Refining the Stars: Reducing the Keck Observatory Calibration Error with a Cutting-Edge Calibration Screen

Honors Thesis
Presented in Partial Fulfillment of the Requirements for the
University Honors Program
Colorado State University

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Spring 2025

Abstract

The Keck Observatory's telescopes are among the most advanced and productive in the world, enabling groundbreaking astronomical research [4]. However, the current calibration system - consisting of shining projectors onto the uneven dome surface - introduces an error of approximately 30%, impacting observational data and discoveries. This honors thesis details the development of the 1/10th scale prototype as seen in Figure 1- where the full scale would be 12-meters in diameter to fit the 10-meter telescope - for an improved calibration system, designed by an interdisciplinary team including three mechanical engineering students and two electrical engineering students. The goal is to reduce said errors to an initial target of 6% or less.

Figure 1 - Final prototype assembled and functional front (left) and back (right) view.

The design process lasts a full academic year, relying on a strong relationship between mechanical and electrical subsystems to achieve precise alignment and innovation. While the mechanical engineering team develops structural aspects, motion mechanisms, mounting mechanisms, and stability, the electrical engineering team establishes control systems, safety mechanisms, lighting aspects, and power distribution systems. The prototype leverages non-conventional solutions developed by a team of engineering students dedicated to learning and simulating real-world operational conditions.

This senior design project is a significant step in the Keck Observatory's observational capabilities, allowing this year's team to generate ideas and determine feasibility to pass on to next year's team for further development. By addressing these current limitations of the telescopes, the team's efforts in this project will help the W.M. Keck Observatory remain the leading ground telescope in scientific

discovery with more accurate astronomical data in addition to contributing to the improvement of calibration systems as a whole. The outcomes of this project include team collaboration, design methodology, testing, prototyping, and understanding the improvements that can be made with cost and time constraints, providing a foundation for future development of the full-scale system in the years to come.

Central Themes

This project embodies several key themes that played a crucial role in shaping both the success of the project and my development as an engineer. The first main theme was *innovation and problem-solving* with the project having a large focus on designing and implementing a calibration screen for the Keck Observatory, requiring in-depth knowledge of engineering principles and proactivity to learn. This included knowledge in manufacturing, electrical circuitry, structural integrity, and light distribution concepts. Research into new concepts like telescope functionality and magnification features combined with a willingness to dive into the unknown was essential to generating an innovative solution. The second main theme was *interdisciplinary collaboration* where the success of the project was deeply rooted in the strong connections between different engineering disciplines, ensuring all components worked cohesively. The last main theme was *personal and professional growth* with encouragement to embrace invaluable lessons in leadership, teamwork, conflict resolution, and adaptability.

Broader Context

The Keck Telescopes, which have been in operation since 1992, have faced consistent calibration inconsistencies affecting the quality of telescope performance and data collection [1]. Initially, rushed installations of current calibration projectors led to discrepancies between the expected and actual performance of the system and the night sky conditions. This, in turn, impacts everyone using the telescope including astronomers, researchers, telescope operators, technical staff, partnering institutions, and the broader scientific community.

Calibration is an essential process to telescope operation, ensuring the accuracy of data collection. By improving the calibration error, more reliable scientific analysis and discoveries are expected. Improving the calibration methods is intended to enhance telescope operations with a new instrument known as FOBOS (Fiber-Optic Broadband Optimal Spectrograph). FOBOS requires precise light separation for heightened deep-imaging spectroscopy where resolving this problem leads to a more streamlined system that ensures Keck remains competitive, expands partnerships, and continues global scientific discoveries.

The current calibration process includes simulating the twilight sky using weak projector light sources and aiming the mirrors at the rough interior of the observatory. This has resulted in non-uniform illumination, leading to discrepancies in results. Proposed solutions include higher powered light sources which increase energy consumption, a smoother calibration surface, which can disrupt telescope operations temporarily, or installing calibration screens which may obstruct telescope views.

While the calibration system remains imperfect, the Keck telescopes' accuracy affects the reliability of research, threatens Keck's standing as the leading facility in astronomical discovery, and reduces the attraction of scientific insight into such discoveries, overall decreasing the value of the telescopes and institution.

The Keck Observatories are at the top of the culturally significant Mountain Mauna Kea, Hawaii, at a 13,796-foot elevation with wintry conditions. Seismic activity must be considered due to the active volcanic environment. Hence, the observatory and its respective components must be adept to temperature fluctuations, seismic activity, and high altitude. Ideally, the 1/10th prototype design will lead to immediate construction and use in the observatory following implementation of FOBOS, lasting at least 30 years with minimal maintenance. The project will leave out details that do not impact the calibration system itself such as modifications to telescope key features other than lighting and surrounding surfaces.

Research

Throughout the project, it was essential to keep in mind key questions that the team would either answer with the development of the prototype or questions that guide the team to successfully generate a scalable solution to the problem at hand. Such key research questions include but are not limited to:

- How can the precision of light source calibration enhance the Keck Observatory spectroscopy requirements with the new installation of FOBOS (Fiber Optic Broadband Optical Spectrometer), a deep-imaging spectroscopy tool?
- How can the team ensure uniform illumination in the Keck Observatory to improve current calibration methods?
- What environmental factors impact the calibration system and how might such informed design decisions be mitigated?
- What challenges arise in scaling the 1/10th scale prototype to a full-scale calibration system?

- Can this solution increase the amount of scientific relevance and discoveries by the Keck telescope? In other words, can it bring into focus what lies beyond its current limit of 13 billion light years?

Due to the scale of such a project and the fact that there were many possibilities to work with throughout each stage - research, concept development, design, prototype, testing - there are many questions that the team either answered or used to guide the development of the project, but such a list was shortened for the purposes of this paper.

Throughout the project, five focal areas drove progress including light consistency, material requirements, maintenance, system compatibility, scalability, and safety to meet 19 requirements and guidelines that the Keck Observatory team provided. While this year's project has a focus on trying new ideas and coming up with results to pass to the next team for further development, the team was able to generate a calibration system prototype of a modular, hexagonal screen array to improve calibration error from 30% to 9%. Such a screen is composed of interlocking hexagonal panels that make up a larger array offering scalability, efficiency, and ease of maintenance. Panels can be prefabricated with hexagonal templates that the Keck Observatory has in place for their mirrors to minimize on-site operations when originally implementing the solution.

The calibration system utilizes fiber optics to transmit light in different wavelengths, as required by Keck, through a P95 acrylic diffusion panel to offer scattered, more uniform illumination [10]. By dispersing light as much as possible throughout the diffusion panel, a common material for outdoor lighting while enduring environmental fluctuations, the calibration error reduces since illumination of the screen is improved. The hexagonal screen is engineered to withstand Mauna Kea's extreme conditions including temperature, altitude, high wind speeds, and seismic activity. Its Lambertian surface provides consistent reflectivity across the needed spectral range, ensuring long-term performance.

<u>System Compatibility -</u> It is essential that the solution chosen is compatible with the telescope and all other equipment within the dome. This includes the screen not impeding telescope operations like jib cranes, telescope or deck movement, or other equipment. This involved choosing a proper location that is conveniently out of the way and ideally at 30 to 90 degrees from horizontal since most equipment performs best at such angles [4]. This influenced the decision to place the screen at a 45-degree angle from horizontal and mounted to the two steel girders supporting the dome for improved stability and structural integrity.

Material Requirements - As specified by the Keck Observatory, the materials used within the solution must enhance illumination while being resistant to yellowing from the sun, durable in the wind, and easily cleaned of volcanic dust. The screen consists of frosted P95 diffusion panels which improve diffusivity through type V equiangular distribution of light, spreading light in as many directions from the source as possible. Such material is common in outdoor applications of lighting, displaying proof of non-yellowing to UV light exposure with its UV-stable substrate composition [2]. Additionally, the aluminum housing offers reflectivity which was proven in testing to enhance the amount of W/m^2 entering through the screen by preventing the light from being absorbed into the edges of the panel [3]. Without the aluminum reflectivity, the light coming through the screen averaged around 4 W/m^2 or less while with the reflective lining, the light distributed further throughout the panel, averaging 18 W/m^2.

Maintenance - As specified, the calibration screen must be made of a material that is non-yellowing under UV radiation and easily cleanable of any volcanic ash. By utilizing data from the EPA's UV index in Fort Collins, the acrylic panels were placed in the sun and showed no signs of degradation over an extended period [8]. Additionally, based on Curbell Plastics' overview of different acrylic material properties, the P95 acrylic proves to have high diffusion properties in LED lighting, smudge and fingerprint resistance, and non-yellowing features over extended periods [9]. The acrylic tested in the sun was also subject to standard dish soap and water multiple times to assess the cleaning capabilities that the Keck Observatory uses with the mirrors, proving to clean the acrylic effectively and limit degradation.

Light Consistency - The screen uses a Lambertian reflective surface for uniform light distribution - 310 nm to 2500 nm - reducing calibration errors from 30% to 9% [10]. Brightness variation stays within 5% across the screen and temporal stability is maintained within 0.1% per minute and 10% over two months. Fiber optics and diffusion panels ensure even light distribution, meeting observational requirements. The Lambertian P95 acrylic guarantees reliable reflectivity and durability, minimizing UV-induced yellowing.

Environmental Resilience - Considering the calibration screen needs to withstand environmental conditions on the mountain, data measuring seismic activity, temperature, average wind speeds, and altitude were critical to the design [5][6]. To mitigate the wind speeds accelerating in the dome - with the limit of keeping the dome open up to 50 mph wind speeds - aluminum sheet metal is implemented on the sides of the screen to disrupt the wind and create an airfoil around the screen, thus eliminating any force that could attempt to push the screen off the wall and damage the telescope. Such a design was influenced by the McLaren Elva sports car that utilizes a small panel to create an airfoil around the car, acting as a windshield [7].

Safety - While the Keck Observatory is consistently implementing cutting-edge optical equipment for ever-improving scientific data capturing, there are strict protocols and operational features that were implemented into the design - red and green light for go-no-go indication and an emergency stop - to ensure that the calibration system does not pose any hazard or danger to personnel working. There is an additional motion sensor that, when triggered by motion, shuts down all calibration screen systems for optimal safety of personnel within the dome. A door switch may also be used to shut down operations assuming this indicates personnel entering the facility.

Scalability Challenges - The design of each hexagon panel can be scaled up to match the full size of a Keck mirror while maintaining the observatory's hexagonal template and the mechanism that is used to transport a fragile hexagon of that size. The screen will be mounted on two main steel girders, with each panel transported separately through the common equipment gates at the telescope base. Positioned at a 45-degree angle, the screen ensures optimal performance. Fiber optics were chosen for their ability to transmit multiple wavelengths, meeting the observatory's diverse equipment requirements.

Personal Contribution

Throughout this senior design project, I played a critical role in ensuring the success of our team in developing the calibration screen for the Keck Observatory. My contributions spanned technical development, project management, stakeholder communication, and overall team coordination.

One of my primary technical contributions was the development of the testing module, the final prototype light adaptor module with fiber adaptors, and fabricating the aluminum housing and diffusion panels. This involved extensive design iteration, material selection, and precise fabrication to ensure compatibility with the existing system. All of such hands-on, technical contributions were integral to the functionality and durability of our design. This also involved maintaining a strong connection to the electrical engineering side of the project, ensuring that there is seamless cross-integration of mechanisms and structures.

Beyond technical contributions, I took on the role of project coordinator, keeping our team on track to meet critical deadlines and milestones. I was responsible for structuring our project timeline, assigning tasks, and ensuring that each deliverable was completed efficiently. I also organized and led team meetings, providing agendas, setting objectives, and ensuring that discussions remained productive and solution-focused in addition to fostering interpersonal relationships with key stakeholders.

Maintaining strong communication with key stakeholders was a crucial part of my role. I ensured prompt responses and proactively planned interactions with sponsors and advisors. By fostering clear and consistent communication, I helped align the team's work with the expectations of all stakeholders for smooth development processes.

My largest role was delegating tasks and ensuring that all deliverables and project goals were being met with quality work, always challenging my team to go above and beyond in achieving the project scope. Overall, my contributions to the senior design project combined technical expertise, leadership, and project coordination to drive our team's success. By balancing hands-on development with strategic planning and stakeholder engagement, I played a key role in bringing the project from concept to completion.

Educational & Life Impact

My senior design project has been more than just an academic challenge; it has been a defining chapter in my journey as an engineer and a leader. Working on the calibration screen for the Keck Observatory has not only deepened my technical knowledge, but also refined my ability to lead a team, collaborate across disciplines, and navigate complex project dynamics. Throughout the development of the prototype, organizing team efforts, and coordinating with key stakeholders, I've learned how to bridge the technical challenges with practical execution. This experience has shaped my approach to problem-solving while reinforcing my passion for engineering.

From a technical standpoint, this project has provided me with invaluable hands-on experience with fiber optics, lighting mechanisms, sheet metal fabrication, and solving a problem for highly precise applications. Such skills are directly transferable to my future in aerospace and mechanical engineering. Understanding highly technical systems like the Keck Observatory telescopes has strengthened my ability to analyze and solve engineering challenges, making me an adaptable engineer.

The most profound lessons I have learned extend beyond my technical capabilities. As the project coordinator, I have had the responsibility of ensuring the team remains on track with deliverables, maintained strong interdisciplinary connections, and successfully engaged with key stakeholders. I have learned how to balance technical problem-solving with effective leadership, ensuring that our team operates as a cohesive unit. This role has taught me the importance of clear communication, proactive problem-solving, and fostering a positive yet productive team environment.

This experience highlights my adaptability and capacity for problem-solving and dedication to fostering a positive and improving team structure. As I move forward in my career, the lessons I have learned from my senior design project will remain integral to my professional growth. Whether working on complex aerospace systems or tackling new mechanical engineering challenges, the combination of technical expertise and leadership skills will serve as a strong foundation. This experience has reinforced my aspiration to pursue my goals of becoming an impactful engineer and starting my own sustainable business one day. This also reflects my commitment to engineering solutions that make a tangible impact and will guide future endeavors in engineering, entrepreneurship, and innovation.

Conclusion

The development of the 1/10th scale calibration prototype for the Keck Observatory is a crucial component to the improvement of accuracy in astronomical discovery and data. By reducing the current calibration error of 30% with a uniformly lit screen, our team has laid the foundation for a more precise calibration system to be further developed by the next senior design team, awaiting future implementation. This project represents a scalable solution for a durable screen while also highlighting interdisciplinary collaboration as the individuals on the team enter into new engineering challenges.

Beyond technical learning, problem-solving, and invaluable hands-on experience, I learned a wide range of soft skills in teamwork, adaptability, and communication that will prove helpful throughout my careers in engineering, entrepreneurship, and beyond.

While this prototype acts as the initial proof of concept, its findings will aid in future development efforts for improved, large scale telescope calibration. By improving Keck's calibration capabilities, the observatory remains at the forefront of discovery.

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