The Endless Mantra: Innovation at the Keck Observatory

by

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ABSTRACT

A study of historical, current, and future developments at the Keck Observatory revealed a thriving philosophy of innovation. Intended to defy obsoletion and keep the observatory competitive over long time scales, this philosophy continues to resonate with Keck Observatory scientists.

The Keck Observatory consists of two 10-meter telescopes situated near the apex of Mauna Kea on the big island of Hawaii. Three main innovations keep the observatory competitive. The observatory contains the first modern active optics-controlled segmented primary mirror, principally designed by Dr. Jerry Nelson. Though it currently reigns as the world's largest aperture at 10 meters, monolithic mirror supporters still question its viability. The observatory also links both primary mirrors together as a single 20-meter telescope using interferometry. Finally, the observatory employs both a natural and laser guide star adaptive optics system. Forward-thinking Keck scientists, however, are researching multi-conjugate adaptive optics systems.

As a result of its innovations, Keck has retained its position as a major player in the realm of observational astronomy for over a decade.

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It's hard not to squint. Sunlight pours over Mauna Kea, the tallest point on the big island of Hawaii. Rays occasionally reflect off low cumulus clouds or the snow-dusted apex of distant Mauna Loa. Silver jeeps, branded with 'Keck Observatory' in light blue letters, shimmer in the sunshine. An azure sky spans above, red gravel stretches below, and the silvery-white domes of twelve observatories[1] dot the 60-square kilometer mountaintop preserve.

The Keck Observatory telescopes, named Keck I and Keck II, each sit in a 100-foot tall spherical shell. Though it is not yet dark, the observatory is buzzing in preparation. An engineer walks through the labyrinth of concrete floors and walls, dictating commands into a hand-held radio. A voice, embedded in static, responds. They are testing the optics. A few corridors away, a small tank of oxygen feeds a technician while he paints glue on the backs of spare mirrors in the mirror barn. At 13,796 feet, the partial pressure of oxygen is one-third that of sea level.

Inside the Keck II dome, scientists either walk up a winding staircase or take an elevator to the crowded second-story deck. On this level, more than forty scientific instruments connected by multicolored cables launder light streaming in from the universe. Peering over a railing, one can watch workers scurrying around a monstrous 10-meter primary mirror sitting on a hydraulic, nearly frictionless base. A single strong person could spin the telescope around.

Over the years, both telescopes peered at a host of astronomical objects. Faint supernova. Stellar wobbles. The oldest-known quasars. Analyzing these observations profoundly altered astronomers' views of the universe. They learned that the universe is accelerating; extra-solar planets reside in the Milky Way; and heavy hydrogen atoms thrived during the Big Bang. In January 2005, Keck II pointed to Saturn's moon, Titan, to image a probe plunging into its interior.

To sustain these observations, Caltech, the National Optical Astronomy Observatories, the National Aeronautics and Space Administration, and the University of California system feed the observatory $11 million annually. Keck scientists use the money to defy a world of obsoletion — where digital cameras, laptop computers and mobile phones grow old after six months. After over a decade operation, Keck is still a major player in the world of observational astronomy.

Keck scientists avoided antiquation by adopting a risky and challenging philosophy of constant innovation. By turning cutting-edge technologies to observatory essentials, they upped the ante in the observational astronomy game. But scientists don't compete for technology's sake. Each improved instrument feeds into a single bottom line: to produce the world's best science and understand the universe. Today, scientists at the observatory are developing two main innovations. One is a technology called adaptive optics, which transform once-blurry images into clear portraits of the cosmos. The other is interferometry, which links the two 10-meter mirrors together to act as a single 20-meter telescope.

This push to remain in the vanguard began nearly thirty years ago, when an exuberant astronomer named Jerry Nelson offered a radical solution to building the biggest telescope in the world. At that time, his colleagues began tossing around a phrase: *The world's premier instrument.* The simple expression turned into a mantra, which resonated over time.

This mantra began early in 1977, after an atypical letter from the National Science Foundation (NSF) arrived at the Lick Observatory. Nestled on Mount Hamilton near San Jose, California, the Lick Observatory belongs to the University of California at Santa Cruz, and it then represented the astronomical powerhouse of the entire University of California school system. A few curious scientists at the NSF wanted to know: What was in Lick's future?[2] The observatory's acting director, Robert Kraft, called some of California's brightest scientists for their opinion. It was a good question.

As a result, four scientists soon gathered at the Lawrence Berkeley Laboratory in Berkeley, California, grappling for answers. Together, Dave Rank, Joe Wampler, Harland Epps, and Jerry Nelson represented the University of California campuses at Santa Cruz, San Diego, Berkeley, and the affiliated Lawrence Berkeley National Laboratory.[3]

They were unhappy that the rapidly encroaching town of San Jose was polluting the sky above Lick Observatory with city lights. Other telescopes were outperforming their meager 3-meter instrument. Meanwhile, the National Academy of Sciences' 1970s decadal survey said astronomers nationwide were itching for larger telescopes. The survey pointed out the skyrocketing number of astronomers eager to observe the cosmos' curiosities but noted that there weren't enough telescopes to keep up.[4]

To change that situation, the group decided to best the noted Hale telescope, on a mountain in northern San Diego County called Palomar, in both size and location. With a monstrous aperture of five meters, Hale had reigned as the largest telescope in the United States since 1949. And since Caltech owned the telescope, its scientists dominated the field of astronomy. But Hale now looked through the choking russet smog of southern California. We could do better, the UC team decided. It was time for some competition.[5] It was time for Caltech to sweat.

Over the next two years, the four scientists ping-ponged ideas back and forth; at times, using slow, overhead lobs, at others, using fast-paced serves. Fiercely competitive teams formed; the score always ran neck-in-neck. The game lasted until University of California President David Saxon chose a final design project. It would result in the largest optical telescope in the world, and it would eventually sit on Mauna Kea.

Nelson was the odd man out in this group. He was primarily a physicist making a move into astronomy. With a only few years of astronomical research behind him, the young Feynman-educated postdoc suddenly found himself among a group of well-established astronomers.

"In 1977, I was minding my own business, doing astronomy, studying cataclysmic variables, having a good time," Nelson remembered. "And John Gaustad, who happened to be the chairman of the Berkeley astronomy department, called me up one day and asked me if I would be willing to serve on a UC

Committee to look into the future of astronomy at the University of California….I said, 'Oh, that'd be fun.' And I said it all in ignorance. I really paid no attention to telescopes, in the sense that engineering does."

Nelson had some experience studying the regular pulses of light emanating from a spinning neutron star known as the Crab Pulsar. He also got his hands dirty building a sixty-inch telescope to study the infrared sky from Mount Wilson. And he had an astronomy merit badge from Eagle Scouts. Other than that, his formal education in astronomy was meager.

"I think when I was an undergraduate, I only took one introductory quarter of astronomy at Caltech," Nelson said. "That was it." Nevertheless, Nelson suddenly found himself caught up in a world of telescope design. He went to the committee meetings to listen and learn, and afterwards perused blueprints, read books and articles, talked to people, and calculated. A couple of months later, he arrived at a realization:

"…It seemed to me that to build a telescope just a little bit larger — like the Soviets built a 6-meter telescope in the mid-seventies, which never worked very well, unfortunately — that didn't appeal to me," said Nelson. "That seemed kind of chicken."

He offered a radical suggestion to the committee: Let's make a telescope twice as big as Hale. Ten meters across. It was as if an overly zealous high-school chemistry student suggested building a four-story volcano out of sodium bicarbonate and vinegar. Sure, that's one way to win the science fair.

Nonetheless, his committee colleagues decided to placate him. Come up with a design, they dared him. The challenges in creating such a telescope were seemingly limitless. A piece of glass ten meters across would sag under its own weight, deforming its shape. Even if the glass could somehow sustain its shape, supporting it would require a colossal steel structure hundreds of feet tall. And even if such a structure could be built, maneuvering it would be impossible. The idea was toast.

But Nelson knew that building a telescope the old-fashioned way, with one giant piece of glass, wasn't going to work. Instead, he proposed to piece many small mirrors together into a precisely-shaped parabolic primary mirror. By using numerous segments instead of one solid piece, the mirror would neither be heavy nor require an enormous support system. In fact, the mirror would weigh nearly the same as Hale but collect four times as much light due to the fourfold increase in surface area. Also, he added, it would cost much less.[6]

"In other fields," wrote Nelson in his proposal, "instruments such as cyclotrons, bubble chambers and large particle accelerators have increased by factors of at least two. A factor of two increase [in size from a 5-meter] to a 10-meter aperture appears to be a scientifically compelling jump, allowing us to see twice as far, study seven times as many objects or study objects four times more rapidly." A 10-meter telescope could lead to countless unimaginable discoveries, he argued. A leap in aperture size would result in a leap in understanding.

But Nelson's team members worried about two particular aspects of his design — how to hold the mirrors in the right positions and how to polish them into the correct shapes. "Roughly speaking, nobody had solved these problems before," Nelson said, "so everybody thought it was impossible. 'Get real,' they told me. 'That'll never work.'"

With nearly a hundred years of collective research experience in astronomy between them, the three dissenting members were understandably doubtful: A young divisional fellow at Lawrence Berkeley Lab was proposing to discard telescope-making techniques pioneered by Galileo in order to position chunks of glass to form a parabolic mirror with an accuracy of four nanometers — as unimaginably small as the size of two DNA molecules set end to end. Nelson was ambitious. Or, alternatively, crazy.

The primary mirror of a telescope is an exquisitely crafted object. Smoothed into absolute precision, it carefully directs each ray of light to a focal point. If the shape of the mirror is slightly deformed, the rays won't focus properly. The telescope will be as useless as a badly tuned Steinway.

Wampler, Epps and Rank worried about the telescope's shape. If it was made of segments, would light rays leak through the cracks? Would it hold its perfect parabolic shape and focus all the light correctly? The slightest deformity could ruin the entire project. But they also knew the leap in size was extremely appealing. A 10-meter telescope sounded incredibly attractive and was likely to be far more appealing to the decision-making politicos of the University of California system. A 10-meter telescope would represent a huge advance for observational astronomy. So the three began to devise their own ideas for a 10-meter telescope — but without the segments.

Meanwhile, Nelson enlisted the help of Terry Mast. Mast and Nelson, friends as undergraduates from Caltech, began to discuss the technological challenges in making a segmented mirror. The two worked together as postdocs at the Lawrence Berkeley Lab, a campus of drab brown buildings, loading docks and eucalyptus trees lodged into a fog-swathed mountainside overlooking Oakland. Inside the lab's industrial landscape, Nelson, Mast and an engineer named George Gabor pondered how to fit numerous mirrors together without allowing a single photon of visible light to slide through the cracks. They also puzzled over aligning the segments. Gluing segmented mirrors into some sort of structure was like hanging a sweater on a clothesline. Two hours later, the sweater isn't in the same shape — stretched vertically by the tug of gravity, it is forever deformed.

"… I realized we were going to have to have some sort of active control system," said Nelson. "We were going to have to sense where the mirrors were and move them around with pistons, which nobody had done." In this way, one could continually adjust the position of each segment, forcing them to constantly work in concert as one giant, perfectly-shaped primary mirror.

But Nelson's colleagues balked at the idea of synchronizing mirrors down to nanometer-level precision. The idea, though theoretically feasible, seemed hopeless in practice. Nelson thought otherwise. Generating computer models and programs, and "perpetually pitting our code against our intuition," Nelson was determined to find a solution. "Our style was [to be] ever-skeptical about everything," he said.

After their computer program spat out a solution, Nelson and his colleagues debated its meaning. Were they looking at a product of genius or errors in the code? Indeed, one of Nelson's 1978 black hardbound logbooks bears a note saying, "we made many runs to see if it was a bug instead." Today, stored in an archive, the thick logbook is nearly bursting at its seams; neatly taped onto the graph paper are outputs from computer programs printed on a dot matrix computer, envelopes containing data saved on 4 x 6 cards of microfiche, programming subroutines, derivations clearly written on binder paper, excerpts from the Kitt Peak National Observatory "Next Generation Telescope Reports," and comments like, "LPSDOR calculates the pseudo-inverse of the M by N matrix A with M not less than N" written in a tight, small hand.

Nelson, Mast and Gabor decided to tessellate hexagonal segments together to form a circular primary mirror. They would use devices called edge sensors to determine each mirror's position within four nanometers. The sensors would send the information to piezoelectric actuators — like tiny pistons that move upon applying voltage — which were glued to the backs of each mirror segment. Months later, Gabor built a working model.

To his UC group, Nelson proposed a number of designs, which included anywhere from 6 to 91 hexagonal segments. No one at the time was familiar with this approach, but it had been anticipated. In 1932, the Italian physicist Guido Horn d'Arturo created a 71-inch mirror composed of sixty-one segments for the University of Bologna Observatory. "Although composite-mirror telescopes have come into their own…little or no mention is ever made of their inventor," *Sky and Telescope* magazine reported.

Nevertheless, Nelson doesn't credit any historical inspiration. "I guess I came up with it on my own," he said of the segmented mirror idea, "but it is kind of obvious. Bathroom floors have been segmented for thousands of years." Nelson also points out the segmented nature of radio astronomy dishes and solar panels.

Even with this design in hand, Nelson's group needed to solve yet another problem. They had no idea how to polish the mirrors into varied shapes, which, like pieces of a puzzle, would collectively form a contour known as a paraboloid. Polishing a mirror into a paraboloid was easy enough. But polishing each segment into a section of a paraboloid was a difficult endeavor. This meant each segment had to be an oddly asymmetric shape. All the opticians Nelson's group talked to didn't know how to do it. They said it was simply too hard.

“One of the ways that I tend to work on things is...just [to] chew on it, and sleep on it, and dream about it, and talk to people about it, and ask dumb questions, and build little models,” said Nelson.

He started reading about Bernhard Schmidt, a shy and peculiar Estonian telescope maker who reportedly had an affliction for the bottle. “He used our tavern day and night and would run out quickly time and again to observe,” a Swiss proprietress of the Lindengarten restaurant told *Sky and Telescope.* “We used to make out very well with him.” Nevertheless, Schmidt became world-famous for his optical innovations.

In the late 1920s, Schmidt experimented with glass plates. He attached a strong vacuum suction to the back of a plate. The suction slowly deformed the glass out of shape. After using tools to polish a circular shape into glass, he’d release the suction. The glass would pop into a peculiar shape; if it wasn’t what he wanted, he repeated the process. This laborious guess-and-check method was the only way Schmidt knew how to construct an asymmetrically curved piece of glass.

Nelson brought Schmidt’s technique to the attention of a fellow Lawrence Berkeley Lab member, Jacob Lubliner. Lubliner specialized in the theory of elasticity — how things deform — and was thrilled to adapt it to solve their problem. The group again started using computer models. They were particularly concerned with stresses within the mirror. For example, a log of wood is harder to chop along its width versus its length. This means the log can handle more stress, or weight, along its width.

Nelson, Mast, Gabor and Lubliner tested various types of glass for stress.[7] After months of deliberation, they settled on Zerodur, a ceramic material strongly resistant to expanding or contracting with changing temperatures. To polish it, they attached a number of mechanical arms to a segment’s edges and loaded these arms with weights. This deformed the once-flat glass into a curved shape. After using tools to grind and polish a circular shape into the glass, they removed the weights. The glass then relaxed into its correct asymmetric shape.[8] They used less of a Schmidt-style guess-and-check method and more of Nelson-style computer modeling one. Reliance on computer models to calculate the deformities played a crucial role in their mirror polishing.

Nelson’s colleagues were highly skeptical. Decidedly more comfortable with the traditional method of building telescopes — with one single monolithic mirror — they renounced the segmented approach as obviously dysfunctional.

Nelson and his strongest challenger, Joe Wampler, spoke on the phone many times in an effort to find a middle ground, often exchanging bitterly harsh words. Nelson, who kept a meticulous log of telephone conversations in a thin, dark blue bound notebook, wrote “Wampler will only back down if Saxon says he wants a cheap innovative design to be pursued,” after a conversation in May, 1978. A few days later, Wampler told Nelson “segments are flat [out] impossible — a waste of our energy and money.”

It was war.

By May 25, 1978, a majority design report, written by Harland Epps, Sandra Faber and Joseph Wampler, scathingly critiqued the segmented mirror design. "The segmented approach in principle might cost less than the monolith design," the authors began benignly, "but will require a substantial research and development effort and a much greater risk of cost overruns." Epps, Faber and Wampler cited problem after problem, outlining horrific scenarios of distorted and misaligned mirrors. The committee suggested not only sticking with a monolithic design but reducing the aperture to eight meters, which "would be much easier to make, figure, and transport."

The minority response, written solely by Nelson, prominently bears a quote by Edwin H. Land — the physicist who invented the Polaroid camera — on the cover page: "For scientists and engineers, optimism is a moral duty." Nelson's deeply technical report runs significantly longer (seventeen pages versus the majority opinion's two) and systematically exhorts the values of a segmented mirror.

The two groups butted heads over two main issues: whether a monolithic mirror would break and whether computer programming was a valid problem-solving method for fashioning a segmented mirror.

"Probably the greatest risk," Nelson wrote of the monolithic approach, "is that the mirror will break. The enormous cost implications of such an event cannot be overemphasized. This could occur while transporting, polishing, handling for aluminizing, or completely spontaneously. A 3-meter blank for the NASA Infrared Telescope broke on the polishing table spontaneously, with no external loads at all." In addition, Nelson added ominously, astrophysicists at Kitt Peak National Observatory were also trying to design a 10-meter telescope. Theirs might start operating in 1985. A University of California monolithic mirror wouldn't be in operation until 1989. It was a race, he suggested, and we might lose.

To prove his point, Nelson obtained a copy of a stress analysis for a 10-meter meniscus monolith from Corning Glass Company. The meniscus monolith was a thinner, lighter version of typical heavy monoliths. Looking over their math, Nelson identified a simple mathematical error,[9] resulting "in a very serious underestimate of the actual stress," at almost three times the recommended limit of 750 pounds per square inch. "The mirror will break," he pointed out in a letter to his colleagues. Corning eventually corrected their problem by proposing to construct a slightly thicker mirror.

Yet Epps wasn't worried. He said some of the world's most experienced optical manufacturing experts were confident they could build a 10-meter monolith.[10] Epps was more concerned about Nelson's problem-solving methods. In a letter to Lick Observatory Director Donald Osterbrock, who had returned from sabbatical, Epps wrote, "My computer has never made a mirror...but it has designed some that couldn't be made...Quite often a design that looks terrific in the computer can't be built at all, or more often, can't be held to the required tolerances. Often, too, a system that looks 'so/so' in the computer turns out in practice to be the optimal choice as a *real* device."

But Epps wasn't convincing Sandra Faber. She jumped from the Wampler camp into Nelson's. "I was steadily more impressed with the Nelson-Mast team as time went by because they were operating like physicists," she said. "They had the technical knowledge the other team didn't have." She considered Nelson's claim that a monolithic mirror might break. It was too expensive to build and test a monolithic mirror, but a segmented mirror lent itself to prototyping and testing on small scales, said Faber. By August of 1979, Lubliner had successfully polished a quarter-scale test segment. Suddenly, the segmented approach seemed safer.

As refinements continued over the ensuing months, both camps only grew more polarized. In August of 1980, both submitted their final proposals to a self-named Greybeards Committee, which Lick Observatory Director Osterbrock put together by selecting two astronomers from each UC campus with a large astronomy research department. Like a jury, the eight-member committee, which included Osterbrock himself and University of California President David Saxon, deliberated on the Berkeley campus. A simple majority vote would decide the fate of the telescope.

After a 5-3 vote, President Saxon announced that the segmented mirror proposal was more scientifically sound and technically excellent. "He has no doubt we know how to use a large telescope and would make great discoveries with it," wrote Osterbrock.

Ironically, President Saxon would have likely chosen a monolithic mirror if the project began just a few years earlier. Testing and modeling a segmented mirror design would have been impossible without the advent of computer programming and high processing speeds, which coincided perfectly with the University of California's decision to build a new telescope. Nelson and Mast resided in the heart of Silicon Valley, the birthplace of the desktop computer. Their innovative approach was due largely to being in the right place at the right time.[11]

While a segments approach was the only way to construct a large telescope in the 1970s, the University of Arizona's mirror laboratory can now safely construct meniscus monolithic mirrors 8.4 meters in diameter, reigniting the monolith versus segment debate.[12] MIT astronomer Paul Schechter, who has observed with the Hubble Space Telescope and the Magellan Telescopes, continues to support monolithic mirror design. Theoretically, he concedes, the actively controlled segmented mirror at the Keck Observatory should work. "In practice," he explained, "it's hard to get the positional information you need. You don't have enough light from the [astronomical] objects. If you can do it with one mirror, do it with one mirror."[13]

Once the segmented mirror design was chosen, plans moved forward. To find the best possible site for the 10-meter telescope, a designated team of astronomers looked at mountaintops spread across the globe: one in the Canary Islands, one in Spain, two in California, and one in Hawaii. They were looking for a locale with few clouds, slow winds, and low water vapor. The mountaintop's latitude also mattered. Certain science-rich astronomical objects in the Milky Way's core, known as the Galactic bulge, were only visible from specific latitudes. Prioritizing all these requirements wasn't an easy task. For example, Fuente Nueva in the Canary Islands provided the best overall seeing, but the committee recommended

Mauna Kea. The Hawaiian mountaintop's relatively constant temperature and access to the Galactic bulge appealed to the site selection team.

The rest of the endeavor dealt with the politics and production of the telescope. Caltech, formerly a competitor, became a partner. In an ironic turn of events, the UC system joined hands with its rival after Caltech obtained a $70 million private donation from the W.M. Keck Foundation to fund the project. After a months-long debate, the team decided to locate the observatory's headquarters in Waimea, Hawaii. Over time, they also partnered with the University of Hawaii, the National Optical Astronomy Observatory, and NASA.

Twenty-five years after Saxon's decision, the weathered Keck Observatory sits atop the tallest point in Hawaii. Each telescope consists of 36 hexagonal segments, 168 edge-sensors and 108 piezoelectric actuators. Keck I began taking images in 1993; Keck II came on line three years later, in 1996. After a long battle of wits and years of construction, one might think scientists would relax, in a moment of respite, to enjoy the largest telescope in the world. But the mantra to be the world's premier instrument never left their minds. They continued to innovate.

Even in their initial talks, UC astronomers considered building two telescopes and applying interferometry, or the practice of merging together light from multiple telescopes. The technique is common in radio astronomy — the Very Large Array in Socorro, New Mexico combines the light from twenty-seven radio telescopes — but interferometry with shorter-wavelength infrared light is still in its infancy. The hope to link two telescopes together for interferometry drove astronomers to commission an exact replica of Keck I. They succeeded. In March 2001, the twin 10-meter telescopes locked on a distant star and combined their light-gathering power to act as a single 20-meter mirror.

But another innovation had captured Nelson's attention. At the 1991 American Astronomical Society meeting in Seattle, Robert Fugate, of the Starfire Optical Range in Albuquerque, New Mexico, presented a talk about a new technique called adaptive optics. This technology dramatically minimizes the blurring effects of turbulence in Earth's atmosphere, allowing a telescope to peer into the cosmos almost as if Earth had no atmosphere at all.[14] In fact, the name adaptive optics comes from optical systems adapting, or changing, their configuration in response to the constantly changing atmosphere.

Soon after the talk, Nelson envisioned applying such a system on a 10-meter telescope, the largest of its class to support adaptive optics. By combining the largest telescope in the world with the technology to sharpen the night sky, the Keck Observatory could again revolutionize observational astronomy. Astronomers could study objects that were once too small and blurry to view. The technology would lead to yet another leap in understanding.

Furthermore, adaptive optics might allow Keck to continue as number one. As of May 2005, the world contains thirteen other telescopes six meters or larger,[15] which provide tough competition for the Keck Observatory. Images taken at the Cerro Tololo Inter-American Observatory, located on a mountainside near La Serena, Chile — a city known for its mild climate, white sand beaches, and extraordinarily clear weather — rival Keck's. Now, it takes more to be the world's premier instrument.

Realizing this, Nelson and a group of astronomers created the Center for Adaptive Optics at the University of California at Santa Cruz. The center opened in 1998. Nelson serves as its director, and helps support adaptive optics technologies at several observatories — including Keck, which is now in its twelfth year of operation.

These days, Keck engineers constantly test, clean, and repair the observatory's two telescopes daily, but most astronomers rarely visit the arctic conditions atop Mauna Kea. Instead, they work in a remote observing station, some thirty kilometers away in tropical Waimea, in a complex of white single-story buildings that artfully circle an open garden with sweeping views of the mountain. From Waimea, the telescopes atop snow-capped Mauna Kea appear smaller than the tiny green leaves sprouting from foliage dotting the gardens.

Upon a quick glance, the entire compound could be easily mistaken for a bed and breakfast; indeed, the dormitory-like visiting scientists' quarters sit a few yards away from the control rooms. Large, segmented hexagonal windows grace high ceilings jutting above pale blue roofs that cascade into white Tuscan columns. The focal point of the garden, a thick green patch of grass, forms a hexagon. Yet Keck's scenic bliss is misleading; inside, scientists still work diligently, trying to solve the intricacies of adaptive optics, with the mantra resonating in their ears.

In his book *Planets and Perception*, astronomer William Sheehan compared observing through the atmosphere to "watching a motion picture in which the camera is out of focus except for occasional sharp frames thrown in at random."[16]

Astronomers define those few, precious moments of clarity as good seeing. Conditions of good seeing refer to dark, clear nights with a steady atmosphere. The nineteenth-century Harvard University astronomer William Pickering[17] offered an example:

"To understand better what is meant by the terms a 'steady' atmosphere and good 'seeing,' let us imagine that our observations are all made at the bottom of a pool of water," he wrote. "As long as the weather remains calm we get along very well, but as soon as a breeze springs up we had best pack up our telescopes and go home."

When light from distant astronomical objects passes through Earth's atmosphere, it bends and branches in many directions — a process known as refraction. This bending occurs as the light travels from one medium to another, such as separate layers of the atmosphere. Scientists assign each layer of atmosphere an index of refraction. This number tells scientists how much light will refract as it passes through a particular layer. The denser the material, the higher the index of refraction, and the more the light will bend.

The atmosphere continually shifts and moves around the Earth. Hot parcels of air rise while cold parcels fall; trade winds and jet streams move at hundreds of kilometers per hour. Positively and negatively charged particles collide into one another in the ionosphere. Temperatures and densities constantly fluctuate within the Earth's atmosphere, creating different indexes of refraction each second. Every beam of light takes a unique path down the tumultuous, turbulent sheath surrounding the Earth.

A star radiates plane waves — cosmic light traveling in equally spaced, parallel lines like the ripples from a stone thrown into a pond. The pristine waves, virtually unaltered as they traverse hundreds of light years through the dark and nearly empty expanse of space, crumble in the final 1,000 kilometers of their journey into a telescope's primary mirror. When they slog through Earth's continually turbulent atmospheric layers, the plane waves accumulate bumps, like a straight strand of hair that curls in humidity. Furthermore, their spacing is no longer even; some waves sit in a close, tight bunch, whereas others spread over varying distance scales.

Modeling turbulence involves notoriously complex mathematics. Scientists still yearn to understand its small-scale intricacies, using supercomputers to study problems like minimizing air currents over an airplane wing. However, computers can effectively model more large-scale phenomena, such as turbulence in Earth's atmosphere. And with computer models at their fingertips, engineers began to design telescopic systems that could adjust for such turbulence using two main variables.

As they journey through Earth's atmosphere, bundles of light rays can still retain their parallel and equally spaced original form. Thick urban smog, however, destroys much of this pristine structure. Yet a mountaintop, underneath clear skies, catches many more parallel and equally spaced light waves. That's one of the reasons mountain summits appeal to astronomers.

The wavelength of light also affects the size of those bundles. Shorter wavelengths are highly susceptible to atmospheric jostling; as a result, visible light waves don't march together as well as infrared ones. The diameter of these bundles is called the Fried parameter, or coherence length. In order to model atmospheric movement, computer programmers must properly determine the coherence length. On Mauna Kea, the Fried parameter is around 0.2 meters for visible light and 1.35 meters for infrared light.

The atmosphere moves constantly, but varies in speed. Fast-moving winds across the Great Plains create rapidly changing atmospheric turbulence; slow-moving winds in the middle of the Pacific Ocean slow the rate of activity. The time it takes for a bundle of light to retain its shape before waves fall out of phase is called the coherence time; this represents the second crucial variable in assessing atmospheric turbulence. On Mauna Kea, the coherence time is some 10 milliseconds for visible light and 50 milliseconds for infrared light.

Using this information, astronomers from both the Keck Observatory and the Lawrence Livermore Laboratory collaborated on designing the Keck's first adaptive optics system. It was partially modeled on the 3.5-meter New Technology Telescope in Chile, operated by the European Southern Observatory, the first ever to employ the new technology. Designing the system took over five years. By 1999, Keck II was the first telescope five meters or larger that used adaptive optics.

Every night at the Keck Observatory, a bumpy, mangled, windswept mess of light arrives at the telescope's primary mirror and goes through an exhaustive laundering process called Natural Guide Star Adaptive optics. The system requires locking on to a nearby star, 14th magnitude or brighter. As light from the star enters the telescope, adaptive optics counters the atmosphere's blurring effects by effectively transforming the light back into long plane waves — the way the light was before it encountered the atmosphere.

The system has one big limitation: it can only launder the light from a bright star. It can't readily fix the light from a rocky moon or a distant galaxy. Light coming from oddly-shaped objects don't radiate in plane waves. In order to use adaptive optics in these cases, astronomers must slew the telescope toward the object of interest — for example, a galaxy — and look for a natural guide star sitting close to the galaxy. If the star and the galaxy sit close together, astronomers assume the atmosphere distorts the light from each object in the same way and correct both accordingly. But if the galaxy and star are more than twenty arcseconds apart, the method breaks down. Keck II is unable to get a clear look at the object.

Yet the technology still allows Keck observers to see objects they could never image before. For example, astronomers have long been interested in Titan, Saturn's largest moon, because they think it resembles a primordial Earth. In 1989, scientists at the California Institute of Technology beamed radio signals at Titan's surface. The resulting topographical data indicated Titan contained continents scattered within a hydrocarbon sea. But astronomers wanted infrared data, which would explain how energy from the Sun makes its way down to Titan's surface.

But Titan, at over a billion kilometers away, only spans 0.8 arcseconds of the sky. That's like looking at the period at the end of this sentence from 130 meters away.[18] "If you don't use adaptive optics, Titan is a point source," said University of California at Berkeley astronomer Imke de Pater. Titan appears as a small, glowing dot in the night sky — featureless as distant Alpha Centauri. "You don't see any structure at all," said de Pater.

Before the advent of adaptive optics, de Pater used a technique called speckle imaging, which takes extremely short-exposure images. Astronomers confidently assume the Earth's atmosphere stays still during this period of time. With the Earth's atmosphere effectively frozen in place, astronomers can obtain images without any blurring effects. Yet anybody who has tried to snap a photograph of the night sky with a regular-speed camera knows the technique is problematic. Only a few photons hit the camera, creating a dim — albeit focused — image.

Astronomers solved this problem by creating a composite of hundreds of speckle images. Yet this technique also had its limitations: astronomers could only image Titan in certain wavelengths of light.

Imaging at other wavelengths, which would allow astronomers to probe features like the moon's mysterious surface, was impossible. While many photons streaming from the Sun reflect off Titan's outer atmosphere, fewer photons reflect from the orange moon's surface. A quick snapshot can't capture enough elusive infrared surface-photons to create an image.

A quick snapshot also couldn't identify the high atmospheric clouds, theoretically predicted since Voyager I spacecraft flew by the orange moon in November 1980. To study these clouds, astronomers at the United Kingdom Infra-Red Telescope used a technique called spectroscopy, which allowed them to deduce the chemical composition of an object. They found a slight shift in Titan's chemical composition from one night to the next. Clouds dancing across Titan's moon likely explained the shift, but nobody had observed them. Astronomers could only see large-scale structural changes on the orange moon. Yet clouds were almost certainly on Titan.

The first time Antonin Bouchez — then a graduate student at Caltech, but now a postdoc at Keck — imaged Titan with adaptive optics, the difference was stunningly clear. Using a camera that let in infrared wavelengths of about 2 micrometers, he and two other colleagues probed Titan's surface for clues. They observed distinct white clouds in Titan's southern hemisphere. Before the team made their discovery, scientists believed clouds on Titan should cluster listlessly along the moon's equator. Temperature changes drive cloud movement, but the temperature in Titan's troposphere wasn't changing much. Scientists knew this from using computer models, created with data from the Voyager fly-by, to predict how much energy from the Sun makes its way to Titan's surface. As a result, few expected clouds to amble around the moon.

Yet the clouds did just that, lethargically moving from Titan's north to south pole in a 15-year cycle. While the temperature in Titan's troposphere remains constant, nobody realized that the moon's surface temperature changes slightly from season to season. As a result, clouds form and saunter around the moon. This creates a condensation and precipitation weather cycle just like Earth's — except on Titan, the methane clouds unleash methane rain.

Now, by using adaptive optics, scientists can map cloud movement in Titan's atmosphere to understand the moon's seasonal patterns. In the process, they may glean clues about the Earth's origins. And that's what they hoped for again on January 14, 2005, as they gazed at Titan's orange glow. They hoped adaptive optics would continue its magic.

Sixteen minutes and eight and a half seconds after midnight, Hawaiian Standard Time, on that much-anticipated day, the European-engineered Huygens probe sank into Titan's surface. Named after the Dutch astronomer Christiaan Huygens,[19] who discovered Titan in 1655, the robotic Huygens probe used its six instruments to make as many atmospheric measurements as possible within its three hours of battery life.

Sixteen hours before Huygen's descent, anxious members of the Keck Observatory were engaged in various predictive conversations. Situated in an ideal location to observe Titan, which was only visible in regions in and around the Pacific Ocean that day, the Keck Observatory was ready to image Huygen's plunge. And as the largest telescopic eye in the world, the Keck was most likely to capture Huygen's trail.

Friction between the probe's heat shield and Titan's atmosphere was expected to create a bright fireball lasting up to thirty seconds. And although it was night on Earth during Huygen's descent, it was mid-day on Titan where the probe was to land. Keck astronomers predicted the probe's fireball to be as bright as Titan's clouds, hopefully causing just one pixel to flare to an intensity twice as bright as the cloud cover.

Staff members had been waiting for this day with baited breaths, one question lingering in their minds: Will we see the fireball? The most commonly held opinion: "I have no idea."

The morning began with wind gusts up to ninety kilometers an hour raging on Mauna Kea. Snow from a recent storm encrusted the telescope dome and roads with ice. Not a cloud polluted the sky, yet high winds and perilous icy conditions posed a great risk to both the telescope and the observing assistants on the mountain. At around one p.m., staff members of another Mauna Kea-based telescope, called Gemini North, decided to cancel observations for the night and go home.

Observing support manager Bob Goodrich worried about merciless weather destroying the fragile telescopes. Winds, including gusts, must be below eighty kilometers an hour before observing assistants can open the Keck's protective domes. "Standing outside, you should feel no snow or ice hitting your face," he had warned the previous day.

Every evening, two support astronomers make the journey from Waimea to Mauna Kea to open the dome, monitor the telescope's instruments, and fix any hardware problems. Within the one and a half hour car ride, the astronomers witness a diversity of climates: fog enveloping the low hills, the sunny plains of Parker Ranch, the solidified rocky a'a and smooth pahoehoe lava near Hale Pohaku — one of the many homes of the friendly Nene goose, the Hawaiian state bird — and eventually the frigid and windy mountaintop.

As Gemini astronomers trudged down the mountain, Keck observing assistants waited at Hale Pohaku with a vehicle prepared for the weather. "Should the winds look like they are dropping significantly, the night crew will carefully work their way to the summit," Goodrich wrote in a late afternoon email. The future looked grim.

In Waimea, astronomers wearing t-shirts and shorts waited. "I bet they'll decide to open the dome half an hour beforehand," said support astronomer Al Conrad. He shrugged. "That's just what I think."

On the mountain, Keck observing assistants assessed the situation. They checked anemometers, or wind-gauges, at the Mauna Kea Weather Center. Only one hard-and-fast rule guides the assistants: If winds are above eighty kilometers an hour, the dome stays closed. Otherwise, they make a judgment call. Wary of fast-moving particles, which scratch mirror surfaces, observing assistants shine a flashlight into the night sky, searching for bits of dust or snow. Or they put a piece of paper inside the dome to see how many particles it catches over time. They might even consult with a support astronomer in Waimea.

An hour before midnight, winds on the mountain died down to nearly sixty kilometers per hour. Some forty minutes before Huygen's plunge, that day's observing assistant, Joel Aycock, gave his orders: open the dome.

Thirty kilometers away, antsy and amused astronomers trickle into a room labeled Remote Operations 2 — Keck II's control room. Surprisingly nondescript, the room contains several computer workstations equipped with three monitors apiece. A framed photograph of the Keck's bright white domes against a brilliant sunset bears the label "You are observing here" next to an arrow pointing to the telescope on the right. A television sits in the corner of the room; while observing, astronomers maintain a continuous videoconference with an observing assistant sitting in the control room atop Mauna Kea.

Fifteen minutes before entry, Bouchez and de Pater sit at the workstation closest to the television, ordering the telescope to take ten-second exposures of Titan with a near-infrared camera. A methane filter, corresponding to about 1.7 microns of infrared light, allows them to image the outer layers of Titan's methane-rich atmosphere. An abnormally large number of staff members sit along the couch and linger in the back, carrying cameras to document the momentous occasion. "I want to take a picture of the ensuing chaos," one says.

As photons from Titan spill into the Keck Observatory's adaptive optics system, they embark on a journey just as complicated as their trek through the atmosphere. The photons bounce from one instrument to another in a manner reminiscent of George Rhoads' *Archimedean Excogitation*, a sculpture in the Boston Museum of Science. His 27-foot tall tower features billiard balls flying down ramps, turning gears, whirring wheels, and flipping levers before coming to their final resting place.

Photons also bound off several instruments in an adaptive optics system. After they hit the primary mirror, the photons are directed onto a tip-tilt mirror, which moves back and forth on one axis to correct waves of light that are evenly spaced and parallel but arriving at different angles.

After the photons leave the tip-tilt mirror, they hit a device known as a deformable mirror. This frisbee-sized device continually flexes into the opposite shape as the incoming light waves. As a result, light waves bouncing off its surface straighten out.

The photons continue their journey. They hit a parabolic mirror — known as a collimator — which channels the light into a long, straight column. This column is directed into a dichroic, also known as a beamsplitter, which separates the light beam into visible and infrared wavelengths. The visible light enters an instrument that analyzes it; the infrared light enters the camera.

The visible-light photons enter a Shack-Hartmann wavefront sensor, which is an array of tiny lenses that evenly separates the photons to create 400 individual images of Titan. Each image is smaller than the bundles of light falling onto the telescope. In this way, the wavefront sensor catches each bundle like a strainer catching pasta. If the wavefront sensor's images were bigger than the bundles, some bundles of light might pass through, uncorrected, like fettuccini slipping through a large-holed strainer.

Each lens has a property termed the centroid, which measures how off-center the image is: too far up, down, left, or right. A computer analyzes this information and translates the data into a three-dimensional Zernike function; mathematically, a Zernike function looks like a congested combination of cosine and sine waves mixed with high order polynomials. Graphically, it looks like a potato chip.

This information from the wavefront sensor is cycled back to the deformable mirror, which then adjusts its shape to model the Zernike function. In this way, the wavefront sensor continually drives the deformable mirror, which reads in data up to 670 times a second and subtly changes its shape every time. It must work faster than the smallest changes in the atmosphere's movement, or coherence time. If the deformable mirror works too slowly, photons will jostle around midway through the correction. This will eventually produce a blurry image, much like the elongated lines of light created during a long-exposure photograph of speeding cars.

The infrared-light photons, meanwhile, travel into the camera — now fully laundered by the deformable mirror and ready to produce a crisp image. By the end of their journey, Titan's photons have bounced off at least fifteen surfaces. Aluminized surfaces are approximately 97% reflective, which means that each bounce reduces the amount of light reaching the camera. According to Bouchez, the total efficiency of the entire Keck optical system — including the telescope, adaptive optics system, instruments, and the detector — is about thirty percent.[20] About one third of the photons hitting the primary mirror end up in the camera, making it the least light-efficient instrument at Keck.

According to Harvard University astronomer John Huchra, thirty percent is "actually very good." Though every mirror in the system throws away three percent of the light that hits it, said Huchra, "some of those losses would hold in space as well as on the ground."

On this night, astronomers hoped for a perfectly-functioning system. Necks stretched to glimpse each new image of Titan — a bright orange ball with dark blotches of red, likely liquid hydrocarbons, and occasional bright, white patches of surface ice. The CCD camera changed position slightly as it snapped each new image of Titan. This dither pattern, as its called, eliminated the chance that a few bad pixels on the CCD might corrupt the photographs.

As the computer updated each image, people threw nervous glances at the minute-hand of a small clock hanging on the wall. Fifteen minutes before impact, de Pater echoed everybody's thoughts: "We have no idea what will happen."

“If we see anything, it’ll probably be bad news for Huygens,” a support astronomer predicted.

“Well, Huygens has been dead for so long it doesn’t matter,” another replied, to laughter.

12:16:08.5

“I see exactly what we were supposed to see with SL9,” said support astronomer Joel Aycock, his voice emanating from the television speakers, “Nothing.” He was referring to comet Shoemaker-Levy 9, which crashed into Jupiter in an unexpectedly spectacular fashion to the delight of astronomers, since most had predicted it to be invisible from Earth.

Conrad went into this office to clean up some of the images, subtracting background radiation from the Earth’s upper atmosphere and from the telescope’s instruments. Though the adaptive optics system can produce crisp images, astronomers always sharpen them further. Computer codes eliminate tens of image-corrupting biases, such as scattered light and malfunctioning CCD cameras. Perhaps cleansing the image would yield an elusive bright pixel. Conrad printed out a picture and brought it into the control room, pointing to a spot in Titan’s southern hemisphere.

Most of the bystanders spent a few silent minutes looking at a perfectly uniform, though otherwise magnificent, picture of the distant moon. They quietly dispersed. It had been a long, stressful day. Despite the disappointment, the idea that one could hope to see something as big as a bonfire some billion kilometers away is a monument to adaptive optics.

Huygens probe or not, adaptive optics observing is always dramatic. Less than 24 hours after Huygen’s no-show, de Pater and a host of support astronomers continued their regular observations of Titan. During a routine 30-second exposure, using the same near-infrared camera, the normally well-focused moon slipped into a hazy, dark red blur. The tip-tilt mirror suddenly failed to operate. A slight commotion ensued; de Pater called two support astronomers into the control room. After restarting the adaptive optics system, Aycock, the observing assistant on Mauna Kea, looked into the video camera.

“Open the loops,” he said, referring to the connection between the wavefront sensor and the deformable mirror. This stopped the adaptive optics system from processing the light, allowing Aycock to reboot the system.

“Hold on,” said De Pater. A computer script dictating the imaging sequence was near completion.

“Opening loops,” she said, as she typed a few commands into the computer. Aycock rebooted. De Pater and her colleagues waited, looking at the television screen.

"You can close the loops," he said, making sure the telescope was still focused on Titan. De Pater returned to the computer, typed in some commands, and waited for a crisp image of Titan to appear on the screen. Instead, the dark red blur re-appeared. The control room let out a collective groan. Aycock and de Pater repeated the process a few times to no avail.

"We haven't done anything in the last fifteen minutes," Aycock pointed out. After factoring in the cost of maintaining and building the observatory, each second of observing time costs about a dollar, according to support astronomer Randy Campbell.

Her familiarity with adaptive optics likely allowed de Pater to keep a calm composure during the control room crisis. The occasionally unpredictable adaptive optics system and spontaneously rough wind conditions on Mauna Kea were typical problems astronomers encountered at the Keck Observatory. And de Pater knew what Keck Observatory support astronomer Doug Summers once said: "After every problem you solve, there's always a new one." It may as well be the mantra of adaptive optics — equal parts impressive and complex, the relatively new technology employs tens of people both at the Keck Observatory and at the Center for Adaptive Optics in Santa Cruz.

A few years ago, Keck Observatory members realized the Natural Guide Star adaptive optics method wasn't always cutting it. The adaptive optics process could only correct the light from a small patch of night sky surrounding the natural guide star. On good days, when the weather is still and clear and the wind is a mere breeze, the patch could be up to 20 arcseconds across. On bad days, it can get much worse — 10 arcseconds or less.

This concerned Keck engineers because astronomers aren't always observing such small patches of the sky. Astronomers are interested in observing objects spread across the telescope's field of view, such as distant galaxies and quasars. In addition, finding natural guide stars isn't an easy task. Only about ten percent of the sky contains stars 14th magnitude or brighter. And dust obscures such visible stars from some of the most interesting areas of the sky — such as the supermassive black hole at the center of the Milky Way.

To expand their available celestial acreage, Summers and others are currently working on a Laser Guide Star Adaptive Optics system, which creates an artificial point source-like star. This will allow astronomers to image over ninety percent the sky, not just patches containing 14th magnitude stars. The laser system includes a half meter telescope, mounted to the side of Keck II's primary mirror, which throws a thick bright orange laser beam into a layer of the stratosphere about ninety kilometers above Earth's surface. Tuned precisely to 589 nanometers, the laser illuminates a cylinder of sodium atoms half a meter in diameter and about 8 kilometers long, creating a deep orange artificial guide star lingering in the atmosphere. The system is so new it is labeled as a 'shared risk' instrument.

"That means: If it breaks, please don't cry," said Nelson.

Only one other astronomical telescope in the world — at the Lick Observatory — uses an artificial guide star. The Keck's 10-meter telescope, however, poses far greater technical challenges than Lick's 3-meter aperture.

Both Lick and Keck mounted the laser on the side of the telescope, instead of centering it above the secondary mirror, which creates a host of previously-unanticipated problems. The portion of the primary mirror closest to the mount images a circular star, but the furthest portion images a pencil-like cylinder. This results in numerous optical aberrations, including astigmatism, which create a blurred and distorted image. Although the side-mount hardware cost less than a central mount, the Keck team ended up spending a couple of man-years developing software to solve the unforeseen problem. And while Lick Observatory ignores this problem, because a 3-meter aperture only creates a small error, the Keck Observatory cannot disregard it.

In addition, it's hard to track light from the large, column-like artificial star due to the turbulent, low altitude of the sodium layer. For this reason, even the laser guide star system employs a natural guide star — although this one can be much fainter, at 18th magnitude — to assist in focusing the telescope. Since the system employs two stars, it uses two wavefront sensors — one collecting light from each star.

Once the natural star is in focus, its wavefront sensor sends the information to the laser guide star's wavefront sensor, which determines the altitude of the sodium layer and tracks the fake star through the night sky. In this way, the laser guide star system can yield an image correction over most of the celestial sky.

Yet, as usual, there is another technological hurdle. The light from the laser guide star travels inside an imaginary cone — with its tip at the bright star and base on the telescope's mirror — like light streaming from a flashlight and landing on a wall.

Each point of light from an astronomical object relays its own cone of light into the telescope's mirror, but the object cones doesn't exactly match up with the guide star cone. They're slightly off kilter — which means light traveling from Cone Guide Star doesn't follow the same turbulent path as light traveling from Cone Astronomical Object. This means the deformable mirrors moving hundreds of times a second to adjust the light from Cone Guide Star aren't exactly adjusting the light from Cone Astronomical Object.

If the astronomical object lies close enough to the guide star — within about ten arcseconds — their cones nearly match up. In that case, an adaptive optics correction on the guide star also corrects the light streaming from the astronomical object. If the astronomical object lies farther than ten arcsconds from the star, the cones don't match up. The adaptive optics performance begins to degrade. The problem is prevalent, but not significant, on a 10-meter class telescope. Yet adaptive optics on the next generation of telescopes — such as a 30-meter telescope — will have to deal with such problems.

Scientists are working to correct such degradation using a system awkwardly called multi-conjugate adaptive optics. Multi-conjugate adaptive optics utilizes multiple lasers, wavefront sensors, and deformable mirrors to image the turbulence within a cylinder above the primary mirror, instead of a cone. That way, astronomers can accurately correct for atmospheric turbulence while imaging a large swath of the night sky. Multi-conjugate adaptive optics, however, presently resides only in the realm of theory. No astronomical observatory has been able to design, let alone implement, such a system. But in 1977, no astronomer had designed an active-optics controlled segmented primary mirror either. Innovation isn't a deterrent, it's just a hurdle.

As the Keck Observatory ventures into the future, it is still vying to be the world's premier instrument. For example, Observatory director Fred Chaffee, for example, envisions a visible light adaptive optics system for the telescopes. Such a system would allow astronomers to sharply focus the blurry visible light from astronomical objects and provide even more clues about the universe. "If we can pull it off — it requires a lot of technology we don't have yet — then Keck would reign supreme," he said. Nelson echoes Chaffee's claim. "That's an arena where the 10-meter telescopes might stay ahead of 30-meter ones," said Nelson of visible-light adaptive optics imaging. "If Keck plays their cards right, they will still be the best institution," Nelson said. "As telescopes get bigger, adaptive optics only gets harder," he said.

But the 10-meter class of telescopes face many competitors. Today, the Very Large Telescope complex in La Silla, Chile, consists of four 8-meter monolithic mirrors, each only twenty centimeters thick. By using honeycomb mirrors — which are mostly filled with empty air, like Hexcel skis — the University of Arizona glass laboratory can now construct large, thin monolithic mirrors. Because of this, some astronomers believe each of the telescopes produces better images.

In addition, two groups are fervently competing for funds to construct far larger telescopes. The Giant Magellan Telescope design incorporates seven 8.4-meter mirrors acting as a single 24.5-meter diameter. The Thirty Meter Telescope design incorporates 1,080 1-meter mirrors functioning as a single 30-meter diameter. The Nelson-Wampler debate continues with different characters. Members of the Giant Magellan Telescope adamantly believe in building a telescope out of the fewest segments possible; the Thirty Meter Telescope team thinks otherwise.

Nevertheless, that day remains in the future. Until then, Nelson and the Center for Adaptive Optics will continue to support the Keck Observatory. Perhaps Keck's astronomers will crack the visible light adaptive optics problem. Perhaps they will implement multi-conjugate adaptive optics. But whatever they do, they will keep listening to the mantra. Innovation will continue. And Nelson, who sparked the dedication to innovation, continues to monitor Keck's successes.

"I always feel like this is my personal telescope," Nelson once said, "so I deserve to always know everything that's going on. Whereas the administration, they always feel like, 'Wait a minute — the administration does all sorts of things in private and its nobody's business.'...And you know, I accept that, but at an emotional level I always feel very paternalistic about it. Thus, I feel like I want to know everything about it, even stuff that’s irrelevant. So I’d ask questions and poke around.”

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[1] University of Hawaii 0.6-meter Telescope, circa 1968; University of Hawaii 2.2-meter Telescope, c. 1970; NASA Infrared Telescope Facility, c. 1979; Canada-France-Hawaii Telescope, c. 1979; United Kingdom Infrared Telescope, c. 1979; Caltech Submillimeter Observatory, c. 1987; James Clerk Maxwell Telescope, c. 1987; Subaru Telescope, c. 1999; Frederick C. Gillett Gemini Telescope (Gemini North), c. 1999; Submillimeter Array, c. 2003; Very Long Baseline Array Antenna, c. 1992. Together, the observatories image the sky in optical, infrared, submillimeter, millimeter, and radio wavelengths.

[2] Two astronomers correctly predicted why the National Science Foundation (NSF) sent Lick Observatory such a letter. On August 5, 1977, Dean of Physical Sciences Leonard V. Kuhi and Professor of Astronomy Hyron Spinrad sent a letter to University of California Chancellor Bowker, saying "This perhaps reflects the present view of several lower-level committees at NSF that the next major instrument funding should go to a university and not to a national center (such as Kitt Peak National Observatory at Tucson). It is not clear whether high echelons at NSF feel the same way."

[3] These four were not the only ones planning the telescope's future. They worked under an umbrella called the UC Telescope Planning Committee; the four astronomers formed the Technical Subcommittee. Other subcommittees were responsible for other problems. For example, the Site Survey team worked extensively to choose a site for the 10-meter telescope.

[4] The National Academy of Science's 1970 Astronomy Survey Committee report noted that "The available collecting area has not increased during the past decade at as great a rate as the number of active astronomers or the demand for time to observe faint objects."

[5] In an undated 1979 Science Subcommittee interim report, Sandra Faber wrote, "Obvious competitors include the 5m at Palomar and the 4m at CTIO, the latter because of its fine seeing." Details of the report are in the Lawrence Berkeley Laboratory Archives, ARO-2465, Box 7.

[6] "Famous last words," Nelson said, reminiscing on his low-cost proposal.

[7] They tested stiff, light, low-expansion glasses such as Cervit, ULE and Zerodur.

[8] Much later, in the early eighties, the group learned that cutting the polished mirrors into a hexagonal shape again distorted each mirror's curvature. They solved the problem by attaching harnesses to the back of each mirror and reapplying forces on the mirror's surface until the mirror bent back into its desired shape.

[9] Corning used a base-10 logarithm in their computation instead of a natural logarithm (base e).

[10] For example, Epps cited a January 2, 1978 letter from Don Davidson, founder of Davidson Optronics Inc. "I am confident the blank [mirror] can be fused and slumped to shape on the job," Davidson wrote.

[11] According to a January 21, 2005 interview with Dr. Barbara Schaefer, a longtime friend of Dr. Jerry Nelson and a current support astronomer at the Keck Observatory.

[12] In the 1970s, three limitations prevented any mirror lab from casting big mirrors. First, the larger the mirror, the longer it takes to cool. The cooling process can take over a year. Secondly, the more massive the mirror, the more it bends under its weight and the harder it is to support. And finally, removing the

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correct amount of glass from a mirror blank is both tedious and time-consuming. Collectively, these three factors made constructing a monolithic mirror a risky business.

[13] Harvard University Professor Dr. John Huchra, who has observed with both monolithic and segmented telescopes, is a member of the National Academy of Science and a senior astronomer at the Smithsonian Astrophysical Observatory. He offers an insightful look at the current monolith versus segmented debate:

"Frankly, the astronomical community doesn't care," said Huchra. "First of all, the telescopes won't be built for at least ten years, so the average astronomer won't see it. Secondly, there are six thousand members of the AAS [American Astronomical Society] and about two thousand hours of observing time per telescope. That's generous, assuming good seeing conditions 60% of the time. And there are 17 telescopes 8-meters or larger in the world. That averages to twenty minutes of telescope time per astronomer per telescope." Even if every astronomer managed to twenty minutes at each of the seventeen telescopes (a virtually impossible task), it amounts to less than six hours of observing time. For deep-sky observers, that could be two photographs.

[14] "Adaptive optics is a technology that corrects in real time for the blurring effects of atmospheric turbulence, in principle allowing Earth-bound telescopes to…'see' as clearly as if they were in space," astronomer Peter Wizinowich and his colleagues wrote in a research paper published in *Publications of the Astronomical Society of the Pacific.*

[15] Multiple Mirror Telescope, 6.5 meters; Magellan I, 6.5 meters; Magellan II, 6.5 meters; Very Large Telescope I (VLT I), 8 meters; VLT II, 8 meters; VLT III, 8 meters, VLT IV, 8 meters; Subaru, 8 meters; Gemini North, 8 meters; Gemini South, 8 meters; Large Binocular Telescope I (LBT I), 8.4 meters; LBT II, 8.4 meters (both LBT I and II are on the same mount); Hobby-Eberly, 11 meters (9.2 meter effective aperture).

[16] This observation resulted from astronomers making motion pictures of the Moon and double star 85 Peg from the 0.6-meter refractor at Lowell Observatory. Details of the motion picture appear in J. Rösch, G. Courtès and L. Dommanget, "Le Choix des Sites d'Observatoires" *Bulletin Astronomique de l'Observatoire de Paris*, 24 (1963). The astronomers realized they captured "occasional good frames," which used the full resolving power of the telescope, out of thousands of unfocused ones.

[17] While observing from Arequipa, Peru from 1891 to 1893, Pickering came up with theories that active volcanoes on the Moon threw up "water-vapour and carbonic acid" and fluctuating dark spots on the Moon's surface was really "organic life resembling vegetation." He was really seeing the effects of Earth's turbulent atmosphere.

[18] Using a small-angle formula, $D = \alpha d/206{,}265$, where D is the diameter of the object (in the case of a period, 500 micrometers, or 5×10^{-7} kilometers), and α is the angle subtended on the night sky (in this case, 0.8 arcseconds), one can calculate *d*, the distance to the object, to be approximately 130 meters.

[19] Though Christiaan Huygens is famously known for discovering Titan, it should be noted that he was one of the best physicists, astronomers and mathematicians of his time. He and his brother, Constantijn, constructed telescopes with extremely long focal lengths to increase their magnifying power. Fascinated with the notion of timekeeping, Christiaan Huygens looked to both the heavens and simple mechanical tools, like the pendulum, to improve measurements of time. His work helped formulate Newton's third law (every action has an equal and opposite reaction). Huygens also spent many years studying the reflection and refraction of light.

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[20] According to Bouchez, an extremely faint 24.8 magnitude star imaged at 2.2 micrometers produces approximately 4 photons per second on Keck's camera. If the telescope was in space, however, it would receive about 14 photons per second.

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