Optical Design and Fabrication for an Extremely Large Telescope
Optics Working Group
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[*Note: this summary addressed the GSMT point design and did not consider other concepts such as multiple-mirror telescopes (MMTs) or interferometric arrays*.]

It is clear that any telescope much larger than 8-meters in diameter will have a segmented primary mirror. The difficulty and cost of fabricating, polishing, transporting and coating large mirrors increase rapidly above that size.

Three large segmented-mirror telescopes already exist -- Keck I, Keck II and Hobby Eberly. Others are in work or have been proposed, including the Gran Telescopio CANARIAS (GTC), the Large Aperture Multi-Object Spectroscopic Telescope (LAMOST), the Mexican Infrared-Optical Telescope (TIM) and the Southern African Large Telescope (SALT). These projects serve as the starting point for the design of any extremely large telescope.

One of the design issues that may drive the entire telescope design is wind buffeting. The deflection of a telescope in the 30-100 meter range under ordinary gusts of wind will be many wavelengths of light. This could be reduced by an enclosure with minimal openings, for example one similar to a scaled up Keck dome, but such an enclosure would be relatively expensive and may introduce local seeing problems. A trade study will be needed to balance the cost and performance factors among the telescope structure, the active and adaptive optics systems, and the enclosure design.

The fundamental resonant frequency of a telescope in the 30-100 meter range will be at or below 1 Hz. To avoid exciting resonances of the telescope structure, the active alignment system of the primary mirror should be operated at a relatively low frequency. A typical wind-buffeting spectrum has significant energy up to a few Hz. On such a large structure, it is likely the wind will be able to deflect mirror segments by optically significant amounts at frequencies that cannot be well corrected by the active optics system.

In addition to quasi-static deflections, the wind could excite resonances in the structure that have large dynamic amplification factors. Therefore, it is very important to characterize the wind spectrum in terms of spatial and temporal variations of pressure, to characterize the input for structural analysis.

To produce diffraction-limited images in the near infrared with a telescope larger than 30 meters will require not only an advanced (possibly active) structural design and an active optics system, but also an effective adaptive optics system. It is important that the active optics and adaptive optics systems complement each other. The two systems will share responsibilities according to bandwidth:

Active optics (low bandwidth)
- Segment position control
- Segment figure correction
- Position control for secondary and tertiary mirrors
- Figure control for secondary and tertiary mirrors

Adaptive optics (high bandwidth)
- Image stabilization
- Atmospheric compensation
- Correction of local seeing effects
- Fast correction of mirror figure errors

The active optics will likely include a hierarchical system of actuators to keep the primary mirror segments in position and to maintain the position of the secondary mirror relative to the primary. There will be relatively coarse actuators with a range of tens of millimeters to compensate for gravity sag and thermal

distortion of the telescope structure, and finer actuators with a resolution of a few nanometers for precise segment alignment. In addition, each large mirror will have figure control actuators to maintain its optical shape and possibly to make adjustments to compensate for other factors such as the change in radial position of segments due to thermal expansion of the telescope structure. These figure control systems will likely be needed on each primary mirror segment, on the secondary mirror and probably on other mirrors in the system (tertiary, quaternary, etc).

The adaptive optics system will compensate image motion and atmospheric distortions, but will probably also need to compensate for local seeing effects and dynamic distortion of the primary mirror. The secondary and tertiary mirrors may form part of the adaptive optics system with fast tilt and/or fast figure control capabilities. If these mirrors are made adaptive, this would extend their "active optics" capabilities described above into higher bandwidths.

The telescope structural design will depend, in part, on the size of the primary mirror segments, since each will need to be supported rigidly. Preliminary discussions with blank fabricators and optical finishers indicate the finished cost of segments will hit a cost break point above about the 2-meter size, that is, the cost will jump significantly higher as the segment size increases above this range.

Per square meter, the primary mirror of the Hobby-Eberly Telescope was an order of magnitude less expensive than the Keck primary. There were several reasons for this cost savings including the simplified support system made possible by the fixed gravity orientation, however one of the key differences was that the spherical HET segments were polished on a continuous polishing (CP) machine (sometimes called a planetary polishing machine). Optical finishers have given us estimates that the cost of polishing segments on a CP machine would be about a factor of five lower than the cost of finishing mirrors on the type of traditional machine used for polishing telescope mirrors. Continuous polishers are normally used to make flat mirrors and optical windows, but they can also be set up to produce long-radius spherical mirrors.

The CP machine needs to be ~ 4 times the diameter of the optic produced, and the practical size for segments finished this way will be below about 2.5 meters. Another promising technique for producing low-cost finished surfaces, replication from a master optical surface, is also limited by practical constraints to a similar size range. Similarly, the largest existing facility for ion figuring is 2.5 meters diameter.

Several other factors also favor segments no larger than about 2 meters. Transportation costs increase by an order of magnitude once the size of the mirrors, in their shipping crates, exceeds the size that can be shipped in a standard container (~2.5 m). The cost (per square meter) of glass mirror blanks and the cost of the mirror handling equipment and the coating facility also increase above this range. And if alternative materials such as silicon carbide or beryllium are required it may be difficult or impossible to obtain satisfactory blanks larger than 1.5 to 2 meters.

On the other hand, as the segment size gets smaller the telescope structure must have a greater density of rigid mounting points, and the number of mirror position sensors and alignment actuators increases. Both of these will increase cost. The number of sensors and actuators will also have a strong impact on the reliability of the system.

Preliminary estimates indicate the optimum segment size is probably in the 1-2 meter range. The size and capacity of existing fabrication equipment is not an issue, because for the number of segments needed by an ELT a dedicated facility will almost certainly be required. The cost to equip it with custom machines can be amortized over hundreds of segments.

One of the key factors in the design of the telescope optics is the decision whether the primary mirror must be spherical. Low-cost optical fabrication techniques such as planetary polishing and replication favor spherical optics. Fixed-elevation telescope designs such as the Hobby-Eberly Telescope also use a spherical primary. For steerable telescopes, however, the optical design can provide better performance with fewer elements if the primary mirror is aspherical. The choice between spherical or aspherical primary mirror will affect the number, size and placement of the other mirrors in the system, which will drive the telescope structural design. Therefore, this decision should be made as early as possible in the

development effort. The choice will depend, in large part, on the feasibility of extending low-cost polishing techniques to the production of aspherical mirrors.

Before the optical design can progress beyond the what-if stage, the requirements for the science instruments must be defined. We need strawman instrument designs that will define the needs of the science instruments regarding:
- Focal ratio
- Field of view
- Physical size of focal plane
- Image quality
- Curvature of field
- Control of distortion
- Emissivity
- Control of stray light
- Photometric stability
- Location and size of instruments
- Number of instruments that must be available simultaneously

These factors must be defined for each category of instrument interface, as described in the section on instruments.

It is not necessary at this point to design every possible type of instrument. However, we need to divide the anticipated instruments into classes having similar requirements and then develop the design of a typical member of each class, at least to a point where the requirements on the telescope optical system are understood.