Energy Research and Development Division

FINAL PROJECT REPORT

Installation and Soft Cost Reduction for Horizontal Single Axis Trackers

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Installation and Soft Cost Reduction for Horizontal Single Axis Trackers is the final report for the Installation and Soft Cost Reduction for Horizontal Single Axis Trackers project (Contract Number: EPC-17-015) conducted by Nevados Engineering, Inc. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

The large-scale solar industry has historically focused on flat land for project installations. In 2019, more than 70 percent of all large-scale solar projects in the United States were installed with single axis trackers for higher efficiencies. The tools and equipment to operate these projects were designed for flat land installations, which were still the norm. However, flat land is not widely available and is often expensive and dedicated to other uses such as housing, roads, and farming. The needs of the rapidly expanding solar industry for land and lack of flat land are creating a demand for sloped land for large-scale solar installations. This can limit potential installation sites, require substantial earth work for site preparation, and result in substantial environmental degradation during the process.

This project demonstrated a novel single axis solar photovoltaic tracking system suitable for sloped and rolling terrain. The project will help solar developers build projects on lands closer to electric load centers and interconnection points that typically would not be considered, creating more site options. The project will also help overcome barriers to the achievement of California's energy goals by increasing the available land for installing solar photovoltaic and reducing construction costs by eliminating the need for grading soil and environmental mitigation costs, resulting in a 10 percent reduction in project budget and a 15 percent reduction in project schedule time.

Keywords: Single axis tracker, HSAT, solar, PV, flat land, all terrain, ATT, Row Controller, Block Controller, California Energy Commission, U.S. Department of Energy, Renewable Portfolio Standards

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EXECUTIVE SUMMARY

Introduction

Solar power is a key element of meeting California's goals to increase the use of renewable energy and reduce greenhouse gas emissions. Senate Bill 100 (De Leon, Chapter 312, Statutes of 2018) established a state policy that renewable energy and zero-carbon resources, including solar energy, supply 100 percent of electricity sales to consumers by 2045.

More than 70 percent of all large-scale solar projects installed in the United States in 2019 used single axis trackers. The large-scale solar industry has embraced single axis trackers because of the efficiency gained from rotating the modules to follow the sun. The solar industry developed around flat-land installations, but demand for flat land is already high for roads, schools, buildings, houses, parks, and other purposes, as well as for the rapid increase in solar projects. The only way to satisfy the solar industry's high demand for land is to shift to using sloped terrain. However, tools and equipment for installations on sloped and rolling terrain are lacking. Currently available tools and equipment can be modified to work on contoured land, but can lead to inefficiency and inaccuracy. Reconfiguring sloped and rolling terrain into flat land for solar project installation requires expensive earth-moving activities that create additional costs for environmental remediation and engineering associated with those activities. Fitting single axis trackers to contoured terrain more easily and cost effectively could eliminate the high costs and other effects of earth moving, reduce the costs of solar power plant installations, increase the speed with which they could be installed, and reduce the overall electricity costs for consumers.

Achieving an effective all-terrain tracker requires substantial development in software, controls systems, and structural design — tasks that have held up their development. Challenging issues for development include (1) how to operate all-terrain trackers on sloped terrain to capture the most sunlight without casting inter-row shadows, and (2) how to fit an all-terrain tracker structure onto natural land with a single, simple, and low-cost solution. Nevados developed solutions to these issues through prior research and has commercialized the technology as part of this project.

Project Purpose

In this project, Nevados Engineering, Inc. addressed all aspects of solar development on sloped and rolling terrain, including software, controls systems, monitoring systems, and hardware options from project speculation to operating life. Nevados applied for funding from the California Energy Commission to (1) prepare an all-terrain tracker for manufacturing, (2) refine and prove the ability of in-house energy prediction and tracker tilt calculation software to design solar power plants, and (3) prepare a proprietary controls system for production. Through this project, Nevados developed a commercially ready product to design solar power plants, manufacture products for those plants, and operate the finished plants.

In addition to development efforts, Nevados analyzed costs to ensure that the control systems and mechanical structures designed will be cost-effective in the industry. Through detailed engineering and supply chain development, Nevados developed a product that will compete on flat land with conventional single axis trackers (at scale) and also compete at lower production volumes if grading costs would be necessary to install conventional flat-land trackers.

Through these advancements, Nevados is poised to help the large-scale solar industry in California and throughout the county grow to meet renewable portfolio standards that require increased procurement of electricity from renewable energy resources. These advancements will enable low-cost construction, and high-efficiency operation, of solar power plants to help transition California and the rest of the United States away from fossil fuels and toward a renewable energy future.

Project Approach

To address the large engineering effort to develop a new solar tracker and engage with customers and suppliers to ensure that products are cost-effective and meet customer needs, Nevados created a team that included mechanical, electrical, and software engineers as well as advisors, customers, and suppliers under the direction of a principal investigator with an engineering background. The principal investigator engaged with customers and industry advisors to understand industry needs, plan for future industry expectations, and begin educating the industry on better ways to solve contoured land issues. Other engineers from the team led manufacturing efforts with suppliers to create supply agreements, reduce manufacturing costs, develop quality programs, and plan project logistics.

Research was spearheaded from the Nevados offices with staff engineers performing work and guiding the efforts of contract engineers. The project team developed products by creating specifications, running computer modeling, and conducting prototyping and testing. Testing was done in the office lab and at the demonstration site in Davis, California. The team then installed commercially ready products at the demonstration site for long-term testing as well as at three customer sites.

The team faced multiple technical and nontechnical barriers during the project. To address technical barriers, Nevados hired in-staff engineers and specialized contractors to develop products where necessary.

The project team addressed the performance on the various products, ranging from cost to operability, by creating specifications and costing goals and working toward those goals. The first step in product development was to create a specification. As the team gained knowledge about the product during development, it updated specifications to meet the growing understanding of needs, costs, and customer demands.

The project included an ad-hoc technical advisory committee with a fluid and changing group of advisors to gather the information needed to develop a product the industry desired. The team solicited input on technical tasks from contractors and customers, input on product specification from customers and industry advisors, and input on product costing from customers and suppliers.

Project Goals and Objectives

This research was to develop the products needed to transition away from the flat-land paradigm on which the solar industry developed.

Software necessary to operate solar trackers on contoured land requires more complex computations than those for flat terrain operation. The software must be able to determine how to operate an all-terrain tracker most efficiently on contoured terrain and generate highly accurate power generation estimates for the power plant so that the project can secure reasonable financing for construction. The software currently on the open market can estimate power generation only for flat-land installations and develop row operation plans for flat-land projects. The only way to estimate power generation using current is to simulate numerous iterations of a fixed tilt installation at the site to imitate how the tracker would operate, while analyzing power generation and shadow fall between rows. This strategy requires thousands of cumbersome iterations and results in very poor accuracy. Nevados planned to create software that could yield power generation estimates with a single physics-based run and to do so with a higher degree of accuracy than presently available.

Control systems capable of efficiently and reliably operating on non-flat terrain are not available on the open market. Nevados planned to develop an in-house controller with expanded capabilities to allow control and monitoring of more aspects of the all-terrain tracker to maximize efficiency.

Structures capable of operating on nonflat terrain are available but are currently limited in their application and cost. Nevados planned to develop a structure that had ubiquitous application on flat, sloped, and rolling terrain and at a price point that was competitive with existing flat-land trackers.

Project Results

All planned and desired results were accomplished. The major conclusions resulting from the research demonstrate that all-terrain tracking is possible at, or near, flat-land pricing and that the software necessary to enable high-accuracy, all-terrain tracking energy generation estimates is possible. These conclusions were demonstrated in the office lab, at a demonstration site, and at customer sites.

The project also resulted in several other developments. Nevados can now generate row-by-row tilt schedules for single axis trackers on contoured terrain to eliminate casting of power-robbing shadows from row to row in the morning and evening. This work is done using a simple model created for each site using the first-of-its-kind Nevados High-Definition Modeler software. The model can generate tilt schedules in a single run and use the schedules to estimate power generation for the life of the project, which is necessary to secure financing for construction.

In addition, because of further development of the Nevados all-terrain tracker structure, Nevados can now accurately design power plants to withstand wind loads present in contoured terrain environments and use a lower-cost and proprietary flexible joint to do so for less than the cost of using a typical U-joint.

Additionally, customers have come forward with interest in purchasing this equipment for sites on sloped, rolling, and relatively flat land to offset the high costs of installing conventional trackers. One customer has identified nearly 100 megawatts of installations for which it plans to use Nevados equipment. Another customer is working with Nevados to supply optimized operation plans for an existing single axis tracker installed on slightly rolling terrain that is suffering from inter-row shadowing that dramatically reduces power generation in the morning and evening.

Going forward, Nevados plans to further refine the current products. The mechanical design will go through a design iteration for lower cost manufacturing in addition to coordinating with preferred local manufacturing facilities. Further industry certifications will also be completed to make each Nevados product a stand-alone product.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Nevados presented at the National Renewable Energy Laboratory Industry Growth Forum, staffed a table at Solar Power International 2018, attended Solar Power International 2019, published an article on Energy Central, and spoke with myriad solar developers about the Nevados all-terrain tracker.

Benefits to California

Nevados' all-terrain tracker will benefit California ratepayers by reducing installation costs and enabling faster installation and adoption of solar power plants throughout California, thereby providing more solar energy to meet California's renewable portfolio standards at a lower cost.

The software's ability to provide power generation estimates with a higher degree of accuracy helps to secure reasonable financing, which, in turn, results in lower-cost solar power plant energy for purchase — a feature that will especially appeal to project developers, engineering firms, and project owners.

The all-terrain tracker controllers can increase performance of a solar power plant by up to 7 percent over conventional controls and can be used to repower existing solar power plants with power generation increases of up to 40 percent for the worst-performing sites. Operations and maintenance companies that manage existing power plants as well as customers purchasing new power plants and operating older power plants will especially appreciate these benefits.

Ratepayers will benefit from the ability of the Nevados physical structure to operate on all terrains while being cost-competitive with flat-land trackers. The end result is more renewable energy installed at lower cost and in less time. Further, the Nevados all-terrain tracker will accelerate adoption of solar power plants, not only in California, but throughout the world to help to mitigate climate change contributions from fossil-based power plants.

CHAPTER 1: Introduction

Goals and Objectives

This project developed a slope-friendly horizontal single axis tracker (HSAT) hardware design, control system, software, and power generation estimation tool that will dramatically reduce installation costs and radically expand the application capabilities of ground-based solar power plants. The design by Nevados can be installed on sloped, rough, and rolling terrain, eliminating the need for soil grading typically necessary for HSAT installations and reducing project costs by 3 to 10 percent. The technology also expands the potential locations for HSATs to areas where previously only low-efficiency fixed tilt systems could be installed. If installed on a south-facing slope, the technology can increase output by up to 7 percent compared to other HSATs. This project focused on further developing Nevados' equipment, certifying and testing the equipment, reducing manufacturing costs, analyzing the business case the equipment presents, and completing pilot manufacturing runs to bring the benefits of the HSAT to the market as a cost-effective product.

Barriers Requiring Technological Advancement

Current HSATs require expensive land grading because they cannot follow natural terrain, which lengthens construction schedules, requires environmental mitigation, and limits site locations. According to the National Renewable Energy Lab (NREL), the direct costs of flattening land range from 3 to 14 percent of project cost, and indirect costs (environmental studies, permitting, delays) range from 0 to 5 percent. The additional costs make wholesale solar uneconomical in many areas, including near load centers where flat land is at a premium.

Increasing viable locations is important as wholesale solar power moves from remote California deserts to populated areas where suitable flat terrain is not readily available. Nevados developed a novel HSAT system that will enable development of commercial and utility-scale solar power plants closer to load centers. Nevados' novel approach enables solar installations to follow the natural terrain of any project site, and a networked controller on each row automatically adjusts each row to maximize sunlight collection without casting shadows on neighboring rows. The net effect is a fleet of HSATs that maximize power generation of the solar power plant regardless of terrain. This will facilitate installation of HSATs in more locations, including places that might not be feasible or cost-effective with current technology.

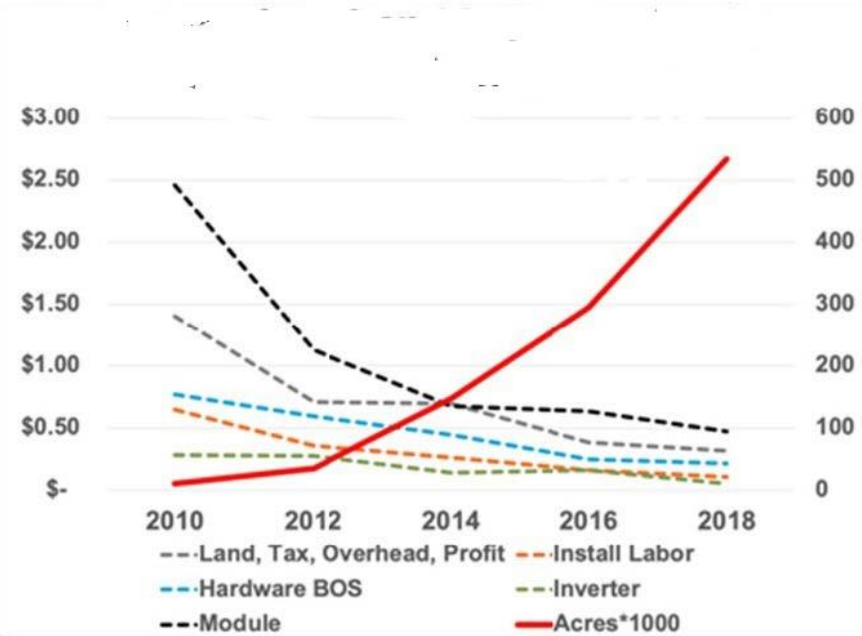
Justification for Funding

The solar industry is primed for the tracking system Nevados developed, but funding for hardware innovation in the solar industry has decreased since the industry's rapid rise that began in 2006. The decreased level of private sector investment makes it difficult to find early-stage investors for hardware-focused solar companies without a strong performance record or a large order backlog. Nevados had already found strong industry interest in its proposed product but required funding to finish developing the product and to ready it for commercial installation and commercial-level manufacture. This EPIC grant allowed Nevados Engineering, Inc. to develop its slope-friendly HSAT to a point where the company had a proven product and was able to secure order contracts.

CHAPTER 2: Project Approach

Renewable Portfolio Standards (RPS) have been adopted throughout much of the United States with more states expected to follow. Those RPS goals are expected to result in a five-time increase in solar installations through 2050, and possibly more. With the demand for flat land sites for conventional solar power plants already exceeding available flat land, there will be no choice but to install solar trackers on natural sloped and rolling terrain (**Error! Reference source not found.**).

Figure 1: Increased Demand for Land



Source: Nevados Engineering, Inc.

This project focused on creating products to facilitate the move from flat-land installation sites to contoured land sites to accelerate the growth of solar installations in California and the U.S. Enabling this transition will enable to meet its RPS goals in the time expected and at, or below, the costs expected. The expected outcomes of this project were a commercially viable structure that could fit to natural terrain, a control system to operate that structure efficiently, and software that could identify the optimum tilt angles for every row of every project installed to maximize the power generated from those solar installations. Table 1 summarizes the key tasks in the statement of project objectives.

Table 1: Summarized Statement of Project Objective Tasks

Component	Metric Description
Business	Solicit feedback from customers on future requirements for trackers
Business	Reduce cost of goods sold
Controls	Develop Nevados' proprietary row controller and current sensor within industry-expected cost targets
Controls	Demonstrate remote monitoring, control, and operation of complete control system
HALT	Survive ultimate strength testing of wind load torque
HALT	Survive 7300 cycle of max expected operating wind load torque (extended to 14600)
HALT	Survive 500-hour salt spray test with no red rust
HALT	Test minimum torque tube engagement necessary to survive max wind speed without failure
HALT	Analyze effects of grit on bearing wear over 35 years
Industry Cert	Complete bankability study with third-party engineering firm
Industry Cert	Complete Underwriters Laboratory (UL) listing #3703 with current design
Industry Cert	Pass ingress protection (IP) 65 testing of row controller, block controller, and current sensor
Structure	Increase post install tolerances to +/-12" to reduce rework risk on non-flat terrain
Structure	Complete wind tunnel study analyzing structure on slopes of up to 37% and submit to professional engineer for analysis with ATT structure
Structure	Test and quantify tunable friction coating options for bearings
Structure	Develop next generation of Nevados' ATT flex joint eliminating the u-joint
Structure	Develop installation, operation, and maintenance manual
Structure	Reduce manufacturing and construction time for the individual components
Software	Demonstrate operation of the high-definition performance model in the lab and in the field within 10% accuracy or better (achieved 2% accuracy versus measured production)
Software	Create software test plans, commissioning strategy, and remote update process
Software	Create controls interface and improve usability based on customer feedback
Software	Contract with independent security firm to analyze the security of the Nevados controls system

HALT = highly accelerated lifetime testing.

Source: Nevados Engineering, Inc.

The commercially viable structure is the physical backbone that enables installation of high-efficiency solar projects on non-flat terrain. Nevados calls this structure an "All Terrain Tracker" (ATT) (Figure 1). This structure supports the solar modules, includes an electro-mechanical rotation mechanism to change the tilt of the solar modules throughout the day, and resists all normally expected forces from extreme weather events and corrosion that could undermine the solar power plant. The innovation of this structure has to do with its ability to fit to rolling and sloped terrain as easily as flat terrain and to be cost effective when compared to other products on the market that require expensive and damaging modifications of the soil to enable installation. This structure is also relatively simple and straightforward and has received comments from professionals in the industry ranging from "Easy and obvious to understand" to "Enables installation on available terrain that otherwise is not cost effective" and "This is the easiest tracker we have ever installed."

Figure 1: Nevados Test Site Shows Exposed Module Mounting Tube and Allowable Angles

Source: Nevados Engineering, Inc.

Nevados developed a new control system (Figure 2), named Nevados All Terrain Controls (ATC), that was necessary for operating on contoured terrain.

Figure 2: Nevados All Terrain Controls Row-Controller

Source: Nevados Engineering, Inc.

This control system eliminates the need for installing power wire from an alternating current (AC) source, or communications wire, because it is self-powered and communicates through wireless antennas. The ATC enables the ability to operate the ATT throughout the day with row-by-row tilts calculated to avoid inter-row shadows. The ATC also enables real-time monitoring of the health of the controllers and the solar modules, as well as real-time monitoring of potential inter-row shadows, to ensure optimum operation of the solar power plant. No system like this was on the market, so Nevados had to develop its own system. Nevados is making this system available on the open market for other tracker manufacturers to use since it is many steps beyond the capability of what is currently being sold. Through the term of this award, Nevados was able to reduce to costs of the ATC to be competitive on the open market.

Installing and operating a power plant on flat land enables assumptions about parallelism between rows and a constant plane for all of the solar modules. This in turn allows all rows of the solar project to be rotated at the same angle and at the same time to maximize captured sunlight without casting shadows between rows. Casting shadows is the death knell for solar power plants since even a tiny shadow can reduce power generation by 10 percent or more. The challenge on non-flat terrain is that assumptions about parallelism and constant plane can no longer be made. Instead, the shadow fall from each part of the solar power plant must be analyzed to see if it impedes sunlight collection on a neighboring row. No software existed in the solar industry for this purpose, so Nevados created a software called Nevados High-Definition Modeler (HD Modeler) that can analyze shadow fall throughout the solar field, determine row-by-row tilt schedules to eliminate inter-row shadowing, and produce energy generation estimates for the power plant before and after it is built. This software provides the optimum tilt angles to the controllers to operate the ATT on non-flat terrain and is what truly enables efficient and accurate operation of single axis trackers in all-terrain environments.

CHAPTER 3: Project Results

The intent of this award was to develop the Nevados ATT structure and controls into commercially viable products and to prove the accuracy and validity for the HD Modeler for analyzing and optimizing the Nevados ATT power plants. All tasks fell within specific categories as further explained in the following paragraphs.

Structure

At the beginning of the award, a more complex and less robust version of the bearing assembly had been completed. That design had not achieved UL3703 listing and was too expensive for sale. The final design dramatically reduced costs and made the part available for manufacturing in most steel fabrication shops, albeit with a slightly reduced maximum deflection capability.

The initial Gen1 and Gen2 designs of the Nevados ATT bearing assembly use an agricultural u-joint to transmit torque and to handle misalignment.

This design was modified and tested throughout the award to reduce costs associated with manufacturing. This was achieved through various cost reduction activities for parts manufacturing and factory assembly of the bearing assemblies. The final Gen4 design eliminated the u-joint from the assembly. The original u-joint design was selected to reduce time to market. While the u-joint design enabled Nevados to reach a competitive pricing level in the industry, a more basic design would enable even further competition in the industry. The pricing targeted was based on general industry information at the time. Further cost reduction was focused on removing expensive welding operations and decreasing the number of expensive fasteners in the design.

Post Top Tolerance Increase to Aid Installation

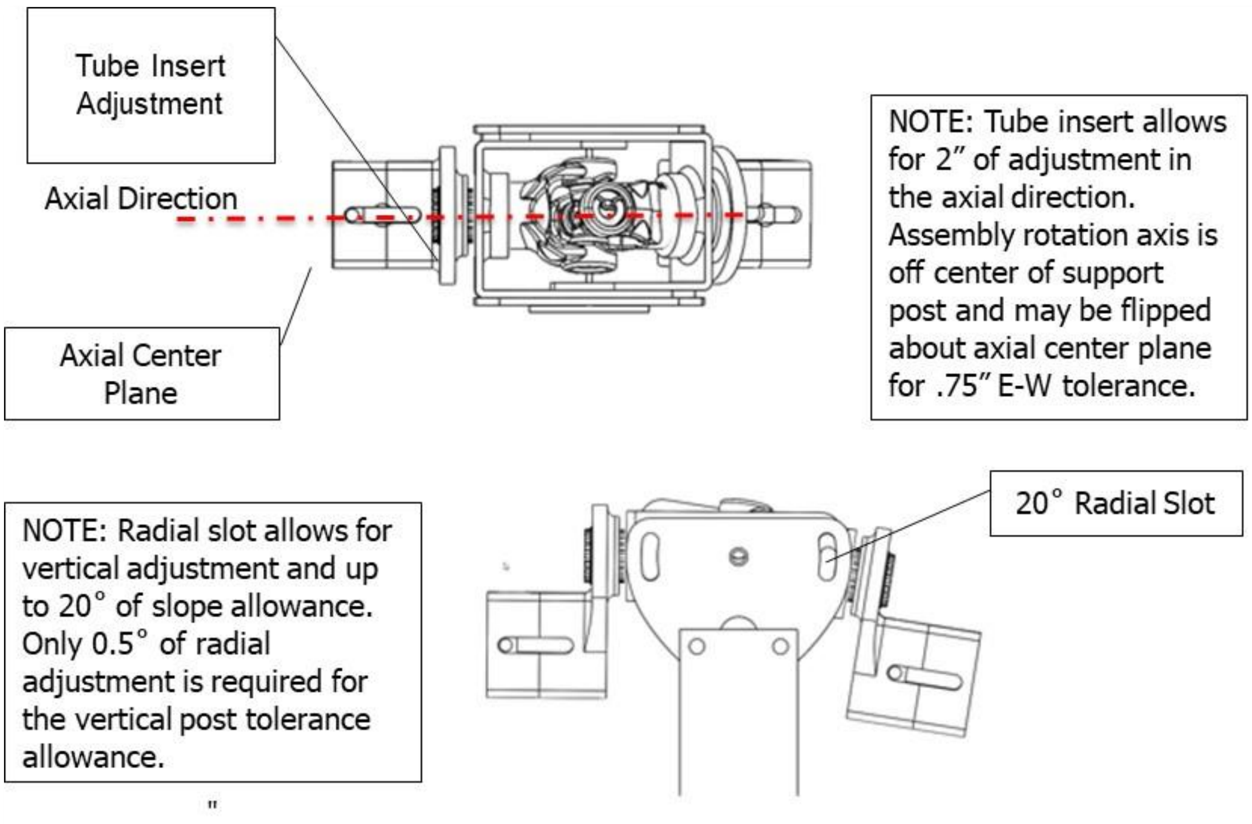
In addition to cost reduction activities, the Nevados ATT was designed to be easier to install with a focus on reducing construction times for each bearing assembly by 10 percent and increasing foundation installation tolerances from +/-3” to +/-12” (Table 1, Figure 3 and Figure 4). Reduction in bearing assembly time directly affects final parts costs because the assembly time requires labor. The installation tolerances are important because the mounting posts are driven into the ground and are expensive to replace if they are outside of tolerance. Post rejection rates of up to 10 percent are not uncommon and can increase total projects costs by up to 1 percent in a very low-margin industry.

Table 2: Increase in Post Top Tolerances

Version	Purpose	Design Parameters
Gen 1	Testing at the Nevados test site	Slopes of up to 20°, articulation of up to 10° at each bearing, and row lengths of up to 90 modules. Meets all American Society of Civil Engineers (ASCE) 7–10 requirements. Post tolerances: +/-2” N-S, +/-0.75” E-W, +/-2” vertical
Gen 2	Commercially ready product prior to Gen4	Slopes of up to 20°, articulation of up to 10° at each bearing, and row lengths of up to 90 modules. Meets all ASCE 7–10 requirements. Post tolerances: +/-3” N-S, +/-3” E-W, +/-6” vertical

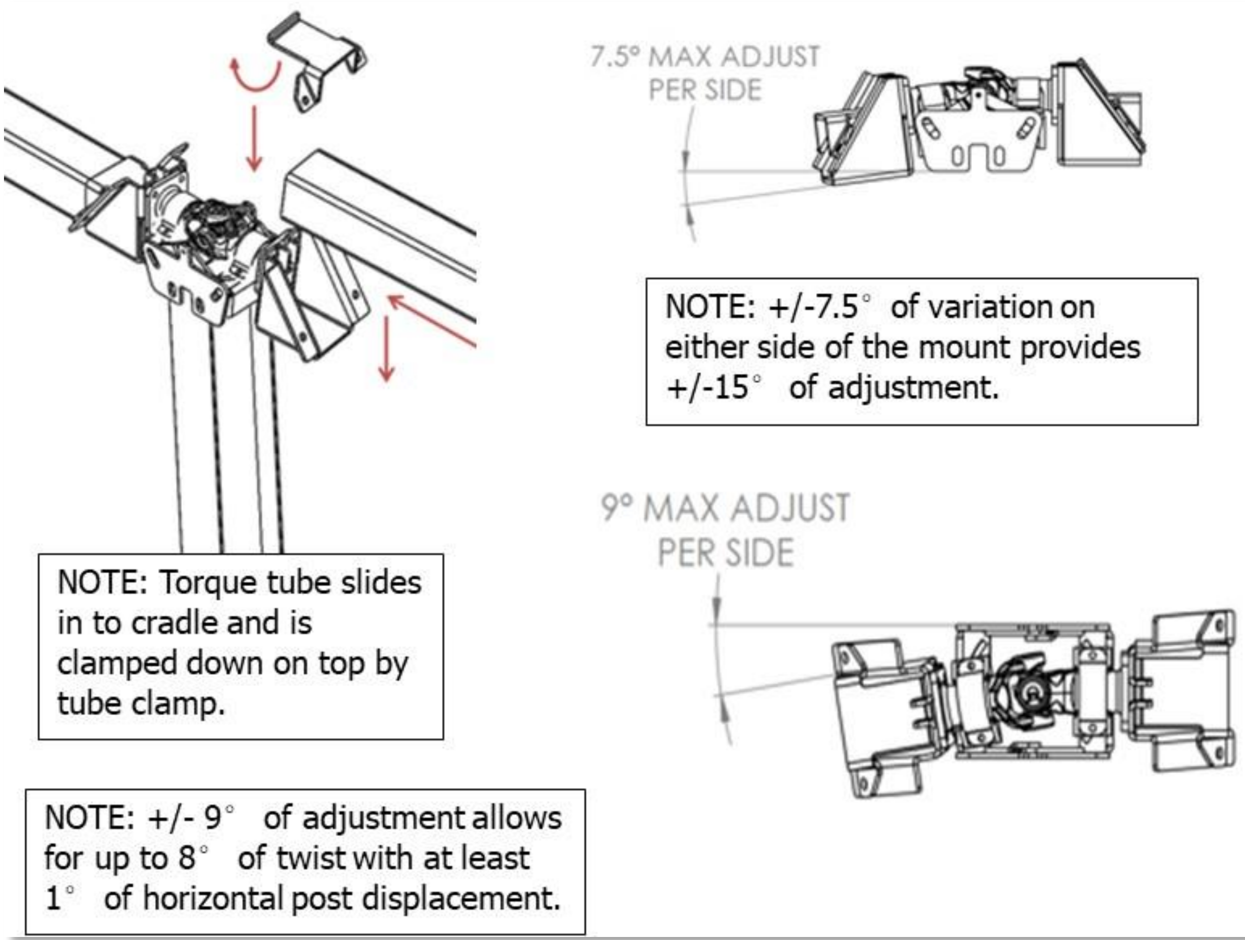
Source: Nevados Engineering, Inc.

Figure 3: Gen1 Tolerance Capabilities



Source: Nevados Engineering, Inc.

Figure 4: Gen2 Tolerance Capabilities



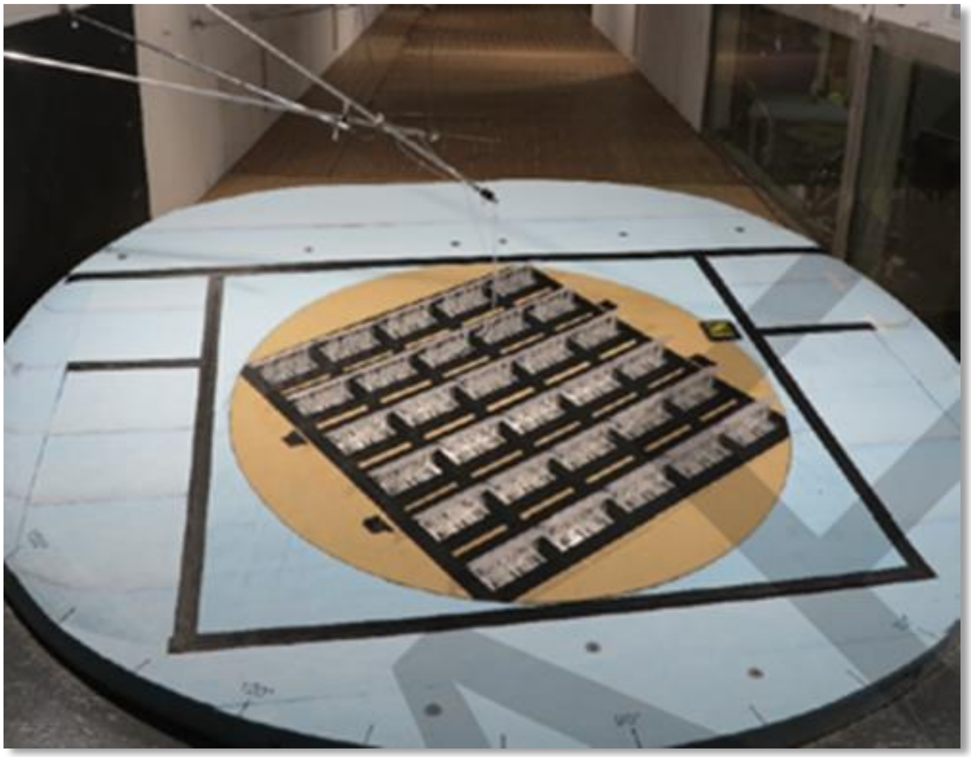
Source: Nevados Engineering, Inc.

Wind Tunnel Study and Frictional Damping

At the beginning of this award Nevados had completed one wind tunnel study using a previously accepted analysis technique for determining wind loads on contoured terrain. During this award, Nevados further tested terrain-based wind loading and developed detailed analyses to understand how the ATT would react in high wind conditions.

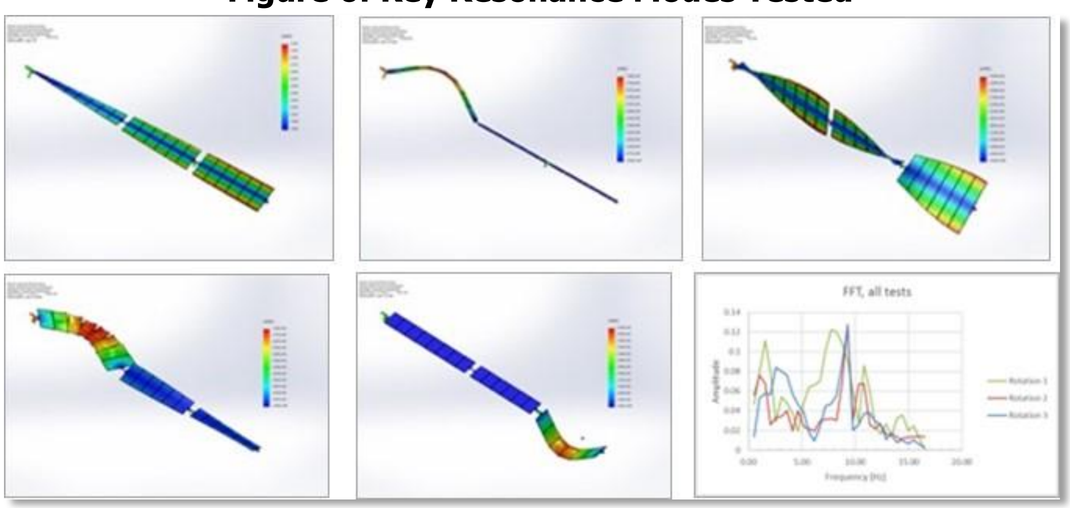
Further work was performed with CPP Wind Engineering Inc., a wind tunnel study consulting firm, to quantify wind loads on the structure in flat and variable terrain environments (Figure 5) and to analyze the damping developed inherent to the Nevados ATT bearing assemblies to enable a tunable damping ratio from 1 to 10 percent. One of the most common failure modes for single axis trackers is due to wind dynamics. A single axis tracker functions like the wing of an aircraft and creates substantial upward or downward forces depending on certain variables. In addition, at certain angles, the tracker row will become unstable and begin rotating back and forth at a natural frequency, which will quickly destroy the tracker. These loads, and dynamic responses, must be analyzed with wind tunnel studies to understand how much strength, stiffness, and damping must be built into the structure (Figure 7).

Figure 5: Example Test Rig at CPP Inc. for Wind Tunnel Testing



Source: Nevados Engineering, Inc.

Figure 6: Key Resonance Modes Tested



Source: Nevados Engineering, Inc.

Through theoretical analysis and empirical testing, Nevados determined that damping in the bearing assemblies has the potential to remove the need for secondary damping systems, such as a dashpot (damper). The damping achieved in this testing exceeded the goals in the statement of project objectives, which is a positive result that enabled Nevados to eliminate external dashpots from the structure.

Controls

The statement of project objectives started with demonstrating basic tracking capability using OTS controllers with a 95 percent or greater uptime over the course of a day and remote-control capabilities, but transitioned to the ultimate goal of proving out the Nevados all terrain controls (ATC) as a separate, complete, and commercially ready product. This included finalizing the Nevados block controller (BC), row controller (RC), and current sensor (CS). Each BC calculates and stores tilt schedules for the life of the project.

Shadows on solar modules have an outsized effect on the power generation from the solar panels and must be avoided at all costs. Since the Nevados ATT is designed for installation on sloped terrain, the expected shadow fall is not consistent and there was no available software to determine that shadow fall. Because of this, Nevados developed custom and proprietary software that is used to develop the tilt schedules for each tracker row to eliminate, or at least minimize, the potential for inter-row shadowing. The tilt schedules are sent to the RCs throughout the day. The RCs then control the tilt of each row per the tilt schedules from the BC and monitor power generation on each row with a CS.

Each BC is housed in a weatherproof enclosure and can oversee up to 200 RCs. One RC is mounted on each tracker row, and one CS is also mounted on each tracker row (Figure 8).

Figure 7: Nevados Control System (Block Controller, Row Controller, Current Sensor)

Source: Nevados Engineering, Inc.

Initial steps focused on design and manufacturing of these components with production files independently verified by other electrical engineers and provided for review, and first articles tested and reported on along with costing analysis.

Controls Testing and Validation

Due to development of new controls components, Nevados had to test the components to ensure accuracy and robustness for field deployment. This work was done throughout this award.

Testing and validation of these components involved functional testing with 5 percent accuracy requirement for the current sensor, passing IP65 (Waterproof Code) environmental requirements, shake table testing without failures to simulate forces found during shipping, extending operating range of the BC from –4°F through 149°F (–20°C through 65°C) up to –40°F through 185°F (40°C through 85°C), submitting the RC for UL listing, proving remote control capability of the Nevados ATC including all day tracking with 99 percent up time, creating software and firmware quality and commissioning strategies for the BC, having the ATC analyzed for security best practices, and developing and improving a graphical user interface (GUI) to access and control Nevados ATT installations. An accuracy of at least 5 percent was deemed necessary because the effect of shadows on power generation is so significant that even a minor shadow will result in at least a 5 percent reduction in power generation. IP65 was selected as the industry standard for outdoor electronics equipment, as were shake table tests to determine the robustness of the BC during shipping and typical temperature ranges the components would experience. A UL3703 (Solar Trackers Standard) approval, or similar, is necessary for the RCs to be approved with the steel structure by the local construction authorities, and remote-control capability through the GUI for the ATC is necessary for basic operations and maintenance activities.

Commissioning strategies are critical for correct operation of any electromechanical structure, while ensuring secure communications and internet access is an absolute requirement by most jurisdictions for critical national infrastructure.

Current Sensor Linearity and Accuracy Testing

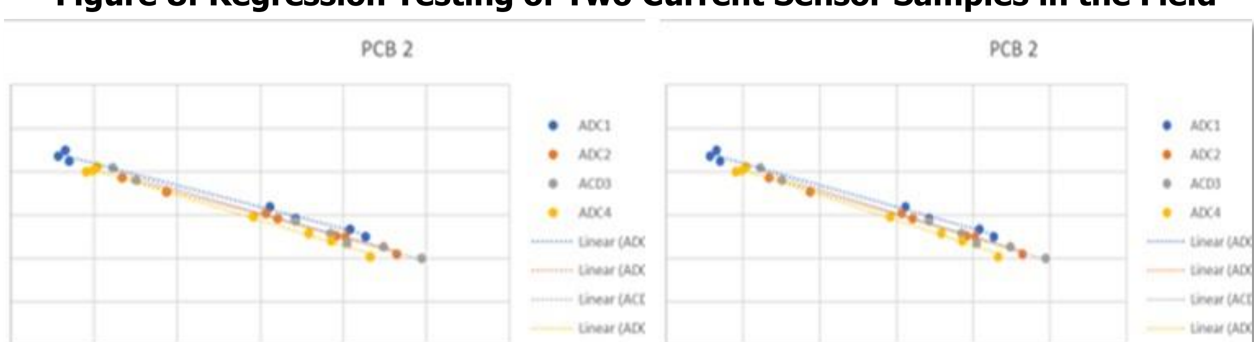
The Nevados CS was tested in the lab at various temperatures to analyze accuracy in expected operating environments. Ambient temperature, a temperature-controlled oven, and a dual temperature refrigerator were used for this purpose. A typical testing process follows.

Test Procedure (Cold):

1. Place lightweight insulating enclosure containing CS printed circuit board and temperature sensor inside refrigeration chamber.
2. Monitor temperature sensor until reading is 14°F (–10°C). Wait an additional 30 minutes.
3. Record average analog-to-digital-converter output over a 20-second period.
4. Remove lightweight insulating enclosure from refrigeration chamber.
5. Monitor temperature sensor. When temperature warms to within 5°F (3°C) of the next target (50°F [10°C]), record average analog-to-digital-converter output over a 20-second period.

A handheld, high-quality multimeter current sensor was used to verify readings, and a final calibration equation was created. The linearity of the collected test data was very good on average (Figure 9). The linearity percentage error was below the 5 percent target.

Figure 8: Regression Testing of Two Current Sensor Samples in the Field



Source: Nevados Engineering, Inc.

The objectives of less than or equal to 5 percent linearity and accuracy were intended to detect a shading event of greater than 10 percent power reduction. This test demonstrated that the current sensor prototype is able to provide this level of sensory feedback sufficient for shading detection.

IP65 Testing

The CS, RC, and BC were tested to the IP65 standard with successful completion of each unit. Figure 10 shows the results of the RC IP65 testing.

Figure 9: Successful IP65 Testing of the Nevados Block Controller, Row Controller, and Current Sensor

1.0 SUMMARY

The Nevados Engineering, Inc. Nevados Row Controller was subjected to IPX5 – Protected against water jets, per IEC 60529 Edition 2.2. No water ingress was observed inside the enclosure as a result of testing, therefore, Nevados Row Controller complies with IEC 60529 criteria. All post-test visual inspections were conducted by NTS engineering staff.

Test Article Description: Part Size: 10" x 10" x 5", Weight: 5lbs

Figure 1: Nevados Engineering Inc. Row Controller

QUANTA LABORATORIES

Certificate of Conformance

This is to certify that the results from the test(s) requested by Nevados Engineering are on file under Quanta Laboratories Job No. QL-19-0265 and conform to the specification(s) stated in P.O. No. PO00010. These results apply to the following equipment and are available for review upon request.

Model No: Nevados Row Controller

S/N: n/a

*** Dust Ingress Test ***

(IEC60529 IP6X)

Quanta Laboratories 03/14/2019 Date

QUANTA LABORATORIES

Certificate of Conformance

This is to certify that the results from the test(s) requested by Nevados Engineering are on file under Quanta Laboratories Job No. QL-19-0091 and conform to the specification(s) stated in P.O. No. 20190125. These results apply to the following equipment and are available for review upon request.

Model No: Nevados Current Sensor

S/N: N/A

*** Water & Dust Ingress Tests ***

Quanta Laboratories Date

Pages: 11

QUANTA LABORATORIES

Certificate of Conformance

This is to certify that the results from the test(s) requested by Nevados Engineering are on file under Quanta Laboratories Job No. QL-19-0093 and conform to the specification(s) stated in P.O. No. 20190125. These results apply to the following equipment and are available for review upon request.

Model No: Nevados Block Controller

S/N: N/A

*** Water & Dust Ingress Tests ***

Quanta Laboratories Date

Pages: 12

Source: Nevados Engineering, Inc.

Block Controller Shipping Loads Testing

The Nevados BC features a small number of parts and a simple mechanical design that appears to carry low risk for damage during shipment (Figure 11). The testing provided by Westpak, 3rd-party independent test laboratory, followed International Safe Transit Association Procedure 3A and included the following tests shown in Table 3.

Extended Operating Temperature Range

The initial operating temperature range identified for the Nevados BC was –4°F through 149°F (–20°C to 65°C). However, this range was deemed insufficient for commercial and industrial operating due to the high likelihood of nearing or exceeding those temperature limits at many potential installation locations. In the interest of extending the operating life of the BC as much as possible, it was decided that a broader operating temperature range was necessary. The operating temperature range was extended to –40°F through 185°F (–40°C through 85°C).

Figure 10: BC Disassembled after Visual Inspection and Operational Testing

Source: Nevados Engineering, Inc.

Table 3: Westpak Testing Topics

Test Input	Standard Referenced	Inspections
Atmospheric Preconditioning	ISTA 3A-2008	External Only
Initial Drops	ISTA 3A-2008	External Only
Random Vibration with Top Load (in Bag)	ISTA 3A-2008	External Only
Random Vibration without Top Load	ISTA 3A-2008	External Only
Final Drops (in Bag)	ISTA 3A-2008	External Only

Noted: Random vibration with top load and final drops were conducted with the package system placed inside a sample bag containing dunnage packages.

Source: Nevados Engineering, Inc.

Many single board computer (SBC) products were evaluated for this task and the ConnectCore 6UL SBC Pro from Digi (Figure 12) was ultimately selected. The 6UL SBC Pro has several characteristics which make it the best choice for this project's application:

1. Storage temperature: –58°F to 257°F (–50°C to 125°C)
2. Operating temperature: –40°F to 185°F (–40°C to 85°C)
3. RJ-45 ethernet connector for link to site local area network
4. Zigbee (XBee) compatibility via universal serial bus (USB) or native socket
5. Micro secure digital memory card socket for data storage
6. Higher-reliability 4GB embedded multi-media card storage for operating system and critical data
7. Extensive software support from the manufacturer, an established energy industry vendor

Figure 11: Digi ConnectCore 6UL SBC Pro

Source: Nevados Engineering, Inc.

Submitting the Row Controller for Underwriters Laboratory Testing

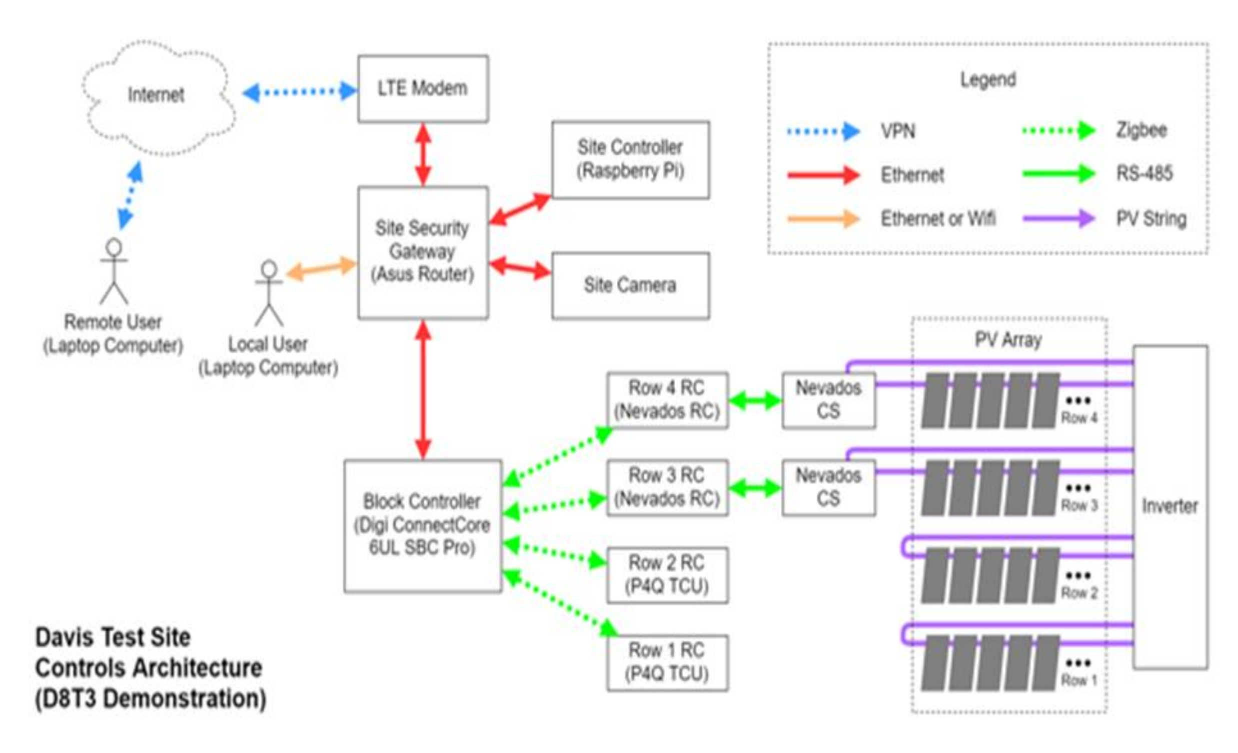
The Nevados Row Controller was submitted to TUV Rheinland PTL, LLC for certification to the industry standard UL 3703, the standard for safety for solar trackers. Gaining the UL 3703 certification on the Nevados row controller is required for mass market sale due to the value of the UL listing in bankability, permitting, and overall product maturity. The UL 3703 standard was chosen because this component is part of the overall tracker system controls architecture. The UL 3703 listing will be updated as new custom controls are added to the tracker system. The UL 3703 certification is divided into five phases designed to subject the product to thorough construction, durability, safety, and reliability testing standards.

The first phase of the UL 3703 review is currently in process (Phase 1: Construction Check, Document Review, and Testing Plan per UL 3703). This will result in a construction review letter from the reviewers that details design guidance as recommended and a recommended testing program for Phase 2: Testing for Enclosure Material and Outdoor Use.

Proving Remote Control Capability of the Nevados All Terrain Controls Including All Day Tracking With 99 Percent Up Time

Nevados has designed a row controller (RC), the purpose of which is to rotate the ATC, and the associated solar modules, throughout the day to follow the sun by driving the direct current (DC) motor in a slew drive. The RC also communicates wirelessly to the Nevados block controller (BC) and collects string current measured by an attached Nevados string current sensor (CS). The purpose of this task is to demonstrate that the Nevados RC can "communicate with BC to report status and errors and receive necessary information to track the sun throughout the day" within the design of the Nevados "Release C" controls architecture. The controls architecture shown in Figure 13 was used to control two rows at the Nevados test site in Davis, California.

Figure 12: Nevados Test Site Configuration



Source: Nevados Engineering, Inc.

RC functionality was demonstrated through a full day of tracking using rotation schedules generated by Nevados software. Rotation commands are sent by the BC to the RC, and RC status is logged by the BC throughout the day. Figure 14 shows a sample of the log file, which is captured at regular intervals for every row throughout the day. The RC and BC performed perfectly throughout the test day in question.

Creating Software and Firmware Quality and Commissioning Strategies for the Block Controller

Developing a consistent and known software and firmware commissioning strategy is key to ensuring reliable deployment of the components running software that can be easily changed. In addition, due to the high degree of variation between sites that the Nevados ATT is targeting, there will be many instances where variables must be changed between sites. Knowing how the different variables affect operation of the software and hardware systems enables faster and more consistent tuning of the control systems for each site. To satisfy this goal, Nevados developed failure modes and effects analysis for software setup and bug correction scenarios and developed strategies to address each scenario. A snapshot of some of that work is provided in Figure 15.

Figure 13: Portion of Row Controller Log File Collected by the Block Controller

```
2018-11-12 14:56:20: Node,   Item,                                        Value,       Unit
2018-11-12 14:56:20: ===============================================================
2018-11-12 14:56:20: Row3,   statuspollattempt,                           true,     boolean
2018-11-12 14:56:20: Row3,   automode,                                    true,     boolean
2018-11-12 14:56:20: Row3,   batteryvoltage,                            26.278,       volts
2018-11-12 14:56:21: Row3,   panelvoltage,                              26.571,       volts
2018-11-12 14:56:21: Row3,   charging,                                    true,     boolean
2018-11-12 14:56:21: Row3,   motorspeed,                                     0,
2018-11-12 14:56:21: Row3,   errorband,                                     10,
2018-11-12 14:56:22: Row3,   movecount,                                      0,
2018-11-12 14:56:22: Row3,   movecountlimit,                              1500,
2018-11-12 14:56:22: Row3,   emergencystop,                              false,     boolean
2018-11-12 14:56:22: Row3,   softwaremoveenable,                          true,     boolean
2018-11-12 14:56:23: Row3,   rotationlimitalarm,                         false,     boolean
2018-11-12 14:56:23: Row3,   motorovercurrent,                           false,     boolean
2018-11-12 14:56:23: Row3,   motorovertemp,                              false,     boolean
2018-11-12 14:56:23: Row3,   blockingalarm,                              false,     boolean
2018-11-12 14:56:24: Row3,   currentangle,                                9.89,     degrees
2018-11-12 14:56:24: Row3,   currentangleraw,                              989,
2018-11-12 14:56:24: Row3,   targetangle,                                10.00,     degrees
```

Source: Nevados Engineering, Inc.

Figure 14: Portion of the Software Setup and Bug Correction Scenarios

System: Software Commissioning
Subsystem:
Component:
Design Lead: Nathan Hadlock
Core Team: Nevados Energy

Potential Failure Mode and Effects Analysis (Design FMEA)

Key Date:

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date
Update row controller connection mapping pairing through the block controller	Incorrect MAC addresss entered	No communication between row controller and block controller	4	Human error (typo)	6	None	10	240	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019
Update row controller connection mapping pairing through the block controller	No communication through XBee	No communication between row controller and block controller	4	Assembly error	6	None	10	240	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019
Update row controller connection mapping pairing through the block controller	Incorrect device id entered	Panel row is not at the correct rotation	3	Human error (typo)	6	None	10	180	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019
Update row controller connection mapping pairing through the block controller	Configuration file not saved	No communication between row controller and block controller	4	Human error (typo)	6	None	10	240	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019
Update row controller location mapping	Incorrect location entered	Panel row is not at the correct rotation	3	Human error (typo)	6	None	10	180	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019
Update row controller location mapping	Incorrect device id entered	Panel row is not at the correct rotation	3	Human error (typo)	6	None	10	180	Develop quality site commissioning acceptance procedure	Software development team & 2/15/2019

Source: Nevados Engineering, Inc.

Analyze the All Terrain Controller for Security Best Practices

The Nevados ATC has been developed to meet the security requirements for energy industry equipment. In addition to following security best practices, Nevados contracted with CloudNexa to provide a detailed security review of its best practices. Overall Nevados' processes were sufficient, although a few items the project team had initially overlooked were identified and fixed.

Developing and Improving a GUI to Access and Control Nevados All Terrain Tracker Installations

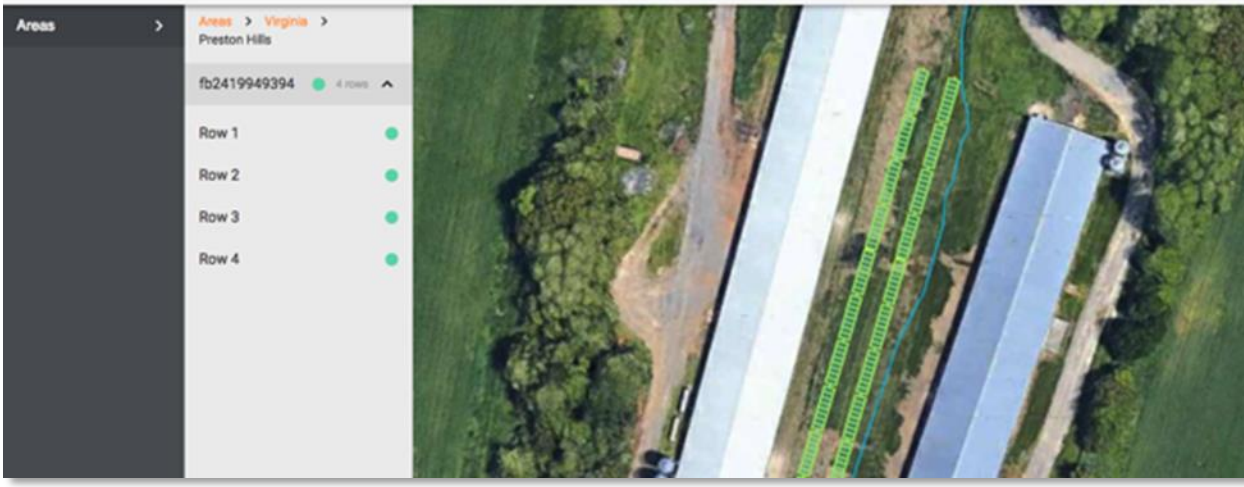
The Nevados ATT GUI has been under development for three years with various iterations throughout its life. The GUI became commercially ready software during this award period and went through a number of reviews and updates using customer feedback. Figure 16 shows the final GUI, which is continuously being developed to provide additional functionality for site design, production estimates, and row tilt schedule creation. The main strategy from the beginning was to focus on content. Nevados' main view starts at the highest level and enables the user to quickly see the status of all deployed sites, where color indicates if there is a problem or not. Green means no problems and red means there is a problem.

By zooming in on a project by selecting a state, a project dot, or by using on-screen zoom tools, an actual project site can be identified (Figure 17).

Figure 15: Nevados Graphical User Interface Main View

Source: Nevados Engineering, Inc.

Figure 16: Example of Customer Site as Viewed Through Nevados Graphical User Interface



Source: Nevados Engineering, Inc.

Software

Custom software was required to operate the controls systems, to determine optimum tilt angles for the trackers without casting shadows from one to the next, and for estimating energy production. None of this software existing in a format that Nevados could use, so all aspects needed to be developed outside of a few libraries available from NREL regarding sun positioning and energy generation calculations. The software development tasks began with the development of hardware and software requirements versus what was commercially available. Three separate revisions of hardware and software were identified and are listed in Table 4, Table 5, and Table 6. The separate versions differ in the Nevados-specific products that were available, with the full Nevados product line displayed in Release C, Table 6.

Table 4: Controls Releases for Nevados All-Terrain Tracker – Controls Release A

Component	Hardware & Enclosure	Functions	OTS Software	Custom Software	Connectivity
Site security gateway	Router, virtual private network (VPN) server	VPN server Port forwarder	VPN server router		Camera and Digi device plug in here
Site camera	Optional	View site conditions		ONVIF-compatible IP camera viewer	Connected by USB to gateway
BC	Raspberry Pi 3 with 128 GB memory in Zymbit enclosure	Controls trackers with OTS control software	Raspbian (Pi operating system)	BC App B.0 Zigbee-based controller command API	Connected to trackers via Zigbee
RC	OTS controllers	Rotate tracker rows to desired position	OTS firmware		Connected to BC by Zigbee wireless

Source: Nevados Engineering, Inc.

Table 5: Controls Releases for Nevados All-Terrain Tracker – Controls Release B

Component	Hardware & Enclosure	Functions	OTS Software	Custom Software	Connectivity
Site security gateway	Router, VPN server in ruggedized enclosure	VPN server. Port forwarder	VPN server Router		SC, camera, all-sky camera, met package, inverter, and BCs
SC	Industrial Linux board with 128 GB memory	HTML server for site control. HTML server for data access. Database for logs.	Python, or other. MySQL. Apache	SC App B.0. Data access App B.0	Connected by USB to Gateway.
Site camera	Optional	View site conditions		SC App B.x	Connected by USB to Gateway.
All-sky camera	Optional	View sky conditions for future expansion	IP camera viewer	SC App B.x	Connected to SC by WiFi
Meteorology package	Optional	Obtain site met conditions		SC App B.x	Connected to SC by Wi-Fi
Inverter access	Optional for string inverters	Obtain total power output		SC App B.x	Connected to SC by WiFi
BC	Industrial Linux board with 128 GB memory	Command from SC to RCs Send status from RCs to SC Send commands to RCs Read and send string current from CSs	Python, or other	BC App Zigbee-based API to control OTS trackers (Python)	Connected by Zigbee to individual OTS tracker units. Connected by Zigbee to CSs.
RC	OTS or Nevados RC	Rotate tracker rows to desired position as commanded by BC.	OTS control firmware	Nevados custom software for Nevados tracker	Connected to BC by Zigbee wireless.

Source: Nevados Engineering, Inc.

Table 6: Controls Releases for Nevados All-Terrain Tracker – Controls Release C

Component	Hardware & Enclosure	Functions	OTS Software	Custom Software	Connectivity
Site security gateway	Router, VPN server in ruggedized enclosure	•VPN server •Port forwarder	VPN server Router		SC, camera, all-sky camera, met package, inverter, and BC
SC	Industrial Linux board with 128 GB memory	•HTML server for site control •HTML server for data access •Database for logs	Python, or other MySQL (data base) Apache (web app server)	SC App – Release C.0 Data Access App – Release C.0	Connected by USB to Gateway.
Site camera	Optional	View site conditions		SC App C.x	Connected by USB to Gateway.
All-sky camera	Optional	View sky conditions for future expansion	IP camera viewer	SC App C.x	Connected to SC by WiFi
Meteorology package	Optional	Obtain site met conditions		SC App CXs	Connected to SC by WiFi
Inverter access	Optional for string inverters	Obtain total power output		SC App CXs	Connected to SC by WiFi
BC	Industrial Linux board with 128 GB memory	•Download rotation schedules •Pass command from SC to RC •Send status from RC to SC •Send rotation commands to RC	Python, or other	BC App Zigbee-based API to control RCs	Connected by Zigbee to OTS units. Connected by Zigbee to CSs.
RC	Nevados RCs	Rotate trackers to desired position as commanded by BC	Proprietary embedded software	Nevados custom software for RCs	Connected to BC by Zigbee wireless.

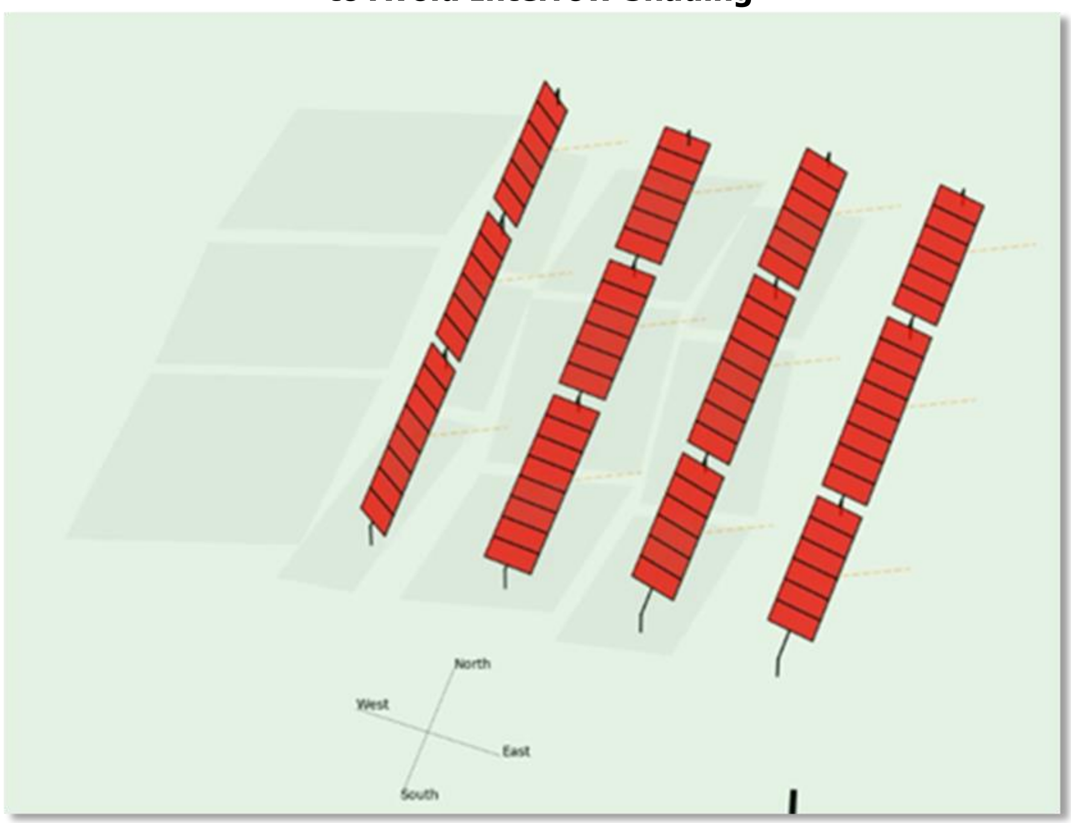
Source: Nevados Engineering, Inc.

This activity enabled Nevados to identify which hardware components were best suited, which programming languages to use, what the controls architecture needed to look like, and whether any software was commercially available for use. The result was an expedited product testing and rollout schedule using commercially available options as needed.

The energy production prediction software was tested through various stages starting with shadow fall analysis, then energy prediction within 10 percent of a simulation using high-quality weather information collected on site for the day in question. The Nevados HD modeler was used generate rotation schedules and estimate electrical output (Figure 18, Figure 19). The HD modeler estimated the AC yield of PV Evolution Labs' (PVEL) site with an accuracy of 0.031 percent with respect to actual power data from the site. Initially, each row is oriented to be as sun-facing as possible, and then each row is individually back-tracked so that it shades no other row.

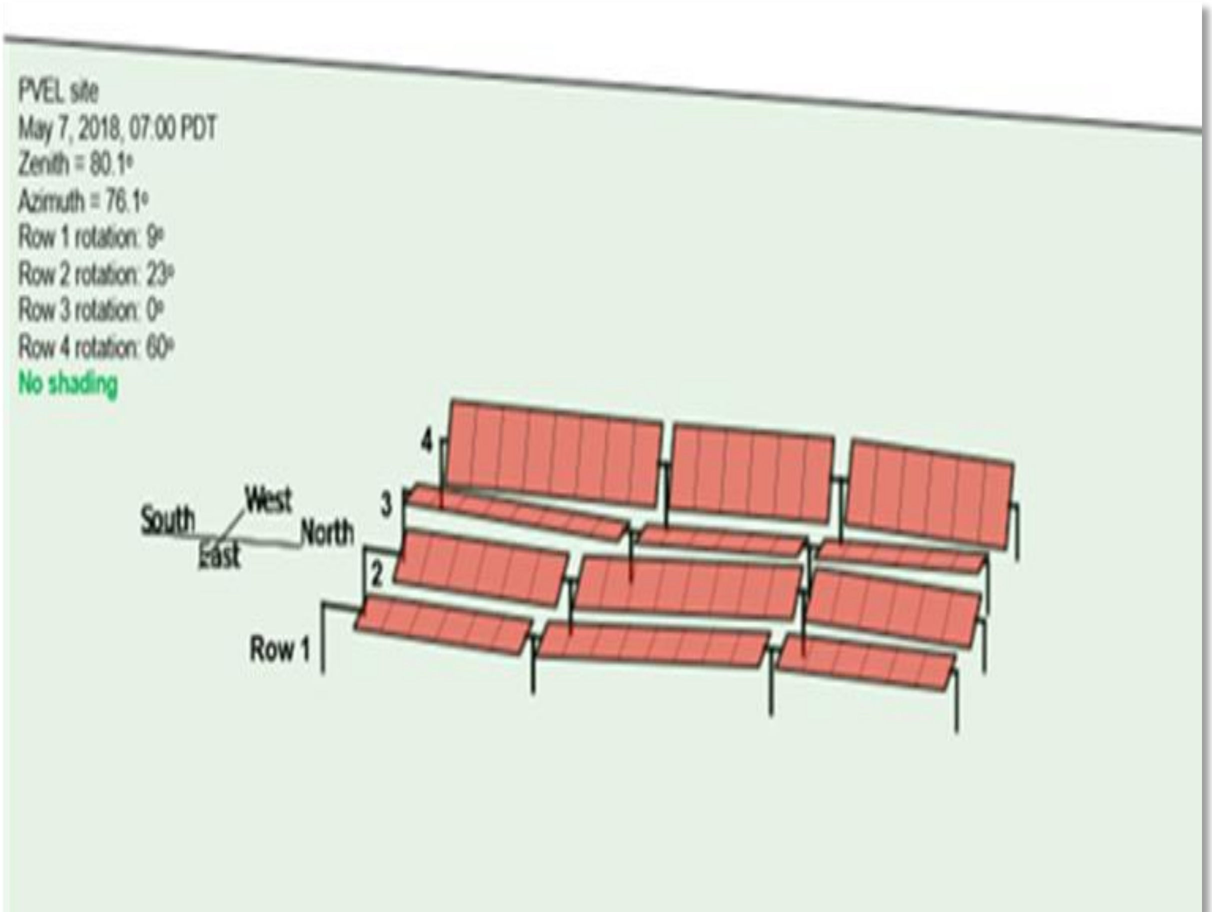
Other tests focused on functionality for remote access and control of the trackers over the course of one day.

Figure 18: Analysis of Shadow Fall from Each Row to Avoid Interrow Shading



Source: Nevados Engineering, Inc.

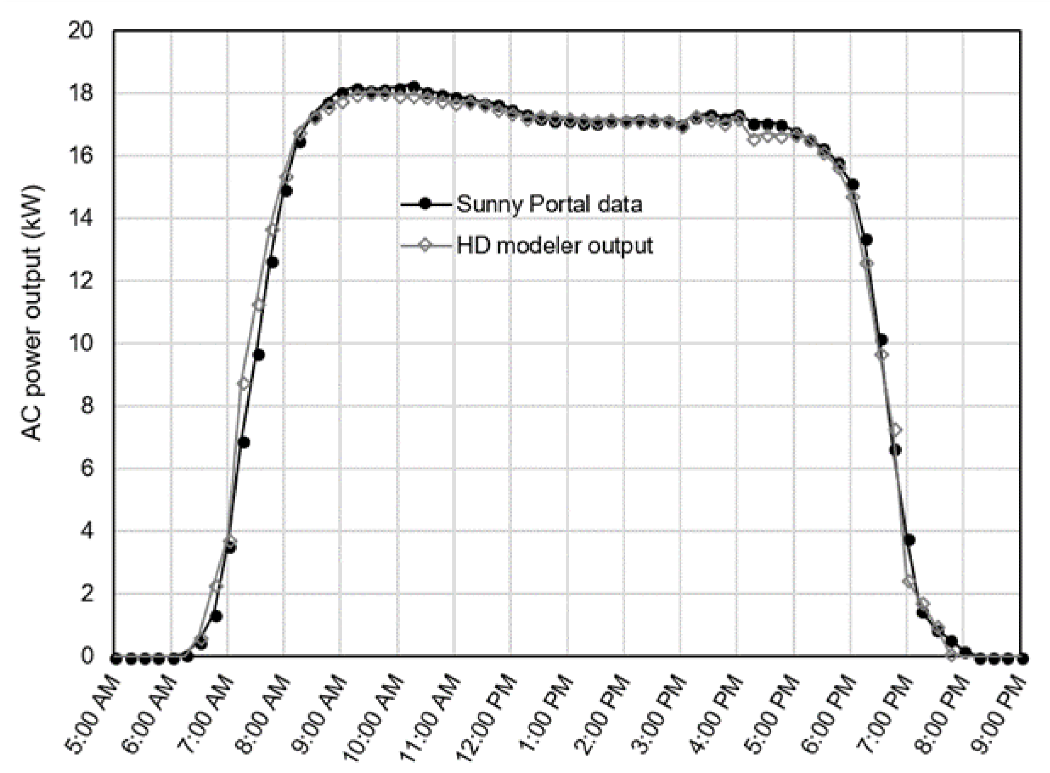
Figure 19: Sample Functionality of Nevados HD Modeler Variable Backtracking Algorithm



Source: Nevados Engineering, Inc.

Power output estimated by the HD Modeler is shown in gray and actual power output is shown in black (Figure 20).

Figure 20: AC Power Output from PVEL Array on May 7, 2018



Power output estimated by the HD Modeler is shown in gray and actual power output is shown in black.

Source: Nevados Engineering, Inc.

Cloud Detection

This technical task evaluated the effectiveness of the Nevados cloud detection algorithm. Cloud detection is important in a solar tracker field — and lacking in almost every tracker field built to date throughout the world — because a solar module will generate more power when turned to be horizontal during cloud events than when it is turned to face the sun. This is because there is no direct light coming from the sun, so the panel will create more power by enabling every point in the sky to reflect light to it. The cloud detection algorithm uses data from the Nevados current sensor as input and returns a binary yes-or-no as to whether the sun is behind a cloud. A custom-built all-sky camera was used to validate the output from the algorithm (Figure 21). For each time point at which the algorithm was used to detect clouds, an all-sky camera image was taken and manually classified as either cloudy or not cloudy. The results of the algorithm's performance have been summarized in a truth table. This truth table, and the F1 score resulting therefrom, will be used as a performance benchmark for future iterations of the Nevados cloud detection software.

Figure 17: Custom All-Sky Camera Installed at Davis-PVEL

Source: Nevados Engineering, Inc.

Images and current data were collected from the PVEL pilot site at 298 time points between July 9 and August 24, 2018. Fortunately for solar power production, but unfortunately for this project, Davis, California does not experience much cloud cover during the summer. Therefore, time points consisting of actual clouds were scarce: only 14 of the 298 images featured the sun behind a cloud. Half the cloudy time points were placed in the training set and the other half in the test set.

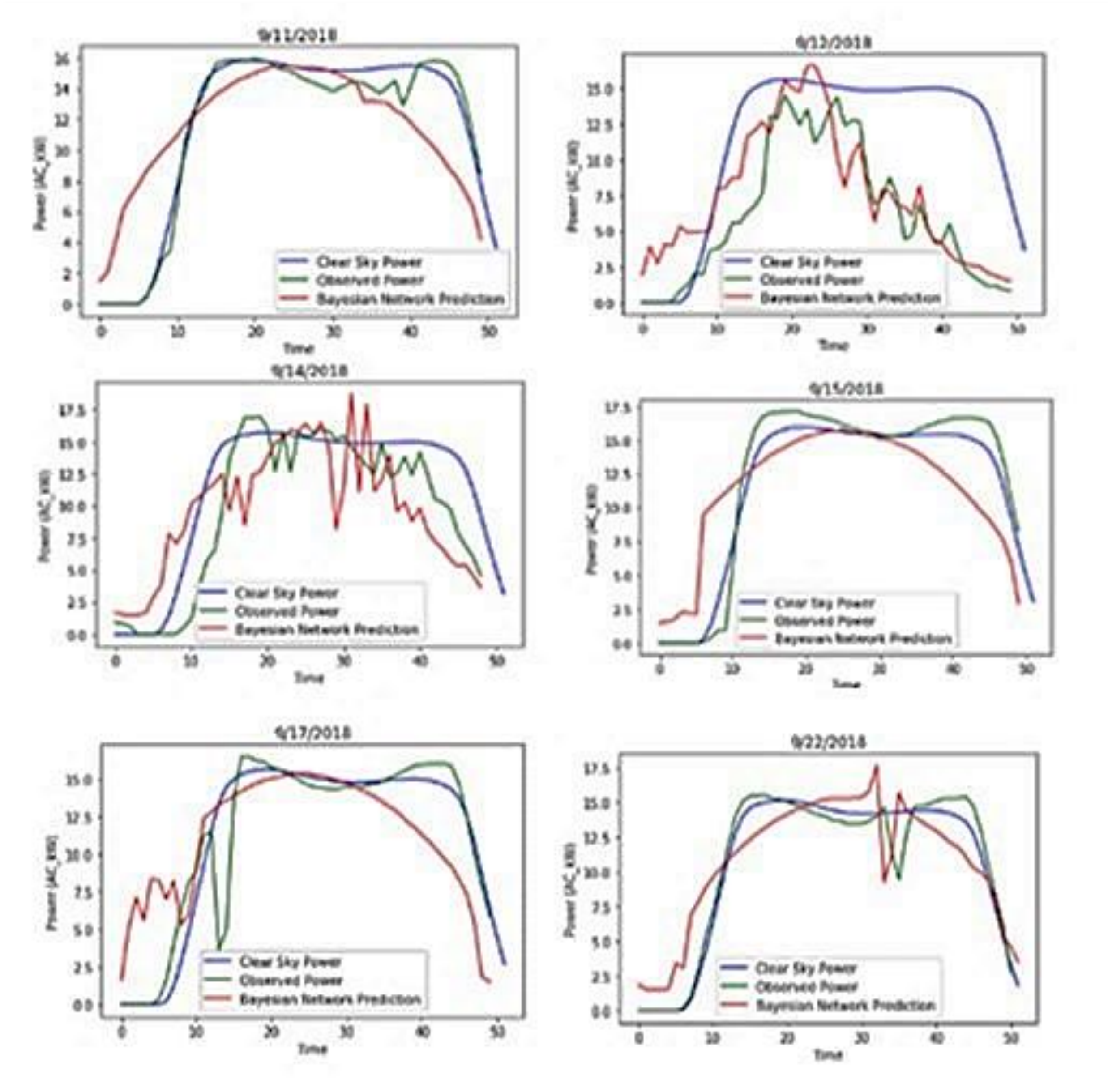
For the test set, there were five true positives, 141 true negatives, one false positive, and two false negatives. The precision of the algorithm was 0.833 and the recall of the algorithm was 0.714, resulting in an F1 score of 0.385. This F1 score will be used as a benchmark for future iterations of the cloud detection algorithm.

Bayes Network

The goal of this task was to distinguish between various causes of string current anomalies. String current anomalies can be created by inter-row shading, cloud cover, failing solar modules, and bad wiring. Knowing which mode is affecting power generation can help to figure out a resolution for repair to return to full power output. To accomplish this task, we used a Bayesian network, a type of probabilistic graphical model, as the basis of prediction whose inputs are derived from a wide range of environmental conditions, including cloudy skies. The results of this predictive model are then compared to Sandia's National Laboratory industry standard PVLIB software to understand the relative error in identifying a string anomaly.

Nevados HD Modeler has been previously shown to estimate the power output of tracker arrays with good accuracy (less than 5 percent) on clear, cloudless days. From a performance modeling perspective, clouds introduce the challenge of less predictable direct and diffuse irradiance compared to a clear sky and the associated uncertainty in output power. For this task, the Nevados team upgraded the HD Modeler to use a Bayesian network to predict power output for cloudy and/or hazy skies. The power estimated by the HD Modeler was compared to Sandia's PVLIB software and the observed power output over the course of six days, which consisted of a mixture of clear and cloudy skies at the Nevados pilot site in Davis, California. Observed power, power predicted by the Bayesian network model, and power predicted by the HD Modeler for a clear sky for six partially cloudy days in September 2018 (Figure 22).

Figure 18: Observed and Predicted Power September 2018



Source: Nevados Engineering, Inc.

There were times at which the power anomaly predicted by the HD Modeler lagged behind the observed anomaly. These lags are primarily due to the method by which observed power was calculated: while HD Modeler can predict instantaneous power output for any given time, the observed power is only recorded by the inverter every 15 minutes. Each data point reported by the inverter is, assumedly, an average over the past 15 minutes. An attempt was made in the HD Modeler to report this same average power, but the unknown differences in the averaging techniques are the likely cause of the apparent time lag.

The Bayesian network model was incorporated into the HD Modeler, which was shown to predict most of the current anomalies with a root mean square error of 14.48. The ability of the Bayesian network to classify anomalies on a broad scale is highly accurate. However, its ability to predict the precise power output is relatively low compared to direct calculation methods. With more collected data from operational power plants, Nevados expects the accuracy of the Bayesian model to improve. Based on this analysis for a small site, Nevados believes the Bayesian network model has potential, and this test validated its ability to identify atmospheric anomalies on a macro scale.

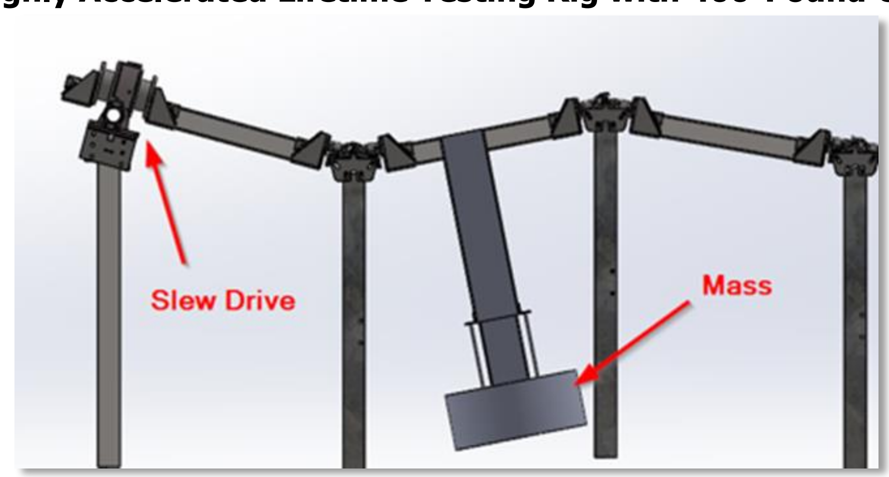
Highly Accelerated Lifetime Testing

Solar power plants, and the components used in them, are expected to last for 10 to 40 years of operation. To achieve the reliability needed to ensure equipment can last this long, highly accelerated lifetime testing (HALT) is necessary to collect the necessary information in a reasonable amount of time. The various HALT activities are detailed in the following sections.

Structural Highly Accelerated Lifetime Testing

Nevados performed multiple highly accelerated lifetime testing (HALT) tests on various iterations of its structure and controls to simulate maximum loads that the structure might experience in one-off situations and repetitive loads that might occur in high-wind conditions that are within the operating wind speeds of the structure. The structure was required to be cycled for 7,300 cycles at maximum wind speed torque and was tested once to 56 years with that load. Every iteration of the Nevados ATT bearing assembly was tested in this manner (although not all designs were tested to 56 years), and the testing rig used is shown in Figure 19.

Figure 19: Highly Accelerated Lifetime Testing Rig with 400-Pound Counterweight

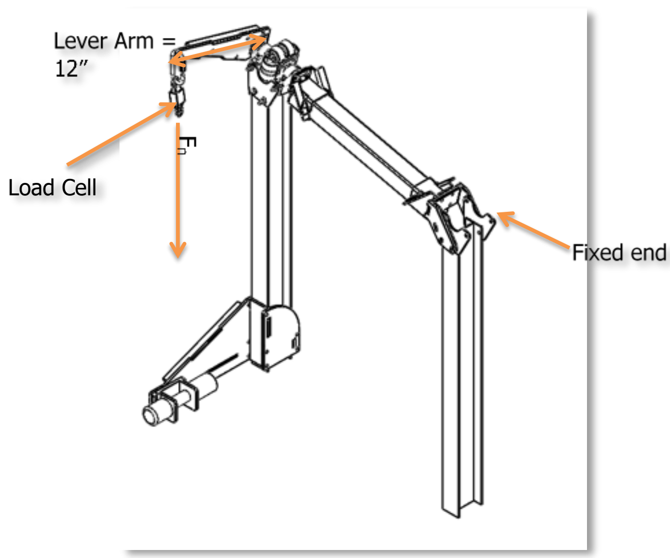


Source: Nevados Engineering, Inc.

The rig applies torque through a high-speed slew drive through a first torque tube, then through the first bearing assembly, through a second torque tube with the counterweight attached, and into a second bearing assembly. The first bearing assembly transmits the cycling torque load to rotate the counterweight and is the bearing assembly that is analyzed for wear and failure. All revisions of the Nevados ATT bearing assembly that were considered to meet the deliverable requirements passed this load cycling test.

To mimic the torsion loads Nevados anticipates in the design scenario of a 105-mph wind loading event, the project team applied the maximum expected torque delivered to a post top (not including the slew drive) after applying the American Society of Civil Engineers (ASCE) 7–10 correction factors. To create this torque through the bearing assembly system a normal force was applied to a lever arm offset from the rotation axis of the driveline. That force was sized to exceed the minimum torque load required. The end opposite the applied load was fixed to a successive post. Since the assembly rotates some non-zero angle due to deflection of the various fixed brackets, the final normal force was adjusted for the rotational displacement angle achieved when the load was applied. Figure 24 shows a computer aided drawing image of the flex plate assembly.

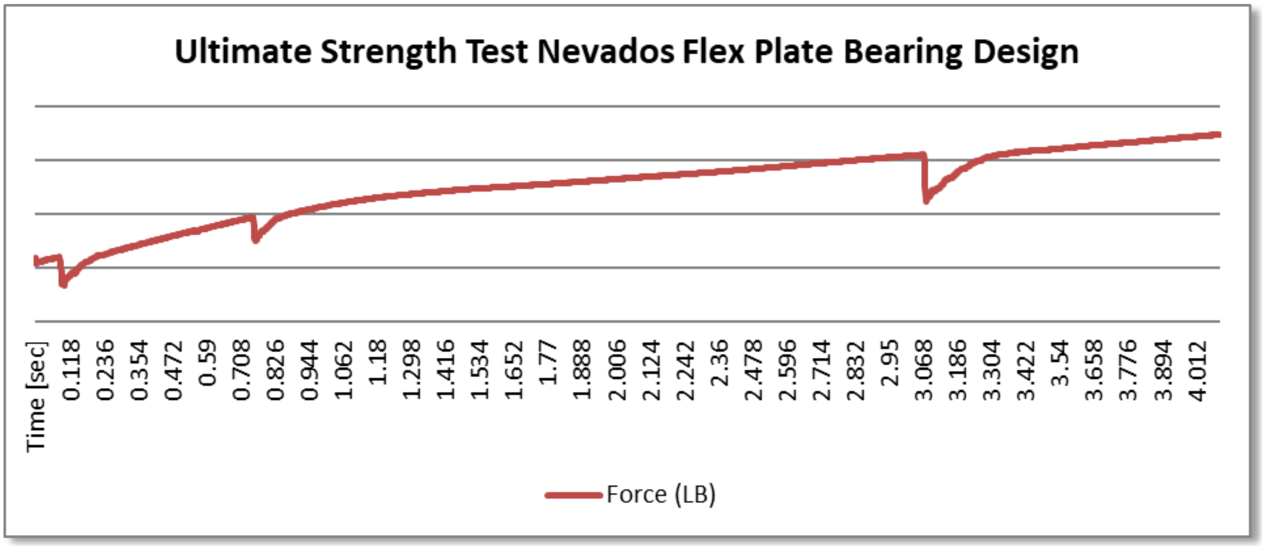
Figure 20: Ultimate Strength Testing Rig



Source: Nevados Engineering, Inc.

The Nevados flex plate bearing design passed the strength test as shown in Figure 21.

Figure 21: Factored Load Curve for Flex Plate Bearing Design



Source: Nevados Engineering, Inc.

Corrosion Testing

Corrosion testing was performed in a salt spray chamber to ensure the structural coatings could withstand 500 hours without corrosion, and they did. This testing was performed as part of the UL3703 testing Nevados completed; Figures 26 and 27 show images of that test. The UL3703 was contingent in part on successfully completing this test, which the Nevados ATT equipment did.

Figure 22: U-Joints and G90 Ref Card @ 600H

Source: Nevados Engineering, Inc.

Figure 23: Full Coating U-Joint @ 600H

Source: Nevados Engineering, Inc.

This corrosion test was a success. All components that were Dacromet coated survived the test as per the guidelines in the Statement of Project Objectives of "equal to or greater than 500H No Red Rust." The components that presented red rust were not structurally compromised, and bonding properties were left unaffected. The surfaces that contained red rust were less than 5 percent of the total surface area, despite looking like much more, due to the aqueous solution of the salt spray test dripping and transporting iron oxide to lower regions of the part. This is a documented shortcoming of a B117 salt spray evaluation. The red rust was not evident on the higher surfaces. The learning from this testing reinforces the design choice to get all U-joint components coated in Dacromet 320L and then assembled. This supply chain has been set up and is in the process of running a prototype batch.

Coatings Wear Testing

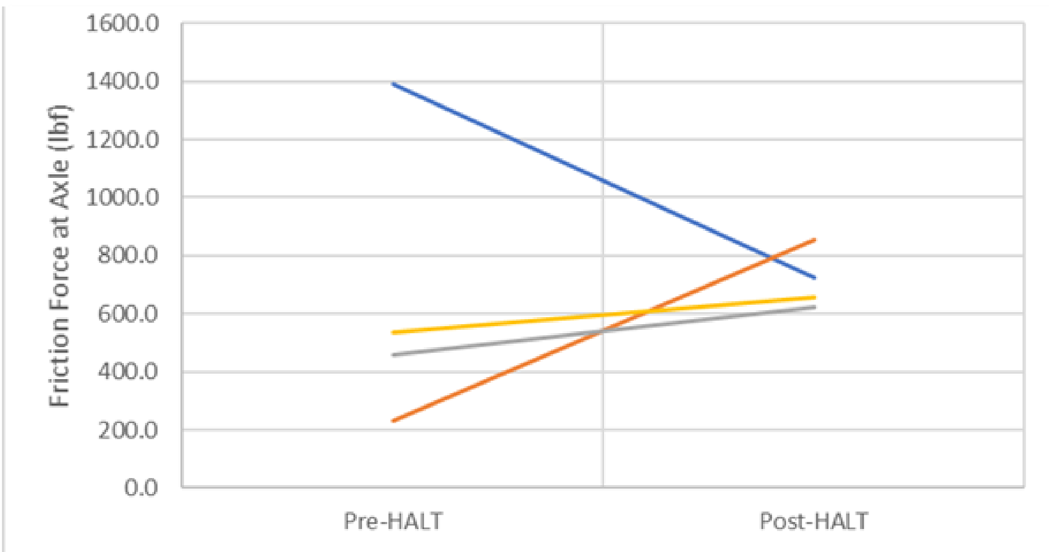
The bearings were tested to determine which material coatings would last the longest and provide the most reliable friction damping. The coating comparison test was intended to assess several surface coating types against key performance characteristics. Four bearing shafts were used in the test with a different coating on each. The baseline shaft was coated with Dacromet 320L. The other coatings tested were Geomet 321P, Anolube 7959, and Dynaloy. Each of these was identified as a potential replacement for Dacromet, and all of them were subjected to a HALT test. Upon completion of the HALT test, each coating was then subject to two performance evaluations: a friction test and a conductivity test.

The wear test setup placed two coated bearing shafts on the HALT rig for 7300 cycles to mimic a full 20 years of operation. This number of cycles was enough to identify differentiation in the wear patterns among the different materials. No weight was applied to the torque tubes due to the high clamping load of the bearing straps that were multiple times larger than the load expected from modules on a torque tube.

After the wear test was complete, a load cell and lever arm were used to analyze the torque of the system created by the friction around the bearing. Also, conductivity testing was completed to determine if electrical bonding was maintained. The results of those tests are shown in Figure 28 and Table 7.

- Geomet showed the lowest visual wear and increase in resistance over time and was selected as the coating of choice.
- Dynaloy and Anolube lost all differentiating friction forces after the HALT test. They also showed the highest amount of debris buildup in the bearing gutters.
- Dacromet despite performing similarly to Geomet in the friction force test, showed the poorest wear characteristics of all four coatings. This may be indicative of a galling effect that the coating exhibits with time.
- All coatings exhibited greater than 600 friction pound force after the HALT test, which indicates adequate damping capability for long-term wind stability of the structure.

Figure 24: Friction Force Change Over 20 Years



Source: Nevados Engineering, Inc.

Table 7: Resistance Measurements Change Over 20 Years

Type	Delta Ohms
Dynaloy	0.3
Anolube	0.1
Dacromet 320L	0.1
Geomet 321P	6.4

Source: Nevados Engineering, Inc.

Wind Tunnel Studies

Results of a commissioned wind tunnel study were used in the Nevados ATT design, as well as being provided to the professional engineer (PE) for review. The focus of the new study was to create a dataset that Nevados could use to determine how different topography conditions would affect the wind loading on the ATT. A common phenomenon in fluid dynamics when encountering sloping topography is the acceleration of the wind speed. This is witnessed on features like hillsides where the wind speed gradually increases as one approaches the peak of the hill. This report explored the loading limitations of the tracker as currently designed on the Gen 2 system (directly applicable to the Gen 3 and 4 systems, too) and how those loads vary according to the selected terrain.

To create a suitable benchmark for comparison, a 20° loading case was selected and then compared to a base case tracker loading on flat unobstructed terrain. The new method for determining slope loads recommended by CPP Inc. follows the Kzt (Topographic Wind Factor) formula as delineated in the ASCE 7–10 standard, Chapter 26. This method allows for determination of a loading case for any slope type and variable topography covered within this particular approach. As the peak loads can be highly variable using this method, a correlation factor of the peak loads was used to design the structure to the baseline flat-land loads as a benchmark for how much of an increase can be accommodated through the Kzt formula.

The updated wind analysis approach proposed by CPP Inc. offers Nevados a highly versatile method of determining the expected wind loads on the tracker structure when installed on a slope. Unfortunately, the use of the Kzt method is almost entirely dependent on the site terrain conditions and does not provide a simple way of analyzing an individual site to determine where the ATT can be installed. This may present some issues when trying to make broad statements about the effects of sloped terrain without accounting for other topographical factors. Without the ability to establish a general rule of thumb on determining installation limitations for the tracker, Nevados will have to assess each project site independently. This most likely will result in more front-end work on the tracker layout for a project site but will more accurately ensure that the ATT is correctly installed on suitable terrain and will prevent excessive exposure to compromising wind effects.

Detailed reports of the wind tunnel study are not included in this report due to the extensive nature of the graphs, tables, and discussion.

Minimum Engagement Testing

Finally, a unique coupling failure test was run to identify the minimum engagement necessary for the torque tube to be supported by the bearing assembly without dropping out, and a minimum engagement was determined. Minimum torque tube engagement refers to the minimum length of torque tube engaged by the tube cradle and tube cradle clamp. This is a critical safety and performance metric. If the minimum engagement is specified too low, the system could fall apart during a wind event due to heaving. The minimum engagement must be specified to the degree that the system can operate for 20 years without requiring adjustment of the torque tube after installation. Since Nevados' design is unique in the market, the company has to characterize this minimum engagement. There is no literature or standard in the industry that would enable Nevados to draw a reliable conclusion specific to its system.

The first step in this process was to determine the minimum engagement that resisted substantial loads and shaking forces. This was determined by loading a test rig 20 feet in length with concrete blocks to simulate the weight of solar modules (Figure 29, Figure 30). That torque tube was then shaken vigorously by a Nevados employee to determine if the torque tube would fall out. Once the team determined the minimum engagement that would not fall out, the loaded torque tube was subjected to 12,775 cycles, or the equivalent of 35 years. The torque tube remained engaged throughout the 12,775 cycles. This test will be repeated as necessary to determine the minimum engagement.

Figure 25: Test Row with Weighted Buckets and Forklift for Fall Protection

Source: Nevados Engineering, Inc.

Figure 30: 1" Minimum Engagement Necessary to Retain the Torque Tube in High Wind Conditions

Source: Nevados Engineering, Inc.

The one-inch engagement survived the simulated heaving test without weights. When the weights were added to the torque tube and heaving was simulated once again, the one-inch engagement survived the test. The one-inch engagement also survived the simulated 35-year cycle test of 12,775 cycles. Through this testing it was determined that the minimum engagement should be one inch.

Industry Certifications

To prove the Nevados structure, controls, and software were commercially ready, Nevados engaged with multiple firms to obtain various industry certifications. Those certifications included submitting information for professional engineer (PE) reviews of the structure for wind and snow loads, safety testing to obtain UL2703 and UL3703 listings, updated bankability reports as changes were made to the Nevados offerings, and IP65 ratings for the Nevados ATC components. Nevados was also required to create and submit an installation, operations, and maintenance manual to the engineering firm performing the bankability study. Reports on the UL and IP listings are provided earlier in this report, but the installation, operations, and maintenance manual and bankability reports are too long for inclusion in this report. A sample of the information submitted to the PE for review follows.

A PE report is used by local permitting authorities to confirm that the tracker has been designed to operate within the environmental conditions common to the location in which it is being installed. UL2703 and UL3703 safety testing primarily looks at electrical bonding to ensure that personnel will not be shocked accidentally due to poor conduction paths in the event of an electrical short from the solar modules to the structure. Bankability reports are necessary for financiers and project developers to get comfortable financing and installing the equipment in question.

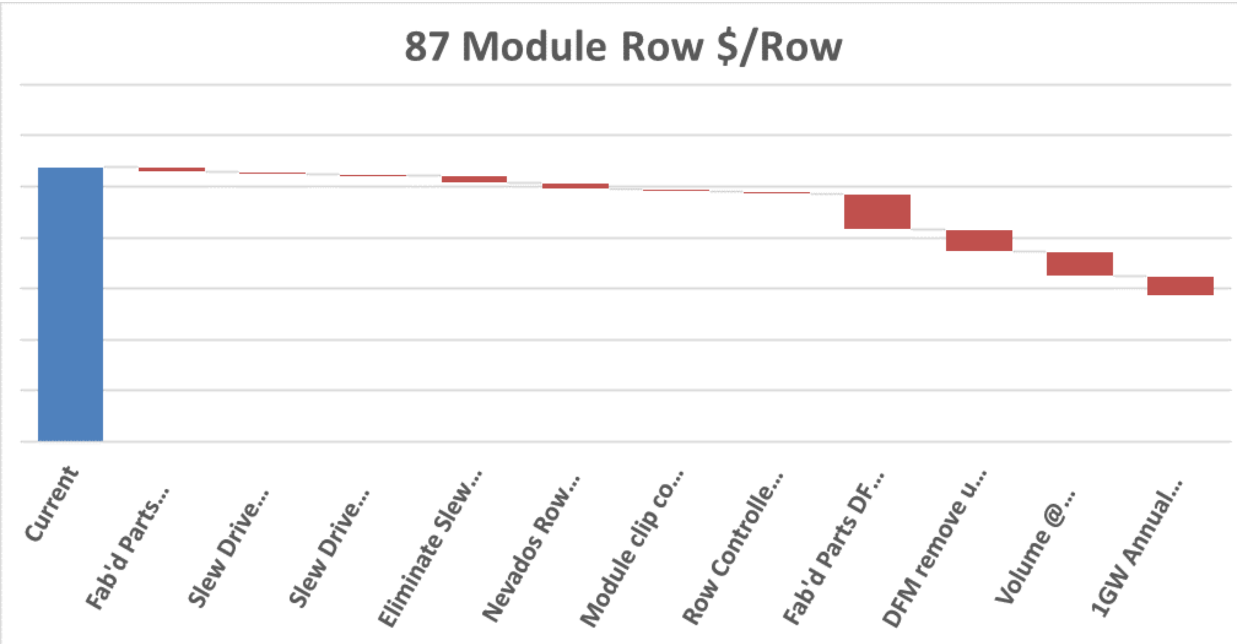
Business

Nevados engaged in various business-related activities throughout this award. One activity, cost analysis and reduction, has already been discussed. Other activities included soliciting feedback from potential project development partners regarding the updated mechanical designs and the monitoring software. This was necessary to ensure that Nevados was developing a product that would meet the needs of the industry. The results of those activities can be seen in the final flexure plate design for the Gen4 bearing assembly and the updated GUI previously discussed.

Another task was to analyze geographic regions of the United States to understand what conditions are needed to provide a land opportunity increase for solar tracker power plants using Nevados equipment, and that study identified that rolling terrain was the primary condition.

The final activity was to analyze the effect on project financials for a customer by having customers purchase low-margin equipment directly from Nevados' suppliers. Having customers purchase equipment directly could reduce costs on a per-project purchasing basis, but likely is a non-starter due to risk shifting to the customers instead of the supplier (Nevados). The most important aspect of the business activities was to reduce the cost of the Nevados ATT to a competitive price. That work was accomplished. The long-term view of pricing is identified in Figure 31 and results in a cost that is competitive with, or better than, all other single axis trackers currently on the market for variable terrain.

Figure 26: Future Cost Reductions for the Nevados All Terrain Tracker



Source: Nevados Engineering, Inc.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Presentations, Conferences, and Articles

Nevados presented at the NREL Industry Growth Forum (IGF) in May 2018 (Figure 32), in Denver, Colorado; staffed a table at Solar Power International (SPI) 2018; attended Solar Power International 2019; published an article on Energy Central; and spoke with myriad solar developers about the Nevados All Terrain Tracker (ATT). The article can be found at [https://www.energycentral.com/c/ec/all-terrain-tracking-systems-optimizing-production-value-variable-terrain.](https://www.energycentral.com/c/ec/all-terrain-tracking-systems-optimizing-production-value-variable-terrain)

Figure 27: Nevados Presentation at the IGF and SPI in 2018

Source: Nevados Engineering, Inc.

Nevados intends to use the results of this research to provide high-value products to the solar industry. The near-term markets for this technology are selling the Nevados ATT to solar developers throughout the United States. The mid-term goals are to expand throughout North America, and the long-term goals are to enter the international market. The Nevados ATT will stimulate growth in the solar market by providing a cost-effective and elegant solution for installing solar power plants on flat, sloped, and rolling terrain in environments throughout California, the United States, North America, and the world. Marketing efforts are underway to further educate the market on the Nevados ATT, and those efforts will continue to develop as Nevados grows.

Nevados is using the results of this research to provide high-value products to the solar industry. The ATT has already been deployed at three commercial sites and has been specified for almost 100 megawatts in 2020 alone. The ATT has been selected due to the ease of installation at the respective sites.

CHAPTER 5: Conclusions and Recommendations

The Nevados team successfully completed the objectives of the grant to prove that a single axis tracker can be installed on contoured terrain at the same, or similar, price point as installing on flat terrain, and that software necessary to operate on any terrain is attainable. The Nevados All Terrain Tracker is a commercially ready, cost-effective product that is available for purchase, and the software with energy prediction and tracker tilt calculation ability to design solar power plants is in operation.

The project team decided earlier than expected to develop a proprietary control system and Nevados also now has a fully operational control system to sell on the open market to retrofit existing tracker installations that are underperforming. In addition, the project team developed a web-based user interface that meets current security requirements and offers a quick and easy birds-eye-view of the solar power plant and any operational issues that might be occurring with the trackers.

The core of the Nevados ATT technology is the bearing assembly that allows articulation of the driveline at every support post and that evenly distributes axial loads along the length of the row. The Gen2 bearing design is cost effective and can bring the benefits of all terrain tracking to the industry, but the Gen4 design is what will allow the Nevados ATT to compete on flat, sloped, and rolling terrain equally as well. Developing the Gen4 design was a huge challenge with almost 24 months of effort put into the design before a breakthrough occurred that allowed its advancement. The Gen4 design dispenses with casted parts, detailed machining, and bearing surfaces, and facilitates production of the Nevados ATT by almost any steel fabrication factory without the need for tools that a typical steel fabrication factory would not have. In addition to cost reduction activities, the Nevados ATT was designed to be easier to install with a focus on reducing construction times for each bearing assembly by 10 percent and increasing foundation installation tolerances. Reduction in bearing assembly time directly affects final parts costs. The installation tolerances are important because, once driven into the ground, mounting posts are expensive to replace if they are outside of tolerance. Post rejection rates of up to 10 percent are not uncommon and can increase total project costs by up to 1 percent in a very low-margin industry.

The biggest challenges that the project faced had to do with funding and personnel. It has been difficult to raise funding in the cleantech hardware space; therefore, EPIC funding played a critical role in the project’s success. EPIC support helped Nevados build a strong team capable of developing consistent and better understood processes to accomplish this work. Coming out of this award, Nevados is better prepared to further develop market-ready products and respond to industry needs.

Going forward, Nevados plans to further refine the current products. The mechanical design will go through a design iteration for lower cost manufacturing in addition to coordinating with preferred local manufacturing facilities. Further industry certifications will also be completed to make each Nevados product a stand-alone product.

CHAPTER 6: Benefits to Ratepayers

The project focused on creating products to facilitate the move from flat-land installation of solar power plant sites to all terrain sites to overcome the dearth of available flat land and to accelerate the growth of solar installations, leading the state to a 100 percent clean energy future.

Lower Costs

Installing the new solar tracking system on sloped, rough, and rolling terrain will eliminate the need for soil grading and related remediations typically necessary for solar installations, resulting in 3 to 10 percent reductions in total project cost. This also increases application zones for the system to areas where, previously, only low-efficiency fixed tilt systems could be installed and can increase output by up to 7 percent over other tracking systems if installed on a south-facing slope. These cost savings will ultimately reduce overall electricity costs for consumers.

Economic Development for Broader Adoption

Nevados developed a commercially ready product to design solar power plants, manufacture products for those plants, and operate the finished plants. Through further development, testing, and certifying of equipment, pilot manufacturing and business case analysis that will lead to anticipated manufacturing cost to $0.128/Watt or less, the technology will be competitive in the industry, facilitating commercialization and subsequent economic development.

Environmental Benefits

The new tracker removes the need to grade topsoil, helping preserve the environment at the site. Reduced soil grading can eliminate use of millions of gallons of water sprayed on dry disturbed soil to mitigate dust at construction sites. More broadly, the new tracker maximizes power generation of the solar power plant and facilitates development of more solar power plants at previously incompatible sites — more quickly and at lower cost — thus increasing the volume of available solar-powered energy and moving California closer to its Renewables Portfolio Standard goals.

LIST OF ACRONYMS

Term	Definition
AC	Alternating Current
ATC	All Terrain Controls
ASCE	American Society of Civil Engineers
ATT	All Terrain Tracker
BC	block controller
CS	current sensor
Digi	company name
GUI	graphical user interface
HALT	highly accelerated lifetime testing
HD Modeler	High-Definition Modeler
HSAT	Horizontal Single Axis Tracker
IGF	Industry Growth Forum
IP	ingress protection (when discussing control systems)
Kzt	Topographic Wind Factor
MySQL	name of a software product
NREL	National Renewable Energy Lab
OTS	off-the-shelf
PE	professional engineer
PVEL	PV Evolution Labs (company name)
RC	row controller
RJ-45	technical cable specification
RPS	Renewable Portfolio Standards
SBC	single board computer
SPI	Solar Power International
UL	Underwriters Laboratories
USB	universal serial bus
VPN	virtual private network
Zigbee	product name of component in the XBee family produced by DIGI

APPENDIX A:
Inventions, Patents, Publications, and Other Results

Table A-1: Patents Active and Inactive

Docket Number	Status	Relation Type	Application No.	Country / Region
NEVA00001 AU	Filed	Original Filing	2015360309	Australia - (AU)
NEVA00001 EP	Inactive	Original Filing	15866905.1	European Patent Convention - (EP)
NEVA00001 JP	Filed	Original Filing	20170550094	Japan - (JP)
NEVA00001 MX	Filed	Original Filing	MX/a/2017/007690 I	Mexico - (MX)
NEVA00001 US	Filed	Original Filing	15/533,189	United States - (US)
NEVA00001 WO	Inactive	Original Filing	PCT/US2015/065382	Patent Cooperation Treaty - (WO)
NEVA00001 ZA	Inactive	Original Filing	2017/04576	South Africa - (ZA)
NEVA00001-1V US	Inactive	Original Filing	62/091,385	United States - (US)
NEVA00002 AU	Filed	Original Filing	2017346481	Australia - (AU)
NEVA00002 MX	Filed	Original Filing	MX/a/2019/004417	Mexico - (MX)
NEVA00002 US	Filed	Original Filing	16/339,820	United States - (US)
NEVA00002 WO	Filed	Original Filing	PCT/US2017056667	Patent Cooperation Treaty - (WO)
NEVA00002-1V US	Inactive	Original Filing	62/409,098	United States - (US)
NEVA00002-2V US	Inactive	Original Filing	62/468,228	United States - (US)

Source: Nevados Engineering, Inc