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Support for Avalanche Sensing and Communications

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Ty A. Lasky (Principal Investigator)

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ABSTRACT

This report documents the research project “Support for Avalanche Sensing and Communications.” The primary goal of this research was the continued support of avalanche sensing and detection in a key Caltrans District 10 avalanche zone. The impending 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 save the Department of Transportation money. The original avalanche-sensing system was developed under a previous research project. The current research continued support for this system; developed updates to the system design, hardware, and software; and prepared for the final installation of the system. Sensing regimes include snow depth across an 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.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AFRA	Avalanche Flow and Run-out Algorithm
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
CSV	Comma-Separated Values
DEM	Digital Elevation Model
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FMCW	Frequency Modulation Continuous Wave
GB SAR	Ground-Based Synthetic Aperture Radar
GIS	Geographic Information System
GPS	Global Positioning System
INS	Inertial Navigation System
LiDAR	Light Detection And Ranging
NEMA	National Electrical Manufacturers Association
NOAA	National Oceanic and Atmospheric Association
NWS	National Weather Service
PI	Preliminary Investigation
SAR	Synthetic Aperture Radar
SLF	Swiss Federal Institute for Snow and Avalanche Research
SR	State Route
SWE	Snow Water Equivalent
TIA	Telecommunications Industry Association
TLS	Terrestrial Laser Scanning
USDS	Ultrasonic Snow Depth Sensors

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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. The Caltrans Division of Maintenance deals with avalanches in both proactive and reactive modes. Proactive maintenance includes the installation of structures to mitigate avalanches, and avalanche control using guns, propane, and oxygen gas explosion chambers (Gazex® cannons¹) 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 by 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 provided continuing support for avalanche sensing and detection in a key California Department of Transportation (Caltrans) District 10 avalanche zone on Carson Spur near Caples Lake on State Route 88 (SR 88). The 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 could save the Department of Transportation (DOTs) money and lead to safer winter roads with higher mobility. The original avalanche sensing system was developed under a previous research project. The current research continued support for this system; developed updates to the system design, hardware, and software; and prepared for the final installation of the system. Sensing regimes include snow depth across avalanche start zone, camera imaging, temperature, and wind speed and direction.

Research Approach

The current research project built on the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center’s specific experience with avalanche sensing [6], general experience with winter maintenance research, strength in sensing and system integration, and established mechatronic hardware and software base [5,13,14,29-31].

The research project proposal tasks included:

1. Supporting the existing avalanche sensing and communications system

¹ TAS is a French company specializing in natural hazards control solutions. Here, the product of interest is their Gazex system. For more information, see:

<http://www.tas.fr/en/products/prevention-of-avalanche/39-gazex-gazflex-uk>

2. Developing a visualization system
3. Collecting and analyzing data
4. Documenting the system and the research effort (in this final report)_____

Due to the substantial challenges of the site installation, the research project proposal tasks were only partially executed. The site challenges are well documented in earlier research [6], and must be accounted for in any similar future efforts. The previous project did not complete the system installation at the site. As such, Task 1 support was restricted to improvements to the system in preparation for the final installation. Task 2 was limited to the conceptual design of table- and graphical-based user interfaces to support visualization. Task 3 was limited to lab data collection and analysis to better quantify system performance and power usage. Task 4 was fully completed in the form of this final report. The research project focused on the final lab bench testing, system modifications and updates, and the final preparation of the avalanche sensing system for installation on chute 4 of Carson Spur on SR 88.

Overview of Research Results and Benefits

The key deliverables of this research project include:

- The avalanche sensing system ready for installation at chute 4 of Carson Spur
- The final report

The avalanche sensing system was intended to be completely installed at chute 4 on Carson Spur during this research. This was not completely achieved.

CHAPTER 2: AVALANCHE SENSING AND DETECTION BACKGROUND

In addition to the tasks noted in Chapter 1, a Preliminary Investigation (PI) on avalanche mapping was performed in a separate but concurrent effort [12]. This PI reviewed completed research and surveyed consultants and DOT experts in avalanche mapping. The study included a literature search on avalanche mapping as performed worldwide, including the available methods of avalanche modeling and the use of sensing systems for avalanche mapping, avalanche forecasting, case studies, and general overviews. Various avalanche observation and safety as well as avalanche mapping guidelines were also found. Detailed interviews were conducted with avalanche mapping consultants regarding their previous mapping experiences and approaches and map generation methods and technologies. Finally, avalanche experts in several DOTs (Alaska, Colorado, Idaho, Utah, Washington, and Wyoming) were interviewed regarding their states' avalanche mapping experience. Avalanche mapping is closely related to sensing, as mapping identifies avalanche start zones and their hazard levels, thus helping to identify and prioritize locations for future avalanche sensing installations. The information obtained in this PI was quite relevant to the current research project. The PI provides extensive background on avalanche guidelines, modeling, forecasting, case studies, and sensing. The more relevant material from the PI is summarized below, along with added information that is more specific to the current research project.

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 and hydraulics. Statistical models incorporate historical data and leverage them to predict avalanches through statistical methods including Monte Carlo simulations.

Dynamic Avalanche Models

Salm [21] provided an overview of his extended work in snow dynamics and modeling, which 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 use in practice.” The practical model parameters involved are Coulomb friction, Chezy resistance, and the angle of internal friction. As Salm indicated, these parameters (including different topography and climate, involved mass, etc.) must be calibrated from numerous field observations. Salm concluded by citing Malcolm Mellor’s assertion that “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. [10] discussed the applications and limitations of dynamic models as related to snow avalanche hazard mapping. The researchers indicated that dynamic avalanche run-out 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 the limitations of dynamic

models, including friction coefficients, snow mass estimates, the number of variables and dimensions, entrainment, deposition, and flow laws.

Statistical Avalanche Models

Schweizer, et al. [23] investigated avalanche formation, or the complex interaction between terrain, snowpack, and meteorological conditions that leads to avalanche release. Focusing on dry snow slab avalanches, they noted that “dealing with a highly porous media close to its melting point and processes covering several orders of scale, from the size of a bond between snow grains to the size of a mountain slope, will continue to be very challenging.” They described five essential contributing factors: terrain, precipitation (especially new snow), wind, temperature (including radiation effects), and snowpack stratigraphy. This paper provides an excellent summary of avalanche formation and includes many useful references into the literature.

Osterhuber and Kattelmann [19] described the characteristics of warm storms with the potential to generate wet-snow avalanches. They also examined the frequency of rainfall following within three days of snowfall, which tends to be a hazardous combination. They noted that dry snow avalanches usually fail due to an increase in shear stress; wet snow tends to avalanche because of a decrease in shear strength. Some observations suggested that, as the slope angle increases, the wetted volume and the water-holding capacity decrease (see [11]). More qualitative analysis is needed to determine how susceptible any particular snowfield is to rain-induced avalanching.

Floyer and McClung [7] presented a numerical avalanche prediction scheme offering prediction rates greater than 70% for the Bear Pass, British Columbia highway operation. They sought an optimum variable set comprised of variables that effectively discriminated between avalanche and non-avalanche periods. These variables were the amount of new precipitation, the present temperature, the snowpack depth, foot penetration, and the present temperature trend. The discriminant functions built using these variables were used to classify each day into either an avalanche day or a non-avalanche day. The results using the testing data set gave classification rates of 73% for avalanche periods and 72% for non-avalanche periods, with a sample size of 465 periods.

Barbolini and Keylock [1] presented 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 provided a useful way for avalanche experts to produce hazard maps for the typical cases of avalanche sites for which the historical records are either poorly documented or completely lacking, as well as to derive confidence limits from the proposed zoning.

McCollister, et al. [16] investigated multi-scale spatial patterns in historical avalanche data for Jackson Hole Mountain Resort in Wyoming. They presented a probabilistic method that supports the use of historical data by incorporating a Geographic Information System (GIS) with a meteorological nearest neighbors approach. This approach uses concepts related to GIS visualization in order to investigate the relationships between specific weather parameters and the spatial pattern of avalanche activity.

In his M.S. thesis, McCollister [17] presented geographic knowledge discovery techniques for exploring historical weather and avalanche data; much of this work is summarized in [16]. The thesis included 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. [2] presented 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 of slope, morphology, and vegetation. For each of the identified zones of potential release, a second module, named the 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 facilitates the rapid mapping of large areas, in principle does not require any site-specific historical information. Furthermore, this 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.

Avalanche Sensing and Detection Methods

Schaffhauser, et al. [22] investigated terrestrial laser scanning (TLS) and ground-based synthetic aperture radar (GB SAR) to remotely determine snow depth and the snow water equivalent (SWE). TLS was able to determine snow depth with fairly high accuracy, but this is subject to the atmospheric conditions. GB SAR could determine both snow depth and SWE more quickly than TLS and without concern for the atmospheric conditions; however, GB SAR snow depth measurements were less accurate.

Prokop [20] assessed the use of Terrestrial Laser Scanning (TLS) to determine spatial snow depth distribution. He found that TLS provides an affordable and versatile alternative compared to photogrammetry, aerial LiDAR (Light Detection And Ranging), and ground- or space-borne synthetic aperture radar (SAR). Under the proper measuring conditions, the distance between the scanner and the snow surface was measured with an accuracy of less than 4 inches (10 cm) and within 1640 feet (500 m) of the target.

Teufelsbauer [25] linked TLS data to snowpack modeling to enhance 2D and 3D modeling.

Osterhuber, et al. [18] used LiDAR to collect data sets that were then analyzed to determine the targeted area’s snow volume. Repeated scans of the targeted areas were used to calculate changes in snow depth and volume. The imaging of snow cover using ground-based LiDAR is a relatively new application. The reflected signal from LiDAR was strong from dry snow. Good reflectance and laser signal return was also obtained from wet snow surfaces. By repeating target scans, the time-series analysis of the snow’s surface in one, two, or three dimensions can reveal detailed information about the snowpack’s accumulation, ablation, distribution, and redistribution. This research showed that the 1.5 μm wavelength laser commonly used in ground-based LiDAR

systems has more than adequate bidirectional reflectance and signal return from both wet and dry snow surfaces, enabling detailed surfaces' measurements during any time of the snow season.

Brazenec, et al. [3] noted that the National Weather Service (NWS) is exploring technologies for automated snow measurements. One existing technology already being used for some snow applications is ultrasound; however, ultrasonic snow depth sensors (USDS) occasionally produced spurious data. In most cases, meteorological conditions explained such data. As noted in [3], the situations that resulted in degraded data quality from the sensors included extreme cold (temperatures below -20°C), blowing snow, heavy snow, dendrites and large conglomerate snow crystal, and high winds. Heavy snow and blowing snow attenuated the sound wave, resulting in less reliable return signals. Dendrites and conglomerate crystals produced a soft and uneven snow measurement surface that sometimes caused ambiguous return signals. High winds, even with no snow on the ground, resulted in lost return signals at times, which appeared to be related to how firmly mounted the USDS were.

Lehning, et al. [15] discussed the construction of a network of high alpine automated weather and snow measurement stations in the summer of 1996 by the Swiss Federal Institute for Snow and Avalanche Research (SLF). Measurements include wind speed and direction, air temperature, relative humidity, snow depth, surface temperature, ground temperature, reflected shortwave radiation, and three temperatures within the snowpack. Data are transferred hourly to the SLF and used to drive a finite-element-based physical snowpack model.

Scott [24] applied 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 [4] 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 avalanche paths requires more topographic detail than for avalanche start zones and, therefore, a higher-resolution DEM.

Gruber and Haefner [8] researched the combined use of DEMs and satellite imagery data to develop avalanche hazard maps. They noted that the 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 in satellite imagery are essential. The DEM is also needed for geocoding the satellite scenes and for feature extraction. For hazard mapping, the 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. Accurate geocoding requires reference points and a high-resolution DEM.

Vallet, et al. [26] 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. [9] independently investigated aspects of satellite imagery data to develop avalanche hazard maps, assess snow avalanche paths and forest dynamics, and evaluate extraordinary avalanche formation and mobility. There was general agreement among researchers that QuickBird satellite imagery was the best available satellite sensor in terms of ground resolution (2 feet, or 0.6 m) and that it afforded new perspectives for the assessment of natural hazards [9]. Unfortunately, the QuickBird satellite orbit decayed, and the satellite reentered earth's atmosphere in January 2015.² The last image was taken in December 2014. Image archives are available and represent a useful source of information for avalanche research and development.

² For more information about the history of the QuickBird satellite, see: <https://en.wikipedia.org/wiki/QuickBird>

CHAPTER 3: INSTALLATION SITE

The selection of the installation site, along with its preparation, was an intensive and extended portion of the previous research project [6]. Ultimately, chute 4 of Carson Spur on SR 88 met the criteria. Details of the site and the selection process undertaken are provided in Donecker, et al. [6], with a more detailed current site status presented in Appendix C. The aspects most relevant to the current research project are included here.

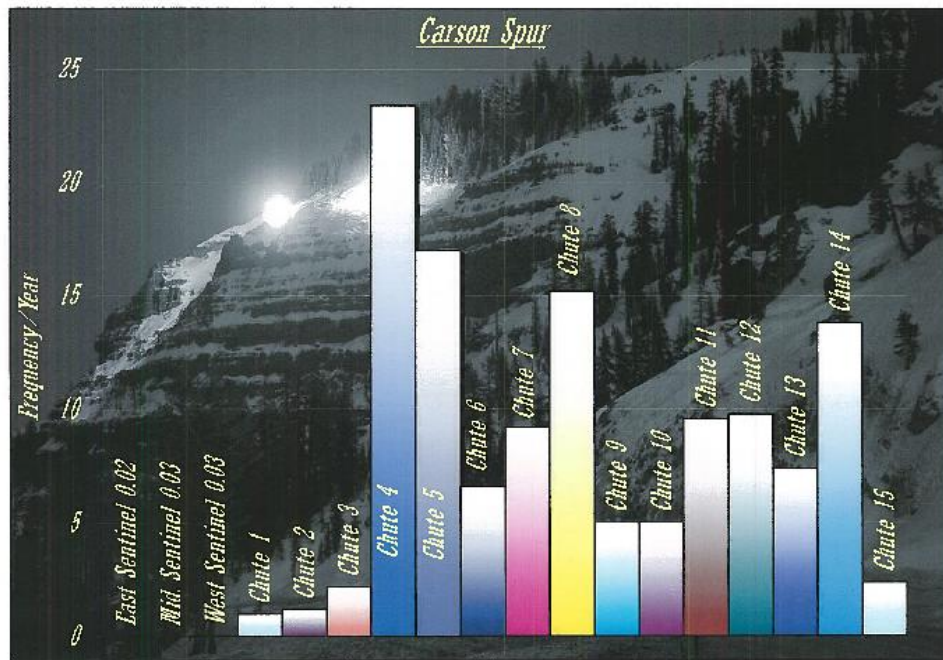


Figure 3.1: Typical number of avalanches per year per chute on Carson Spur at Caples Lake

Figure 3.1 shows the frequency of natural avalanches per season in a typical year. Upon the 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 a 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

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 of sensor station site
4. Installation feasibility of sensor station site
5. Survivability of sensor station
6. Sensor station range from measurement area
7. Good line of sight for sensors without interference from local features such as trees or terrain
8. Potential impact on avalanche control operations

Chute 4 Site

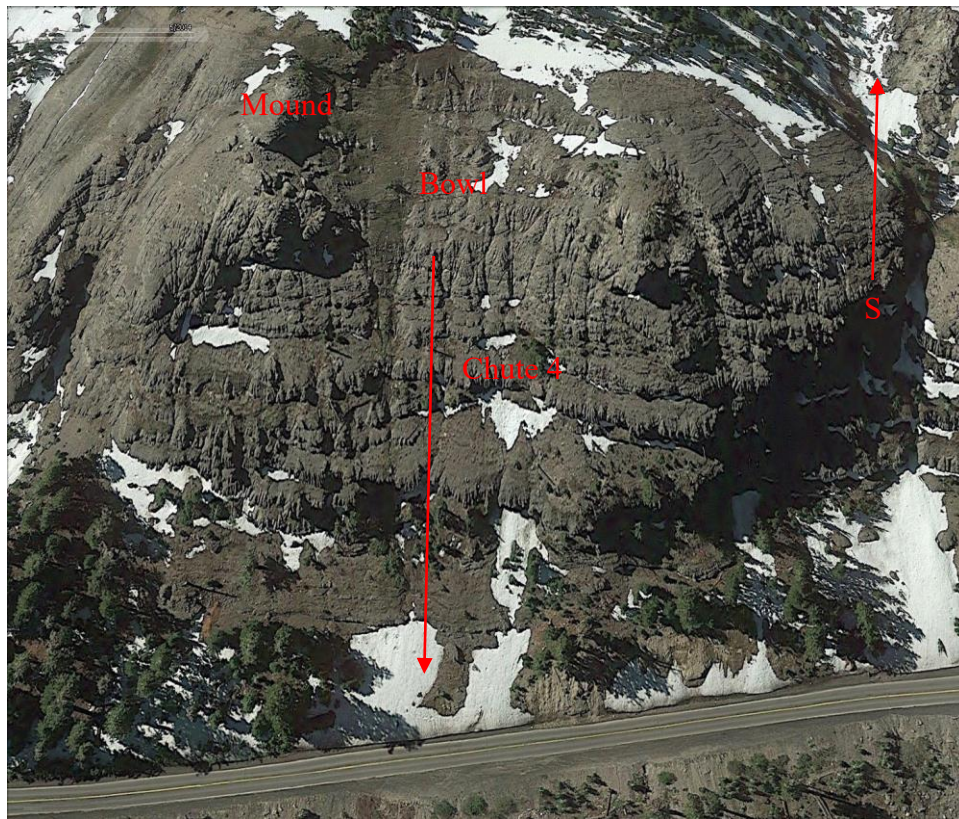


Figure 3.2: Satellite view of Carson Spur chute 4

Figure 3.2 shows the southward-facing Google satellite view of Carson Spur chute 4 above SR 88. This includes locations of the Gazex cannons, the bowl where snow accumulates, the chute path that avalanches follow, and a location labeled “mound” that provides potential system installation locations.

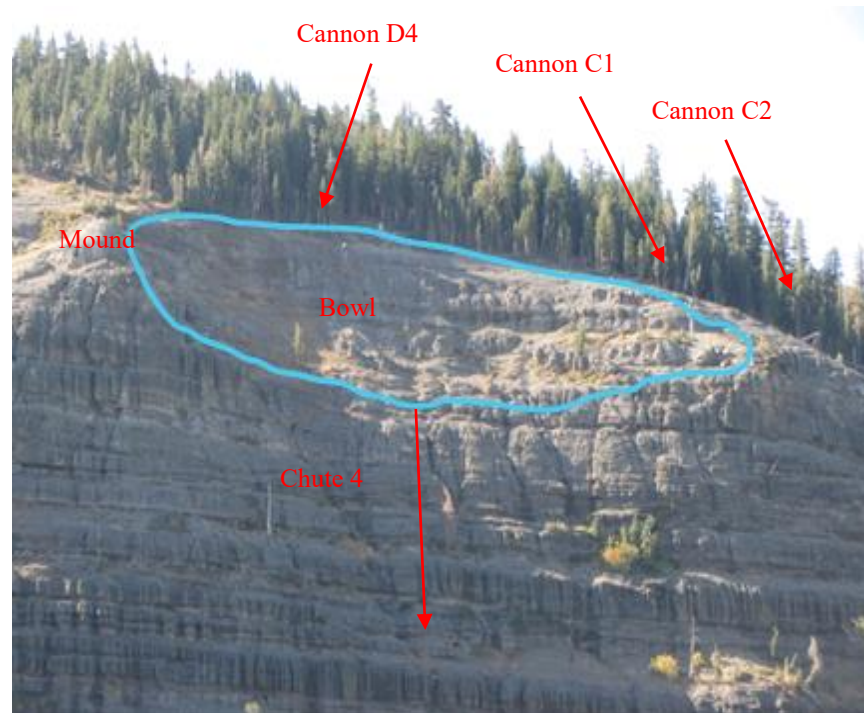


Figure 3.3: South-looking view of chute 4 bowl from the gun mount

Figure 3.3 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 in the top center of the picture below the tree line and another on the right side of the bowl to the center-right of the picture. 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 mixture of propane and oxygen and ignited to create a strong shockwave that starts a controlled avalanche.

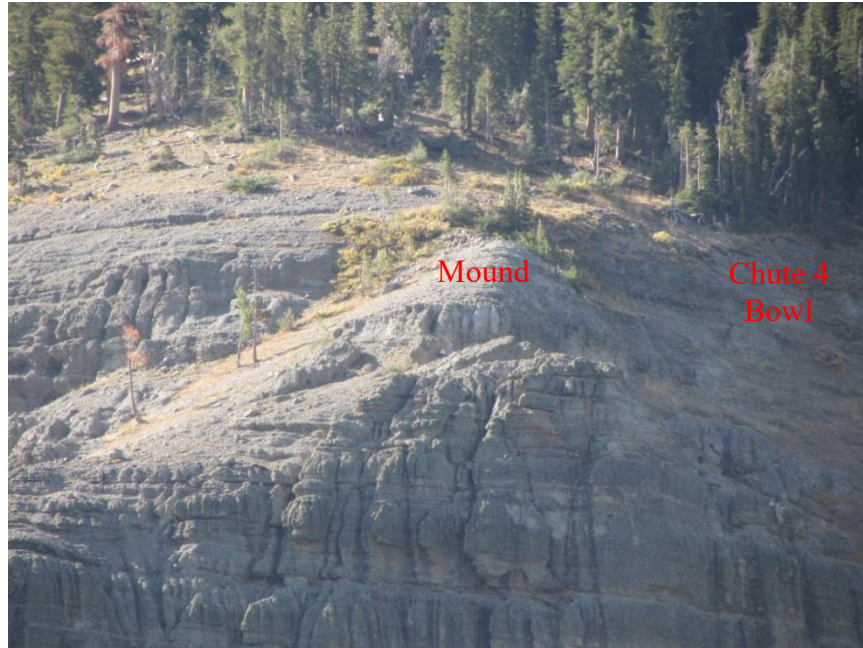


Figure 3.4: South-looking view of chute 4 sensor station site

Figure 3.4 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's 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 deep and coupled with a strong cross wind from the east (from the left side of the picture), an avalanche is typically triggered. Figure 3.5 shows this avalanche start zone outlined in red, as it is the most important of the start zones. This figure also shows a secondary start zone (outlined in cyan) composed of the area around the center top of the bowl. When this location begins to fill and the top becomes overloaded, an avalanche can be triggered from this location, as well. Caltrans indicated that its knowledge of these locations is very important to the avalanche measurement and characterization effort.

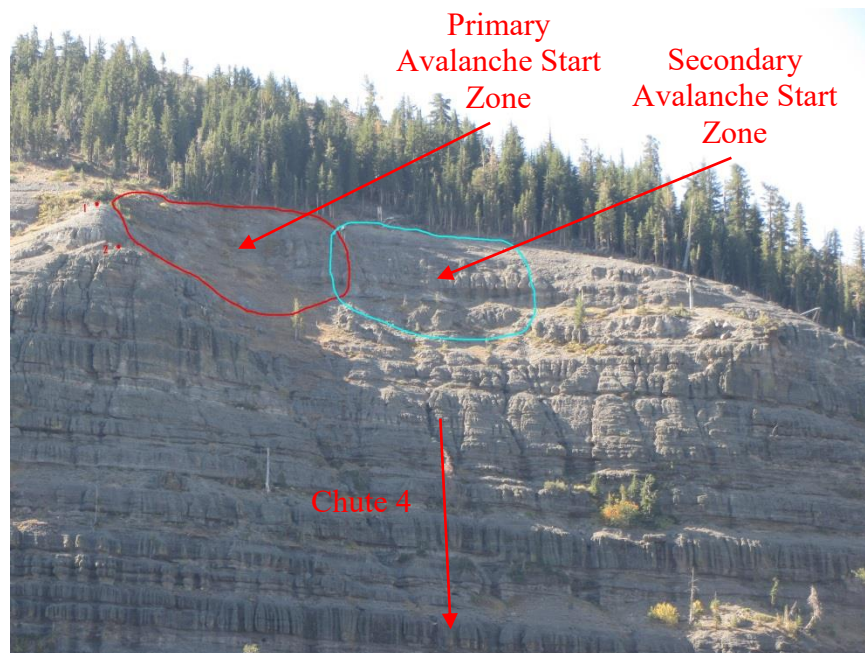


Figure 3.5: South-looking view of the chute 4 avalanche start zones

Key Characteristics of the Carson Spur Area and Chute 4

1. Unique bowl characteristics of chute 4 relative to those of all other locations on Carson Spur: very large, wide, and steep site; surrounded by two mounds; terrain (bowl created by mounds and shelf) allows for very large amounts of snow accumulation due to both wind-blown snow and regular snowfall
2. Snow season conditions: typically very heavy snow fall, possible icy conditions, very windy during storm conditions
3. Chute 4 is a frequent driver of avalanche operations on Carson Spur, according to District 10 personnel
4. Possible sensor station installation 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

Upon the selection of chute 4 as the target research avalanche site, several possible sensor station installation sites were then investigated. Based on the system requirements, the characteristics of the surrounding geology, and the site selection requirements, a final installation site was selected in the previous research project, as detailed in Donecker, et al. [6] and in Appendix C.

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 the sensor measurement of intended locations
4. Sensor station survivability during seasonal weather and avalanche
5. Tower height to keep sensors above the typical seasonal snowpack
6. Enough area to accommodate the tower anchors
7. Geology suitable to accommodate the tower base and anchors

Carson Spur Chute 4 Installation Site

A tower was designed and placed on top of the rock on the mound, as seen in Figure 3.4. With this installation site, the very large mass of rock conglomerate could be leveraged for both the tower base and two of the three anchors. The third anchor was attached nearby, below the base of the rock. Only a very short tower was required to achieve the needed sensor viewing height, since the mound is 11 feet tall at the peak. As illustrated in Appendix B, the tower at this site remains above the snow surface, at least during light winters. According to Caltrans Maintenance, this site should stay relatively clear even in heavier winters, as snow on this mound tends to be blown away by the frequent strong winds.



Figure 3.6: The west view of the final site tower installation and electronics enclosure mounting brackets

Figure 3.6 shows the tower installed atop the 11-foot rock. The base of the tower is almost 2 feet lower than the peak of the rock. This is due to the required machining of the rock surface to create a suitably flat mounting location for the tower base plate. Because of this, the tower is 5 feet tall and roughly 18 inches below grade for an effective extension of 3.5 feet above the peak of the rock. The Unistrut® mounted to the side of the rock provides a custom mounting surface for the electronics enclosure.³



Figure 3.7: The south view of the final site's tower installation

Figure 3.7 provides another view of the installed tower from the standing position at the second site location.

³ For more information about the Unistrut products, see: www.unistrut.com



Figure 3.8: A view of the tower and top plate

The close-up view in Figure 3.8 shows the custom-designed and fabricated tower top plate with the integral guy anchor points and mounting for the generator mast. The tower is vertical with a horizontal top plate, and the guy wires are tensioned to design specifications.

CHAPTER 4: AVALANCHE SENSING SYSTEM

The avalanche sensing system design and implementation was discussed in detail in the previous research project [6]. This chapter overviews the primary objectives and environmental considerations that drove the sensing system's design and development. It includes an overview of the performance analysis, the power budget and the power system, avalanche sensing system software, and additional system design and implementation issues, including modifications and further testing. Detailed individual sensing system component descriptions are provided in Appendix A; a more detailed discussion of the sensing system is provided in Appendix D.

Primary Objectives for the Avalanche Sensing System

The Caples Lake Maintenance staff identified objectives for the avalanche sensing system at Carson Spur:

- Collect data for avalanche characterization, modeling, and trigger optimization
- Provide an alert after an avalanche
- Measure the snow depth at several key points
- Provide local weather measurements
- Relay sensor data to the 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 since there is no on-site power
- Attach sensors to the tower mounted on local terrain adjacent to target chute

Environmental Considerations

Wind Speed

Wind speed considerations are presented in detail in Appendix D. As concluded therein, it is reasonable to expect 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 and Appendix C, the system is designed for 110 MPH continuous wind speeds and gusts above 140 MPH.

Temperature

From Appendix D results, the 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 were 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 the wind and quite a bit longer parallel to the direction of the wind, which is to be expected. Typically, the ice formation is 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 usually melts later in the day.

Snow Depth

The snow level at the installation site is flush with the top of the rock to which the tower was mounted. From discussions with Caples Lake Maintenance Supervisor staff, during typical snowstorms, the wind sweeps the snow across this position and keeps the snow limited to about the level of the top of the rock, i.e. the base of the tower.

Solar Irradiance

It was determined that the typical sun exposure during the winter months is less than one 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.

Performance Analysis

Lab measurements were made characterizing the optimal power consumption of each of the primary components (laser, camera, positioner, embedded computer, wireless modem) in all operational states. In addition, the output power-generating capabilities of the wind generator have been analyzed using real wind data collected over two winter seasons. These results are presented in Appendix D.

Power System

The data of Appendix D 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.

Table 4.1: System power consumption for a single measurement cycle

Time (s)	Action	Power (W)			
		Laser	Camera	Modem	Positioner
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 4.1 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, direction and air temperature) are always on and active due to their 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 (120-second warm-up). At 30 seconds, the camera is turned on so that it will boot up (90-second 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 up (135-second 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 positioner is switched on and the measurements begin. The positioner points to each of 75 predefined locations from 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 dictates that the system be fitted with six batteries.

Based on indications from Caltrans Maintenance, a 15-minute measurement interval is too long to qualify the system for avalanche alerting. The choice of a 15-minute measurement interval is conservative and is based upon worst-case environmental conditions (i.e., long periods of poor lighting and calm winds during snowfall) with continuous operational use (i.e., running every 15 minutes in storm or calm, day or night, 365 days a year). However, AHMCT has developed an adaptive algorithm that will considerably increase the system's overall power efficiency. This would allow a significant decrease in the measurement interval during critical events. In addition, with an adaptive algorithm, the system can run near continuously during high-wind conditions. As such, with sufficient experience and power-use data in real operating conditions, the system algorithms can be adapted to meet Caltrans' needs for an avalanche alert system.

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 Required (55 Ah): 6

The enclosure's internal system can be designed based on these general specifications. The system was designed to house six Optima deep-cycle batteries,⁴ a computer electronics enclosure, a wind generator charge controller, and dump resistors.

⁴ For more information about Optima batteries, see: <http://www.optimabatteries.com/>

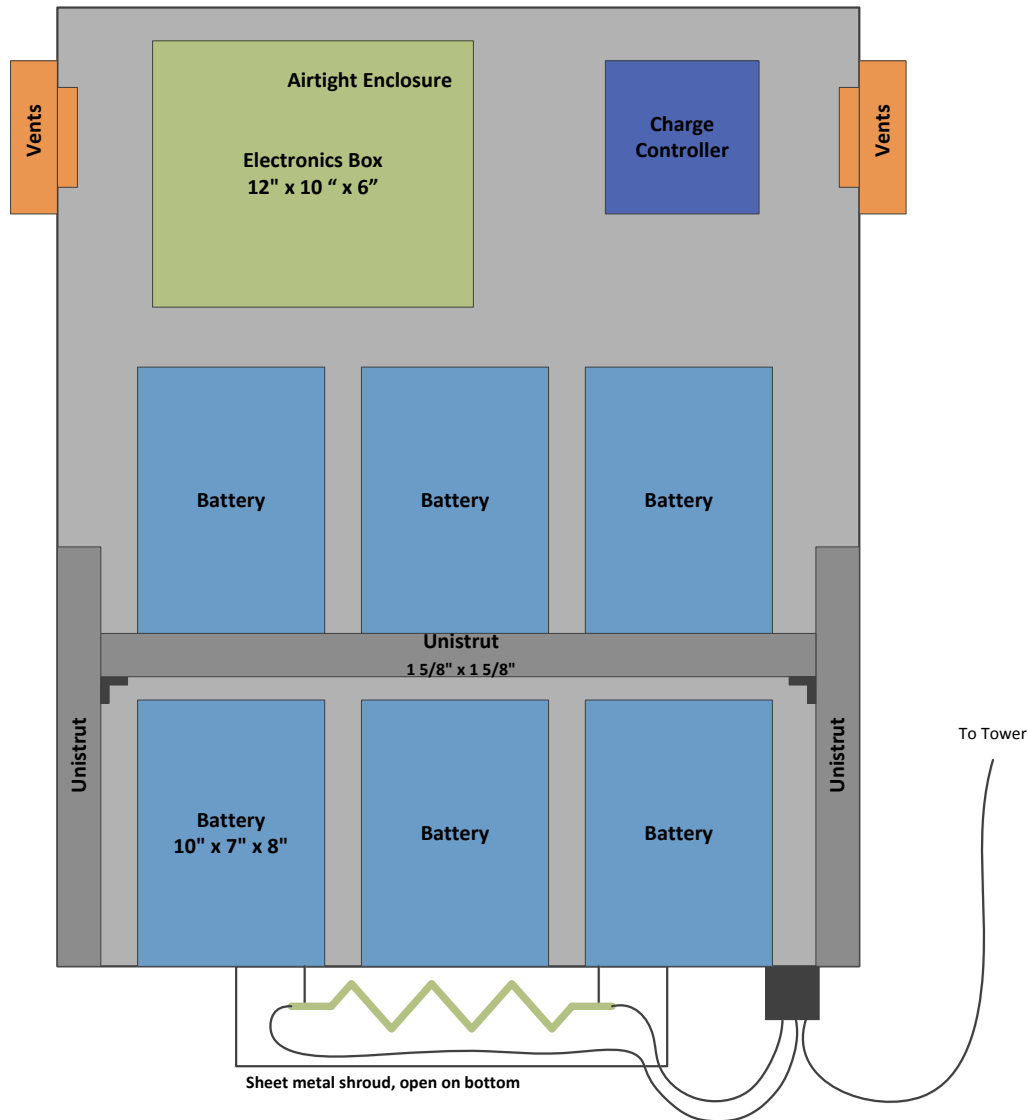


Figure 4.1: Electronics enclosure internal system design

Figure 4.1 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 airtight 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 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 National Electrical Manufacturers Association (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 buildup.

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, 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, the time since the 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
- Measure during adaptive intervals based upon power availability
- Use weather data feeds to aid in power optimization
- Package and compress the data for transmission
- Support remote system management

The measurement routine 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. In 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 one-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 transmitted off-site.

The measurement routine is triggered by an adaptive optimization algorithm that regularly monitors the current battery voltage, the time since the last charge, and the 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 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 ramps 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, it 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 are not complete and are left for future research. Currently, images and tabular data (comma-separated values, or CSV) 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 of 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.

Additional System Design and Implementation Issues

Numerous enhancements were made to the avalanche sensing system design of the previous research project [6]. These can be summarized as follows:

- Resistors relocated for enclosure thermal optimization
- Cable route openings reduced
- Design modification for camera enclosure and mount
- Design modification for distance meter enclosure and mount
- Design modification for positioner mount
- Design modification for wind speed sensor mount
- Design for antenna ground plane and mount

- Full-featured software feed parser developed for the National Oceanic and Atmospheric Association (NOAA) weather service providing current and forecast data

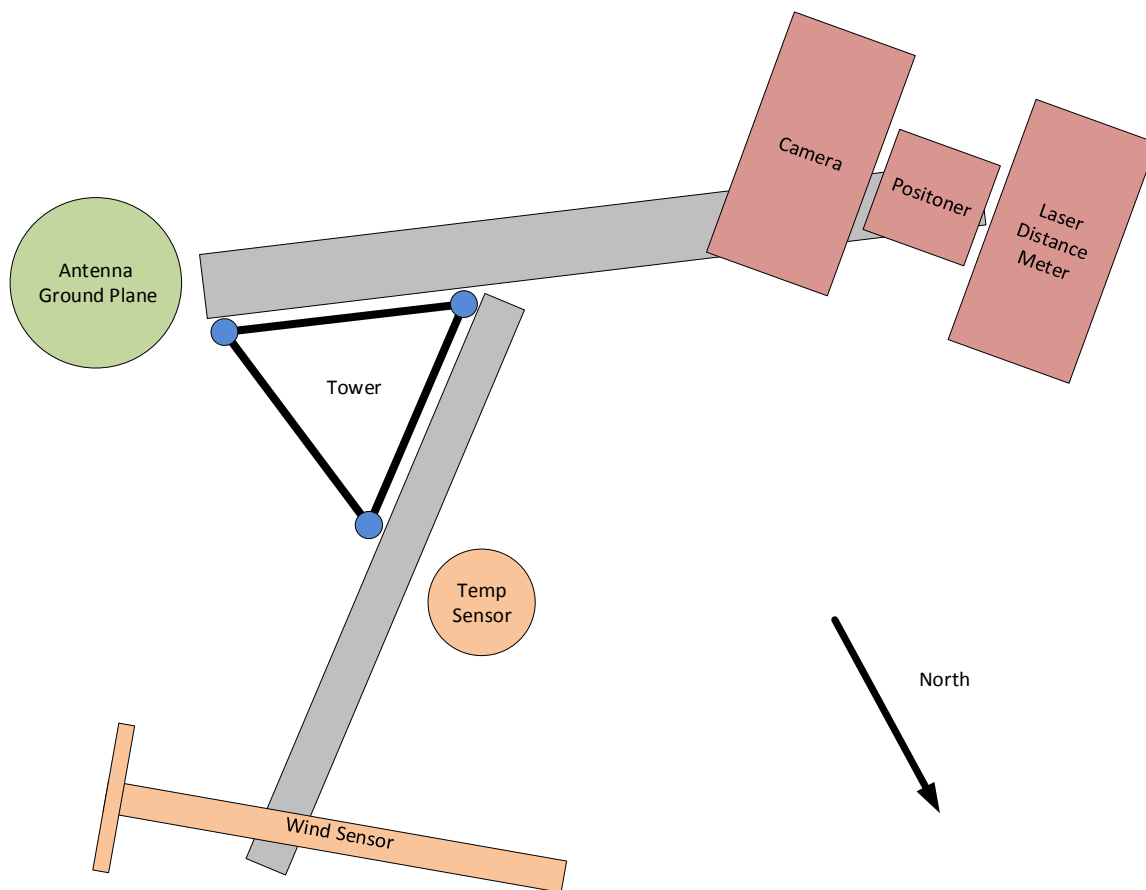


Figure 4.2: Sensor mounting locations on tower (top view)

Figure 4.2 shows a general representation of the various sensor mounting methods and locations. The wind sensor is mounted on a swivel at the end of an 18-inch extension mount towards the northeast, while the temperature sensor is mounted to the north tower leg. The wind sensor is mounted above the height of the top of the tower and is positioned such that it will not interfere with the tower or wind generator when the wind direction changes. The camera and the distance meter are mounted to the positioner 2 feet to the west of the tower leg, such that the sensors are above the height of the tower's top plate. These sensors have the ability to measure and monitor the entire bowl as well as the status of the tower location. The communications antenna and the associated ground plane are mounted to the east tower leg. The wind generator is not shown in Figure 4.2. It is mounted 2.5 feet above the height of the tower so that its blades will not interfere with the operation of the sensors.

A complete NOAA weather feed parser was developed that processes all current and forecast weather data for the local area. The previous weather forecast data extraction method was somewhat limited and less stable.

Depending on the weather patterns, further optimizations in the measurement routine scheduling and predictive power management can reduce the number of required batteries by 33-50%. However, since the enclosure mount is already installed and the enclosure already supports up to six batteries, the batteries will stay in place. Doing so will ensure sufficient battery capacity for the inclusion of sensing equipment and sensor heaters in future research.

CHAPTER 5: CONCLUSIONS AND FUTURE RESEARCH

The key contributions of this research project included:

- An updated review of avalanche sensing and detection methods, models, and systems
- An enhanced avalanche zone instrumentation package with detailed avalanche start zone snow depth measurement capabilities
- Support for real-time avalanche detection and alerting
- Support for optimized avalanche control operations

This type of avalanche sensing system has a strong chance to change the way Caltrans monitors and forecasts avalanches. Additionally, 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. The detailed, real-time measurement of the chute will provide a more accurate estimation of the event and alert the fleet when an avalanche does occur, thus freeing up personnel for other critical winter maintenance operations.

Safety and mobility improvements through the application of avalanche sensing and detection can be 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

- Sensors must be managed to minimize power, as it is easy to exceed the power budget.
- All the components were selected to be survivable in the expected harsh environment or were enclosed in a manner that makes 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 powered up—i.e., some warm-up may be required. A detailed characterization of the sensors must be done, as the device will go through many power and thermal cycles.
- It is quite worthwhile to revisit the system design and implementation. The very solid system from the previous research [6] was significantly improved in the current research effort through carefully targeted subsystem redesigns.

Future Work

Possible future work includes the final system installation and testing at the District 10 instrumentation site, and one full winter of data collection. This testing and data collection, which could occur in a follow-up research project, would further validate the efficacy of avalanche sensing and detection in enhancing Caltrans' avalanche control operations. As part of this possible future testing, AHMCT would develop visualization software to be used by District 10 to improve decision-making for avalanche control. Finally, additional work is needed to characterize and quantify power consumption under various operating conditions at the site, and to adjust an adaptive algorithm in order to optimize the measurement interval based upon the available power.

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APPENDIX A: AVALANCHE SENSING SYSTEM COMPONENTS

Wind Generator

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

Primary Wind Generator Requirements

- Use: Severe Duty
- Rating: 100 W @ 20 MPH
- Survivability: 110 MPH

Figure A.1 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 for all weather conditions.

⁵ For more information about the Superwind 350 wind generator, see: <http://www.superwind.com/>



Figure A.1: Superwind 350 wind generator (courtesy of Superwind)

Key Wind Generator Specifications

- Nominal Power: 350 W
- Nominal Voltage: 12 V DC
- Rotor Diameter: 3.9 feet (1.2 m)
- Speed Regulation: rotor blade pitch control
- Extreme Wind Speed: 110 MPH

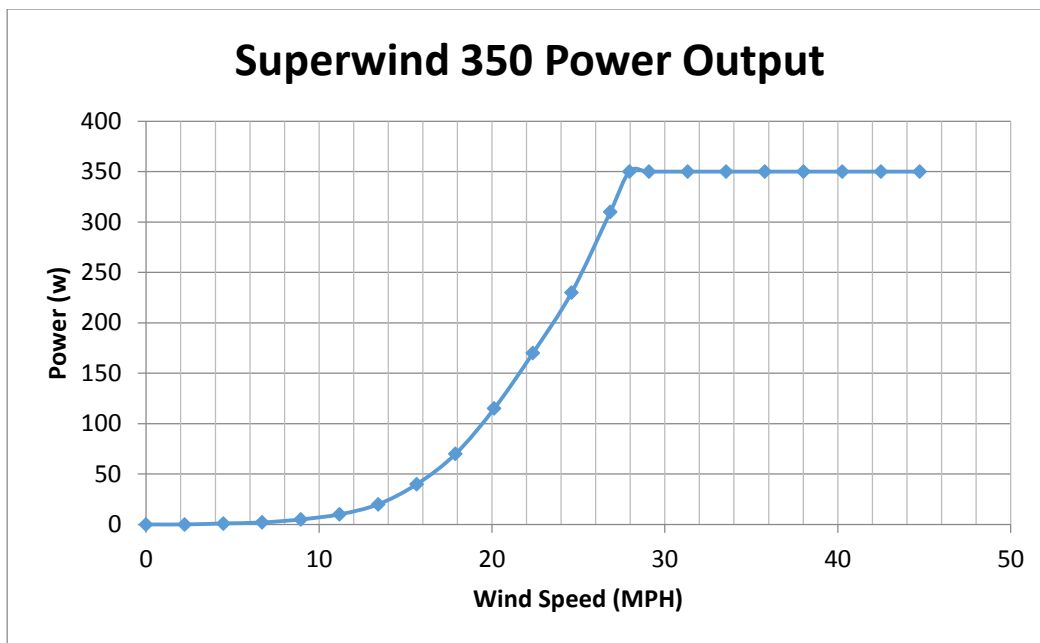


Figure A.2: Power output of the wind generator (courtesy of Superwind)

Figure A.2 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 feet above the top of the tower. A 5-foot mast is mounted through the hole in the tower top plate and anchored to another mounting bracket 2.5 feet 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 selection of the laser distance meter sensor 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 within the range of expected lighting conditions.

Key Laser Distance Meter Measurement Distances

1. Primary avalanche start zone: ~150 feet
2. Secondary avalanche start zone: ~ 275 feet

3. Furthest edge of the bowl: ~ 325 feet

Primary Laser Distance Meter Requirements

- Range: 350 feet
- Resolution: < ¼ inch
- Beam Divergence: < 4 inch beam spot size @ 150 feet
- Operating Temperature: 14 to 122 F

Figure A.3 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 A.3: RIEGL LD90-3100 laser distance meter (courtesy of RIEGL)

Key Laser Distance Meter Specifications

- Range: 490 feet @ 80% reflectivity
- Accuracy: 0.118 inch
- Resolution: 0.079 inch

⁶ For more information about the RIEGL LD90-3100 laser distance meter, see: <http://products.rieglusa.com/category/distancemeters>

- Snowflake clutter suppression
- Operating Temperature: 14 to 122° F
- Storage Temperature: -4 to 140° F
- Protection: IP64

The range specification is dependent on other variables in the current use case such as ambient lighting conditions and the 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 feet. 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 a range of 400 feet. For very dark rock, reflectivity can be very poor, critically limiting the sensor range. Ambient lighting conditions also affect the sensor range. Typically, performance is worst in bright sunlight and best in dark conditions. The range rating 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 feet; 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. In addition, 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.

From Appendix D, the typical minimum air temperature near Carson Spur is about 10° F during the winter months, with occasional dips to 0° F. The laser distance meter's storage temperature specification meets this temperature requirement. However, the operating temperature specification does not. In order to meet the operating temperature requirements, the laser distance meter is contained in an insulated enclosure. In use, the sensor is warmed up to its operational temperature range prior to measurement, as discussed in detail in Donecker, et al. [6].

The installation was designed to accommodate the mounting of the laser distance meter near the top of the tower and 2 feet to the west, thus extending the visibility of the primary start zone. Specifically, the sensor will be mounted to the pan-tilt positioner (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 basis to monitor snow buildup.

Camera

Figure A.4 shows the Axis 1347-E outdoor network video camera,⁷ which was selected to provide remote monitoring of the tower site and visual corroboration of the other sensor measurements, thus aiding in the human analysis of avalanche start zones.

Primary Camera Requirements

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



Figure A.4: 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

⁷ For more information about Axis cameras, see: <http://www.axis.com/>

- 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 feet to the west, thus extending the visibility of the primary start zone. Specifically, the sensor will be mounted to the pan-tilt positioner (discussed below) opposite the laser distance meter. The pan-tilt positioner will be mounted on a bracket structure extending out from the tower. This will allow the camera to aid in the 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 Mechanism

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 lower in elevation and near the bottom of the measurement zones, the system is looking upwards towards the 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. 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.

Key Pan-Tilt Mechanism Requirements

1. Tilt Range: -90 to +20°
2. Pan Range: 360°
3. Payload: (distance meter + camera + enclosures)
4. Operating Temperature: 0 to 122° F

Figure A.5 shows the FLIR PTU-48E, which was selected to meet the primary requirements.⁸ This unit enables positioning both the distance measurement sensor and the camera towards any visible location in the avalanche start zones under all weather conditions.

⁸ For more information about the FLIR PTU-48E pan-tilt unit, see: <http://www.flir.com/mcs/view/?id=53666>



Figure A.5: FLIR PTU-D48E positioner (courtesy of FLIR)

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

Wind Speed and Direction Sensing

Along with the primary sensors, general sensors that monitor factors such as wind speed and direction are needed. Referencing the wind speed ranges in Figure 4.1, the expected maximum wind speed is about 140 MPH. The Young wind sensor, shown below in Figure A.6, was selected

for its impressive specifications, wide adoptability, and its proven use in severe weather environments.⁹ In fact, there are Young wind sensors currently installed on Carson Spur.



Figure A.6: Young 05103V wind sensor (courtesy of R. M. Young Company)

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 the mounting of the wind speed sensor near the top of the tower on a bracket extending 1.5 feet to the north, thus providing appropriate clearance as the wind changes direction.

Air Temperature Sensing

Along with the primary sensors, general weather sensors, including those that monitor temperature, are needed. Figure 4.4 provides the maximum and minimum temperatures. The

⁹ For more information about the Young 05103V wind sensor, see: <http://www.youngusa.com/products/7/5.html>

Young temperature sensor, shown in Figure A.7, was selected for similar reasons as the Young wind sensor above.¹⁰



Figure A.7: Young 41342 temperature sensor with 41003 radiation shield (courtesy of R. M. Young Company)

Key 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, where it is attached directly to the north-most tower leg.

Enclosure

Figure A.8 shows the aluminum enclosure (Hammond model 1418N4ALM12) selected to contain the embedded computer, sensor interface electronics, wind generator charge controller, dump resistors, and 12-V batteries.¹¹

¹⁰ For more information about the Young 41342 temperature sensor, see:

<http://www.youngusa.com/products/2/15.html>

For more information about the Young 41003 radiation shield, see: <http://www.youngusa.com/products/2/11.html>

¹¹ For more information about the Hammond model 1418N4ALM12 aluminum enclosure, see: <https://www.hammg.com/electrical/products/corrosion/1418n4al>



Figure A.8: Enclosure for system electronics and batteries (courtesy of Hammond Manufacturing)

Key Enclosure Specifications

- Dimensions: 36 inch x 30 inch x 12 inch
- Material: Aluminum
- Standards: NEMA 4X

The avalanche sensing system installation site (see Figure 3.8) was designed to support the direct mounting of the electronics enclosure to the Unistrut structure installed on the south side of the rock.

APPENDIX B: SITE INSTALLATION

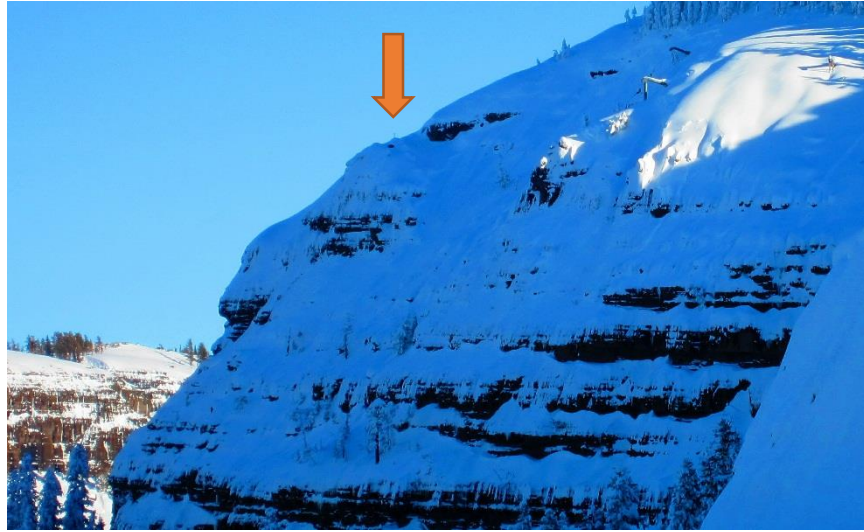


Figure B.1: Winter 2014 on Carson Spur at chute 4. The tower is visible beneath the arrow.



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

APPENDIX C: INSTALLATION SITE DETAILS

Chapter 3 of this report overviewed the final site status. This appendix provides a detailed discussion of the final site status. The site had to meet the requirements of Caltrans Maintenance personnel (sufficient number of avalanche incidents), and provide an installation location where it was feasible to situate the avalanche sensing system under the extremely challenging conditions of the Carson Spur terrain. The site's details and the selection process undertaken to choose the final mounting location are provided in Donecker, et al. [6], including an explanation of the tower and electronics bracket installation. That report also detailed the investigation of other sites and the challenges inherent in system installation on Carson Spur. See Figure C.1 for the Carson Spur chute locations.

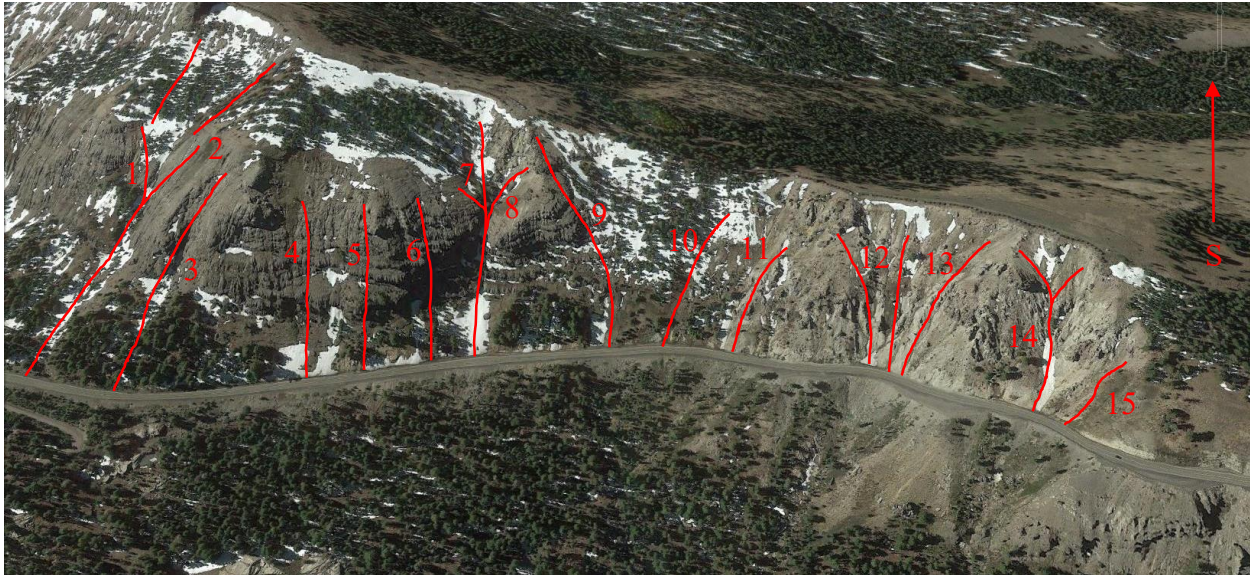


Figure C.1: Carson Spur avalanche chute locations

Carson Spur Chute 4 Installation Site

Installation Site Tower General Requirements

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

Installation Site Tower General Design

- 5 foot Rohn-25 tower¹²
- Guy wires attached to the top of the tower (5 feet)
- Sensors and antenna mounted at 1 foot below the top of the tower
- Wind generator mounted on a mast 7.5 feet from the tower base
- Electronics enclosure mounted to the rock conglomerate at chest height
- Design meets TIA-222-F (Telecommunications Industry Association) standards for 110 MPH wind with 1-inch ice¹³

The wind speed design criteria are critical considerations. Steady wind speed design criteria of 110 MPH were selected based on the closest available quantitative wind data (see Chapter 4 and Appendix D), 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.

¹² For more information about Rohn towers, see: www.rohnproducts.com

¹³ For more information about TIA standards, see: www.tiaonline.org and <http://www.tiaonline.org/all-standards/committees/tr-14>



Figure C.2: The southwest view of the bowl from the top of the final site's tower installation

Figure C.2 shows the view of the bowl from the top of the installed tower. This location has an excellent view of the primary avalanche start zone.



Figure C.3: The tower base bolted to the rock conglomerate

Figure C.3 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 $\frac{3}{4}$ -inch all-thread rods 30 inches long were epoxied into the rock conglomerate.



Figure C.4: The southwest tower anchor



Figure C.5: A close-up of the southwest tower anchor

Figures C.4 and C.5 show the southwest guy wire and anchor location, which is at an angle of 57° relative to horizontal. The anchor is $\frac{3}{4}$ -inch all-thread 60 inches long epoxied to the rock conglomerate. The selected angle allows for the full length of the anchor rod to be centered in the mass of the rock without breakout on the back side.



Figure C.6: The north tower anchor



Figure C.7: A close-up of the north tower anchor

Figures C.6 and C.7 show the north guy wire and anchor location, which is at an angle of 57° relative to horizontal. The anchor is $\frac{3}{4}$ -inch all-thread 60 inches long epoxied to the rock conglomerate. Here, the angle was very similar to that of the southwest anchor. The selected angle ensured that the guy wire avoided interference with the base rock and was not too close to the edge with its large crevices.



Figure C.8: The southeast tower anchor



Figure C.9: A close-up of the southeast tower anchor

Figures C.8 and C.9 show the southeast guy wire and anchor location, which is at an angle of 45° relative to horizontal. The anchor is $\frac{3}{4}$ -inch all-thread 60 inches 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. Additional views of the tower are shown in Figures C.10 and C.11.



Figure C.10: A close-up of the anchor plate and guy wire attachment



Figure C.11: The top plate with mounting for the wind generator mast

APPENDIX D: AVALANCHE SENSING SYSTEM DETAILS

The current sensing system status was overviewed in Chapter 4 of this report. This appendix presents the full current view of the sensing system's environmental considerations that drove its design and development. This appendix includes an appraisal of the performance analysis, the power budget and the power system, avalanche sensing system software, and additional system design and implementation issues, including modifications and further testing. Detailed individual sensing system component descriptions are provided in Appendix A.

Environmental Considerations

Wind Speed

The typical seasonal wind patterns for our installation site were major drivers for the overall system design. Along Carson Spur at the Gazex cannon control shacks there are wind speed meters, 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 resort from the end of 2011 through the beginning of 2013, covering almost two snow seasons. This data enabled the estimation of typical wind speeds used for both the tower design and the wind generator selection.

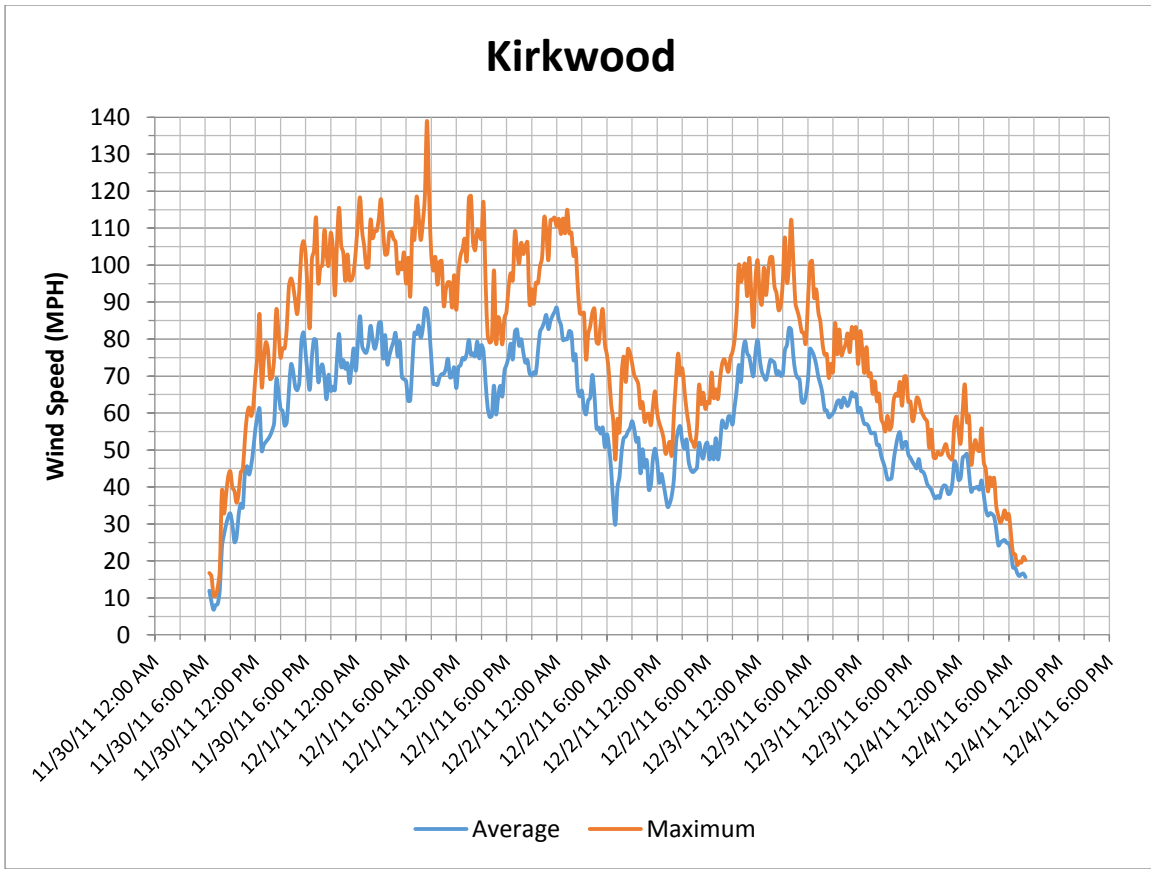


Figure D.1: Kirkwood wind speeds during December 2011 storm

Figure D.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; on 12/1/2011 at 9 AM, the winds were gusting up to 140 MPH.

December 2011 Storm Wind Speeds

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

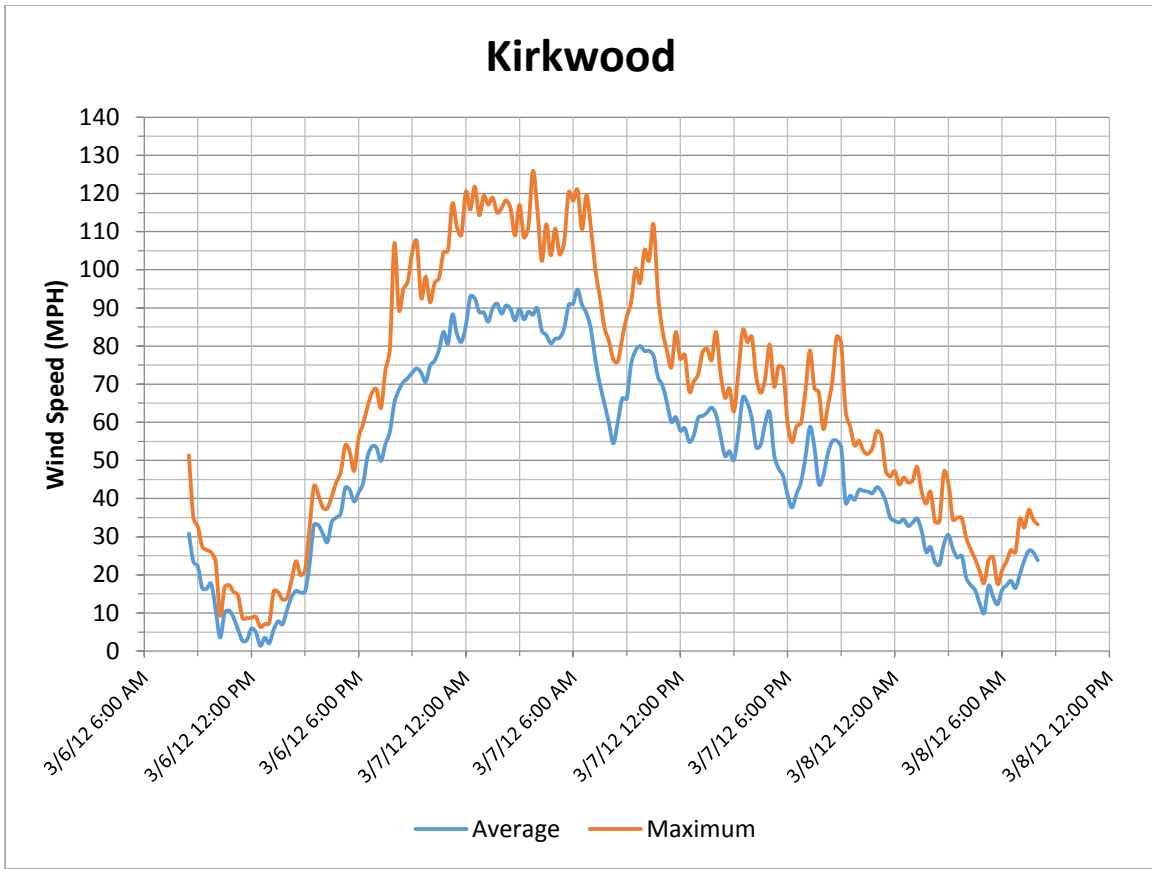


Figure D.2: Kirkwood wind speeds during March 2012 storm

Figure D.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 D.1 at about 90 MPH with gusts up to 120 MPH.

March 2012 Storm Wind Speeds

- Average: 90 MPH
- Gusts: 120 MPH

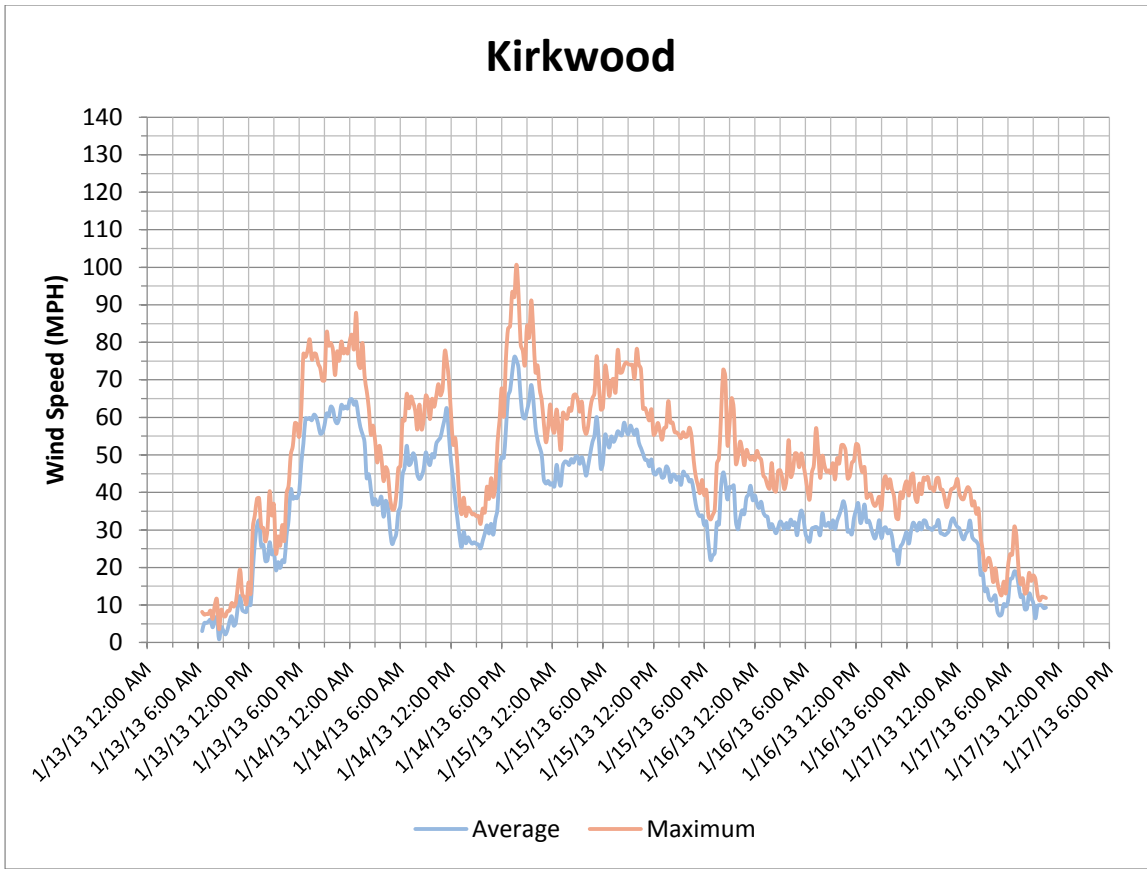


Figure D.3: Kirkwood wind speeds during January 2013 storm

Figure D.3 shows the January 2013 storm at Kirkwood, another sizable storm with high wind speeds that 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.

January 2013 Storm Wind Speeds

- Average: 60 MPH
- Gusts: 80 MPH

Conclusion

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 and Appendix C, the system is designed for 110 MPH continuous wind speed and gusts above 140 MPH.

Temperature

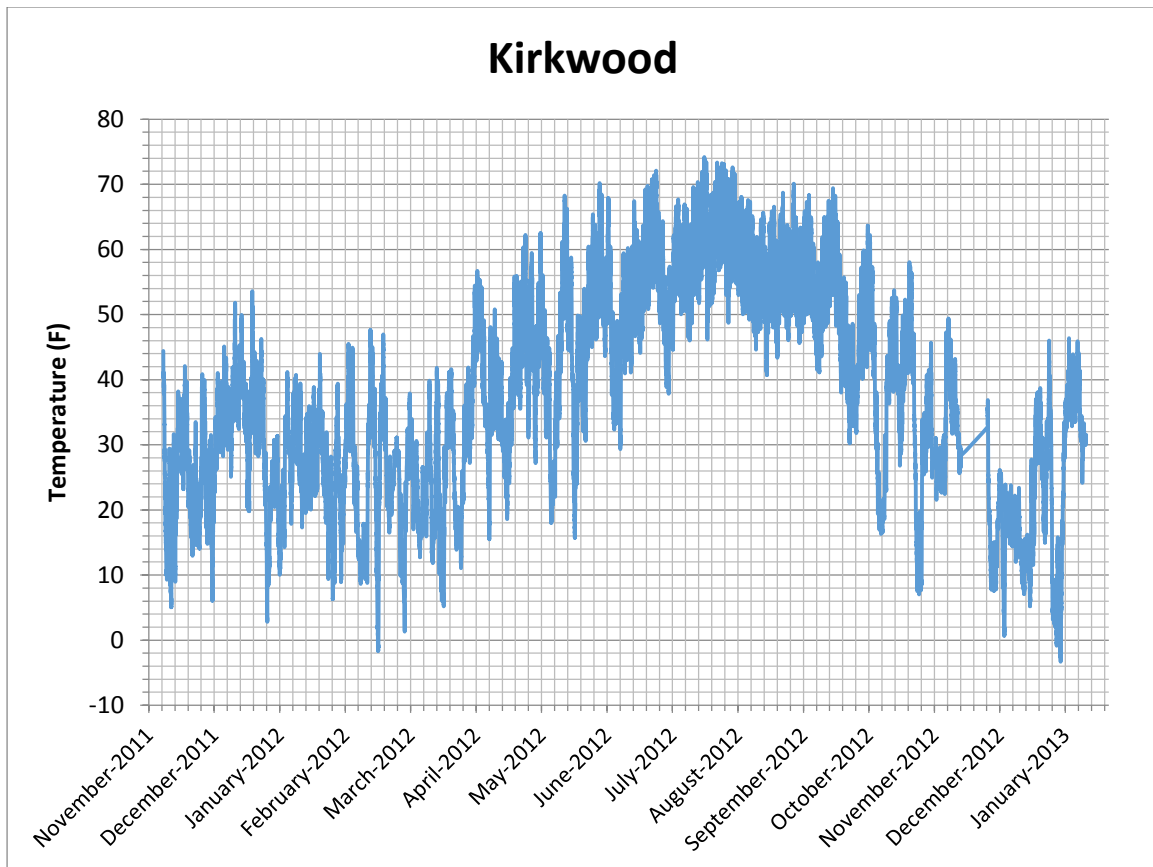


Figure D.4: Kirkwood air temperature November 2011 to January 2013

Figure D.4 shows the air temperature data, from which we can conclude that the 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 were 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 the 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 usually melts later in the day.

Snow Depth

The snow level at the installation site is flush with the top of the rock to which the tower was mounted. From discussions with Caples Lake Maintenance Supervisor staff, during typical snowstorms 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 one 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.

Performance Analysis

Lab measurements have been made to characterize the optimal power consumption of each of the primary components (laser, camera, positioner, embedded computer, wireless modem) in all operational states. In addition, the output power-generating capabilities of the wind generator have been analyzed using real wind data collected over two winter seasons.

Wind Generator

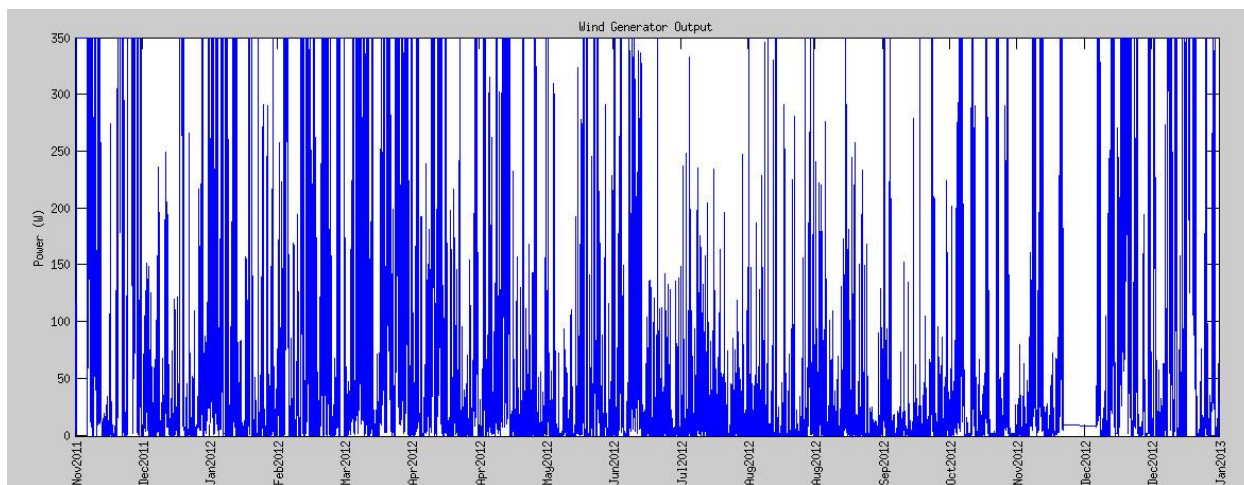


Figure D.5: Analysis of power generation with typical wind patterns

Figure D.5 shows the output of the wind generator given the historical wind input shown in Figure D.4. The maximum power-generation capability is limited to 350 W, although the wind speeds during the winter months far exceed 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 the available sensor data, not an extended period of calm.

Laser Distance Meter

Table D.1: Analysis of laser power consumption

Mode	Power (W)	Time (sec)
Warm-up	9.6	120
Measure	9.6	

Table D.1 shows that the laser distance meter consumes 9.6 W of power when warming up and when making measurements. Measurement time is negligible.

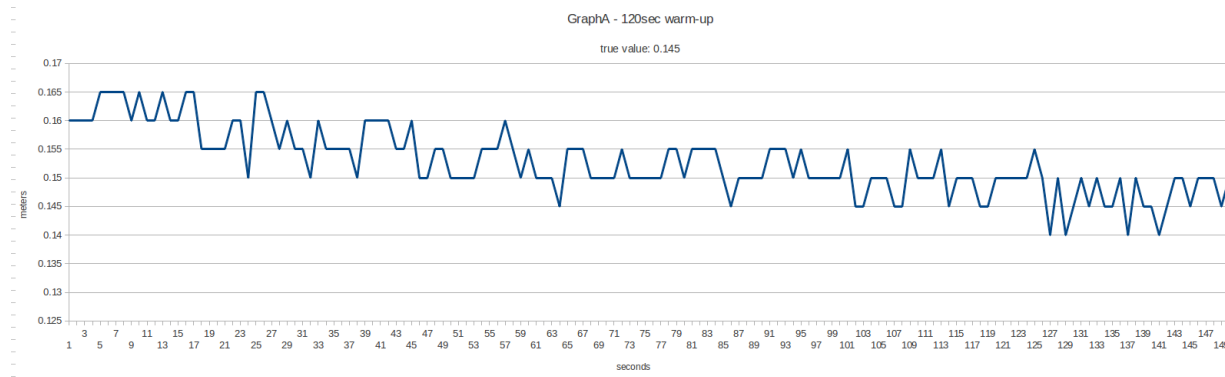


Figure D.6: Laser distance measurement accuracy versus time during warm-up

Figure D.6 shows the measurement results for the laser distance measurement sensor positioned a fixed distance of 0.476 foot (0.145 m) from a measurement target following the initial power-up. In this experiment, the laser was cooled to a temperature of 35° F before being powered on. The manufacturer 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 the experimental results, the laser becomes sufficiently stable after about 130 seconds. The data in Figure D.6 represent the raw data. This data can be enhanced with multiple sample averaging to improve measurements significantly.

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 D.2: Analysis of camera power consumption

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

Table D.2 shows that the camera, regardless of the operational state, consumes 9 W of power. The camera requires a 90-second 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 D.3: Analysis of pan-tilt unit power consumption versus speed

Mode	Power (W)
Idle	7.28
Active	12.6

Table D.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 the experimental measurements of the pan-tilt unit's power consumption and speed versus voltage.

Modem

Table D.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 D.4 shows the power consumption of the wireless 4G modem in various states of operation. As shown in Tables D.1 – D.4, the modem takes the longest time of all components to boot and consumes a significant amount of power compared to the modem when 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.¹⁴ The computer must always be powered, as it must monitor and control the system components.

¹⁴ For more information about the BeagleBone computer, see: <http://beagleboard.org/bone>