Jerry E. Nelson

1944-2017

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
Judith G. Cohen

NATIONAL ACADEMY OF SCIENCES

JERRY EARL **NELSON**

January 15, 1944-June 10, 2017

Elected to the NAS, 1996

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By Judith G. Cohen

Jerry Nelson was the chief designer and project scientist for the two 10m Keck telescopes built jointly by the California Institute of Technology (Caltech) and the University of California (UC) near the summit of Mauna Kea in Hawaii. He was a brilliant physicist, optical engineer, structural engineer, and more who applied his immense talents and insight to develop, demonstrate, and successfully apply new ways to design and build large astronomical telescopes. His ideas enabled the design and construction of the immensely successful twin Keck 10m telescopes, for which he was the project scientist, and their suite of forefront instruments. He worked on designing and building Keck for more than fifteen years. All future large telescopes, both ground-based and space-based, follow his lead in many of their key design decisions.

Early Life and Education

Jerry Nelson was born in Glendale, California, in 1944. He went to local schools there and entered Caltech as an undergraduate in 1961. Although he initially was a math major, after his first year he switched to physics. Freshman and sophomore physics at that time were taught by Richard Feynman, and Nelson enjoyed those lectures enormously. Nelson stated in a 1992 interview for the Caltech Archives, "I loved the way he approached problems and the way he wanted us to think....Two years of Feynman lectures gave me a taste for physics and a predilection for styles to approach and solve problems which I think has stuck with me."

As an undergraduate at Caltech, he worked with professors Bob Leighton, a remarkably ingenious physicist, and Gerry Neugebauer, an astrophysicist, full time over the summers and part time during the academic year. They were building a 60-inch telescope to carry out an infrared sky survey on Mount Wilson with very limited funds. This was at the beginning of infrared astronomy, when detectors were small and difficult to acquire;

theirs was surplus from a defense industry project. They did the design by themselves; the mirror for this telescope was produced by spin-casting epoxy. Nelson helped to design and build a frictionless air bearing that they used to support an aluminum shell into which they poured epoxy and spun it on the bearing. The epoxy would then flow to form the desired parabola, and would, if the spin rate was not too high, cure and harden to produce the desired mirror surface of the telescope, which could then be aluminized. The telescope was assembled and tested in a large open area on the Caltech campus prior to being disassembled, trucked to the summit of Mount Wilson, and reassembled there.

In the late 1960s, the telescope was used to carry out a survey of the sky at 2-microns, far beyond the red limit of any previous telescope. This enabled the detection of approximately 5600 sources, including many previously unknown cool stars. A preliminary catalog[1] of these IR sources was released in 1969 by NASA; many scientific papers on the most interesting sources followed.[2] Jerry later said, "Leighton was remarkably good at building things....He was a very creative guy. He always had clever, obscure ways of building things that worked very well." This description, if one omits the word "obscure," would be quite typical of Nelson's future work, in which the emphasis was on the best possible performance for the minimum cost and risk.

Jerry had the fun of seeing the 2-micron sky survey project to the end, helping to assemble the Leighton dish on a large open space on campus, test it, tune it, and install it at the Mount Wilson Observatory. He spent a summer at Mount Wilson running the telescope and collecting data (at that time recorded on strip charts) all night. This data, when reduced, provided the material for the 2-micron sky survey.

Towards the end of his senior year, Jerry went on a blind date arranged by a friend with Victoria Waere. She had just graduated from Stanford University and started working in Los Angeles. They had such a lovely evening that instead of each going home, they decided to drive to Las Vegas and get married. They got about halfway, then decided to return to Pasadena. On their second date shortly thereafter, they drove to Las Vegas and got married.

Jerry attended graduate school at the University of California, Berkeley, where he got involved in particle physics but decided he did not like working in an environment with very large groups. He preferred a smaller canvas and moved more into what one might call experimental astronomy, including efforts with collaborators John Middleditch and Gary Chanan to detect optical pulsations from newly discovered radio pulsars. Among their goals was to measure the pulsations and spin-down time of the Crab pulsar, at that time a very hot subject. He still was officially a physicist working at the Lawrence Berkeley National Laboratory (LBL) in particle physics. This arrangement was beneficial because he had access to funds to build moderately sized instruments through LBL, which was much easier than getting funding through the university's Astronomy Department. It was during this time that the author met Jerry Nelson; he invited her to his home high in the Berkeley hills, where many Saturdays Jerry and Victoria had open house for their friends. Tilden Park was a five-minute walk from their home, and people brought food to contribute for dinner, so typical of the spirit of Berkeley at that time.

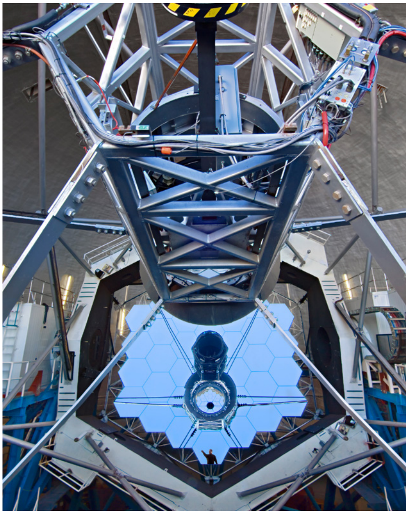

Figure 1. Keck 2 primary mirror, December 2007.
(Photo courtesy of Laurie Hatch.)

Jerry received a Ph.D. in physics in 1972 from Berkeley, working on problems in elementary particle physics. He continued to work at LBL, but more on astrophysics than on physics, where big proposals and big teams were the norm, but he found the smaller teams in astrophysics more compelling. Meanwhile LBL continued to support him and his work. During the period from 1971 to 1981, he wrote 23 papers with a number of young collaborators, primarily Gary Chanan and John Middleditch, on efforts to detect optical pulsations of radio pulsars and other objects suspected to be neutron stars. A typical example of their work is a 1976 paper by Middleditch and Nelson published in the *Astrophysical Journal*: Studies of optical pulsations from HZ Her: A determination of the mass of the neutron star.[3]

In 1977, Nelson was asked by the chair of the Berkeley Astronomy Department, John Gaustad, to serve on a new UC committee whose mandate was to consider the future of astronomy at UC. The largest telescope UC had access to at that time was the one at Lick Observatory at Mount Hamilton, California. The diameter of its primary mirror, which determined the amount of light collected from a point source was 3m, which was about two-fifths of the light-collecting area of the 5m telescope at Palomar Mountain owned by Caltech. The UC astronomy faculty wanted a telescope bigger than any existing optical telescope at that time. Furthermore, the Lick Observatory was very close to San Jose. Light pollution from city was becoming a problem already, and one sure to become more serious as the city and its suburbs expanded with time.

At that time there was a feeling among the astronomy faculty at UC of being second class compared to Caltech, with their 200-inch (5m) telescope. UC wanted to build something really big and aimed for a 10m-class telescope that would be much better than Caltech's Hale telescope at Palomar Observatory. The committee Jerry was asked to join was to be a high-level committee convened to consider the issues involved in building a bigger telescope for UC. There were two subcommittees, each attacking one of the two major issues. The first was the site of such a telescope, given that Mount Hamilton, where their existing telescopes were located, was too close to San Jose and thus ruled out by the rapidly increasing brightness of the night sky from city lights, advertisements, and such. Various mountains in California and Arizona were studied by this group, whereas other groups interested in this issue were exploring sites in Hawaii, northern Chile, and elsewhere abroad.

The second group was working on issues of telescope design, and this was the group Jerry chose to join. He agreed to do so not because his personal scientific interests required it but because it sounded like fun. There were two different approaches within the group. One was to build a telescope much like Caltech's 5m, but bigger by a factor of two or more. The key issue here was how to manufacture, support, and polish such a large mirror at an affordable cost. A number of other groups, including Roger Angel's team at the University of Arizona and a team at the National Optical Astronomy Observatory (NOAO) at Kitt Peak (both in Tucson), were exploring these issues in response to the high-profile Field committee report's recommendations. The staff of the Kitt Peak National Observatory (KPNO) in Tucson were discussing building a 25m telescope.

Roger Angel further developed the spin-casting technique to generate large mirrors with diameters of up to 8.4m in unused space under the University of Arizona football stadium. He fabricated these mirrors using the same concept Bob Leighton had used for his IR telescope, but he had a much harder time owing to the lower wavelengths of light and hence tighter, more accurate mirror surface requirements. Roger Angel's large mirror-casting facility produced a number of 8.4m-diameter Pyrex mirrors; they were used for the Giant Magellan Telescope in Chile and the Large Binocular Telescope in Arizona. Extending this to produce bigger mirrors did not seem feasible, and Pyrex is not the best glass to use for astronomical mirrors.

Joe Wampler, professor of astronomy at the University of California, Santa Cruz (UCSC), led the group advocating scaling up a conventional telescope similar to Caltech's Palomar telescope. This group ultimately converged on a 7m telescope, which had a rather high cost and risk associated with possible breaking of the mirror during the fabrication, mounting, transportation, and installation.

Jerry started reading, collecting blueprints of existing telescopes, talking to people at NOAO in Tucson, where the engineering staff was dreaming of a 25m telescope, and elsewhere. He quickly realized that just scaling up the existing designs was not a viable way forward technically and the predicted cost of fabricating such a large mirror was prohibitive. Simply scaling the weight of the Palomar telescope up to a 10m telescope was frightening. A new paradigm was needed.

It is important to remember that this all was happening as the electronics revolution was rapidly gaining speed. Faster, better, smaller, and cheaper electronics and computers were becoming available. One saw the first mathematical design tools, the beginnings of digital detectors, and other innovations. All of the tools and items needed to design and manufacture a large telescope were improving as well, suggesting that some radical new design might be possible.

Figure 2. Jerry in his office holding Ramagon structure, circa 2009. (Photo courtesy of Michael Bolte.)

Nelson developed a new technology for designing and manufacturing large optical telescopes, radically different from the existing ones. Radio telescopes are made out of panels, but owing to the much longer wavelengths of interest, have much looser surface accuracy requirements, so the panels are much larger and relatively easy to fabricate. Jerry suggested using a large number of small glass segments connected in some way so as to form a mirror larger than that of the Palomar telescope with the desired surface. It should be noted that a somewhat similar concept had already emerged in a short article in the research journal at the University of Bologna, Italy. I read it many years ago while on a visit to the University of Bologna. The goal was to produce a large fixed mirror by cutting segments and this was suggested as a way to produce a large, affordable mirror but World War II intervened.

Major advances in mirror fabrication and control were required to achieve the desired specifications, which were very challenging. The Keck primary mirror consists of 36 hexagonal segments, each 1.8m in diameter, that were designed to produce an image from a point source with 80% of the total energy within a circle of diameter only 0.34 arc sec, small compared to the blur introduced by light passing through the Earth's atmosphere. There were very tight constraints on the smoothness of the mirrors as well. Such constraints were necessary to ensure that the 36 segments would behave like a single large reflective mirror.

Nelson hoped that by using many smaller pieces of glass to provide the large area of the telescope mirror, the manufacture of each piece would be easier and the total cost substantially lower. He also watched as advances in electronics made the design of the necessary mirror control system more feasible. He relaxed both at home and in his office by playing with Ramagon structures (building toys somewhat reminiscent of an Erector set, but no longer available today except on eBay).

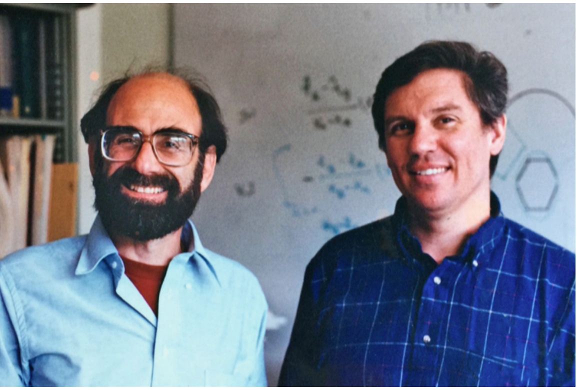

Figure 3. Jerry (left) and Terry Mast in Jerry's LBL office, circa 1984. (Courtesy of W.M. Keck Observatory.)

Nelson's design created a large telescope mirror from many smaller glass segments, taking advantage of advances in electronics control systems. Such a composite mirror would require an advanced control system to maintain the proper figure as the telescope pointed to different parts of the sky, and so the angle of the telescope with the gravity vector varied. Advances in electronics and the rapid improvement of computers and their rapid decrease in cost and size would enable designing and building a suitable mirror control system that would keep the 36 segments aligned properly.

After a lengthy study period, there was a shootout between the two designs being studied for a 10m telescope. A "grey beards" committee was set up to choose between the competing concepts for a big UC telescope. Joe Wampler, who had built several very successful instruments for the Lick telescope, was the lead advocate for a monolithic mirror design scaling up from the 5m Palomar telescope. Jerry Nelson was the leader of a small team of his colleagues advocating the segmented mirror approach. Both cost and technical issues were considered.

The "gray beards" committee met in late 1979 and selected the Nelson design. There were of course some hurt feelings on the other side, the full professors of astronomy being beat out by a very junior person at LBNL. With this decision, Jerry was able to attract and pay more people (being very selective of course) to work with him on more detailed studies of the design. An old friend of Jerry's, Terry Mast, who was at Caltech with him and who at that time was working on cosmic-ray physics at LBNL, joined the team to help with the calculations, as once this decision was made, a lot of technical work was required, and Jerry needed more help quickly, and especially help from people who respected and supported him and understood how he worked. Terry Mast was the first recruit; he worked with Jerry for about a year before actually being on the payroll, but soon Jerry was able to get financial support for this work from LBNL through the director's office. That was very convenient to continuing the design efforts before any other funding source could be identified.

Figure 4. Jerry (left) and George Gabor with the segment measurement and control test station at LBL. (Courtesy of W.M. Keck Observatory.)

The rest is history. The major technical issues that had to be overcome involved fabricating the 36 mirror segments (plus a few spares), then polishing each one to the desired surface. Major advances in mirror fabrication and control were required to achieve the desired specifications, which were very challenging. The 36 hexagonal segments, each 1.8 m in diameter, were designed to produce an image from a point source with 80% of the total energy within a circle of diameter only 0.34 arc sec. After passing through the Earth's atmosphere (which introduces turbulence and spreads out the light from a star), the image of a star at the surface of the Earth is, at a good site on a good night, as small as 0.6 arc sec.

A new design for the mirror support system to accommodate a mirror made of many small pieces of glass had to be developed. The mirror support system required exquisite care to maintain the desired figure as the telescope moved to any part of the sky. This necessitated mounting and supporting each segment, producing a metrology system to record the positions of all the mirrors, calculating the required updates in position and tilt for each segment, and then applying the corrections to each segment appropriately. All of this had to be done in a very short time and all of the required hardware had to be on the back or side of each segment, keeping the front clear for light collected by the telescope.

It took years of effort to design and prototype the mounting and support system for the mirrors as well as a metrology system capable of quickly measuring to sufficient accuracy the position of each segment at a given time. Then one needed to calculate the required correction to the position of each segment, and then using the active control system, make the very small but very precise corrections to the location of each segment to implement the required corrections via the active-control system.

The update rate for the positions of the Keck telescope mirrors is twice/second. This all had to be done at the level of nanometers. The small team of three people had to find commercial sensors that were accurate enough and stable enough. This was beyond the performance specs of almost all existing sensors at that time. They bought samples of commercially available hardware to try them out in the lab.

The mirror support system pushed the technology of the time both in speed for a precise measurement, for calculating the required moves, and for implementing the required very small moves (tilt and piston) for each segment of the primary mirror. Fast chips were required to calculate the corrections, and all moves had to be smooth. The team was most worried about smoothness of motions and accuracy of measurements of small motions of 10 nanometers. Vibrations within the system could not be tolerated, and all motions had to be smooth and repeatable at the 10-nanometer level, with minimal temperature sensitivity.

All of this design effort was prototyped before the decision of the “gray beard’s” committee in favor of Nelson’s segmented mirror design, and the small team was very lucky to get the sustained funding they needed from LBL. Funding such an effort through UC Berkeley would have been much more difficult.

The design and fabrication of parts was in full swing by 1979. Key problems included how to make and polish an off-axis mirror, which led to the development by the team of a process they named stressed mirror polishing. Polishing a mirror to shape a sphere is relatively easy, so the scheme was to deform each segment so that its surface was part of a sphere, then polish it, then let the piece relax into the desired non-spherical shape. This technique of stressed mirror polishing was an important key to success, as polishing non-spherical shapes is immensely harder.

Polishing a sphere is straightforward. For Keck mirror segments, the difficulty was figuring out the correct deformation to apply before the polishing began so that after the stressed mirror is polished and relaxes, the desired shape emerges. If all this can be made to work, the polished mirror will then relax into the desired surface when the constraining hardware is removed. Jacob Lubliner, a professor of engineering at UC Berkeley, was recruited to develop the equations of elasticity that made this process successful. LBL provided funds to build a stressing jig and polish a (much smaller) segment to demonstrate the feasibility of stressed mirror polishing.

With the positive decision from the “grey beards” committee, UC started funding Nelson’s team. He was given several million dollars for a technical demonstration that would produce and control a single segment. Serious fundraising for a UC telescope started, involving high-level UC management. The estimated price at that time (1983) was $50 million dollars. A potential donor, Marion O. Hoffman, offered $50 million dollars for telescope to be named after her husband, Max, but this was not quite enough. There were issues with her family, and UC would have to raise the rest. Mrs. Hoffman died before signing papers for the gift. Meanwhile UC tried to identify additional potential funders, but this was difficult for them to do, being a state-supported institution. To help close the budget issues, they invited Caltech to become a 20% partner. This led to a vigorous internal debate within Caltech, as Roger Angel with his spin-cast 8m mirrors was also a potential partner for Caltech. The Caltech faculty decided in favor of the segmented mirror design.

Meanwhile, the Caltech president began looking for a funder so they could join the UC 10m telescope project. Howard Keck, a very wealthy Caltech benefactor, was interested in the project and willing to provide substantial funding for a telescope for Caltech. Once the “first light” image demonstrated that the segmented mirror technology worked, the Keck Foundation provided 80% of the funds to build the second telescope. UC paid all of the operating expenses for the Keck Observatory until the contributions by Caltech and UC were equal, after which they were split equally between Caltech and UC.

Towards the end of the construction phase, it became clear that there would be a significant cost overrun. To solve this problem, NASA was approached and agreed to join at the 20% level, subject to periodic renewals. The funding shortage towards the end of construction was brutal and made the task of trying to finish the suite of first light instruments, then test and install them on telescope, very difficult for those people, including the author of this memoir. The total cost of the project was approximately $95 million dollars for a single telescope in 1990 dollars.

One of the key vendors for the Keck Telescope project was ITEK, a large commercial optics company with headquarters in Lexington, Massachusetts. There were only one or maybe two commercial companies in the United States with equipment capable of fabricating the Keck mirrors; ITEK was chosen. There were many problems in dealing with ITEK. From the point of view of the project, they were expensive, inflexible, and used to working with government contracts, among other things. At ITEK, the team leaders and best engineers tended to disappear once the contract was signed. ITEK was used to working with defense contractors with lots of money, not "poor" university groups. To maintain progress while not compromising quality or accuracy, Jerry moved to ITEK for a summer. The new glass Zerodur, developed by Schott Glass in Germany, was adopted for this project because of its very low coeffecient of thermal expansion.

The mode of operation Nelson adopted was to first build and test a prototype at Tinsley Optics, a small more research-oriented optics company located very close to Berkeley that was less formal and much cheaper than ITEK. The cutting of the mirrors, which were polished as round pieces, later to be cut into hexagons, caused a small amount of warping and other very low-level problems with the mirror surface. So another process was needed and had to be developed to remove these small undesired effects. The required corrections were very small, but too big to be ignored, and were implemented by a process called ion figuring, that is, firing high-energy atoms at the small patches of area on the mirror surface as required and blasting away very small quantities of glass in each of the N sectors of the mirror surface. Just making the map of departures of each sector of a single mirror was time consuming; one had to calculate the departure of the actual mirror from the desired surface as a function of position, then translate that into how much material had to be blasted at a given area to achieve the final desired surface. All of this had to be computer-controlled and carried out in a vacuum. To achieve the desired surfaces of each segment required further processing. New procedures to give the final tweak to each part of each segment (stressed mirror polishing, ion polishing, and warping harnesses) were developed by the team in order to meet the very tight specifications for the mirror surfaces. ITEK, Kodak, and Tinsley were all heavily involved in developing the processes to produce and test the mirrors.

The mirror support system was also crucial. Each mirror needed to be at the proper position (a function of elevation) to maintain the desired very small image size. They needed to be held stiffly but not overly constrained. They could only be supported from their back (non-reflective) side.

Meanwhile Gary Chanan, another key member of Nelson's team, started thinking about how to make sure the fully assembled mirror, with its N segments as mounted on the telescope, was as close to the desired figure as possible irrespective of where on the sky the desired field for observations was located. The mirror support system had to have sophisticated control algorithms that took into account the telescope pointing. This system is called the ACS (active control system). It was designed using the fastest available (at that time) hardware with the best performance (a compromise between most accurate positioning on the sky and speed of motion of the telescope required to track a star, which is a function of where the star is on the sky). The hardware originally had a MicroVax running the telescope control code, with one microprocessor per segment. The team designed it, purchased the parts, coded the controls, and tested it extensively.

Gerry Smith, the Keck project manager, had substantial experience on big projects, having previously been involved in military projects; he worked as a project manager for the Jet Propulsion Lab prior to becoming the project manager for the Keck Telescope project. He was responsible for allocating labor and funds, maintaining the schedule, and many other duties. There was a constant low level (and sometimes high) of conflict between Nelson and Smith regarding when is each component could be considered "good enough," because trying to make it "perfect" would break the budget.

Figure 5. Keck 1 and 2 Telescopes, December 2007. (Courtesy of Laurie Hatch.)

ITEK (and to a lesser degree Gerry Smith) were used to working with Department of Defense customers. They did not accept Keck people (including Nelson and sometimes Smith, too) as knowing more than ITEK engineers. They did not take schedules seriously and were not used to working according to a schedule. There were very large cost overruns, and this led to tension between Jerry Nelson and Gerry Smith, with the latter trying to adhere to the schedule and budget and the former trying to reach the best possible performance.

The telescope structural design was led by Steve Medwadowski, at that time a professor in the engineering department at UC Berkeley. He needed to keep the total telescope weight as low as possible while not allowing any undesired motions. Once construction started in 1990, Jerry and his family moved to Hawaii. They lived in the small town of Waimea, the location of the Keck headquarters in Hawaii, for five years, to maintain close contact with ongoing issues. Terry Mast, Jerry's right-hand man, also moved to Hawaii with his family.

Jerry became active in a local ocean swimming group that would venture offshore with a small boat following, and people would rotate time on the boat and in the water. His two children attended the Hawaii Preparatory Academy in Wiamea, an excellent private school. After a long illness, Jerry's wife Victoria died of kidney problems in 1992. In 1994, he married Jocelyn Torricelli, whom he met while on vacation in Costa Rica. She was there on a diving trip and lived in Texas at that time.

After Keck 1 became operational, Jerry returned to California to become a professor of astronomy at the University of California in Santa Cruz. While he kept a watchful eye on the erection of the second Keck telescope, his full-time presence in Hawaii was no longer necessary. Jerry became the founding director of the newly created Center for Adaptive Optics at Santa Cruz. Terry Mast joined Jerry at Santa Cruz and returned to his previous position as a research physicist. Jerry continued to advise the Keck Science Steering Committee and the Keck Observatory director on many technical issues. He also began to think deeply about how to build a 30m telescope (TMT), a project that was in its nascent stages. Gary Sanders was the project manager, with Jerry Nelson, who provided early conceptual designs, as project scientist.

Jerry had also become interested in a new area now possible with the exquisite performance of the mirror control system of the Keck telescopes. The image of a point source (a star, for example) is perturbed (blurred) as the light from the star passes through the turbulence within the Earth's atmosphere, whose temperature and winds vary with time, location, and height above the ground. Adaptive optics attempts to correct for and remove or minimize these small distortions, resulting in the image of a point source becoming smaller with better spatial resolution. Fast electronics and fast detectors and fast computers enable one to do this.

A large effort to develop these techniques, which have many uses beyond astronomy, including analysis of medical images, was undertaken at UCSC with support from a major ten-year National Science Foundation grant to establish the Science and

Technology Center for Adaptive Optics, with Nelson as its founding director. Use of these techniques was crucial to many observational projects at Keck, including the study of the region of the center of our galaxy by Andrea Ghez of UCLA, which led to the Nobel Prize in physics (shared with Roger Penrose and Reinhard Genzel) in 2020. In addition, Nelson continued to advise the Keck Science Steering Committee and the Keck Observatory director on many technical issues. Also Jerry became heavily involved in discussions about the possibility of building a 30m telescope by Caltech and UC, with exploration of the project beginning in 2004. Jerry provided early conceptual designs. Gary Sanders was the project manager; he had extensive experience in managing such large-scale projects.

The great success of the Keck Telescope was widely noticed, and there was interest on the part of a very wealthy Caltech trustee in providing substantial seed funding for a 30m telescope. At that time a very rough estimate of the budget to build such a telescope was about $400 million. But the projected budget kept rising, more partners had to be found, and to date (now seventeen years later), the funding and the start of construction are not clear, and there are many issues involving the site that must be resolved before construction could start.

In 2011, Nelson had a serious stroke and was paralyzed on his right side. He only retained control of one finger and his voice was very low. His ability to work was substantially constrained, but he kept thinking about how to improve the performance of the telescopes and related issues as best he could. The author visited him at his office in the Center for Adaptive Optics whenever she was in Santa Cruz; it was always a pleasure to talk about what he was working on, but after his stroke it was depressing to watch him struggle to speak. Giving public talks and traveling became extremely difficult for him. He died in 2017.

Awards and Honors

2012	Benjamin Franklin Medal in Electrical Engineering, Franklin Institute
2010	Kavli Prize for Outstanding Contributions in Astrophysics, The Kavli Foundation, Norwegian Ministry of Education and Research
2010	Foreign Member, Norwegian Academy of Sciences and Letters
2009	Sackler Lecture, Leiden Observatory, the Netherlands

1998	Fellow, Society of Photo-Optical Instrumentation Engineers
1998	Grand Prix Andre Lallemand, French Academy of Sciences
1996	Member, National Academy of Sciences
1995	Joseph Fraunhofer Award/Robert M Burley Prize, Optical Society of America
1995	Dannie Heineman Prize for Astrophysics, American Astronomical Society
1995	Distinguished Alumni Award, California Institute of Technology
1994	George W. Goddard Award, Society of Photo-Optical Instrumentation Engineers
1993	Discover Award, “Sight: Mirror Makers” *Discover* magazine

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