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This report documents the research project "Research and Development for Avalanche Sensing." The primary goal of this research was to develop avalanche sensing and detection for a key Caltrans District 10 avalanche zone. Availability of this system will support avalanche start zone characterization and modeling, real-time avalanche detection and alerting, and optimal avalanche control operations. These capabilities will lead to safer winter roads with higher mobility, and will save the Department of Transportation money. The research included review of best practices for avalanche sensing and detection methods, models, and systems; and design and development of an avalanche zone instrumentation package. Sensing regimes investigated included snow depth across avalanche start zone, camera imaging, temperature, and wind speed and direction. The District 10 site (chute 4 of Carson Spur on State Route 88) is fully prepared for instrumentation with the bench-tested prototype. Final system installation, field testing, and analysis will occur in follow-up research.

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DISCLAIMER/DISCLOSURE STATEMENT

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, and the Division of Research, Innovation and System Information at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

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Advanced Highway Maintenance and Construction Technology Research Center

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Research and Development for Avalanche Sensing

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ABSTRACT

This report documents the research project "Research and Development for Avalanche Sensing." The primary goal of this research was to develop avalanche sensing and detection for a key Caltrans District 10 avalanche zone. Availability of this system will support avalanche start zone characterization and modeling, real-time avalanche detection and alerting, and optimal avalanche control operations. These capabilities will lead to safer winter roads with higher mobility, and will save the Department of Transportation money. The research included review of best practices for avalanche sensing and detection methods, models, and systems; and design and development of an avalanche zone instrumentation package. Sensing regimes investigated included snow depth across avalanche start zone, camera imaging, temperature, and wind speed and direction. The District 10 site (chute 4 of Carson Spur on State Route 88) is fully prepared for instrumentation with the bench-tested prototype. Final system installation, field testing and analysis will occur in follow-up research.

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LIST OF ACRONYMS AND ABBREVIATIONS

4G	Fourth Generation
AFRA	Avalanche Flow and Run-out Algorithm
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off-The-Shelf
DEM	Digital Elevation Model
EVDO	Evolution Data Only/Evolution Data Optimized
GIS	Geographic Information System
GPS	Global Positioning System
INS	Inertial Navigation System
Mbps	Megabits per second
NEMA	National Electrical Manufacturers Association
RF	Radio Frequency
SR	State Route
TIA	Telecommunications Industry Association
TIG	Tungsten Inert Gas

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CHAPTER 1:
INTRODUCTION

Problem

As discussed in the Caltrans 'Snow and Ice Control Operations Guide,' avalanches pose a substantial threat to the safety of the traveling public and Caltrans maintenance workers. Caltrans Division of Maintenance deals with avalanches in both proactive and reactive modes. Proactive maintenance includes installation of structures to mitigate avalanches, and avalanche control using guns, propane and oxygen gas explosion chambers (Gazex® cannons[1]), and other means to initiate "controlled avalanches". When avalanches occur, obstructing the roadway, Caltrans reacts by clearing the road with front-end loaders, graders, plow trucks, blowers, and other heavy equipment.

Caltrans performs avalanche control in several of its districts. The main goal is to reduce the number of naturally occurring avalanches, replacing them with controlled avalanches which are safer and easier to maintain. A key factor in efficient and effective avalanche control is having the best information to help maintenance personnel decide the right time to induce controlled avalanches.

This research project was originally intended to investigate and develop a GPS-based (Global Positioning System-based) driver assistance system to be used in clearing roads after an avalanche. As the initial task in this research and development, Advanced Highway Maintenance and Construction Technology (AHMCT) project researchers met with California State Department of Transportation (Caltrans) maintenance staff at the expected test site, Caples Lake, in District 10. In the ensuing discussions, it became clear that Caltrans Maintenance staff at Caples Lake did not see the need for such driver assistance following an avalanche. Further discussions identified more pressing issues related to preemptive avalanche control measures. A clear need was identified for detailed and automated avalanche sensing to support avalanche control. The necessary research and development were an excellent match for the existing research project team. As such, the project scope was modified to research, development, and deployment of an avalanche sensing system at a key mountain pass of interest to the Caples Lake maintenance yard—Carson Pass on State Route 88 (SR 88).

This research project developed avalanche sensing and detection systems and methodologies to support Caltrans avalanche control activities. The research included evaluation of related state-of-the-art and commercial systems, and guidance and assistance to Caltrans maintenance for site and operation-specific deployment. Sensing regimes investigated included snow depth across avalanche start zone, temperature, and wind speed and direction.

Overview of Research Results

The key deliverables of this project include:

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[1] http://www.tas.fr/en/products/prevention-of-avalanche

- Summary of best practices for avalanche sensing and detection methods, models, and systems (completed)

- Avalanche zone instrumentation and collected data (partially completed as discussed below)

- Final report (completed)

The current work builds on AHMCT's experience with winter maintenance, our strength in sensing and system integration, and our established mechatronic hardware and software base [8,14-16,29-31]. The research tasks included:

1. Formation of technical advisory group
2. User needs meetings with District 10 Maintenance
3. Revision of scope based on first user needs meetings
4. Search for available avalanche sensing, prediction, and detection methods, models, and systems
5. Identify most promising prediction, sensing, and detection models; update / enhance models if warranted
6. Provide guidance and assistance to Caltrans Maintenance for site and operation-specific deployment
7. Instrument one key District 10 avalanche zone, collect data for one snow season
8. Correlate data with prediction, sensing, and detection models
9. Documentation and reporting

The Carson Spur chute 4 site preparation is complete, including the sensor tower and the mounting bracket for the system electronics. The sensing system is fully designed, and the main hardware components have been procured. A lab test version of the complete system was implemented and tested in lab conditions. The system software is currently a lab-level implementation. It is not currently confirmed to be ready for field deployment. The enclosures and the communication methods are to be finalized. The system assembly, installation, data collection, and correlation of data with sensing and detection models will occur in future research.

Tasks 1-4, 6, and 9 were completed in this research. Due to the substantial challenges with site installation which could not be anticipated at the time of the research proposal, remaining tasks were partially executed. The site challenges are well-documented in this report, and must be accounted for in any similar future efforts. The status of the remaining tasks is addressed here.

A portion of Task 5 was not feasible to be completed due to insufficient power at the site. In Task 5, the researchers identified the model presented by Brun *et al.* [5] as showing the most promise and applicability for Caltrans' purposes. This model should be useful for operational avalanche forecasting, and is recommended should the appropriate data be available. The avalanche sensing system developed in our current research provides a substantial portion of the inputs for this model, specifically: air temperature, wind velocity, and snow depth (a partial proxy for snow precipitation). Laboratory testing of the research system indicated that sensing snow density, as required by the Brun model, would require power beyond what can be provided by wind energy. This sensing feature can be added to the system if local grid-level power becomes available at the site. The recommendation from Task 5 to Caltrans Maintenance is to use the substantial sensing data provided by this research system to augment the information currently used by the local expert Caltrans forecasters, in order to improve their ability to forecast avalanches, and to make more informed and optimal decisions for avalanche control. The data provided, even without snow density, is a significant advancement over what is currently available to Caltrans. Currently, the local experts have coarse general weather data, including average wind speed and direction, road level temperature, and current and prior general snowfall information. They have essentially no fine-grained, high temporal resolution data for the local conditions at any specific avalanche start zone. Such data will now be provided by the avalanche sensing system, allowing the significantly enhanced prediction and decision-making noted above.

A portion of Task 7 has not been completed due to the unexpected substantial challenges with site installation associated with the complex geology of the site. Experience gained during the research with the site has indicated that this portion of Task 7 requires additional time outside of the winter season in order to be completed. However, a major portion of this task has been completed, i.e. the tower that will support the sensing and power systems was installed on site, along with the mounting points for the sensing system power, computation, and communications components. These would pave the way for the remaining portion of this task to be completed in future work. With the system installation incomplete, no data was collected; hence Task 8 remains to be completed as well.

CHAPTER 2:
AVALANCHE SENSING AND DETECTION METHODS AND MODELS

Avalanche Sensing and Detection Methods

Bedard [4] investigated avalanche detection using atmospheric infrasound in the range 0.5-5.0~Hz. Dent *et al.* [7] developed density, velocity, and friction measurement methods for dry snow avalanches. Tiefenbacher and Kern [24] presented a large-scale chute that can produce avalanche-like flows in a reproducible manner, along with measurements of velocity and friction. McElwaine [19] overviews several snow sensing and analysis techniques, including a detailed look at optical velocity estimation with error analysis. Vilajosana *et al.* [26] presented use of 2D wireless accelerometers to characterize snow dynamics, and tests the sensors at a large-scale snow chute (see [24]). Gubler and Hiller [10] applied FMCW radar to sense the height of dense flow in avalanches.

Brun *et al.* [5] provided a model that shows promise for avalanche forecasting. The model uses inputs: air temperature and humidity, liquid and solid precipitation, wind velocity, net solar radiation, and long-wave incoming radiation. Armstrong and Armstrong [1] used a long-term weather and snow data set to characterize three individual snow climates in the western United States. Mock and Birkeland [20] developed a binary classification model to classify sites into three categories; the current test site is “coastal,” with abundant snowfall, higher snow densities, and higher temperatures. These characteristics affect the type of avalanche behavior, and thus influence the sensing approach to take.

Scott [23] applied Geographic Information System (GIS) technology and remote sensing to assess avalanche hazards for new road corridors in Alaska. He combined information from approximately seven sources to determine the key inputs for developing an avalanche hazard map: approximate slope angle and aspect; contour intervals; vegetation damage; snow pack characteristics such as cornice build up, avalanche debris, terrain traps, and possible run out zones; average winter wind direction; and snowpack averages.

Chang and Tsai [6] investigated the impact of Digital Elevation Model (DEM) resolution on mapping terrain slope and aspect angles. These are key factors in identifying potential avalanche zones and determining avalanche risk. Identification of an avalanche paths requires more topographic detail than for avalanche start zones, and therefore a higher-resolution DEM.

Gruber and Haefner [9] researched the combined use of DEMs and satellite imagery data to develop avalanche hazard maps. They noted that essential prerequisites include precise topographic information (altitude, slope angle and aspect, for example), which is only observable from a DEM. Hence, high-resolution DEMs of about the same spatial resolution as the satellite imagery are essential. The DEM is also needed for geocoding the satellite scenes and for feature extraction. For hazard mapping, exact geometric position of every image element is critical. Avalanche tracks are always situated in very steep terrain, where geometry is severely distorted in a satellite image. Geocoding requires reference points and a high-resolution DEM.

Vallet, *et al.* [25] developed a helicopter-based avalanche mapping system using aerial photogrammetry and GPS/INS (Global Positioning System / Inertial Navigation System). The system attained approximately 20 cm position accuracy, and 0.01° in attitude.

Wiesmann, *et al*. [28], Walsh, *et al*. [27], and Huggel, *et al*. [12] independently investigated aspects of satellite imagery data in developing avalanche hazard maps, assessing snow avalanche paths and forest dynamics, and evaluating extraordinary avalanche formation and mobility. There is general agreement among researchers that QuickBird satellite imagery was the best available satellite sensor in terms of ground resolution (0.6 m), and opened new perspectives for assessment of natural hazards [12]. Unfortunately, the QuickBird satellite orbit decayed[2], and the satellite reentered earth's atmosphere in January 2015. The last image was taken in December 2014. Image archives are available, and represent a useful source of information for avalanche research and development.

Avalanche Models

Avalanche models are typically divided into dynamic / physical models, and statistical models. Dynamic models attempt to model avalanches based on fundamental physical principles, such as friction, hydraulics, etc. Statistical models incorporate historical data and leverage them to predict avalanches through statistical methods including Monte Carlo simulations [21].

Dynamic Avalanche Models

Salm [22] provided an overview of his extended work in snow dynamics and modeling. This included updated concepts of risk related to avalanches. He indicated that so-called "hydraulic models—although not much is left from hydraulics—are best fit for a use in practice." The practical model parameters involved are Coulomb friction, Chezy resistance and angle of internal friction. As Salm indicated, these parameters must be calibrated from numerous field observations (different topography and climate, involved mass etc.). Salm concluded his discussion by citing the esteemed Malcolm Mellor: "It seems unrealistic and presumptuous to immediately seek complete generality when much simpler materials (than snow) are presenting formidable problems in other branches of solid mechanics. Elegant simplification of complicated behavior is very much needed!"

Jamieson, *et al*. [13] discussed the application and limitations of dynamic models as they relate to snow avalanche hazard mapping. They indicate that dynamic avalanche runout estimates can complement estimates from statistical models, historical records and vegetation damage, and are especially useful when some of these estimates are unavailable or of low confidence. The authors also discussed practical issues related to limitations of dynamic models involving friction coefficients, snow mass estimates, number of variables and dimensions, entrainment and deposition as well as flow laws.

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[2] https://en.wikipedia.org/wiki/QuickBird

Statistical Avalanche Models

Barbolini and Keylock [2] present a method for avalanche hazard mapping using a combination of statistical and deterministic modeling tools. The methodology is based on frequency-weighted impact pressure, and uses an avalanche dynamics model embedded within a statistical framework. The outlined procedure provides a useful way for avalanche experts to produce hazard maps for the typical case of avalanche sites where historical records are either poorly documented or even completely lacking, as well as to derive confidence limits on the proposed zoning.

McCollister, *et al*. [17] investigate multi-scale spatial patterns in historical avalanche data for Jackson Hole Mountain Resort in Wyoming. They present a probabilistic method that supports use of historical data by incorporating a GIS with a meteorological nearest neighbors approach. This approach uses concepts related to GIS visualization. The resulting interactive database tool allows the investigation of the relationships between specific weather parameters and the spatial pattern of avalanche activity.

In his M.S. thesis, McCollister [18] presents geographic knowledge discovery techniques for exploring historical weather and avalanche data; much of this work is summarized in [17]. The thesis presents probabilistic techniques that allow avalanche forecasters to better use weather and avalanche data by incorporating a GIS with a modified meteorological nearest neighbors approach.

Barbolini, et al. [3] present an innovative methodology to perform avalanche hazard mapping over large undocumented areas. The method combines GIS tools, computational routines, and statistical analysis to provide a semi-automatic definition of areas potentially affected by avalanche release and motion. The method includes two main modules. The first module is used to define zones of potential avalanche release, based on the consolidated relations on slope, morphology, and vegetation. For each of the identified zones of potential release, a second module, named Avalanche Flow and Run-out Algorithm (AFRA), provides an automatic definition of the areas potentially affected by avalanche motion and run-out. The definition is generated by a specifically implemented ‘‘flow-routing algorithm’’ which allows for the determination of flow behavior in the track and in the run-out zone. The method requires only a digital terrain model and an indication of the areas covered by forest as input parameters. The procedure, which allows rapid mapping of large areas, does not in principle require any site-specific historical information. Furthermore, the innovative avalanche hazard mapping methodology proved effective in all cases where a preliminary cost-efficient analysis of the territories potentially affected by snow avalanche was needed.

CHAPTER 3: INSTALLATION SITE

The selection of the installation site, along with its preparation, was an intensive and extended portion of the research effort. The site had to meet the requirements of Caltrans Maintenance personnel (sufficient number of incidents), and provide an installation location where it was feasible to install the avalanche sensing system, under the extremely challenging terrain conditions of Carson Spur. Ultimately, chute 4 of Carson Spur on SR 88 met both criteria. Details of the site and the selection process undertaken are provided in this chapter, including the tower and electronics bracket installation.

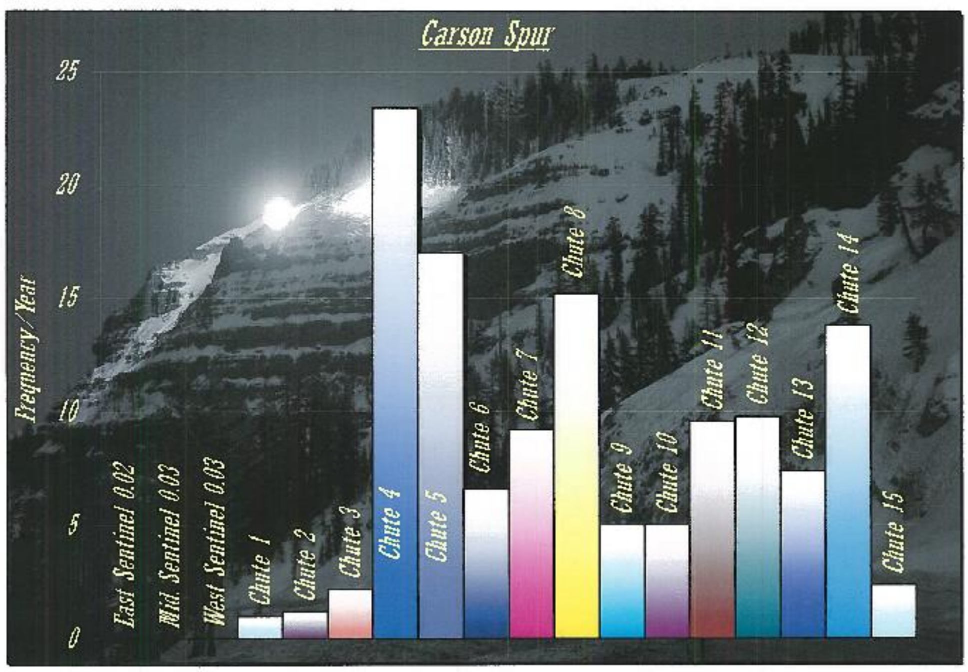

Figure 3.1: Typical number of avalanches per year per chute on Carson Spur at Caples Lake

The graph in Figure 3.1 shows the frequency of natural avalanches per season in a typical year. Figure 3.2 provides the approximate locations of the avalanche chutes diagramed on a Google satellite map facing the south. Upon initial investigation of the properties of Carson Spur and the surrounding areas, it was clear that a handful of chutes had a high frequency of avalanche occurrences. When investigating the possibility of developing a sensor system capable of measuring the characteristics of Carson Spur, the researchers decided, in conjunction with Caltrans Maintenance, that it would be best to select a location with high likelihood of avalanche events. Chutes 4, 5, 8, and 14 were surveyed, as they are the sites with the highest frequency of events.

Table 3.1: Number of avalanches per typical season for high-event chutes on Carson Spur

Chute	Avalanches
4	24
5	17
8	15
14	14

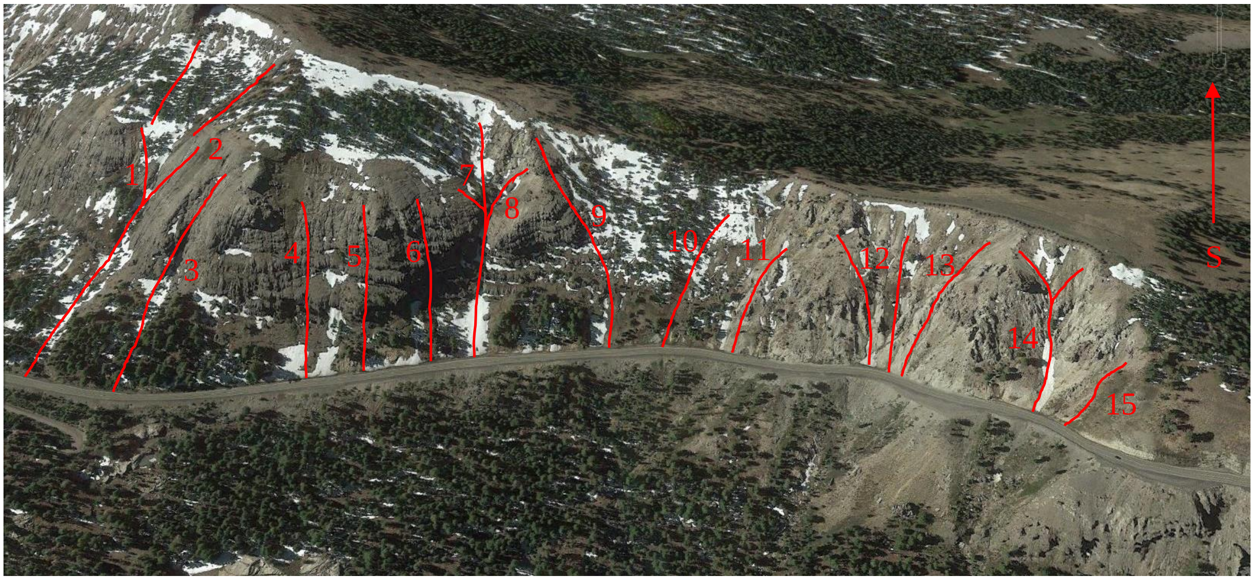

Figure 3.2: Carson Spur avalanche chute locations

Selection Criteria for a Suitable Chute Site for this Research

1. High number of seasonal avalanche events
2. Well-defined/understood snowpack locations
3. Accessibility for sensor station site
4. Installation feasibility for sensor station site
5. Survivability for sensor station
6. Sensor station range from measurement area
7. Chute interference from local features

8. Potential for impact on avalanche control operations

<u>Carson Spur Survey</u>

Figure 3.3: View of Carson Spur chute 4 from the roadway

Figure 3.3 shows the bottom of chute 4 from the roadway with its very wide exit from the bowl above and its direct path to the roadway below. This chute releases a very large amount of snow material on the roadway during an active avalanche, and has a very big impact on road operations and the travelling public. Starting at this location, Caltrans Surveys used stationary laser scanners to measure the entire face of Carson Spur as seen from the roadway below [11]. The intent of this laser scan data collection was to develop slope models of the various chute faces for the purposes of avalanche chute analysis and possible subsequent avalanche flow modeling.

Figure 3.4: Surveying from the roadway below Carson Spur chute 4

Figure 3.5: Surveying avalanche zones along Carson Spur with chute 4 in the distance and a Gazex cannon visible on the rock face

Figure 3.6: Surveying avalanche zones on Carson Spur with chute 4 in the distance

Shortly after the collection of the laser scan survey data of Carson Spur, AHMCT began post-processing of the data. Researchers immediately discovered that while the data was dense and detailed enough for slope modeling, the view from the roadway using the measurement equipment was not sufficient to capture the entire chute slope faces, despite the seemingly clear view shown in the figures above. Surveys did collect good data as viewed from many locations along Carson Spur, allowing for cataloging of all chutes in this area, but could only collect what was immediately visible from the roadway. Some chutes had more favorable slopes and allowed for measurements further up the rock face, while some were obscured due to steep slopes or trees. In general, it was possible to estimate slopes of features of the lower portions of the chutes, but not for the more important upper chute locations.

On-site inspections of each chute along the ridge of Carson Spur followed the initial laser scan survey. From the ridge, an observer can estimate the potential impact of each chute on the roadway below, as well as the features surrounding each of the locations and the areas of snow accumulation. Based on investigation of each of the locations along Carson Spur, chute 4 met the site goals for research. While it had the highest number of avalanche events per year, it also had a very well-defined snowpack collection area (or bowl), limited interference from nearby features, several potentially feasible sensor station installation sites, and site survivability. Overall, chute 4 would have a very large impact in the area of real-time avalanche monitoring. Many of the other chutes (5, 8, 14, etc.) had limitations such as less well-defined chutes in both geometry and interference from local features, less desirable sensor station locations, and overall sensor range issues.

Chute 4 Survey

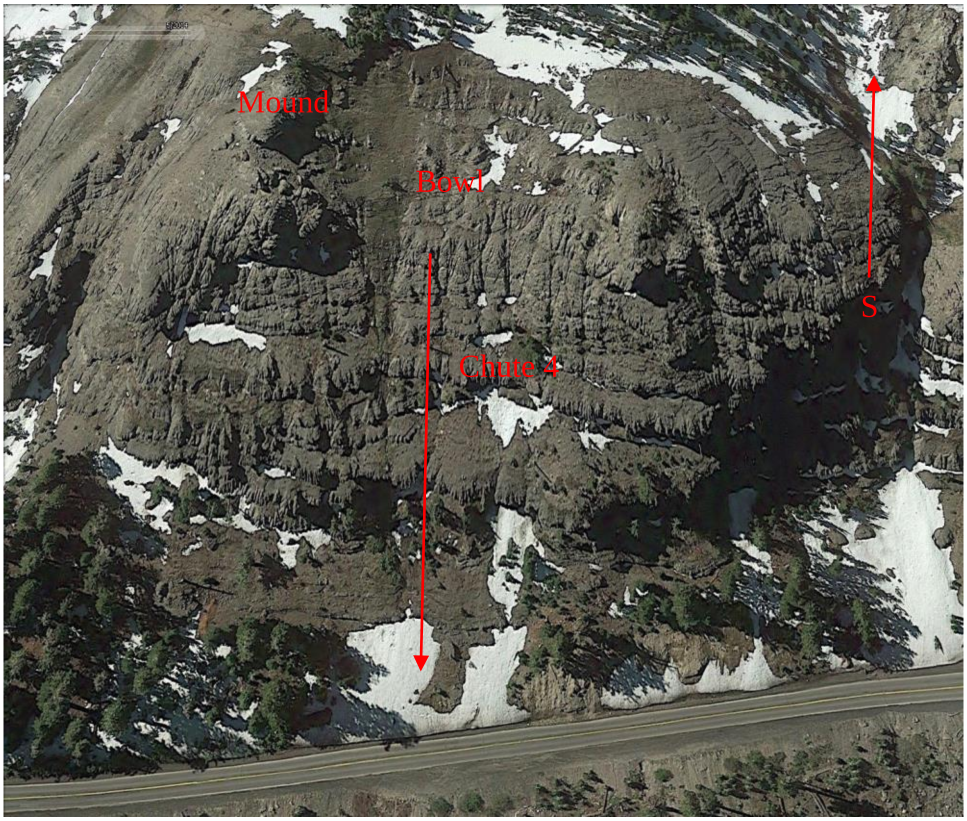

Figure 3.7: Satellite view of Carson Spur chute 4

Figure 3.7 shows the southward-facing Google satellite view of Carson Spur chute 4 above SR 88.

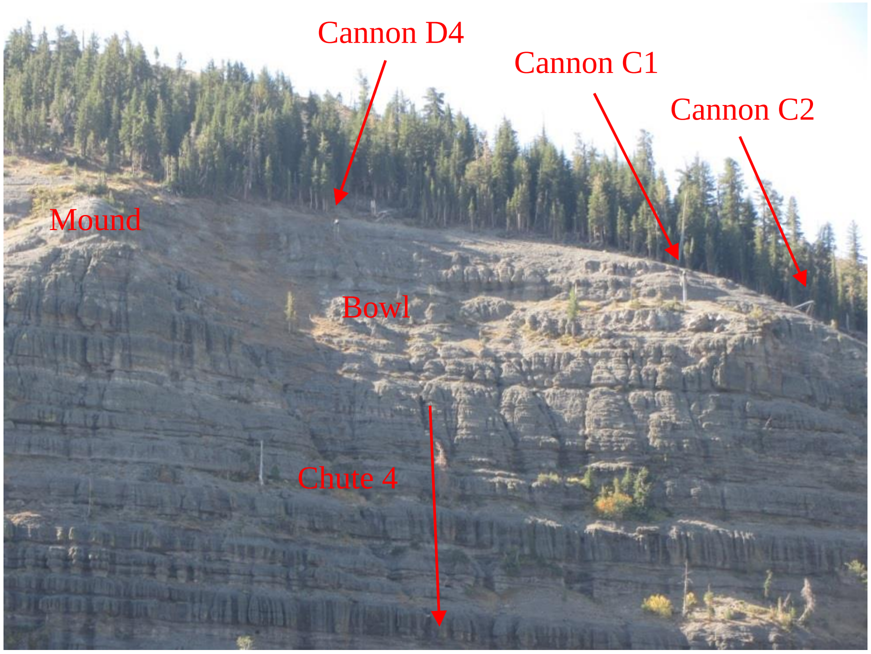

Figure 3.8: South-looking view of chute 4 bowl from the gun mount

Figure 3.8 shows the view from the gun mount across SR 88, where explosive projectiles were launched at the various chutes to dislodge snowpack build-up, before the installation of the many Gazex cannons. One can see the entirety of the chute 4 bowl that encompasses the area from the mound on the left, up along the bottom of the tree line, to the mound on the right, and down to the center of the picture. There is a Gazex cannon (D4) in the top center of the picture below the tree line and another (C1) on the right side of the bowl. Gazex cannons are used in place of traditional explosive projectiles to dislodge snowpack before an avalanche occurs, i.e. to provide a controlled avalanche. The cannons are filled with a propane-oxygen mixture and ignited to create a strong shockwave that starts a controlled avalanche.

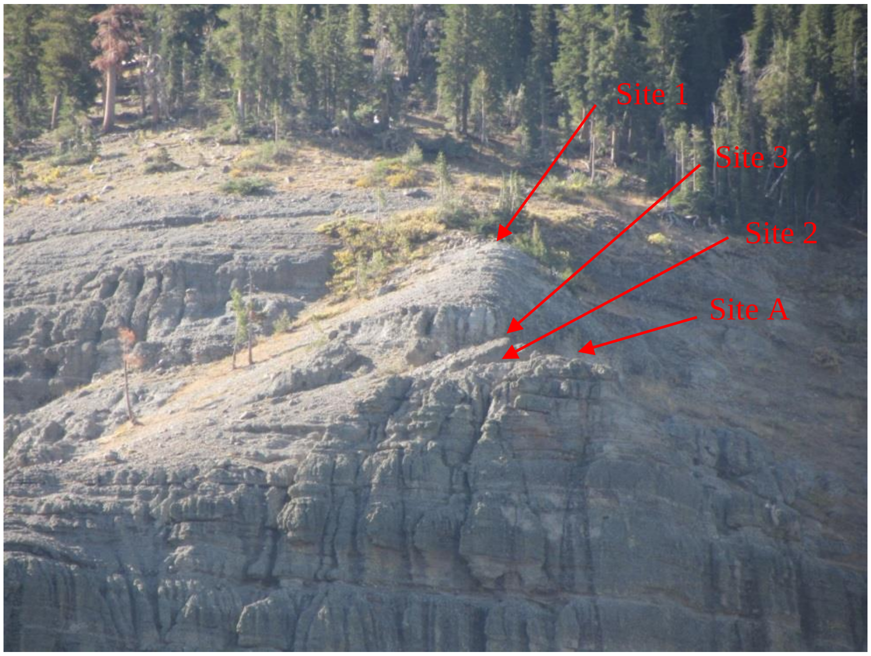

Figure 3.9: South-looking view of the chute 4 potential installation sites

Figure 3.9 provides a close-up of the mound to the left of the chute 4 bowl. This location is very important to the characteristics of the bowl snowpack and the subsequent avalanche release. In general the rock face to the right of the mound beginning at the ridge of the bowl just below the tree-line usually packs with snow, and when this pack is sufficiently full, coupled with a strong cross wind from the east (the left side of the picture), an avalanche is typically triggered. Figure 3.10 shows this primary avalanche start zone outlined in red, as it is the most important of the start zones. This figure also shows the secondary start zone (outlined in cyan) composed of the area around the upper right top of the bowl. An avalanche can be triggered from this location as well, when this location begins to fill and the top becomes overloaded. Caltrans indicated that knowledge of these locations is very important to the avalanche measurement and characterization effort.

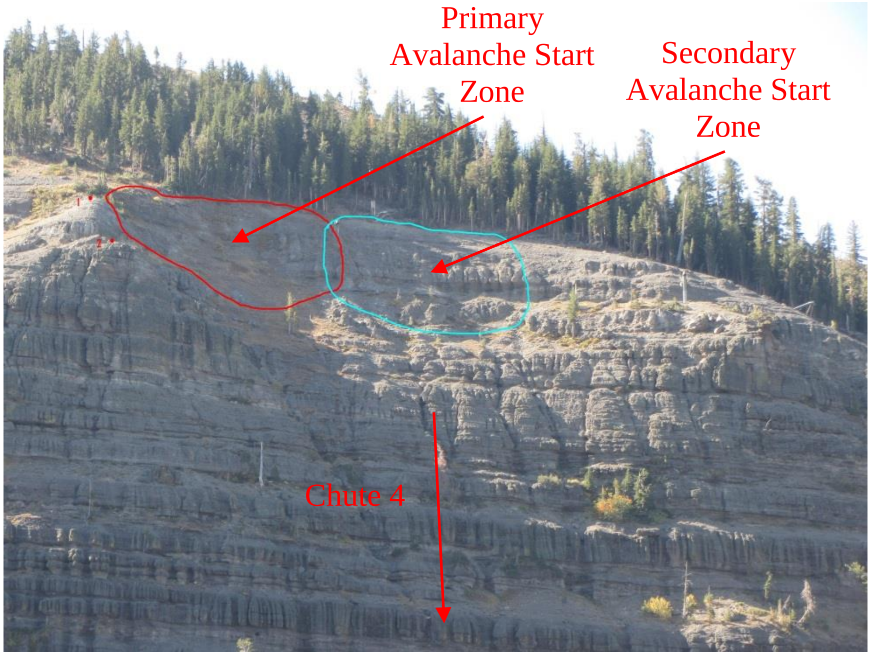

Figure 3.10: South-looking view of the chute 4 avalanche start zones

Key Characteristics of the Carson Spur area and Chute 4

1. Unique bowl characteristics of chute 4
2. Snow season conditions: typically very heavy snow fall, possible ice conditions, very windy during storm conditions
3. Avalanche operations
4. Possible sensor station install locations on the left mound
5. Key measurement points of interest, specifically the upper-left and center of the bowl as avalanche start zones
6. Power limitations, including no power on site, and limited sun exposure for solar power
7. Typically very poor data communications

Figure 3.11: Looking north towards the gun mount from chute 4

Installation of the sensor station at the gun mount or nearby was initially considered, due to the view of a majority of the chute locations. This would provide significant benefits by allowing snowpack measurement and video monitoring of all of the avalanche sites from a single installation. However, in this environment, the range and resolution of commercial off-the-shelf (COTS) measurement equipment, similar to the types discussed in Chapter 4, were not capable of meeting the system requirements from the gun mount. The range from the gun mount to chute 4 is approximately 1,500 ft. As a result, sensor station installation was planned on-site near the chute 4 bowl.

Upon selection of chute 4 as the target research avalanche site, several possible sensor station installation sites were investigated. Based on the system requirements and the characteristics of the surrounding geology, an initial installation site was selected for investigation and installation feasibility.

Primary Sensor Station Site Selection System Requirements

1. Sensor view of the avalanche start zones
2. Sensor view of the majority of the bowl
3. Sufficiently close range to provide sensor measurement of intended locations
4. Sensor station survivability during seasonal weather and avalanche
5. Tower height to keep sensors above typical seasonal snowpack
6. Enough area to accommodate tower anchors
7. Geology suitable to accommodate tower base and anchors

In general it was determined early on that locations above the bowl along the bottom of the tree line were not suitable for proper views of the bowl and would typically be buried by snowpack without a very tall tower. Additionally, installation of a suitable tower of sufficient height would be very problematic due to the seasonal weather conditions, the characteristics of the local geology, and the constraints of installing a tower on a very steep rock face. As a result, it was decided that the best choice for the sensor station installation would be somewhere on the mound to the left of the bowl.

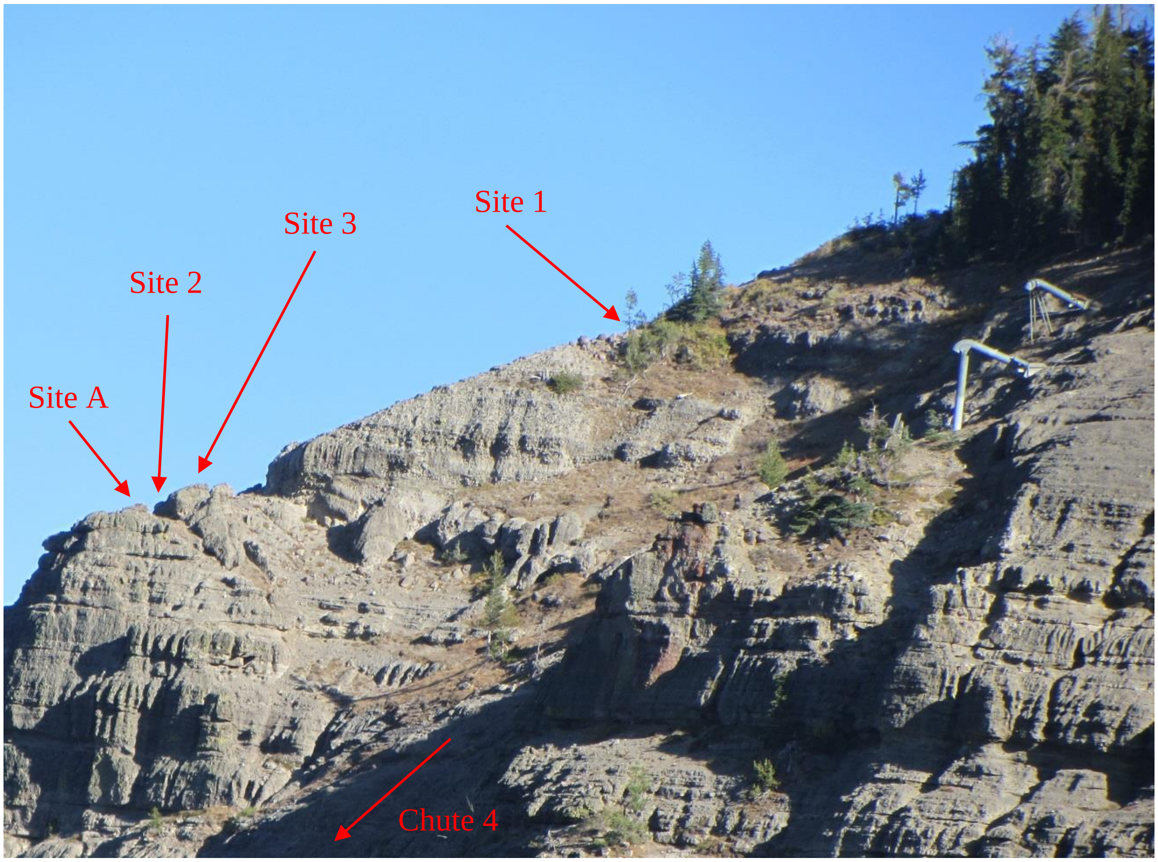

Figure 3.12: East-looking view of chute 4 possible installation sites

Figure 3.12 shows the possible tower installation sites investigated during this research. The first and second markers ("Site 1" and "Site 2") represent the first two site installation investigations, and the third marker ("Site 3") represents the final installation location. Marker ("Site A") represents an additionally considered installation site which is briefly discussed in Appendix A.

First Installation Site Investigation

This first possible tower installation site was selected based on proximity to the avalanche start zones, visual inspection of the surrounding geology, area estimates required for tower anchor locations, and sensor views of the bowl features.

Figure 3.13: Standing on the mound facing north near the first site

Figure 3.13 shows that the mound looks much smaller and steeper in person looking outward than from the gun mount looking upward. This figure is near the base of the possible tower site location. The terrain quickly rolls off to the east and west, making it challenging to install a tall tower at this location due to the requirement for guy wire anchors in this environment given a particular tower height.

Figure 3.14: Looking northwest down the mound from the first site

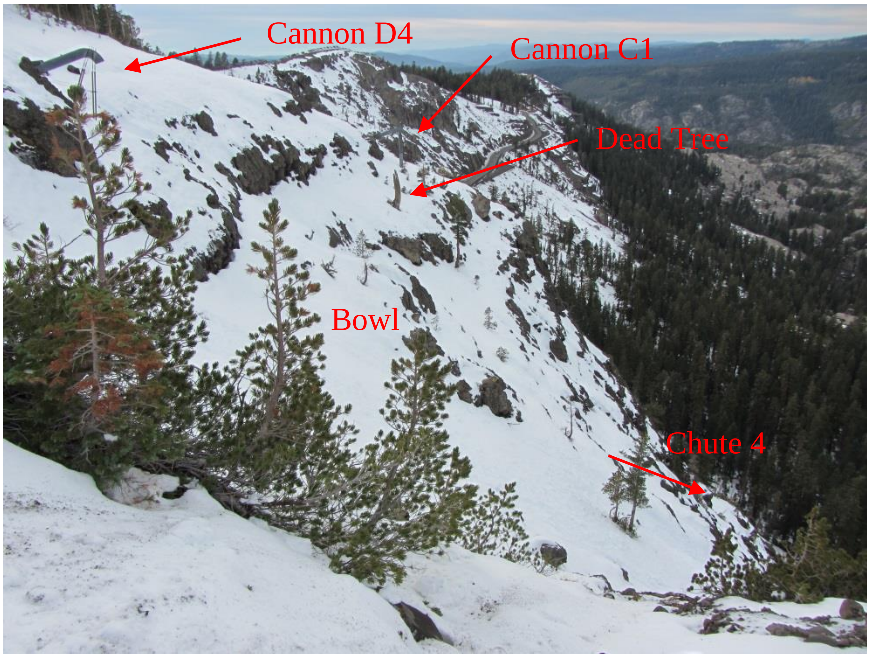

Figure 3.15: Looking west towards the bowl from the first site

Figure 3.15 provides a view for the first site from about 6 ft above the tower site base looking west over the bowl. There is a Gazex cannon in the distance (C1) to the west side of the bowl and another (D4) above the bowl. The area of interest is immediately at the edge of the bowl at the bottom of the picture to the other side of the bowl where the dead tree is sticking up in the center of the figure and on up to the bowl ridge line to the left below the cannon.

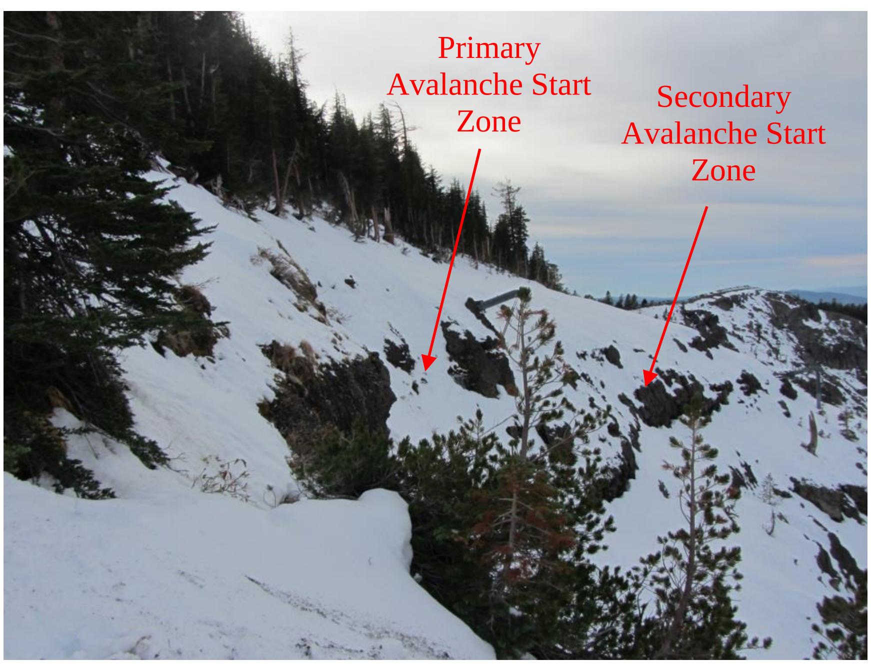

Figure 3.16: Looking west at the avalanche start zones from the first site

Figure 3.16 shows the view for the first site looking towards the top of the bowl from the possible tower site location at about 6 ft above the current elevation. The top of the secondary start zone is underneath the visible Gazex cannon; however, key features of the primary start zone are down and around the corner of the rock face visible on the left side of the figure. It would require a tower sufficiently taller than the current camera elevation in order to see the complete start zone. The trees immediately to the left are about 12 ft tall and are typically nearly buried during a snow storm.

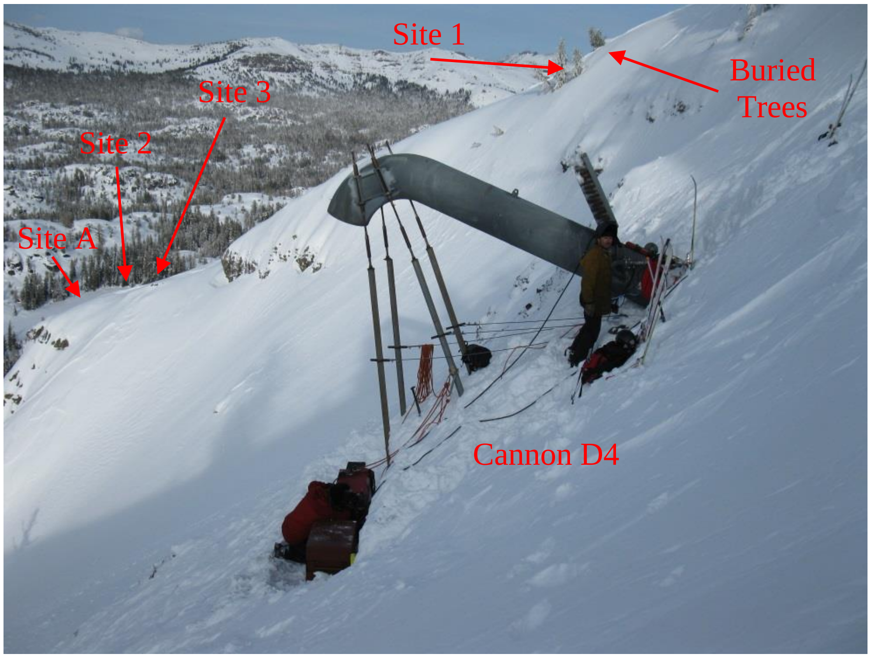

Figure 3.17: View inside of the bowl looking east towards the mound

The 12 ft trees ("Buried Trees") are almost completely covered by snow in Figure 3.17. This figure clearly shows that a tower installed 3 ft below the base of those trees ("Site 1") would be at risk from snow buildup and possible burial during a storm. As a result, a tower at this location must be reasonably tall. Detailed analysis and initial tower design followed the initial site surveys, wherein many pictures and measurements were taken of the surrounding features and geology.

First Site Tower General Requirements

1. Tower tall enough to see the upper-left corner of the primary avalanche start zone
2. Tower tall enough for sensors to stay above snow accumulation
3. Enough area to allow for the necessary guy anchor points
4. Suitable geology at tower base and guy anchor locations

Based on analysis of the collected site survey data, the initial first site design used a tower height of 15 ft. The tower must support a laser distance meter, camera, wind meter, moisture sensor, communications antenna, and wind generator near the top of the tower, under all local environmental conditions. Amongst the many design requirements for the tower design, some of the more critical were wind speed and ice loading. Specific to this location on Carson Spur, wind speeds can reach 110 MPH and ice buildup has been observed under the right conditions of 1 inch or so perpendicular to the direction of the wind. The local environmental conditions and the specifics related to the sensor selection are discussed in detail in Chapter 4.

For the first site, a complete tower design and analysis was performed for a 15 ft tall Rohn-25 guyed tower with all sensors mounted near the upper 1 ft of the tower and the generator on a mast following TIA-222-F (Telecommunications Industry Association) standards for 110 MPH sustained wind with 1 inch of ice accumulation[3].

Figure 3.18: Possible northwest anchor location at the first site

[3] www.rohnproducts.com
www.tiaonline.org
http://www.tiaonline.org/all-standards/committees/tr-14

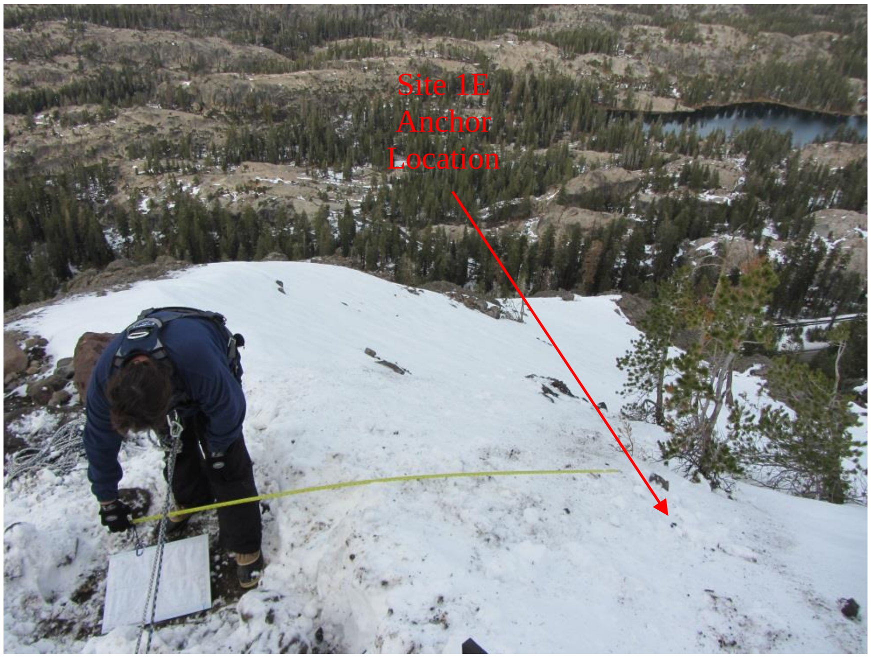

Figure 3.19: Possible east anchor location at the first site

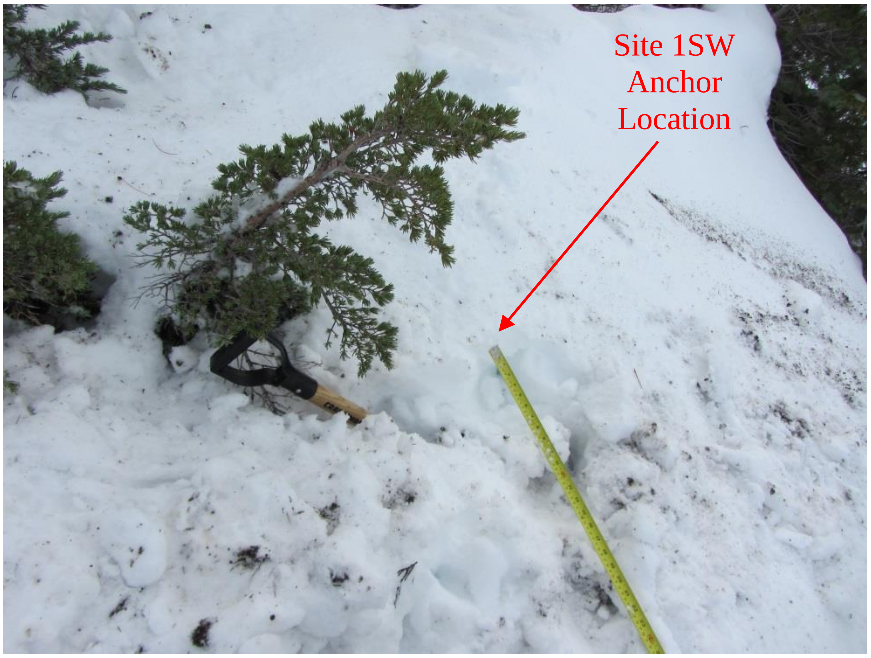

Figure 3.20: Possible southwest anchor location at the first site

Figures 3.18-3.20 show the intended locations of the anchor locations for the first site and tower design. Here, the guy wires were designed to be fairly steep as a result of the quickly falling slopes around the site. Using a larger anchor radius for better tower performance would mean chasing the terrain downhill and/or going off an edge. As designed with the shorter anchor radius, the east anchor location shown in Figure 3.19 is further downhill than the end of the tape measure, which represents the horizontal intersection point. Thus, this anchor point would be very far down the hill.

First Site Tower General Design

- 15 ft Rohn-25 tower
- Guy wires attached to the top of the tower (15 ft)
- Horizontal anchor radius of 8 ft
- Sensors and antenna mounted at 1 ft below top of the tower
- Wind generator mounted on mast at 17.5 ft
- Electronics enclosure mounted at chest height
- Design meets TIA-222-F standards for 110 MPH wind with 1 inch ice

The initial installation investigation commenced following the tower design and analysis for the first site. Suitable methods were needed to mount the base of the tower and anchor the guy wires to the ground. Due to the location and access restrictions on Carson Spur, it is was not possible to use typical construction techniques and materials such as heavy machinery or concrete. The plan was to either drill and epoxy anchor rods into somewhat dense conglomerate rock under the topsoil or use screw anchors directly in the earth. Unfortunately, the site's soil conditions could not support either approach. The ground below the tower base and several of the anchor points consisted of loose soil and large rocks. This precluded the use of glued rods as there was no suitable rock conglomerate near the surface. Several attempts to install various earth-based anchors failed to achieve a suitable depth due to interfering rocks. As a result, the first site was unsuitable.

Primary Reasons for Abandoning First Site

1. Infeasible to fasten the tower base or anchors to the ground with rods and epoxy due to lack of suitable rock conglomerate at reasonable depths
2. Infeasible to fasten the tower anchors to the ground due to loose soil contaminated with rocks inhibiting the installation of screw anchors
3. Concerns about the tower height and visibility from the roadway

Second Installation Site Investigation

With the first site abandoned, the remaining sites further down the grade shown in Figure 3.12 above were investigated. The first site ("Site 1" of Figure 3.12) was located east of the bowl, looking across and down on the avalanche start zones. The remaining potential sites ("Site 2" and "Site 3" of Figure 3.12), which are significantly below the top of the bowl, look upwards towards the avalanche start zones. Investigation of the area near the edge of the cliff started by taking numerous measurements and pictures of avalanche start zone views, possible tower base and anchor points, and geology of local features. In addition to the previously listed overall site selection goals, an additional goal was to find a suitable site as far to the west as possible, to provide the most open view of the primary avalanche start zone. One additionally considered site location ("Site A" of Figure 3.12), discussed briefly in Appendix A, provided the best view of the primary avalanche start zone, but required removal of poorly fastened rock conglomerate that would most likely necessitate a scheduled road closure. As a result this site was rejected.

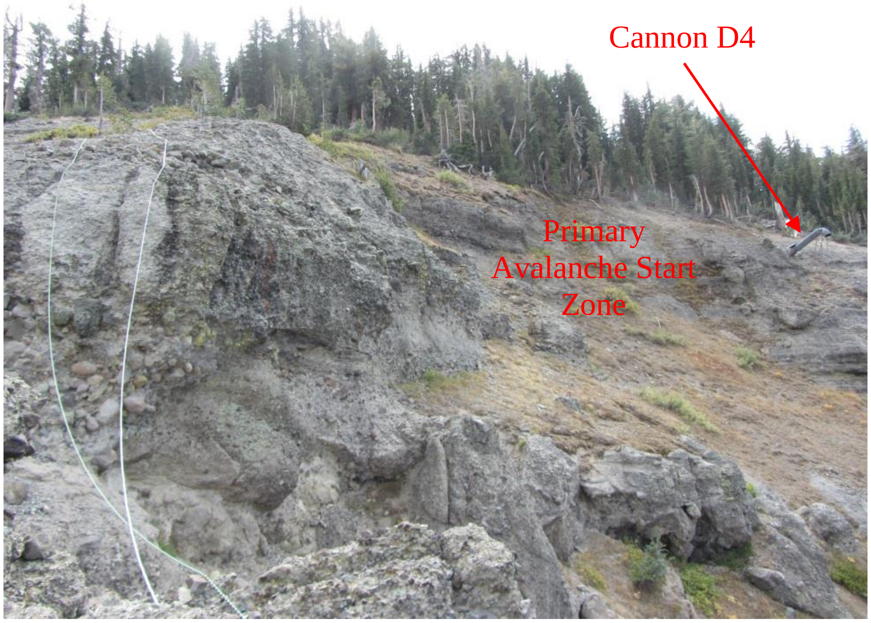

Figure 3.21: Looking south from the second site towards the primary avalanche start zone

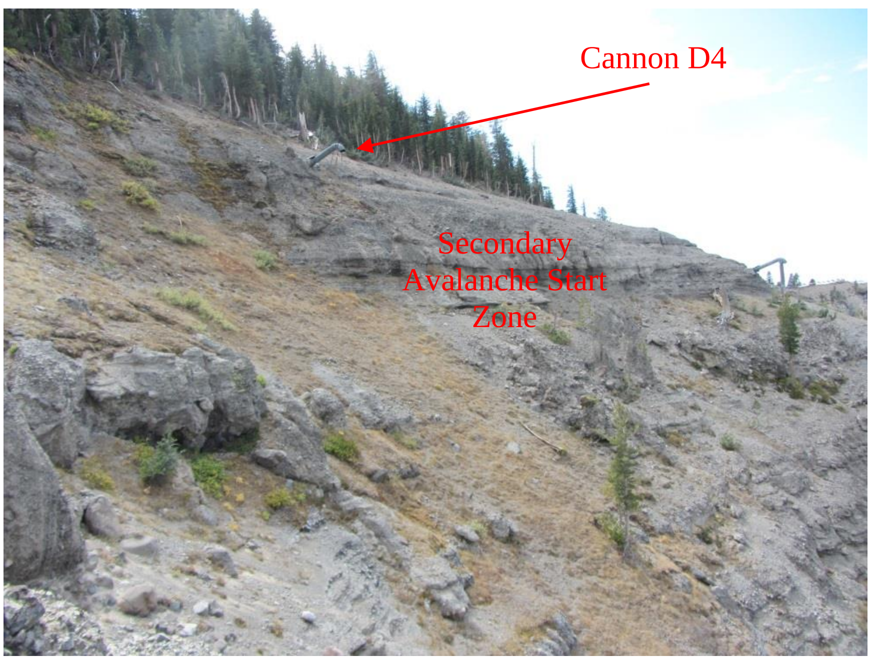

Figure 3.22: Looking southwest from the second site towards the secondary avalanche start zone

Based on the remaining possible tower anchor points and base plate mounting locations, the most westward site possible ("Site 2" of Figure 3.12) was selected to optimize the view of the avalanche start zones (see Figures 3.21 and 3.22). This location provides a view of the entire secondary and almost all of the primary avalanche start zones.

Figure 3.23: The tower base location at the second site

The general tower base location of the second site is shown in Figure 3.23. The peak of the rock conglomerate in this figure is about 11 ft tall with respect to the selected tower base location. Figure 3.17 above includes a marker ("Site 3") pointing to a rock almost completely covered by snow. This marker is pointing toward the tip of the rock conglomerate next to the tower base location.

Second Site Tower General Requirements

1. Tower tall enough for sensors to stay above the snow accumulation
2. Enough area to allow for the necessary guy anchor points
3. Suitable geology at tower base and guy anchor locations

Based on analysis of the collected site survey data, the initial second site tower design height was 14 ft. A complete tower design and analysis was performed for a 14 ft tall Rohn-25 guyed tower with all sensors mounted near the upper 1 ft of the tower and the generator on a mast following TIA-222-F standards for 110 MPH sustained wind with 1 inch of ice accumulation.

Availability of rock conglomerate for base plate attachment was verified by digging at the tower base for the second site. A suitable attachment point meeting the design requirements was found at about 18 inches below the grade shown in Figure 3.23. With the tower base location known, several iterations were performed for tower rotation, anchor radius variations, and subsequent redesigns, all to fit the design to the local features. The resulting second site tower design anchor point locations are shown below in Figures 3.24-3.26.

Second Site Tower General Design

- 14 ft Rohn-25 tower
- Guy wires attached to the top of the tower (14 ft)
- Average horizontal anchor radius of 10 ft
- Sensors and antenna mounted at 1 ft below top of the tower
- Wind generator mounted on mast at 16.5 ft
- Electronics enclosure mounted at chest height
- Design meets TIA-222-F standards for 110 MPH wind with 1 inch ice

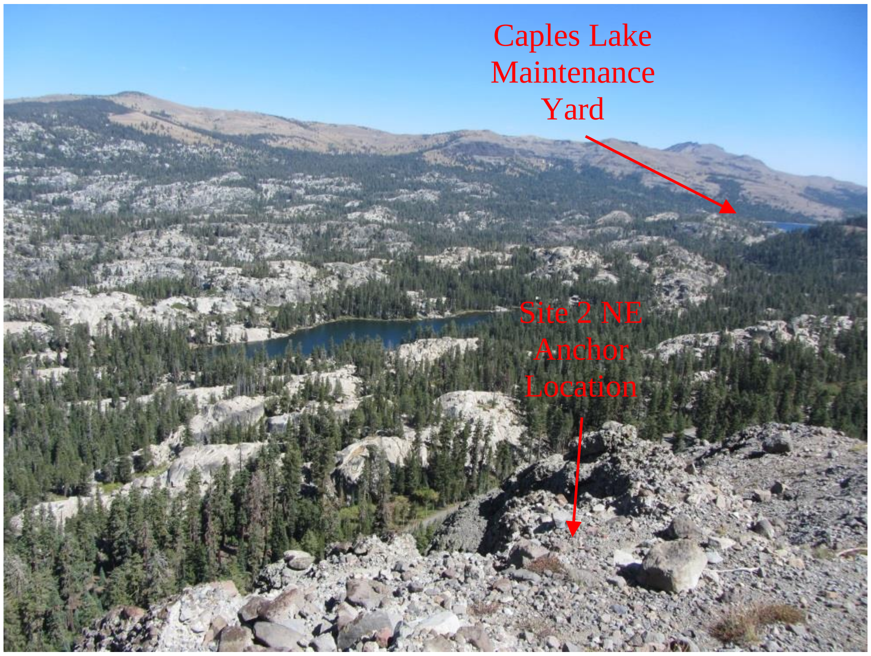

Figure 3.24: The northeast anchor location at the second site

Figure 3.24 shows that the second site's proposed northeast anchor location is very close to the edge of the cliff. It is possible to rotate the tower clockwise and move this anchor location to the right in Figure 3.24, but this would move each of the anchor point locations in Figures 3.25 and 3.26 correspondingly.

Figure 3.25: The northwest anchor location at the second site

With the selected tower rotation, the second site's northwest anchor is located about as high as can be while still providing a suitable anchor installation into a large section of rock conglomerate. Further clockwise rotation of the tower would cause this anchor location to move upwards and to the right in Figure 3.25. This is the location of the unstable rock (see Appendix A).

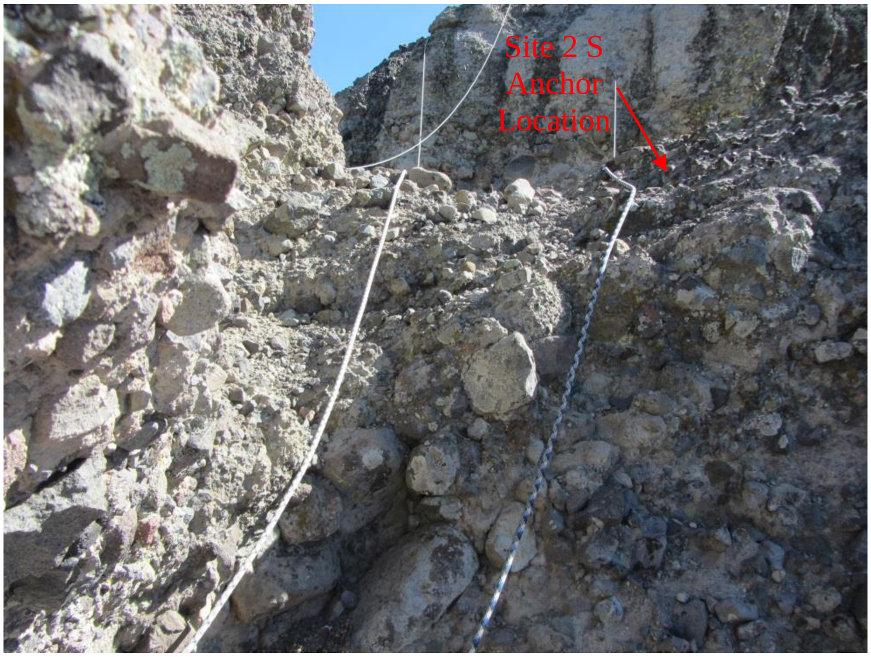

Figure 3.26: The south anchor location at the second site

At the selected tower rotation, the second site's south anchor is positioned solidly into a large piece of rock conglomerate. Any additional clockwise rotation of the tower would cause this anchor location to move quickly off the edge of the rock structure.

Given the near optimal positioning of the tower and anchor points for the second site, test drilling commenced around the northeast anchor location. Unfortunately, at the required depths, the rock in the surrounding area was either not homogeneous enough for the design requirements, or was too close to the edge, risking a breakdown of the heavily fissured rock under the tower's operational loads. As such, the second site was abandoned.

Primary Reasons for Abandoning Second Site

1. Concerns about northeast anchor point location not meeting design requirements while under load due to proximity to and condition of edge of cliff

2. Concerns about northwest anchor point being somewhat close to sizable crevices in the rock conglomerate formations

3. Some concerns about the tower height and visibility from the roadway

<u>Installation Site</u>

Finally, a tower was placed on top of the rock ("Site 3" of Figure 3.12) slightly to the east of the second site location. With this final site, the very large mass of rock conglomerate for both the tower base and two of the three anchors could be leveraged. Only a very short tower was required to achieve the needed viewing height, since the rock is 11 ft tall at the peak. As illustrated in Appendix E, the tower at this site remains above the snow surface, at least during light winters.

Installation Site Tower General Requirements

1. Tower tall enough for sensors to stay above the snow accumulation

2. Enough area to allow for the necessary guy anchor points

3. Suitable geology at tower base and guy anchor locations

Installation Site Tower General Design

- 5 ft Rohn-25 tower

- Guy wires attached to the top of the tower (5 ft)

- Sensors and antenna mounted at 1 ft below top of the 5 ft tower

- Wind generator mounted on mast at 7.5 ft above the base of the tower

- Electronics enclosure mounted to rock conglomerate at chest height

- Design meets TIA-222-F standards for 110 MPH wind with 1 inch ice

The wind speed design criteria is a critical consideration. Steady wind speed design criteria of 110 MPH was selected based on the closest available quantitative wind data (see Chapter 4), along with indications of observed wind speed from local experts. Using the TIA-222-F standards, the system was designed to withstand 110 MPH steady wind with 1 inch ice build-up on the tower and components. Ice build-up patterns for the site are discussed in Chapter 4. The quantitative data (from Kirkwood, the most comparable site available) does show wind gusts up to approximately 140 MPH. Design calculations show that with gusts above 140 MPH, the forces experienced by the tower and the guy wires are well below their maximum sustainable values.

Figure 3.27: The southwest view of the bowl from the top of the final site's tower installation

Figure 3.27 shows the view of the bowl from the top of the installed tower. The view of the primary avalanche start zone is only slightly less than that for the second site.

Figure 3.28: The west view of the final site tower installation and electronics enclosure mounting brackets

Figure 3.28 shows the tower installed atop the 11 ft rock. The base of the tower is about 18 in lower than the peak of the rock. This is due to the required machining of the rock surface to create a suitable flat mounting location for the tower base plate. Because of this, the tower is 5 ft tall and roughly 18 in below grade for an effective extension of 3.5 ft above the peak of the rock. The Unistrut® mounted to the side of the rock provides a custom mounting surface for the electronics enclosure[4].

[4] www.unistrut.com

Figure 3.29: The south view of the final site's tower installation

Figure 3.29 provides another view of the installed tower from the standing position at the second site location. The installed tower is about 1 ft to the east of the second site location.

Figure 3.30: The tower base bolted to the rock conglomerate

Figure 3.30 shows the tower base plate installation. The base plate location was machined into the top of the rock to provide a suitable mounting location for the tower. Four ¾" all-thread rods 30 in long were epoxied into the rock conglomerate.

Figure 3.31: The southwest tower anchor

Figure 3.32: A close-up of the southwest tower anchor

Figures 3.31 and 3.32 show the southwest guy wire and anchor location, which is at an angle of 57° relative to horizontal. The anchor is ¾" all-thread 60 in long epoxied to the rock conglomerate. The selected angle must allow the full length of the anchor rod to be centered in the mass of the rock without breakout on the back side.

Figure 3.33: The north tower anchor

Figure 3.34: A close-up of the north tower anchor

Figures 3.33 and 3.34 show the north guy wire and anchor location, which is at an angle of 57° relative to horizontal. The anchor is ¾" all-thread 60 in long epoxied to the rock conglomerate. Here, the angle was very similar to that of the southwest anchor. The selected angle must ensure that the guy wire avoided interference with the base rock and was not too close to the edge with its large crevices.

Figure 3.35: The southeast tower anchor

Figure 3.36: A close-up of the southeast tower anchor

Figures 3.35 and 3.36 show the southeast guy wire and anchor location, which is at an angle of 45° relative to horizontal. The anchor is ¾” all-thread 60 in long epoxied to the rock conglomerate. Here, a shallower guy wire angle was necessary, as an angle around 57° would have resulted in an extremely short guy wire without adjustability.

Figure 3.37: A view of the tower and top plate

This close-up view in Figure 3.37 shows the custom-designed and fabricated tower top plate with integral guy anchor points and mounting for the generator mast. The tower is perfectly vertical with a perfectly horizontal top plate, and the guy wires are tensioned to design specifications. Additional views are shown in Figures 3.38 and 3.39.

Figure 3.38: A close-up of the anchor plate and guy wire attachment

Figure 3.39: The top plate with mounting for the wind generator mast

CHAPTER 4:
AVALANCHE SENSING SYSTEM DESIGN AND IMPLEMENTATION

Primary Objectives for Avalanche Sensing System

Several objectives for the avalanche sensing system at Carson Spur were requested by the Caples Lake Maintenance Supervisor staff.

- Collect data for avalanche characterization, modeling, and trigger optimization
- Provide alert after avalanche
- Measure snow depth at several key points
- Provide local weather measurements
- Relay sensor data to Caples Lake maintenance yard for display and analysis
- Measure snow accumulation and gather images for the primary and secondary avalanche start zones (critical objective)
- Provide local power generation (no on-site power)
- Attach sensors to tower mounted on local terrain adjacent to target chute

Snow accumulation measurements will use spherical coordinates, and will be with respect to the distance meter. This will be accomplished by first making baseline measurements of the surface of the bowl when snow is absent, followed by differential measurements throughout the winter season. Because of the orientation of the measurement station with respect to the areas under measurement, this will not directly yield vertical snow depth measurements as one would traditionally expect, but rather 3D surface measurements. The goal is to model the maximum volume of snow accumulation in key areas of the bowl that will represent a high risk of avalanche under a known set of weather conditions.

Environmental Considerations

Wind Speed

The typical seasonal wind patterns for our installation site was a major driver for the overall system design. There are wind speed meters along Carson Spur at the Gazex cannon control shacks which collect wind data. However, this data is not currently stored for historical purposes. The Kirkwood ski resort is near Carson Spur, and happens to have several weather stations located at key points on the mountain. The researchers acquired all available historical weather data from the end of 2011 through the beginning of 2013, covering almost two snow seasons. This data enabled estimation of typical wind speeds for tower design and wind generator selection.

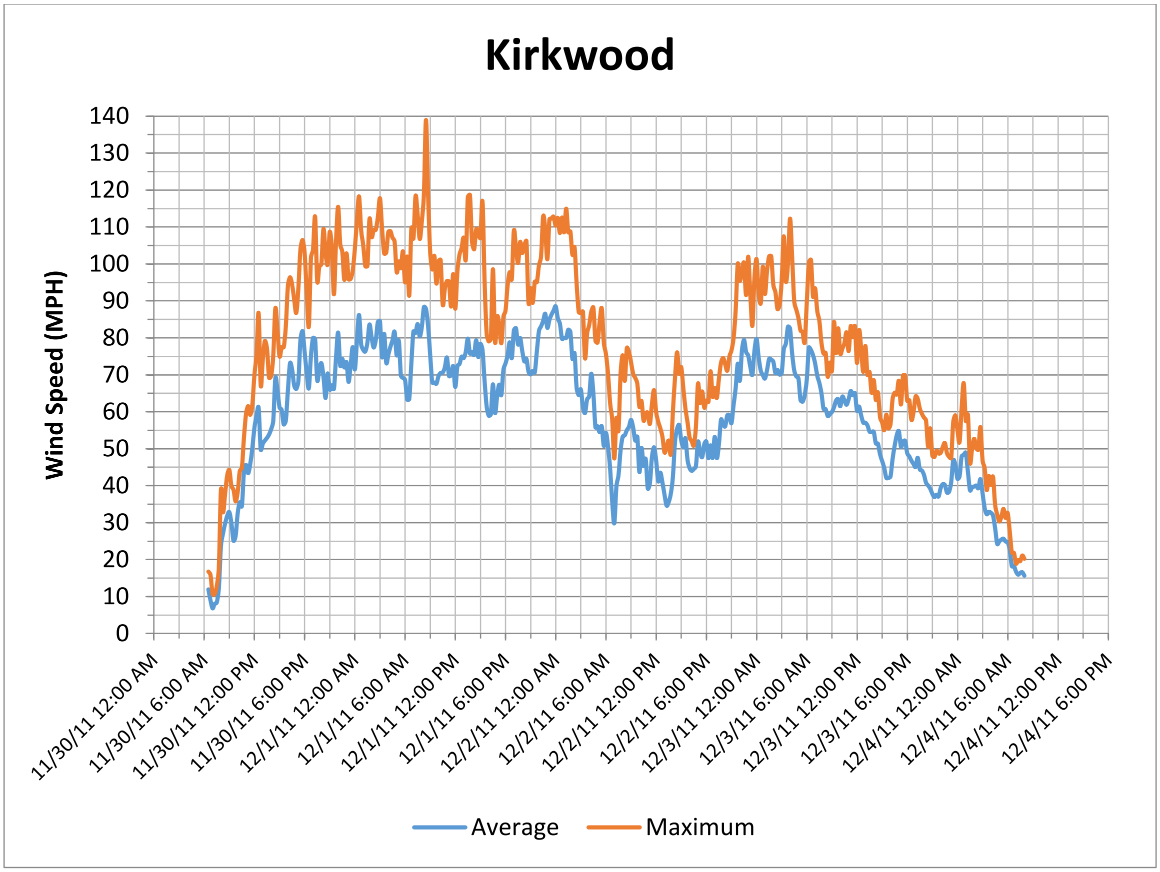

Figure 4.1: Kirkwood wind speeds during December 2011 storm

Figure 4.1 shows the December 2011 storm at Kirkwood. This is clearly a strong multi-day storm with very high wind speeds. Specifically, between 11/30/2011 at 6 PM and 12/2/2011 at 12 AM, the average wind speeds were about 80 MPH with gusts up to 115 MPH. However, on 12/1/2011 at 9 AM the winds were gusting up to 140 MPH.

<u>December 2011 Storm Wind Speeds</u>

- Average: 80 MPH
- Gusts: 115 MPH
- Extreme Gusts: 140 MPH

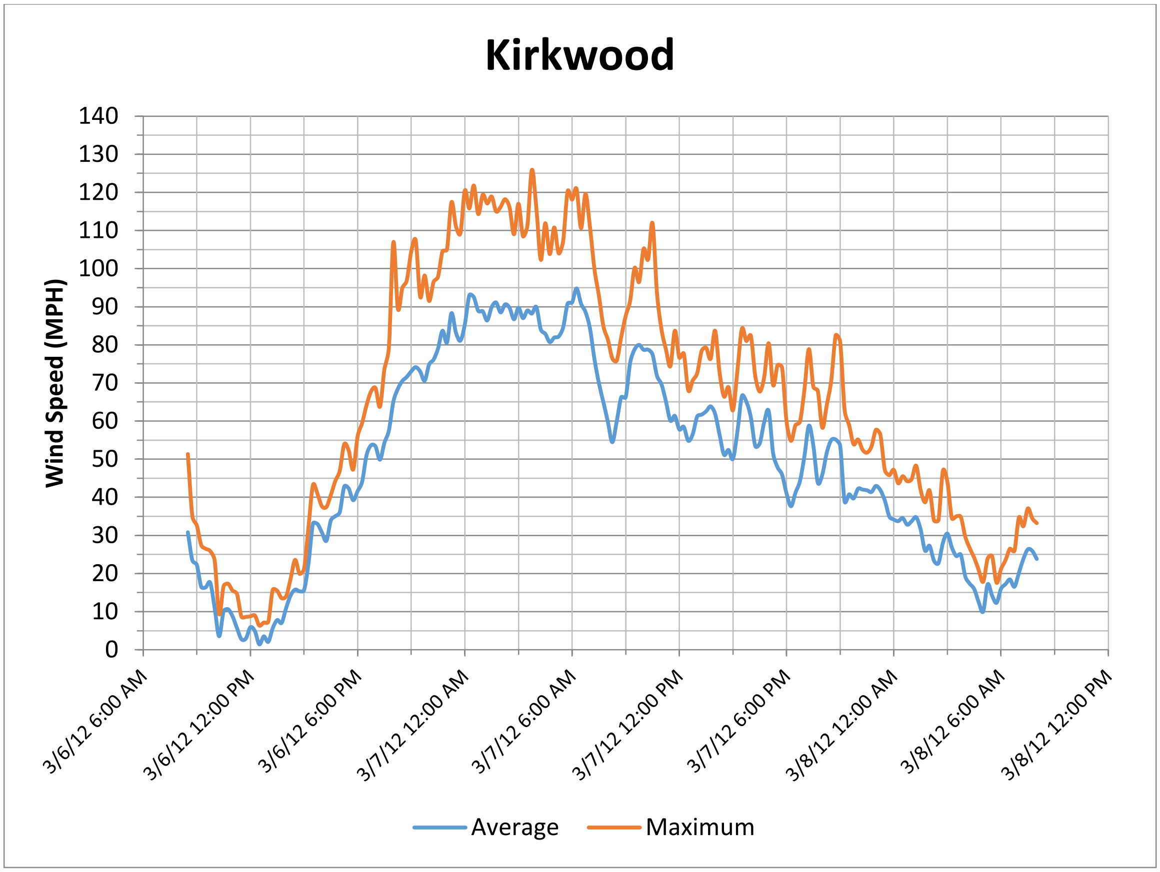

Figure 4.2: Kirkwood wind speeds during March 2012 storm

Figure 4.2 shows the March 2012 storm at Kirkwood. This was another strong storm with very high wind speeds, the majority of which lasted for about a day. Specifically between 3/6/2012 at 9 AM and 3/7/2012 at 6 AM, the average wind speeds were higher than in Figure 4.1 at about 90 MPH with gusts up to 120 MPH.

<u>March 2012 Storm Wind Speeds</u>

- Average: 90 MPH
- Gusts: 120 MPH

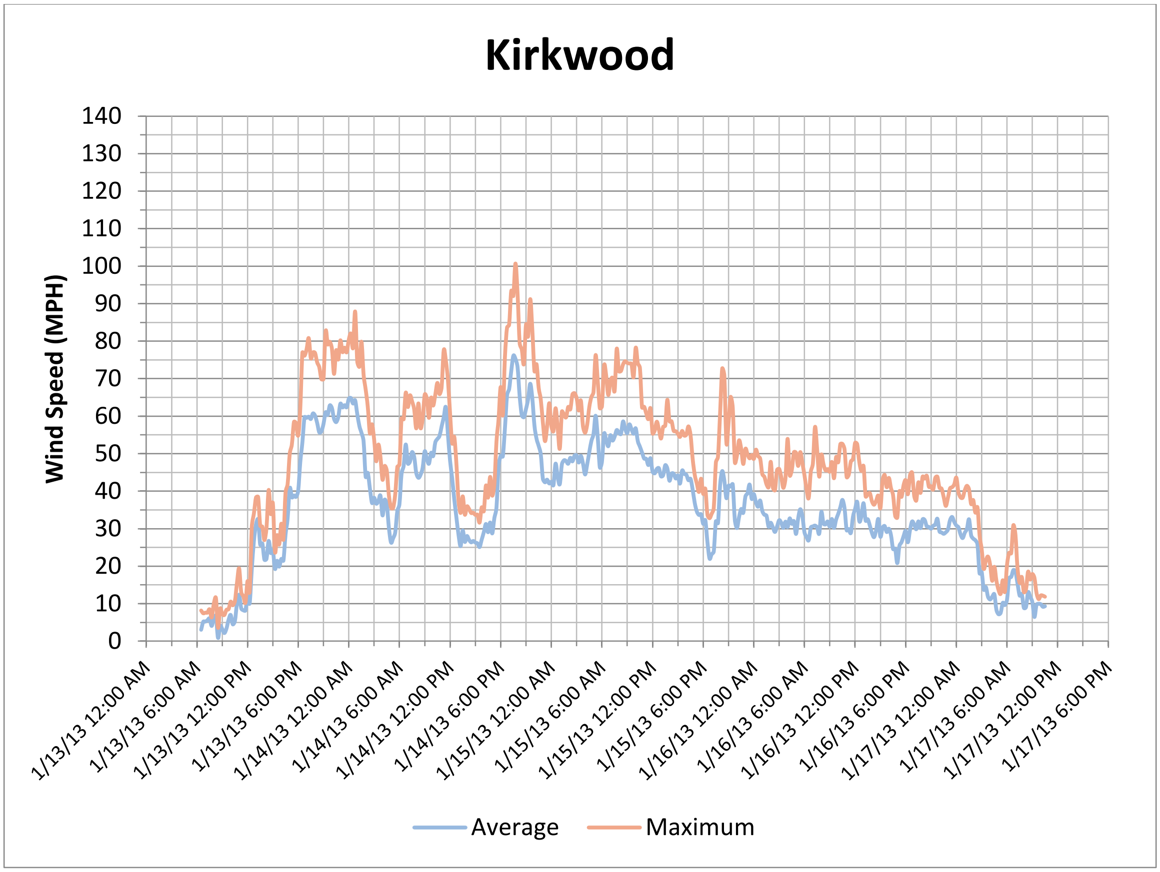

Figure 4.3: Kirkwood wind speeds during January 2013 storm

Figure 4.3 shows the January 2013 storm at Kirkwood, another sizable storm with high wind speeds, which lasted about 2 days. Specifically between 1/13/2013 at 6 PM and 1/15/2013 at 9 AM, the average wind speeds were about 60 MPH with gusts up to 80 MPH over the same period.

<u>January 2013 Storm Wind Speeds</u>

- Average: 60 MPH
- Gusts: 80 MPH

<u>Conclusion</u>

From the wind speed data described above, it is reasonable to expect to see up to about 90 MPH continuous wind speeds with gusts up to about 120 MPH over a typical snow season near Carson Spur. As indicated in Chapter 3, the system is designed for 110 MPH continuous wind speed, and gusts above 140 MPH.

Temperature

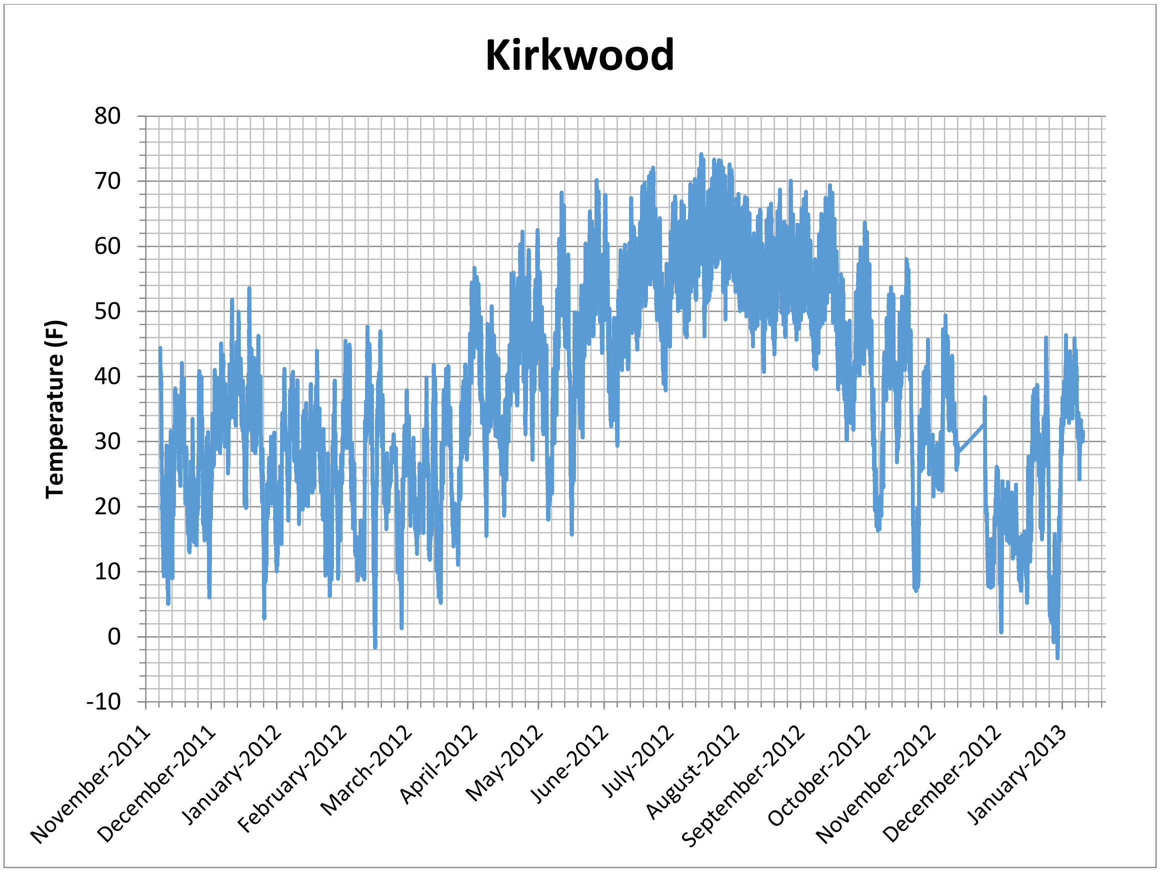

Figure 4.4: Kirkwood air temperature November 2011 to January 2013

Figure 4.4 shows the air temperature data from which we can conclude that typical minimum air temperatures near Carson Spur are about 10° F during the winter months with occasional dips to 0° F.

Ice Formation

The typical seasonal ice formation patterns for the installation site was another major driver for the overall system design. From discussions with highly experienced and skilled Caples Lake Maintenance Supervisor staff familiar with typical weather patterns around the site, it was clear that while ice formations are rare, they do occur. Ice has formed near the site on smaller trees and guy wires up to about an inch perpendicular to the direction of wind and quite a bit longer parallel to the direction of wind, which is to be expected. Typically, the ice formation would be in the shape of a teardrop with a long tail around a circular object. According to local experts, when these rare ice events occur, the ice typically melts alter in the day.

Snow Depth

The snow level at the installation site (“Site 3” of Figure 3.17) is flush with the top of the rock to which the tower was mounted. From discussions with Caples Lake Maintenance Supervisor staff, during typical snow storms the wind sweeps the snow across this position and keeps the snow limited to about this level.

Solar Irradiance

It was determined that typical sun exposure on the site during the winter months would be less than 1 hour per day at the tower installation location. This was estimated through winter month solar simulations on Google Earth and confirmed during site visits. As a result, solar panels are not a viable power generating solution for the system.

System Components

General Requirements for all Components

- Wind Speed (Continuous): 110 MPH
- Operating Temperature: 0 to 122° F

Wind Generator

Since solar power is not a suitable power source at the installation site, use of a wind generator was investigated. Given the characteristics of the wind patterns around Carson Spur, it is essential that a selected wind generator have good power output at low speeds and survivability under very high continuous wind speeds.

Specific Wind Generator Requirements

- Use: Severe Duty
- Rating: 100 W @ 20 MPH

Figure 4.5 shows the Superwind 350 which was selected to meet the primary requirements[5]. This generator has been used in severe operational environments, including the Arctic and Alaska, in unattended automation operation in all weather conditions.

5 http://www.superwind.com/

Figure 4.5: Superwind 350 wind generator (courtesy of Superwind)

<u>Key Wind Generator Specifications</u>

- Nominal Power: 350 W
- Nominal Voltage: 12 V DC
- Rotor Diameter: 1.2 m
- Speed Regulation: rotor blade pitch control
- Extreme Wind Speed: 110 MPH

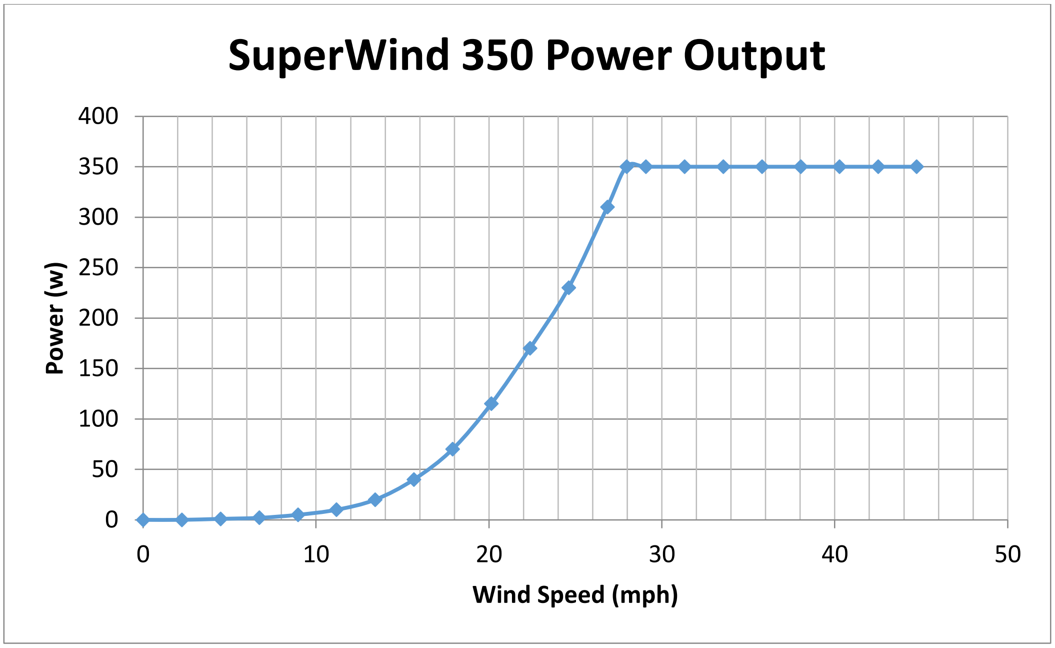

Figure 4.6: Power output of the wind generator (courtesy of Superwind)

Figure 4.6 shows the power output graph for this generator. The Superwind 350 begins producing usable battery charging power at a very low wind speed. The output of the generator continues smoothly up to a peak output of 350 W, at which point several of the advanced features of the wind generator system are employed to handle the higher speeds. At speeds above 29 MPH, the rotor control system adjusts the blade pitch to keep the power output constant.

The avalanche sensing system installation was designed to accommodate generator installation on a mast so that the center of the rotor is 2.5 ft above the top of the tower. A 5 ft mast is mounted through the hole in the tower top plate and anchored to another mounting bracket 2.5 ft below the top of the tower. The wind generator is attached to the top of the mast and the cabling is routed down through the inside of the mast.

Laser Distance Meter

There were very specific criteria for the laser distance meter sensor selection, since distance measurements are critical to the avalanche characterization effort. The necessary range capabilities of the sensor can be determined based on the distance from the tower installation site to key points in the avalanche start zones. Additionally the sensor must have sufficient resolution and detection capabilities given the various materials in the sensing locations under the range of expected lighting conditions.

<u>Key Laser Distance Meter Measurement Distances</u>

- Primary avalanche start zone: ~150 ft
- Secondary avalanche start zone: ~ 275 ft

- Furthest edge of the bowl: ~ 325 ft

Specific Laser Distance Meter Requirements

- Range: 350 ft
- Resolution: < ¼ in
- Beam Divergence: < 4 in beam spot size @ 150 ft

Figure 4.7 shows the RIEGL LD90-3100 which was selected to meet the primary requirements[6]. This laser distance meter was designed to operate in environments with backscatter due to particulates in the air such as raindrops and snowflakes. The clutter suppression feature is integral to detecting the true snow surface and rejecting false measurements due to falling snow.

Figure 4.7: RIEGL LD90-3100 laser distance meter (courtesy of RIEGL)

Key Laser Distance Meter Specifications

- Range: 490 ft @ 80% reflectivity
- Accuracy: 0.118 in
- Resolution: 0.079 in
- Snowflake clutter suppression

[6] http://products.rieglusa.com/category/distancemeters

- Operating Temperature: 14 to 122° F
- Protection: IP64

The range specification is dependent on other variables in the current use case such as ambient lighting conditions and reflectivity of measured objects. Typically, the maximum measurement range decreases as the reflectivity of the surfaces decreases. For a snowy surface, the reflectivity is typically 80-90%, which results in a maximum range of about 500 ft. However in the case of trees and some rock surfaces, the reflectivity can be around 50%, which results in a range correction factor of 0.8, yielding range of 400 ft. For very dark rock, reflectivity can be very poor, critically limiting sensor range. Ambient lighting conditions also affect sensor range. Typically, performance is worst in bright sunlight and best in dark conditions. The range rating is specified for the avalanche sensing system assumes overcast conditions, which would directly match the use case. During the dawn or at night, the actual sensor range will be much higher than 500 ft; however, in bright sunlight the range can be significantly reduced.

In the intended use cases, ambient lighting conditions will be favorable and provide the fully-rated range. Also, the bowl can be expected to contain at least a dusting of snow and thus provide excellent reflectivity. Exact modeling of the empty bowl should use detailed scans during low lighting conditions for maximum accuracy.

The installation was designed to accommodate the mounting of the laser distance meter near the top of the tower and 2 ft to the west, thus extending the visibility of the primary start zone. Specifically, the sensor will be mounted to the pan-tilt unit (discussed below) which will be mounted on a bracket structure extending out from the tower. This will allow the distance meter to make measurements of key points across both avalanche start zones. Additionally, the pan-tilt-mounted distance meter will be used to collect snow levels near the tower on a semi-regular bases to monitor snow accumulation.

Camera

Figure 4.8 shows the Axis 1347-E outdoor network video camera which was selected to provide remote monitoring of the tower site and visual corroboration of the other sensor measurements, thus aiding human analysis of avalanche start zones[7].

Specific Camera Requirements

- High resolution
- Day and night operation
- Designed for outdoor use

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[7] http://www.axis.com/

Figure 4.8: Axis 1347-E outdoor network video camera (courtesy of Axis)

Key Camera Specifications

- Resolution: 2560x1920 (5 MP)
- Day and Night Capabilities: color 0.5 lux, B/W 0.08 lux
- Operating Temperature: -22 to 122° F (-40° F with high power)
- Protection: IP66

The avalanche system installation was designed to accommodate camera mounting near the top of the tower and 2 ft to the west, thus extending the visibility of the primary start zone. Specifically, the sensor will be mounted to the pan-tilt unit (discussed below) opposite the laser distance meter. The pan-tilt unit will be mounted on a bracket structure extending out from the tower. This will allow the camera to aid in setup and configuration of the distance measurement definition points, capturing pictures as necessary along the way. Another primary use of the camera with pan-tilt capability is to park the camera in a known optimal location to reduce the wind cross-section for loading purposes, and inspect the tower site, anchors, base, and tower for ice build-up, damage, potential snow burial, and other unexpected scenarios.

Pan-Tilt Unit

The pan-tilt unit is critical to the avalanche characterization effort, as it supports multiple location measurements for the laser distance meter and the camera. Since the tower installation site is near the bottom of the measurement zones, the system is looking upwards towards the primary and secondary avalanche start zones for the majority of the measurements. The pan-tilt mechanism must also allow the camera to survey the area surrounding and including the tower. As can be seen from Figure 3.12, the view slope from the top of the tower to the top of the bowl is about 1:3, which determines the positive tilt range requirement.

<u>Specific Pan-Tilt Mechanism Requirements</u>

- Tilt Range: -90 to +20°
- Pan Range: 360°
- Payload: (distance meter (3.3 lb) + camera (1.3 lb) + enclosures)

Figure 4.9 shows the FLIR PTU-48E which was selected to meet the primary requirements[8]. This unit enables pointing of the distance measurement sensor and the camera towards any visible position in the avalanche start zones under all weather conditions.

Figure 4.9: FLIR PTU-D48E pan-tilt unit (courtesy of FLIR)

[8] http://www.flir.com/mcs/view/?id=53666

Key Pan-Tilt Mechanism Specifications

- Tilt Range: -90 to +30°
- Pan Range: 360°
- Payload Capacity: 15 lb
- Operating Temperature: -22 to 158° F
- Protection: IP67

The installation was designed to accommodate mounting of the pan-tilt unit when paired with the laser distance meter and camera. The complete assembly will be mounted near the top of the tower extending 2 ft to the west, thus extending the visibility of the primary start zone.

Wind Speed and Direction Sensing

General weather sensors are needed along with the primary sensors, including wind speed and direction sensing. Referencing wind speed ranges shown in Figure 4.1, expected maximum wind speed is about 140 MPH. The Young wind sensor, shown below in Figure 4.10, was selected for its impressive specifications and its proven use in severe weather environments[9]. Caltrans has Young wind sensors currently installed on Carson Spur for use by maintenance personnel.

Figure 4.10: Young 05103V wind sensor (courtesy of R. M. Young Company)

[9] http://www.youngusa.com/products/7/5.html

Key Wind Speed and Direction Sensing Specifications

- Speed Range: 0 to 224 MPH
- Speed Accuracy: 2.2 MPH
- Direction Accuracy: 3°
- Operating Temperature: -58 to 122° F

The avalanche sensing system installation was designed to accommodate mounting of the wind speed sensor near the top of the tower on a bracket extending 1.5 ft to the north, thus allowing for appropriate clearance as the wind changes direction.

Air Temperature Sensing

Air temperature sensing is also needed along with the primary sensor data. Referencing temperatures show in Figure 4.4, expected operational temperature range is about 0 to 75° F. The Young air temperature sensor, shown in Figure 4.11, was selected for its specifications allowing for use in severe weather environments[10].

Figure 4.11: Young 41342 air temperature sensor with 41003 radiation shield (courtesy of R. M. Young Company)

[10] http://www.youngusa.com/products/2/15.html (temperature sensor)
http://www.youngusa.com/products/2/11.html (radiation shield)

Key Air Temperature Sensing Specifications

- Range: -58 to 122° F
- Accuracy: 0.54° F

The avalanche sensing system installation was designed to accommodate mounting the air temperature sensor near the top of the tower attached directly to the north-most tower leg.

Modem

The modem will provide cellular (preferred) or RF (Radio Frequency) communications to transmit the sensor data, including still camera images, to a server. The modem will be installed inside the enclosure. A preliminary communications survey has been performed at the installation site. Additional cellular measurements using higher-end antennas and receivers are needed before the communications method and final modem can be selected. Cellular (4G or fourth generation) communication is desired, and may be feasible with appropriate antenna selection. If cellular communication is not feasible, a direct RF link to the Caples Lake yard would provide a fallback. Specifications for the modem will depend upon the choice of cellular vs. RF communications. Environmental specifications will be the same, but must only meet the environmental conditions of the enclosure interior.

Enclosure

Figure 4.12 shows the aluminum enclosure (Hammond model 1418N4ALM12) selected to contain the embedded computer, modem, sensor interface electronics, wind generator charge controller, dump resistors, and 12 V batteries[11].

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[11] https://www.hammfg.com/electrical/products/corrosion/1418n4al

Figure 4.12: Enclosure for system electronics and batteries (courtesy of Hammond Manufacturing)

Key Enclosure Specifications

- Dimensions: 36 in x 30 in x 12 in
- Material: Aluminum
- Standards: NEMA (National Electrical Manufacturers Association) 4X

The avalanche sensing system installation site (see Figure 3.29) was designed to support direct mounting of the electronics enclosure to the Unistrut structure installed on the south side of the rock on which the tower is installed.

Performance Analysis

Lab measurements have been made to characterize optimal power consumption of each of the primary components (laser, camera, pan-tilt unit, wireless modem) in all operational states. In addition, the output power generating capabilities of the wind generator has been analyzed using real wind data collected over two winter seasons. The final wireless modem was not available for this testing; however, a model very similar to the anticipated modem was tested for power consumption. Similarly, the final computer was not available for this testing; again, approximate power consumption is available for a typical embedded computer of the class expected to be selected and was used in this analysis.

Wind Generator

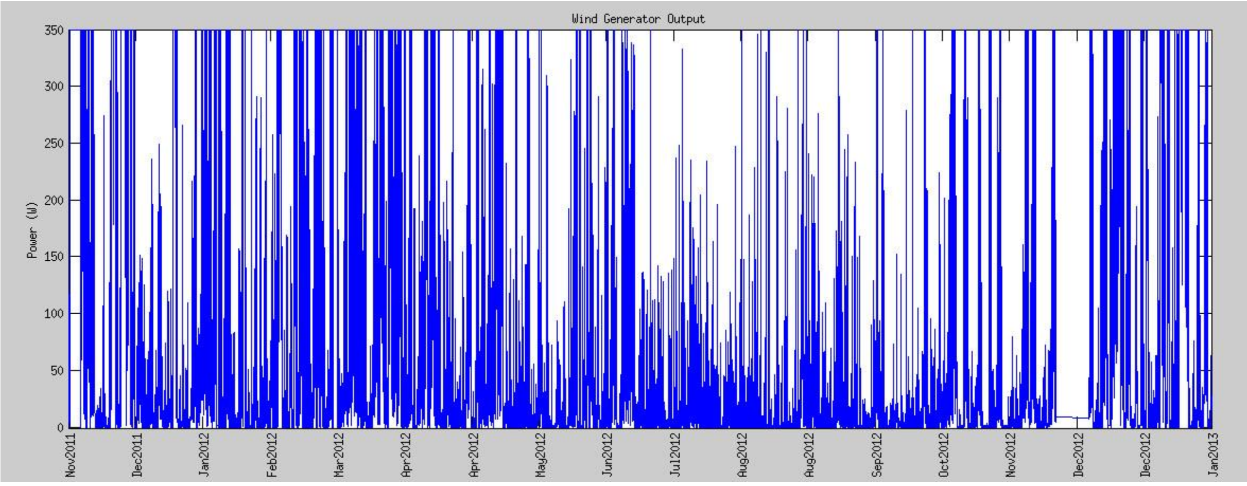

Figure 4.13: Analysis of power generation with typical wind patterns

Figure 4.13 shows the output of the wind generator given the historical wind input shown in Figure 4.4. The maximum power generation capability is limited to 350 W, although the wind speeds during the winter months far exceeds the generator input requirement. There are several periods where significant power generating wind is absent for several days to weeks in a row. Note that the period around December 2012 is a gap in available sensor data, not an extended period of calm.

Laser Distance Meter

Table 4.1: Analysis of laser power consumption

Mode	Power (W)	Time (sec)
Warm-up	9.6	130
Measure	9.6	

Table 4.1 shows that the laser distance meter consumes 9.6 W of power when warming up and when making measurements. Measurement time is negligible.

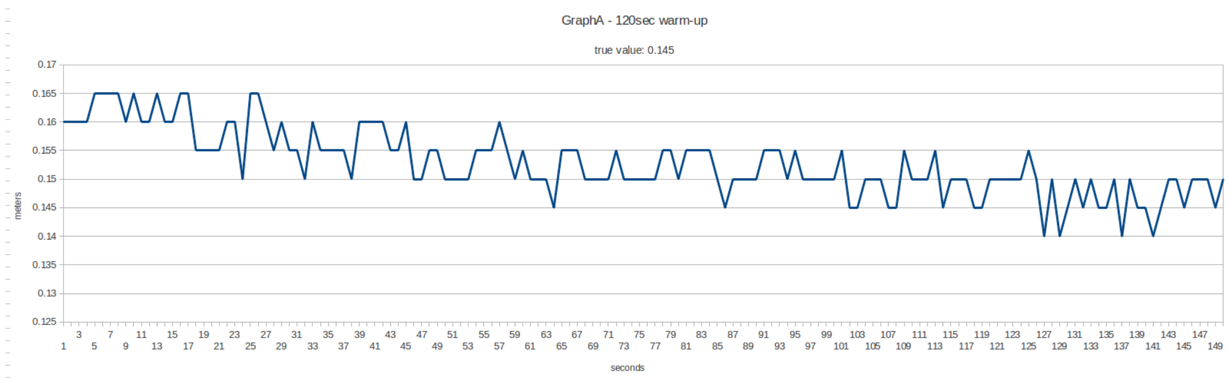

Figure 4.14: Laser distance measurement accuracy versus time during warm-up

Figure 4.14 shows the measurement results for the laser distance measurement sensor positioned a fixed distance of 0.145 m from a measurement target following initial power-up. In this experiment, the laser was cooled to a temperature of 35° F before being powered on. The manufacture recommends that the laser be powered up for 15 minutes prior to making measurements, but this would drastically increase the power budget and reduce the ability to make regular periodic measurements. From experimental results, the laser becomes sufficiently stable after about 130 seconds. The data in Figure 4.14 represents raw data. This data can be improved with multiple sample averaging to significantly improve measurements.

Based on the controlled experiments, the laser distance meter must be warmed up for 130 seconds before use due to environmental cooling after powering off the unit following each measurement cycle.

Camera

Table 4.2: Analysis of camera power consumption

Mode	Power (W)	Time (sec)
Boot	9	90
Active	9	

Table 4.2 shows that the camera, regardless of operational state, consumes 9 W of power. The camera requires 90 seconds warm-up before any video snapshots can be captured. Motion video will not be collected in the current use case. Instead, a small number of pictures will be captured during each measurement cycle.

Pan-Tilt Unit

Table 4.3: Analysis of pan-tilt unit power consumption versus speed

Mode	Power (W)
Idle	7.28
Active	12.6

Table 4.3 shows that when the pan-tilt unit is in motion it consumes 12.6 W. However at rest, it still consumes a significant 7.28 W. This relatively high idle power consumption is due to the internal motors holding the pan-tilt unit still while under load. The overall power consumption was lowest at 14V DC with a small additional speed penalty, based on experimental measurements of the pan-tilt unit power consumption and speed versus voltage.

Modem

Table 4.4: Analysis of modem boot time and power consumption

Mode	Power (W)	Time (sec)
Boot	4.32	135
Idle	1.29	
Transmit	4.8	

Table 4.4 shows the power consumption of the wireless 4G modem in various states of operation. As shown in Tables 4.1 – 4.4, the modem takes the longest time of all components to boot and consumes a significant amount of power compared to that during idle. The modem consumes almost 5 W of power during transmission, which is to be expected.

Embedded Computer

The low-power Linux based computer consumes 1.25 W when powered. The computer is a BeagleBone from BeagleBoard.org[12]. The computer must always be powered as it must monitor and control the system components.

Power System

The data generated from the detailed analysis of the various system components and the power generation estimates can be coupled with operational choices to develop an accurate power budget and thus appropriately size the power system.

12 http://beagleboard.org/bone

Table 4.5: System power consumption for a single measurement cycle

		Power (W)			
Time (s)	Action	Laser	Camera	Modem	Pan-Tilt Unit
0	Laser On	9.6	-	-	-
30	Camera On	9.6	9	-	-
90	Modem On	9.6	9	4.32	-
120	Positioner On	9.6	9	4.32	7.28
130	Begin 75 Point Measurement	9.6	9	4.32	12.6
230	End Measurements	9.6	9	4.32	12.6
235	Transmit Data	9.6	9	4.8	12.6
245	All Off	9.6	9	4.8	12.6

Table 4.5 shows a typical single measurement cycle from a power consumption perspective. Prior to the cycle beginning, all major components are switched off to conserve power. Only the computer and weather sensors (wind speed and direction, air temperature) are always on and active due to the very low power consumption, and the necessity for monitoring and control by the computer. The cycle begins by first switching on the laser to warm-up (130 seconds warm-up). At 30 seconds, the camera is turned on so that it will boot-up (90 seconds boot) and be ready about the same time that the laser becomes available for distance measurement. At 90 seconds, the modem is turned on so that it will boot (135 seconds boot) and be ready for data transmission at about the same time that all measurements are complete. At 130 seconds, when the laser and camera are ready, the pan-tilt unit is switched on and the measurements begin. The pan-tilt unit moves to each of 75 predefined locations where laser distance measurements are made. In addition, 1-2 camera snapshots are taken along the way. At 230 seconds, the measurement data is packaged along with local weather data and transmitted off-site. Upon completion the sensors are again switched off to conserve power. This entire process takes a little more than 4 minutes per cycle.

In total, a single cycle consumes about 1.75 Wh (0.15 Ah). With the goal of collecting data every 15 minutes during active snowfall or windy conditions, the system will consume about 7 Wh (0.58 Ah), which includes 1.25 Wh for the always-on embedded computer. From this, the expected run time for a single 55 Ah battery will be, with proper derating, about 2.75 days without recharge. Combining this duration with the previous wind pattern analysis results, the system includes 6 batteries.

General Power System Specifications

1. Measurement Period: 15 minutes
2. Snow Depth Measurements: 75
3. Pictures: 2
4. Weather Measurement Period: 1 second
5. Windless Run-time Rating: 2 weeks

6. Batteries (55 Ah): 6

The enclosure internal system can be designed based on these general specifications. The system was designed to house six Optima deep cycle batteries[13], a computer electronics enclosure, wind generator charge controller, and dump resistors.

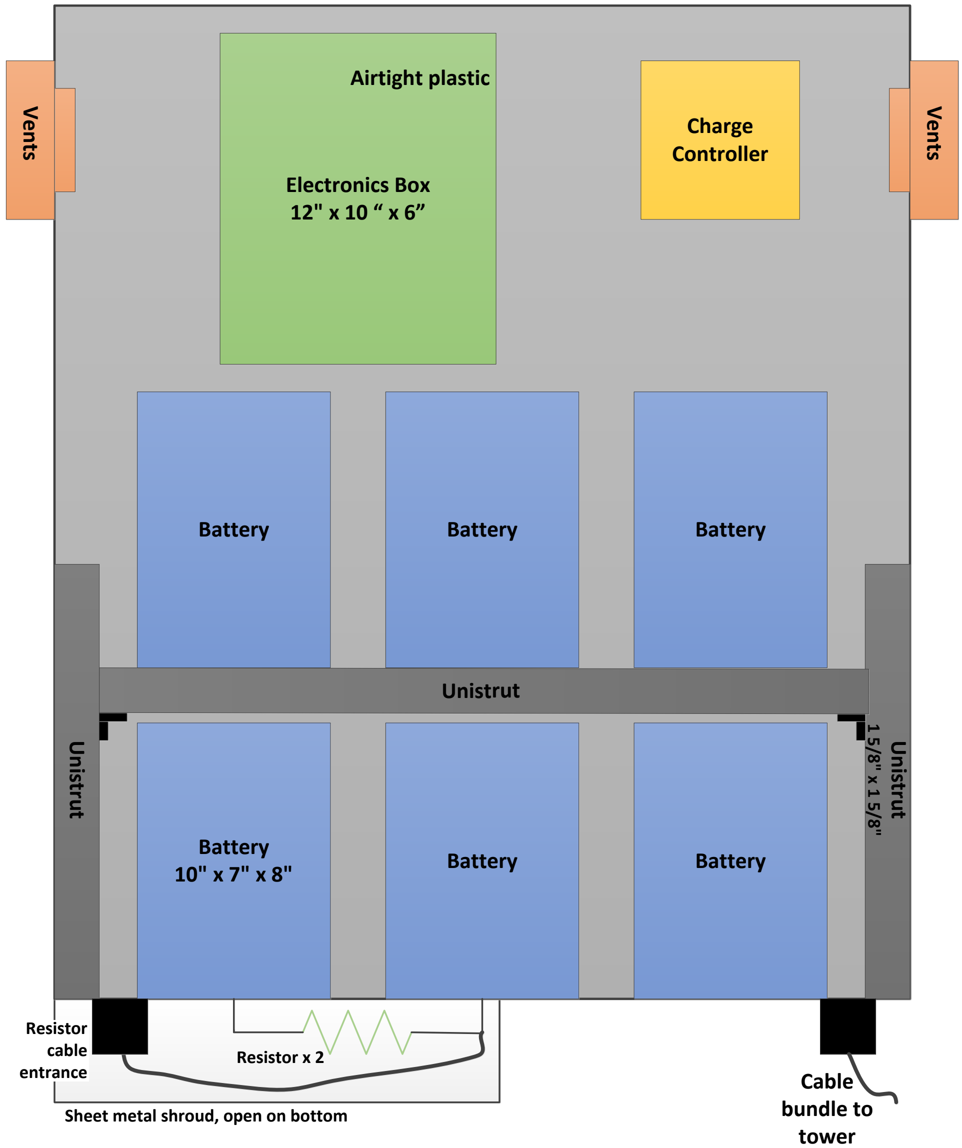

Figure 4.15: Electronics enclosure internal system design

Figure 4.15 shows the system design of the electronics enclosure. There are two rows of three batteries each, supported by an integral support structure made from Unistrut. The air tight computer enclosure is mounted in the upper left corner, while the wind generator battery charge controller is mounted in the upper right corner. Two dump resistors external to the enclosure are

13 http://www.optimabatteries.com/

used to burn off power from the wind generator once the batteries are fully charged. An aluminum shroud surrounds the resistors for safety. The enclosure is a NEMA 4X aluminum enclosure with splash proof vents at the top right and left sides providing cooling for the charge controller. Cable connections to the sensors and generator are routed out an open cable entrance at the bottom of the enclosure. To allow year-round operation, the enclosure is vented. As such, condensation may occur during the winter season. The commercial electronics are sealed in their own airtight enclosure, and all other components are moisture-tolerant. The enclosure is designed to drain moisture accumulation.

Software

The core of the software architecture is the measurement routine. Drivers have been written for each of the sensor devices with I/O interfaces, along with data acquisition drivers for the wind speed/direction sensors, air temperature sensor, and battery voltage monitors. Control of these drivers is performed by the primary measurement routine which is guided by rules based on current battery levels, time since last major wind event, and weather forecasts.

The software has been developed and implemented to perform the following core operations:

- Perform all necessary measurements at periodic intervals
- Optimize measurement sequencing to minimize power
- Adaptive measurement intervals based upon power availability
- Use of weather data feeds to aid in power optimization
- Package and compress the data for transmission
- Support remote system management

The measurement routine is the core algorithm in the avalanche monitoring system software. It is responsible for executing a single measurement cycle. The computer monitors the system clock and, when it is time to execute another measurement cycle, the measurement routine begins by powering the laser. The camera is then turned on 30 seconds later, followed by the modem after another 30 seconds. After another 30 seconds the pan-tilt unit is switched on and the measurements begin. The measurement routine then moves the pan-tilt unit to the first location and makes a distance measurement. It then moves the pan-tilt unit to the next position and makes another distance measurement, repeating until all 75 positions have been measured. At two of the predefined measurement locations, the camera takes a snapshot of the current view. At the end of the measurement session, the data is packaged along with local weather data and transmitted off-site. The time intervals for sensor sequencing and the number of measurement positions can be changed via a configuration file to optimize power consumption versus features.

The wind data is continuously collected at 1 second intervals to ensure all wind gust speeds and durations are recorded for historical and research purposes. When a measurement routine is triggered, the weather data collected over the last fifteen minutes is packaged along with the camera and laser distance measurement data and sent off-site.

The measurement routine is triggered by an adaptive optimization algorithm that regularly monitors the current battery voltage, time since last charge, and current weather forecast. Once a day, the system attempts to connect to an off-site weather feed and parse the information to determine if there is any forecast wind and/or snow over the next few days. The algorithm will ideally schedule measurement routines every 15 minutes, as preconfigured, to collect as much data as possible. However, based on observed wind patterns, days and weeks can go by without enough wind to power the generator and recharge the batteries. This necessitates scaling back of the measurement periods to conserve power. The algorithm follows a set of configurable rules to back off on measurement cycles as the battery voltage decreases. To avoid missing upcoming snow events, the algorithm consumes the forecast data and will ramp up the measurement cycles as the scheduled snow event approaches. This adaptive algorithm also allows the system to operate throughout the year, providing access to all system data streams, as well as remote maintenance in off seasons.

To support remote maintenance, the system is programmed to power up the modem for remote access at a scheduled time each day for a few minutes. If someone connects remotely to the system during this time the system will stay active until the user logs out at which time it will return to its previous power conservation mode.

In addition to providing the primary sensor measurement data regularly to the off-site consumers a significant portion of the software and system architecture is focused on power optimization and conservation. Many features have been developed to ensure that the system stays alive in all scenarios so that no on-site visits are required throughout the year.

The data collection, transmission, and visualization is not complete, and is left for future research. Currently, images and tabular (CSV) data are packaged in a zip file for transmission. We expect to provide camera images of the bowl to allow staff to remotely view conditions in the primary and secondary avalanche start zones. We also expect to provide tabular data for distance measurements to snow surface, wind speed and direction, and air temperature readings. Additional data will include battery levels and other system diagnostic information. A variety of graphical representations will be considered and discussed with District 10 Maintenance Supervisor staff, to determine the best approaches to visualize the available data to optimize avalanche control operations.

CHAPTER 5:
CONCLUSIONS AND FUTURE RESEARCH

Key contributions of this research included:

- A review of avalanche sensing and detection methods, models, and systems
- Creation of an avalanche zone instrumentation package with detailed avalanche start zone snow depth measurement capabilities
- A knowledge base for planning future site installations
- System design and partial installation to provide sensing to support avalanche start zone characterization and modeling, and optimized avalanche control operations

This type of system has a strong chance to change the way Caltrans monitors and forecasts avalanches. The system will modify and optimize snow removal operations. Currently, the Caples Lake snow removal equipment fleet works between Carson Spur and Carson Pass. When they feel that an avalanche is imminent, a worker is tasked with driving back and forth under the site in question, and radioing the fleet when the avalanche has occurred. It then takes the group about 15 minutes to reach the other side. Detailed real-time measurement of the chute can provide more accurate estimation of the event and can be used to alert the fleet when an avalanche does occur, thus freeing up personnel for other critical winter maintenance operations.

The safety and mobility improvements through application of avalanche sensing and detection are significant in Caltrans avalanche control areas. Data-driven avalanche control can increase both the efficiency and the effectiveness of avalanche control. This approach can also increase safety for workers and the travelling public by reducing the number of hazardous naturally occurring avalanches.

Lessons Learned

- It is by nature difficult to find suitable tower base plate and anchor locations for avalanche sites with appropriate local geology on uneven ground. Core samples or test drills may not be valid for installation locations a few feet away[14]. On Carson Spur, the geology is composed of rock composite material with high variability and voids that are unknown until installation is attempted. This significantly increased the difficulty of the installation.

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[14] This hurdle is not unique to the current research sites or team. A French company specializing in avalanche control systems was contracted to install the Gazex cannons on Carson Spur. Each cannon needs 8 holes, 4 for the legs, and 4 for the base. The holes must be 13 – 20 ft deep, and they are drilled and then filled with epoxy. For this job, the contractor underestimated the drill time 80%. The contractors often drilled 3 holes, but then had to move the entire set of holes as they could not get a good 4th hole for installation. They also often needed to pour in substantially more epoxy than anticipated, as the ground contains numerous voids.

- Due to logistical factors, traditional large-scale tower construction techniques cannot be used in the remote and harsh environments where installations are needed. This was true for the Carson Spur installation, even with the assistance of a helicopter to deliver staff, materials, and equipment.

- High wind speed combined with ice buildup represent significant challenges for tower design and survival. Carson Spur has severe wind speeds necessitating tower designs capable of sustaining very high continuous wind speeds.

- Tower installation success can be improved by finding locations that only need a very short tower due to snow levels. This facilitates installation of self-supporting towers without guy wires or anchors. Guy wire and anchor installation is extremely difficult on Carson Spur due to the noted geology.

- The number of suitable installation sites can be increased by separating the tower supporting the sensor equipment and the structure supporting the power generating device.

- Sensor usage must be managed to minimize power.

- All the components were selected to be survivable in the expected harsh environment or were enclosed in a manner to make them so. Even though a sensor is operable in steady state in the current weather conditions, the sensor may not perform to specification when it is first is powered up, i.e. some warm-up may be required. Detailed characterization of the sensors must be done, as the device will go through many power and thermal cycles.

Future Work

Future work includes finalization of the avalanche zone instrumentation package, complete system testing at the District 10 instrumentation site, and one full winter of data collection over the 2015-2016 season. This testing and data collection, to occur in a follow-on research project, will further validate the efficacy of avalanche sensing and detection in enhancing Caltrans avalanche control operations. As part of this testing, AHMCT will develop visualization software to be used by District 10 to improve decision making for avalanche control. This will include detailed avalanche start zone snow surface measurement capabilities, support for avalanche start zone characterization and modeling, and support for avalanche detection and alerting. With the available data and visualization capability, Caltrans staff should develop a strong predictive capability. The system should provide the tools needed to enable this capability, which will lead to optimized avalanche control operations.

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APPENDIX A:
ADDITIONALLY CONSIDERED INSTALLATION SITE

Figure A.1: Looking south towards the primary avalanche start zone

Figure A.2: Additionally considered tower installation site

The view of the avalanche start zones in Figure A.1 was taken from the location marked by the orange arrow in Figure A.2. Caltrans requested that this site be considered as a possible tower installation site due to its superior view of the avalanche start zones. Upon inspection it was noticed that the rock marked by the arrow as well as the surrounding rocks are unattached and resting in their current location. They are unable to support a tower base with a significant bending moment. Note the visible daylight underneath the marked boulder. It is possible that, based on viewing the snow cover in Figure 3.17, this site could support a short tower and avoid snow burial. However, the loose boulders would need to be removed before a proper tower could be designed and installed at this site.

Another configuration could be possible that includes a minimum-height free-standing tower supporting only the sensors, and a nearby installation of the wind generator. The reduced wind loading of a short tower without the wind generator could possibly remove the requirement for guy wires and allow installation as far west as possible. This configuration may be feasible assuming the loose boulders were removed and the resultant medium supports sound baseplate attachment.

Due to the safety concerns of the loose boulders, along with the uncertain characteristics of the ground for baseplate installation, this site was abandoned.

APPENDIX B:
PRELIMINARY COMMUNICATIONS SURVEY

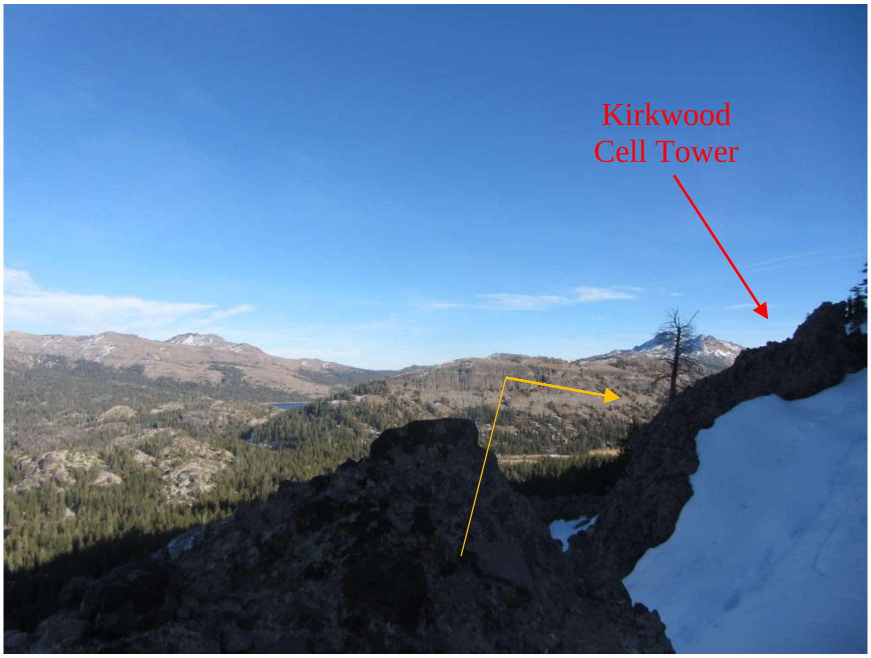

Figure B.1. Looking east from the tower installation site towards Kirkwood

Figure B.1 shows the view looking east from the tower installation site on Carson Spur at chute 4. It may be possible, using a directional antenna, to bounce a signal off the face of the mountain in the background and reach the Kirkwood cellular tower located around the corner of the view to the right.

Cellular Signal Strength Measurements at Various Locations on Carson Spur

- Kirkwood entrance: -85 dBm EVDO (Evolution Data Only/Evolution Data Optimized) 0.8 Mbps (megabits per second) down, 0.18 Mbps up
- Kirkwood core: -32 dBm EVDO 0.8 Mbps down , 0.38 Mbps up
- Turnout E of hiking access: -90 dBm EVDO 0.42 Mbps down, 0.15 Mbps up
- Elsewhere on roadway: < -104 dBm, i.e. almost no connectivity

Additional cellular measurements using higher-end antennas and receivers are planned for follow-on research.

APPENDIX C:
FABRICATION

Figure C.1: TIG (tungsten inert gas) welding the tower top plate fabrication

Figure C.2: The assembled tower top plate

Figure C.3: Close-up of the assembled tower top plate

APPENDIX D:
HAULING EQUIPMENT AND MATERIALS

Figure D.1: Packing out survey equipment from the installation site

Figure D.2: Packing out unused tower components from the installation site

APPENDIX E:
SITE INSTALLATION

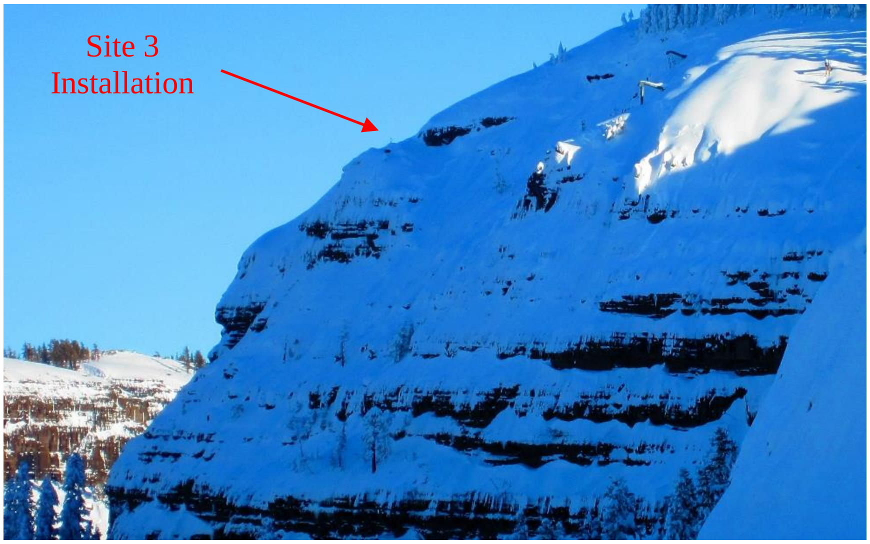

Figure E.1: Winter 2014 on Carson Spur at chute 4. The tower is visible beneath the arrow.

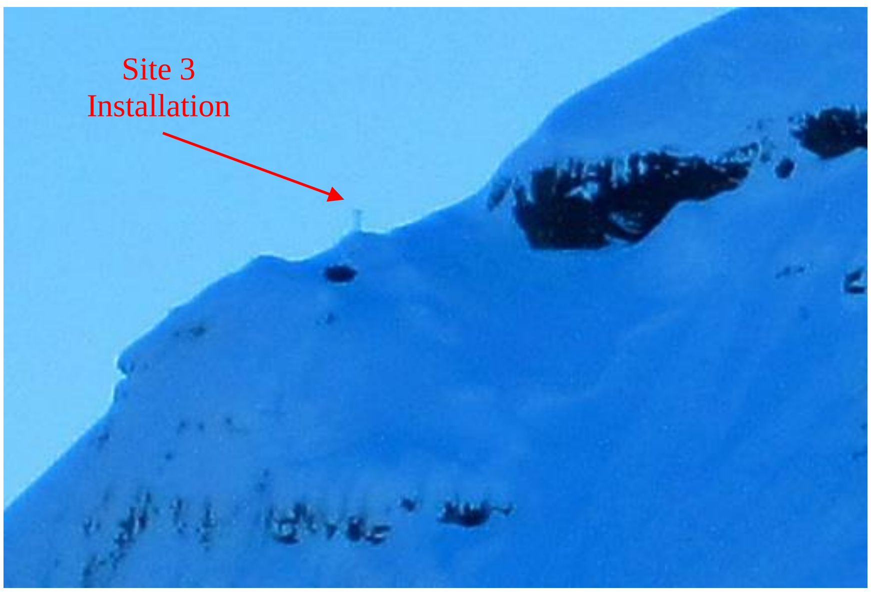

Figure E.2: Winter 2014 close-up of site installation. The tower is visible near the image center.