through to the early August 2021. These results show that Rover 1 experienced the largest displacement during the time period with a 4.7cm and -0.8cm of horizontal and vertical displacement, respectively. Rovers 2 and 3 experienced the second and third largest displacements during the time period, with 4.4cm/-0.3cm and 4.1cm/-1.2cm of horizontal and vertical displacement, respectively. Rovers 4 and 6 experienced the fourth and fifth most displacement with 2.6cm/-0.8cm and 1.0/-0.8cm of horizontal and vertical displacement respectively. Rover 5 experienced negligible/no displacement. Data outages experienced at this site are discussed in Section 1.5.3.

Rover 6 at this site used a lower cost GNSS Antenna (Ublox Ann-mb-00) compared to the GNSS Antenna used at the other rover stations (Harxon GPS600). To give an idea of the achievable accuracy of these rovers, the min, max, and average daily standard deviation values for each rover for the full installation period are shown in Table 4 1. This shows that the average daily standard deviation of the lower cost antennas is 6.5mm vs 2.7mm – 3.7mm for the more expensive antenna. Figure C-10 also shows a typical day of readings taken from rover 2.

Table C-1: Maximum, minimum and average daily standard deviation for each of the GNSS - RTK rovers at the Hooskanaden landslide.

Rover #	Min (mm)	Max (mm)	Average (mm)	Antenna make/model
1	1.8	5.2	2.8	Harxon GPS600
2	2.5	6.7	3.7	Harxon GPS600
3	2.3	6.3	3.5	Harxon GPS600
4	1.9	4.9	2.7	Harxon GPS600
5	1.9	10.0	3.0	Harxon GPS600
6	4.5	10.4	6.5	Ublox Ann-mb-00

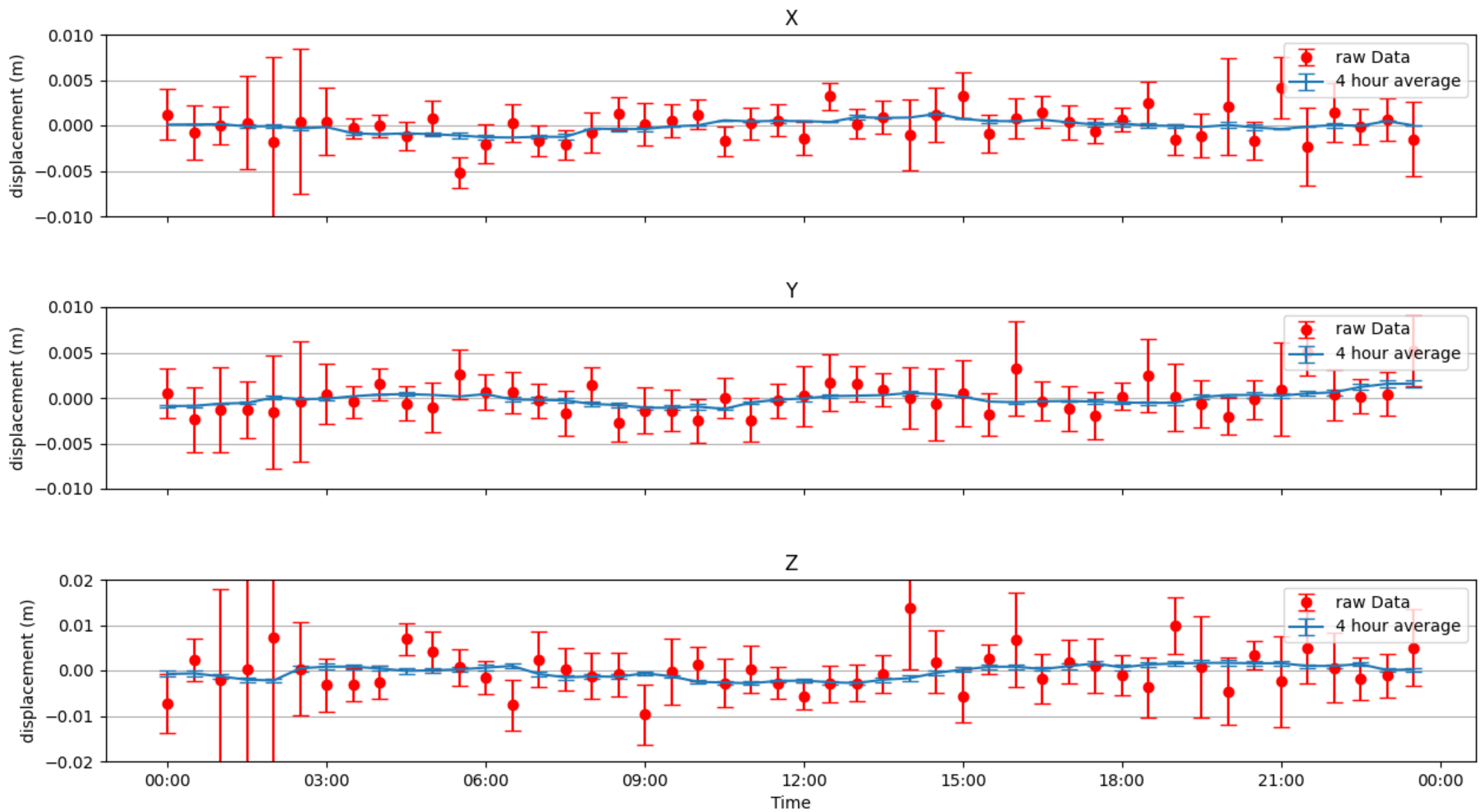

Figure C-10: Typical day of measurements produced by the RTK-GNSS system installed at Hooskanaden Rover 2 for each component of the baseline.

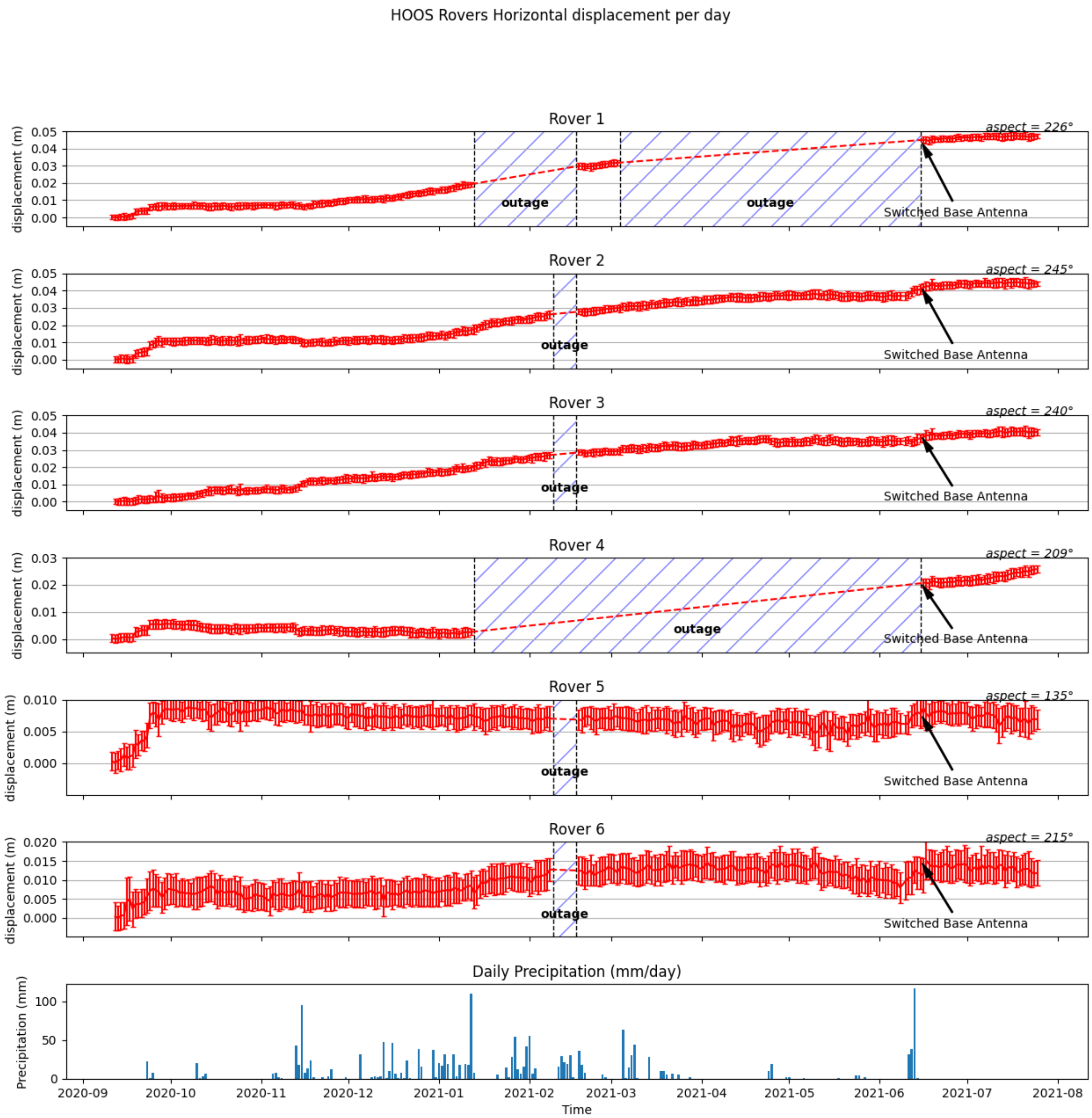

Figure C-11: Graph of Horizontal Displacement over time for each rover at the Hooskanaden landslide from September 2020 to the beginning of August 2021. Error bars represent the standard deviation of daily measurements. The bottom graph shows histogram of the daily precipitation in mm during the same time period. Data outages are represented by the hatched area and dashed line.

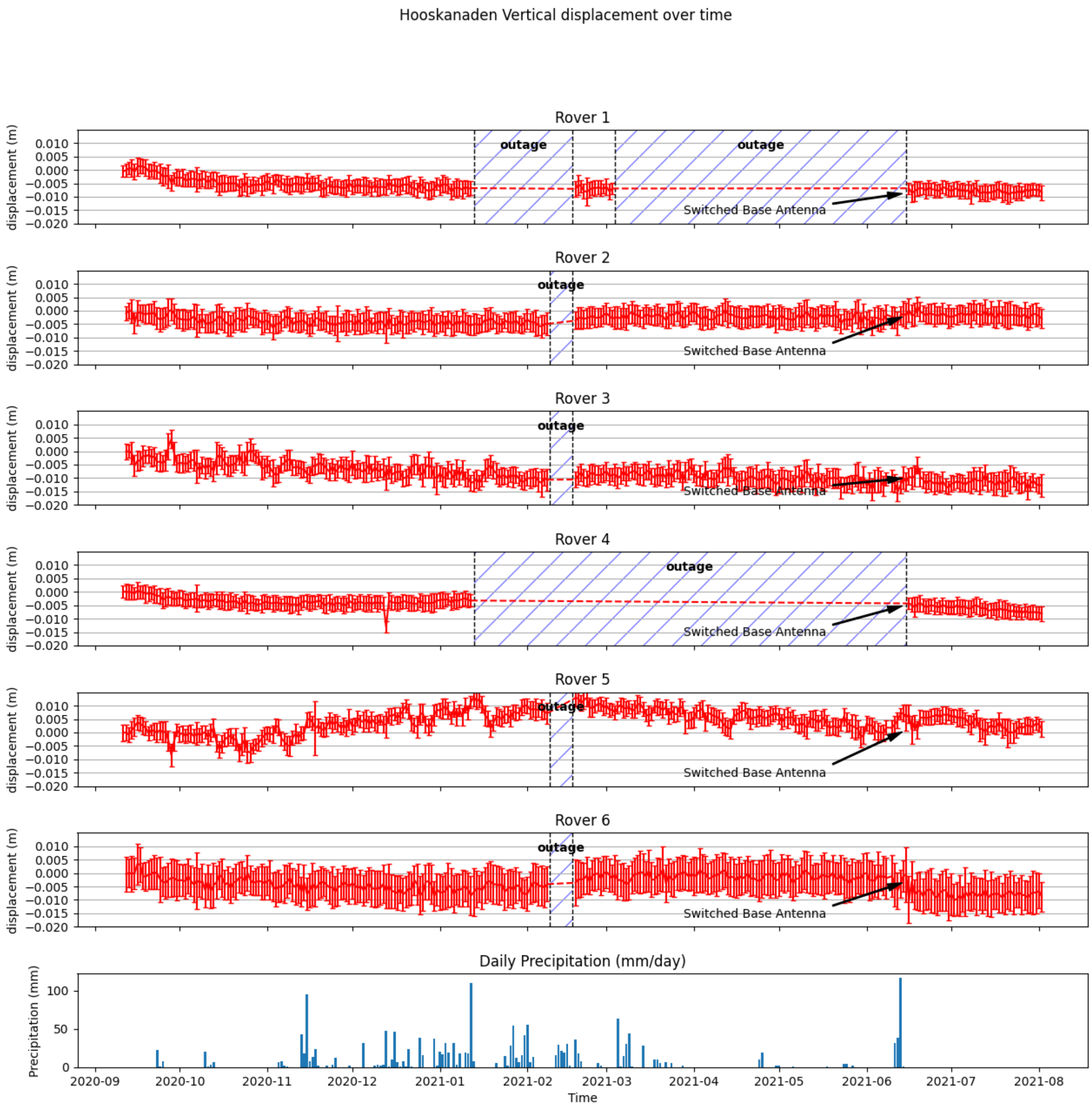

Figure C-12: Graph of Vertical Displacement over time for each rover at the Hooskanaden landslide from September 2020 to the beginning of August 2021. Error bars represent the standard deviation of daily measurements. The bottom graph shows histogram of the daily precipitation in mm during the same time period. Data outages are represented by the hatched area and dashed line.

In addition to visualizing the displacement and velocity of each rover graphically, the data can be visualized spatially within the landslide as shown in Figure C-13. This allows for the relative movement of each rover representing the landslide kinematics to be visualized within the context of the landslide at a high temporal frequency. Comparison of surface movements at Hooskanaden show a clear convergent, high-velocity area associated with earthflows (e.g. rovers 1 and 2), as well as an extensional (rovers 3 and 6) and compressive (rover 5) zones. These data can be corroborated with other surface movement data sources such as lidar, UAS photogrammetry or total station measurements and used in combination for more advanced landslide modelling techniques.

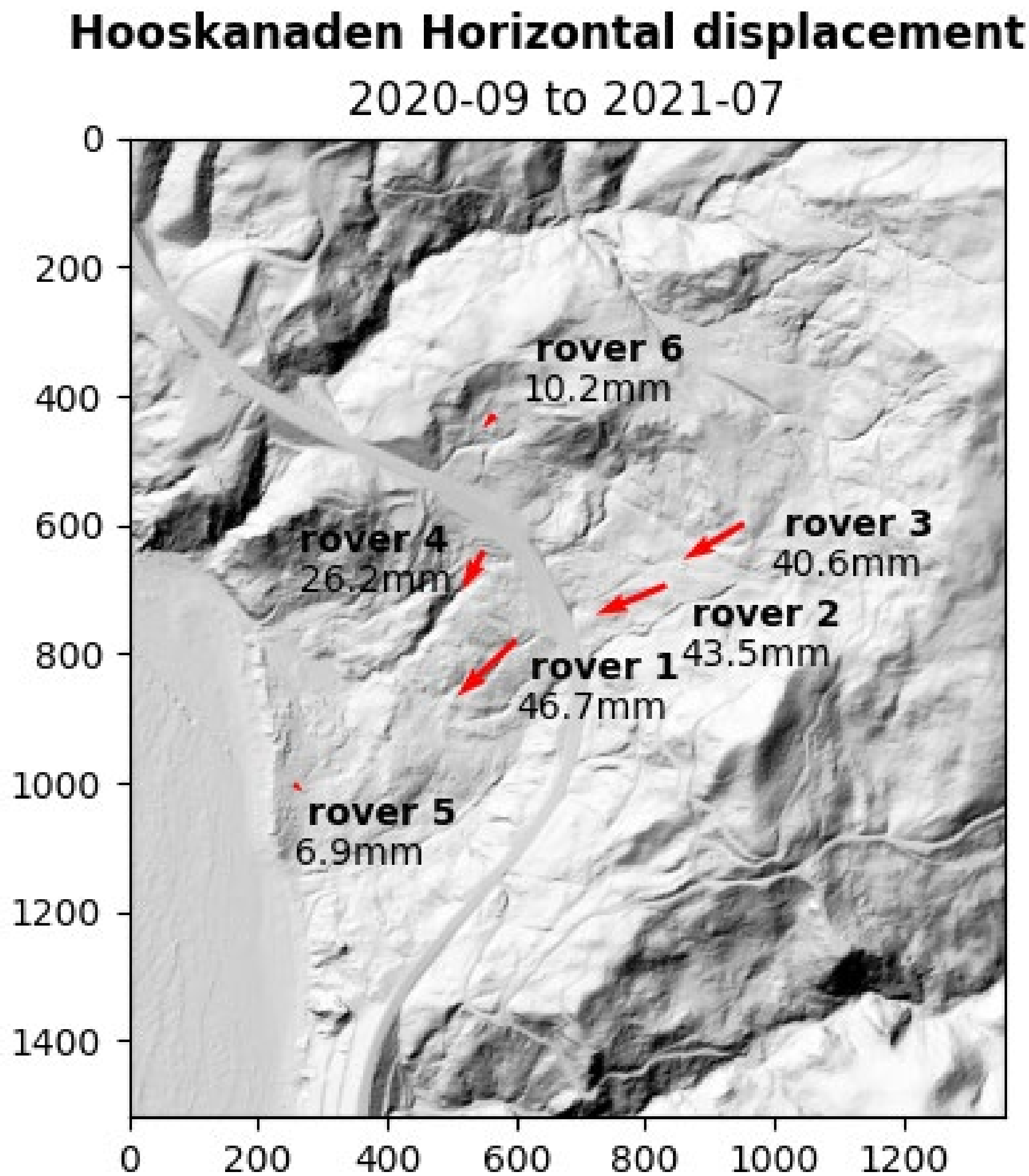

Figure C-13: Map of the Hooskanaden landslide with the overall horizontal displacement from September 2020 to July 2021 for each rover plotted as quiver plot. Vectors are exaggerated at 1:2500 scale. Lidar hillshade basemap from the Oregon Lidar Consortium.

1.5.3 Problems Encountered

Throughout the installation process there were several system failures that resulted in temporary data outages of the systems. An overview of these outages is displayed for Arizona Inn in Table C-2 and Hooskanaden in Table C-3.

Table C-2: RTK-GNSS system outages that occurred at the Arizona Inn landslide including rovers affected, cause of outage, and starting/ending dates.

Outage #	Rovers affected	Cause of outage	Date starting	Date Ending
1	All	Base Radio failure	11/13/2020	12/21/2020
2	All	Base Radio failure	01/13/2021	02/16/2021
3	All	Base GNSS Antenna failure	03/07/2021	06/15/2021

Table C-3: RTK-GNSS system outages that occurred at the Hooskanaden landslide including rovers affected, cause of outage, and starting/ending dates.

Outage #	Rovers affected	Cause of outage	Date starting	Date Ending
1	Rover 1	GNSS Antenna mount failure	01/13/2021	02/17/2021
2	Rover 4	GNSS Antenna mount failure	01/13/2021	06/16/2021
3	All	Base GNSS Antenna failure	02/09/2021	02/17/2021
4	Rover 1	GNSS Antenna failure	03/04/2021	06/16/2021

The first two data outages at Arizona Inn were the result of a loose connection between the radio receiver and the rest of the system at the Base station, this resulted in an outage at the whole site as no correctional data was broadcast to the rest of the rovers. This outage likely occurred due to vibrations caused by abnormally high winds (gusts up to 90mph) preceding both outages. This loose connection was temporarily fixed in December 2021 and then permanently fixed on February 16th 2021. Hence, it should not present further problems at this site. Damage to the solar panel also occurred during this time (shearing of mounting nuts due to wind), and the original nylon nuts were later replaced with stainless steel nuts to prevent this from repeating in the future.

The third outage across the Arizona Inn site resulted from the failure of the Base GNSS Antenna immediately following a large wind/rain storm. It is hypothesized that the antenna experienced water damage from the rainfall. Although the GNSS antenna initially used had an IP67 rating, it was replaced with an alternative GNSS antenna model on June 15th 2021 rated higher as IP69k, which should provide better durability to rain as well as vibrations caused by wind.

The first two data outages at Hooskanaden resulted from the GNSS Antenna mount snapping at Rover Station's 1 & 4 and thus only affected those two rovers. This occurred during the same wind/rain storm as the Arizona Inn Outage #2. The third outage at Hooskanaden was due to the failure of the Base GNSS Antenna and resulted in an outage at the whole site. The GNSS antenna failure occurred following a large wind/rain storm. The base station GNSS antenna was replaced with the GNSS antenna from rover 4 on the 17th of February restoring operation to the rest of the rovers. The GNSS antennas at Rover 1 was also remounted; however, that unit later failed again and was determined to be a faulty antenna. As with the Arizona Inn Base Antenna, the base station GNSS antenna at Hooskanaden was replaced with an alternative IP69k GNSS antenna model on June 16th 2021. The GNSS antennas at Rovers 1 & 4 were also replaced at this time, fully restoring the network.

As a precaution against future wind events, the GNSS Antenna mounts at all stations at both sites were also replaced with a sturdier version on June 15th/16th 2021 to prevent the failures that occurred at Hooskanaden's Rover 1 & 4 from happening again during upcoming winter storms.

1.6 CONCLUSION AND RECOMMENDATIONS

In conclusion, this work explains the use cases and potential benefits of RTK-GNSS monitoring systems applied to landslides. This includes background information on landslide monitoring techniques as well as an overview of how RTK-GNSS systems function. This work also provides an overview of the necessary architecture for constructing a RTK-GNSS system as well as useful considerations for both determining the site feasibility and planning and performing the site installation. Lastly, this work presents the results of having this system installed at two known landslides in Oregon for a one-year period as a proof of concept and shows the analysis results of the collected data. Some retrofits were made to the systems as a result of damages from abnormally strong winds to avoid future damage.

This study shows that low cost RTK-GNSS systems are a viable solution to real-time landslide surface monitoring at two different sites in Oregon. In addition to monitoring, such sensors would likely be very useful to ODOT on understudied landslides as a low-cost, preliminary exploration method of data collection in order to inform future instrumentation plans and/or plan site prioritization. These systems are also effective for monitoring fast moving landslides where the shear surface is well-constrained from past exploration efforts and a need for keeping track of the landside activity is desired.

In addition to the simple data visualization methods outlined above, RTK-GNSS data can potentially be used for a variety of more in-depth quantitative landslide analysis both on their own as well as in combination with other data sources such as lidar or photogrammetric data. These analyses can include any analysis that makes use of landslide surface displacement, velocity, acceleration etc. These were not covered within this project report as it is outside the scope of the evaluation of RTK-GNSS sensors.

Regardless of the landslide dynamics, the considerations outlined in section 1.4 should be assessed in context of the considered landslide prior to installing an RTK-GNSS sensor network. Landslides under dense tree canopy especially should be thoroughly thought through prior to installation due to the impact of sky visibility on RTK-GNSS sensor accuracy.

Lastly, using the framework established in this project, future work could develop an early warning detection system by identifying appropriate velocity thresholds to identify when major events are likely to occur.

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