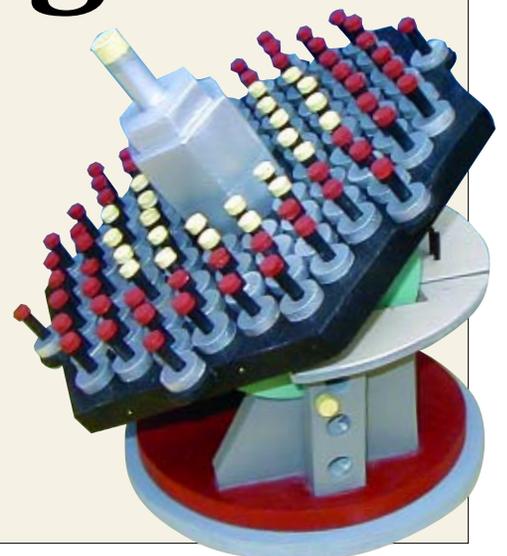




Extremely Large Sparse Aperture Telescopes

A Chevy Instead of a Mercedes?

Aden and Marjorie Meinel



Several astronomical groups are proposing telescopes ranging from 30 to 100 meters diameter. Interesting design options have been developed. The big challenge, however, will be to find the resources to build such extremely large telescopes. Even these preliminary designs may require more innovation to successfully compete for funding in view of the many demands on the funding agencies.

A telescope using a single large segmented mirror is the ideal. Is a sparsely filled aperture an acceptable way to reduce cost? If so, can it meet scientific requirements well enough to satisfy the expectations of astronomers? And can it be done at a cost within the confines of today's economic constraints?

The 10-meter Keck telescope (Mauna Kea, Hawaii) has successfully demonstrated innovative technology at a cost considerably below that of a more conventional telescope. The Multiple Mirror Telescope (MMT) on Mt. Hopkins demonstrated another way to build a larger telescope with available funding: its designers used a sparsely filled aperture to yield the performance of a larger telescope. Below we discuss an evolution of the MMT option.

The designers of the MMT solved a problem that often constitutes the major hurdle to building a large telescope. The cost of a 6.5-meter monolith was considerably beyond the funding available to the Smithsonian Astrophysical Observatory (SAO) and the University of Arizona (UA). The door was opened when the United States Air Force (USAF) gave seven 1.8-meter lightweight telescope mirrors to the University of Arizona. A team from SAO and the UA Optical Sciences Center decided that these mirrors could be combined as independent telescopes on a common mounting. The outer diameter of the cluster would yield the resolution of a 6.5-meter telescope while the mirror area would be the equivalent of a filled aperture of 4.5 meters.

Some doubts were raised by critical reviewers about the possibility of controlling six independent small telescopes well

Concepts for the next generation of extremely large telescopes are being studied by national and international consortia. The ideal would be a filled aperture telescope, either a monolith or one consisting of closely packed segments. But the reality of diminishing fiscal resources presents new challenges.

What about a sparse or almost-filled aperture telescope? Could it meet the requirements of scientists at lower cost?

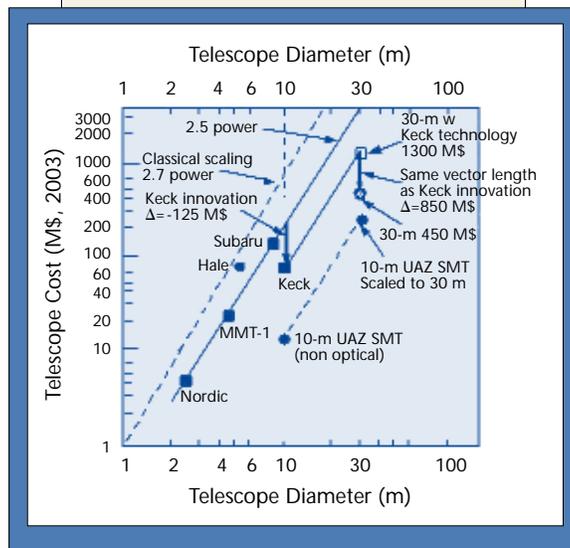


Figure 1. Cost vs. diameter statistics for existing and future telescopes that show how innovation can lower the cost of advanced telescopes below the trend line of today's telescopes.

enough to meet the requirements of astronomers. In view of these doubts, the National Science Foundation (NSF) declined to participate in the MMT's construction. After it was built, however, astronomers made much use of the novel MMT, including phasing the six separate outrigger telescopes.

Before we discuss specific telescope configuration options, it's important to look at how the cost of a telescope depends on the diameter of the primary mirror. The general trends of cost vs. diameter for several classes are shown in Fig. 1. The slope of the cost line follows a 2.7 power relationship for telescopes built in the first half of the 20th century. Considerable engineering innovation lowered the cost relationship to the 2.5 power for the more advanced telescopes. The points for the Nordic, the MMT and the Subaru define this line.

The cost of the 10-meter Keck telescope was considerably below the 2.5 power line, as shown in Fig. 1. This result was achieved thanks to a series of innovations by Jerry Nelson and his team. The vertical arrow indicates the effect of the innovations on the cost. As shown by the arrow, innovation reduced the cost by \$125 million.

If we now extrapolate the 2.5 power slope through the Keck point up to 30 meters in diameter, we see that such a telescope would cost \$1.3 billion. The cost target for a 30-meter telescope has not been firmly established, but it may be about \$450 million. In other words, \$850 million of innovation is required to reach the target. The challenge is to discover additional innovations that can reduce the cost. The best telescope engineers around the world are seeking the answer. The final choice may not look like any existing or proposed telescope.

Figure 1 shows only part of the problem. A multi-conjugate adaptive optical (MCAO) system and multiple artificial laser stars are essential to diffraction-limited performance of a terrestrial telescope. Although various concepts are being developed, a complete MCAO has yet to be demonstrated on a large telescope. We all await this milestone

demonstration. The cost of an MCAO could reach \$100 million to \$200 million. This cost is not included in the cost scaling relationship graph shown in Fig. 1.

The structural philosophy behind 30-meter class millimeter wave telescopes could be adapted for optical telescopes. For example, if one were to scale up the 10-meter University of Arizona Submillimeter Telescope concept to 30 meters it would have a probable cost of about \$200 million. But millimeter wave telescopes do not have the wave-front precision or stability required of an optical telescope. Perhaps such a low cost, lightweight structure could be made active so that the time-dependent perturbations could be removed and a MCAO subsystem could finish the job.

Sparse aperture telescopes

Can a sparsely filled aperture telescope be an option that should be given consideration for the 30- to 100-meter class optical telescopes? Several years ago at JPL we were on a team that explored the characteristics of sparsely filled aperture telescopes. The goal was to reduce the cost of a 100-meter space telescope for exosolar system planet studies.

Sparse aperture options

Several concepts emerged from this study, as reported by Meinel and Meinel.² The first was to make the telescope a standard Cassegrain but with a sparse array of sub-apertures. The array having fewest apertures yet the same resolution as a filled aperture is a Golyay non-redundant configuration. The second concept was to equi-space all the apertures around a single ring and combine them into a Cass telescope. The Golyay-Cass requires different off-axis sections of a conic, but for a ring configuration all off-axis segments are identical.

The third concept was to make each of the individual apertures a separate small Cassegrain telescope. Each of these “outrigger” telescopes sends a collimated beam to a central beam combiner. Since the resulting telescope was

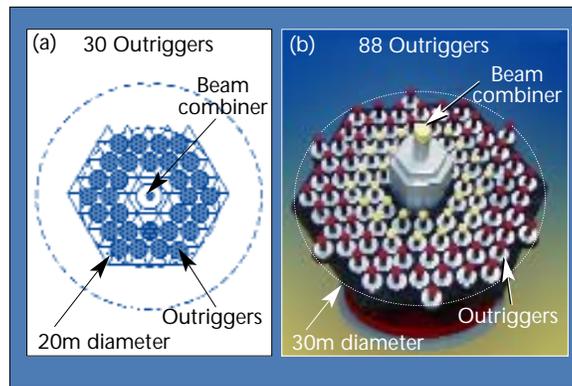


Figure 2. The first phase of a 30-meter sparse aperture telescope could be a 20-meter telescope (a) that could later be increased to 30 meters (b).

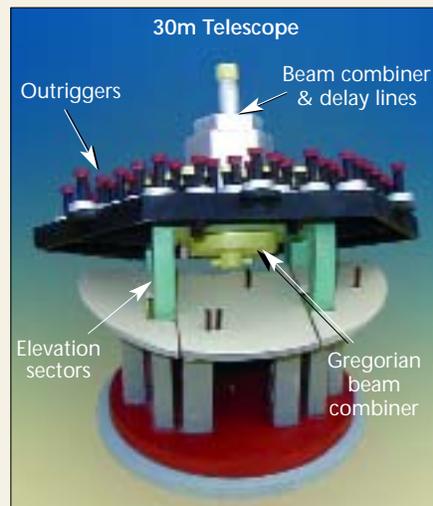


Figure 3. Elevation section through the 30-meter Discus sparse aperture telescope.

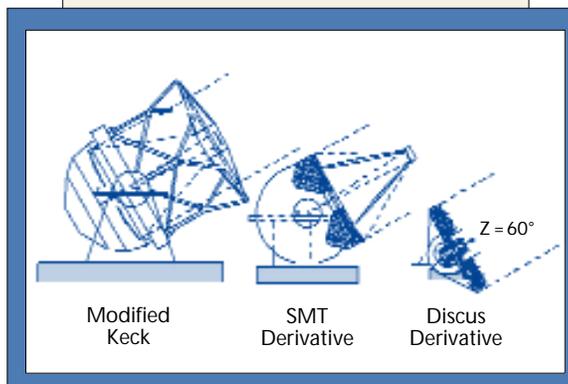


Figure 4. Comparison of the general appearance of three basic telescope configurations illustrating the relative size of each one as well as the size of an enclosure.

flat relative to the system diameter, it was given the name “Discus.”

Increased integration time

An issue in a sparse aperture is a loss of light-gathering ability. A more serious problem is that this smaller amount of energy is spread over a larger area than is the diffraction image from a filled aperture. The result is that one must increase integration time to yield a signal-to-noise ratio (snr) equal to that of a filled aperture.

The computer studies performed at JPL confirmed the original conjecture and subsequent derivation by Fienup that the added integration time is approximately the cube of the inverse sparseness ratio. Few astronomers would be happy with this large an increase in integration time. However, when the cost of an extremely large telescope exceeds fiscal resources it may be necessary to accept some increase in integration time in exchange for the resolution of a very large aperture.

The Golyay non-redundant configurations can yield the maximum resolution for the fewest apertures. Their main problem is that the fraction of the energy in the central maximum in the ring and the Golyay is only a few percent. This means a large amount of power is diffracted into the outer diffraction pattern so that long integrations are required to gain enough snr for image processing to reconstruct the scene as if it had been formed by a filled aperture. For the Golyay 12-aperture configuration, the integration time is 2,210 times that of a filled aperture of the same diameter. This brings us to our current thoughts.

Almost-filled apertures

We explored cases in which the aperture is almost fully filled with a multiplicity of small, independent, “outrigger” telescopes. The goal is to minimize the added integration time and use small Cass outriggers to achieve a large, but low cost, telescope. Suppose that a telescope could be constructed in two phases. The first phase of a 30-meter telescope could be a

20-meter telescope having 30 2.4-meter outrigger telescopes as shown in Fig. 2(a). The integration time increase would be a factor of 12. The final 30-meter telescope would have 88 2.4-meter outriggers in five rings [Fig. 2(b)]. The integration time increase would be a factor of 5.6.

The elevation view in cross-section through the 30-meter diameter telescope in Fig. 3 shows why this configuration was called the Discus.

The 2.4-meter diameter for the outrigger telescopes was selected for practical reasons. Manufacturing and testing facilities exist for a 2.4-meter mirror, which is the diameter of the Hubble Space Telescope (HST) and a number of other space telescopes. Measurement and control of tip, tilt and phasing are required for each of the 88 outrigger telescopes. If the Keck technology were scaled up to a 30-meter telescope, the number of segments could reach or exceed 1,000, each one an off-axis segment of an asphere. Measurement and control of tip, tilt and phasing are required for each of the 1,000 segments. The phasing subsystem for 88 outriggers should be less than for 1,000 segments. But is that gain significant when innovative technology must be found to achieve a cost reduction of \$850 million?

Comparative configurations

Figure 4 shows a comparison of the probable profile of a Keck derivative, a segmented mirror telescope (SMT) derivative and a Discus. This figure also emphasizes that the size of a protective enclosure can be significantly different. A new philosophy regarding shelter is evolving for the 30-meter and 100-meter class telescopes, assuming that a suitable low wind site can be found. But again, is this innovation enough to decrease the cost of a 30-meter telescope by \$850 million? Can combining a number of modest innovations make a significant gain on this large cost? This remains to be seen.

Closing thoughts

We have scaled up the technology advances of the 10-meter Keck Telescope along the 2.5 power cost/aperture trend



Meet Aden and Marjorie Meinel

Aden Meinel received his bachelor's degree in 1947 and his doctoral degree in astronomy in 1949 from the University of California, Berkeley. He received an honorary doctor of science degree in 1990 from the University of Arizona. He was associate director of the Yerkes and McDonald Observatories and the founding director of the Kitt Peak National Observatory. At the University of Arizona, he chaired the astronomy department and also was director of the Steward Observatory and the founding director of the Optical Sciences Center located in the Meinel Building. After retiring from the university in 1985, he was named a distinguished scientist at the Jet Propulsion Laboratory (JPL), California Institute of Technology. Since retiring again in 1992, he has served as a NASA senior scientist at JPL.

Marjorie Meinel received her bachelor's degree in astronomy in 1943 from Pomona College and her master's degree in astronomy from Claremont College in 1944. That year she began her career as a research associate at the California Institute of Technology on the Navy rocket project. At the end of World War II, she and Aden began their family of seven children. In 1971, when she resumed work, she became a research associate at the Optical Sciences Center, University of Arizona. In 1985, she became a member of the technical staff, JPL, California Institute of Technology. Since retiring in 1992, she has served as a NASA senior engineer at JPL.

line to apply to a 30-meter telescope. This extrapolation indicates a probable cost would be \$1.3 billion. While the cost of extremely large telescopes will be high compared to that of the largest current telescopes, it would be many times less than if they were in space.

The chill of the present economic climate is a reality to be faced by those developing proposals for very large science projects. Although to build a \$1.3 billion telescope an international consortium may be required, a cost of \$450 million may be within reach of national funding. But where

can innovations beyond the Keck technology be found in order to lower the cost by \$850 million?

There is a further challenge to keeping the cost affordable. A major reason for having 30- to 100-meter class telescopes is to be able to obtain the same high-resolution imagery as is possible with a telescope operating in space. This high resolution can be closely approximated by cancelling the aspheric blurr by means of a multi-conjugate adaptive optics system plus seven separate laser reference stars. Such an MCAO system could add \$100 million to \$200 million to the cost of the telescope.

With regard to the Discus concept, it too may fall short of the 30-meter telescope cost goal. If so, a 20-meter Discus might be affordable if it began with two rings of outrigger modules, additional rings being added as funding became available. For a fuller presentation of this topic see Meinel and Meinel.²

Is it time to think about a novel telescope that could grow with time? Or, if a more conventional telescope is to be, will there be enough compromises within the science requirements to reach an affordable cost? A Chevy instead of a Mercedes?

Aden and Marjorie Meinel can be reached at ameinel@earthlink.net.

References

1. A. B. Meinel and M. P. Meinel, "Large sparse-aperture space optical systems," *Opt. Eng.* **41**, 1983 (2002).
2. A. B. Meinel and M. P. Meinel, "Sparse Aperture Telescopes for Extremely Large Telescopes" *Appl. Opt.* (submitted).