Giant Optical Devices

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Introduction

There is currently great excitement and enthusiasm for building a giant telescope. In this paper we assess the alternatives and bring together some history and experience to help guide us to a successful telescope. We briefly review possible telescope configurations and then review the history of telescope building, with the goal of gaining insight into the appropriate size for the next generation telescope, and the time scale likely to be involved. We briefly review the major scaling laws for materials to provide some insight into the likely difficulties in building larger optical telescopes. Sensitivities for very large telescopes are given, as a succinct guide to the scientific potential of larger telescopes. We then review some factors that influence the design, cost and schedule of a telescope project. Since Adaptive Optics (AO) is likely to be a key ingredient in the next generation of telescopes, we also review the major scaling laws for AO, to indicate the difficulty of AO for giant telescopes. We end with a strawman design concept for a 25 m telescope, indicating some ideas that may make such a telescope much more cost effective than the 10 m segmented Keck Telescopes, the world's largest telescopes.

Filled Versus Unfilled Apertures and Arrays

We first consider the different kinds of telescope configurations; including filled apertures, unfilled apertures on a common mount, and independent arrays of telescopes.

Filled apertures have the advantages of the being most compact, hence typically the least expensive per m^2. They also have the greatest sensitivity for detecting faint objects, the simplest science instruments, and the largest potential field of view. For these reasons we will shortly narrow our discussions to this kind of telescope.

Unfilled apertures on a common mount, such as the Large Binocular Telescope (LBT), bring advantages in angular resolution, at some expense of increased size for the telescope and enclosure. These open apertures generally have more complex diffraction-limited images with both a smaller core and a broader extent of the over all image. In addition, thermal backgrounds are typically larger or more difficult to reduce due to the more complex pupil shape.

Arrays of independent telescopes have the capability of providing the highest angular resolution with their large baselines. The telescope structures are relatively small and simple, but to bring all the light together coherently requires exacting optical compensation that is complex and expensive. In addition, interferometric arrays generally have a field of view bounded by the diffraction-limited image from a single element of the array. Incoherent addition of signals is much simpler, but then the angular resolution advantage is lost. Tradeoffs are difficult, but generally arrays bring greater angular resolution, less sensitivity, and greater cost than filled arrays. In addition, minimizing thermal backgrounds is more difficult.

We assume here that cost will drive the designs to the most compact configurations (filled apertures) and that the diffraction-limited angular resolution of such a telescope will be sufficiently useful to justify the telescope, without the need (or advantages) for the greater angular resolution of arrays.

The Lessons of History

The long term history of telescopes is shown in Figure 1. We plot the largest telescope size as a function of time, showing the specific telescopes built. Lens and mirrored telescopes are shown separately. The human eye sets the scale, and is shown at the bottom of the vertical log scale. The general trend upwards is clear and in fact the progress over the centuries shows a remarkably exponential growth over 400 years from the time of Galileo to the present. Explanation of such growth is difficult and may be due to a variety of social, economic, and technical factors, but the empirical result is clear. Over the last 100 years the details of telescope projects are better known (costs, technical aspects, scientific interests, etc), but the result is the same exponential growth. The e-folding time of the largest diameter is about 45 years.

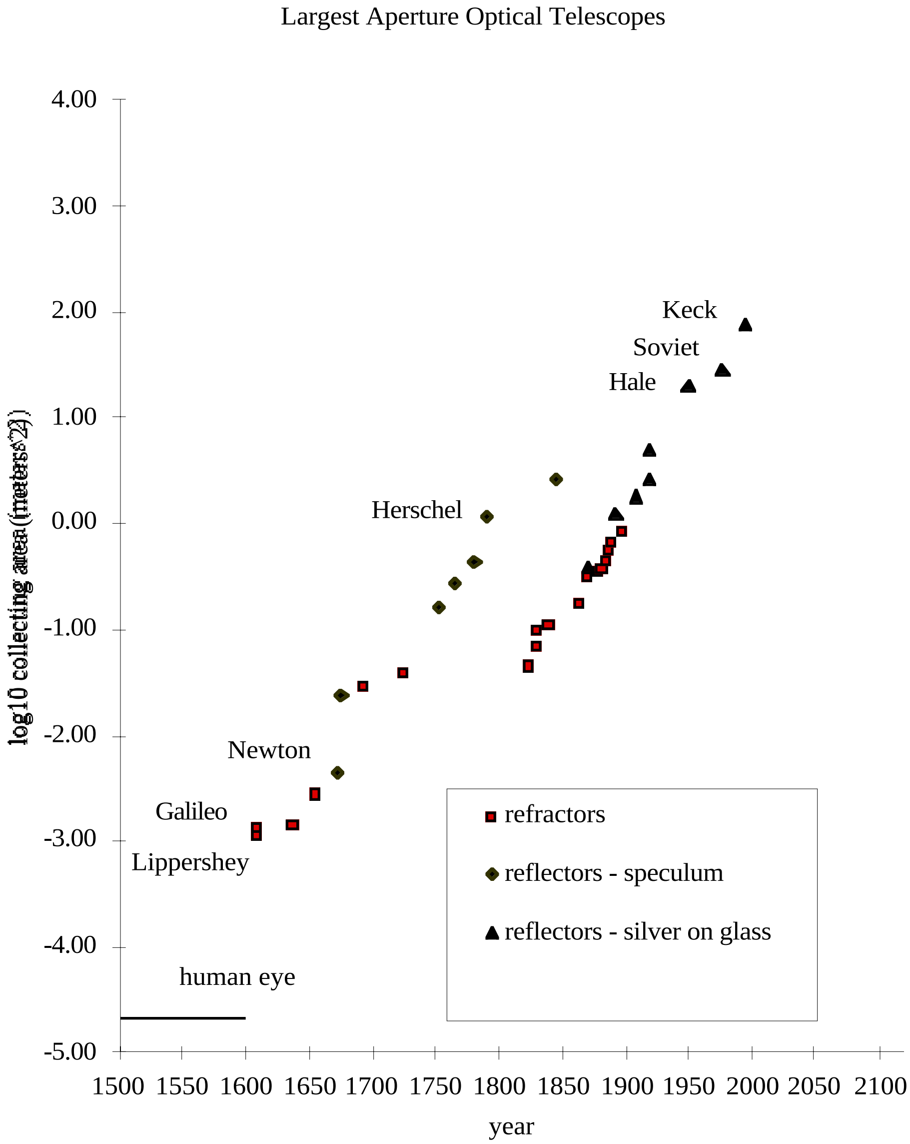

Figure 1.

Extrapolating this growth rate from the Keck 10 m telescope suggests

10 m	1993
25 m	2034
50 m	2065
100 m	2097

Of course history does not explain how one will achieve any future growth in telescope size or why one should expect exponential growth at the historically established rate. Nonetheless, given the obvious value of larger telescopes to most telescope builders and users, it must be assumed that the size is set by inability at that time to make larger telescopes. The historical record provides a cautionary precedent rather than an imperative. As we seek to increase telescope size we will be wise to have some humility and respect for the lessons of history, in spite of their lack of logical justification.

Another lesson of history can be extracted from the historical record. The maximum single step size seems to be roughly a factor of two in diameter:

1.5 m	1908
2.5 m	1918
5 m	1948
10 m	1993

Further, the project duration is typically ≥15 years, with a period of research and development ~ 5 years and a construction period of ~ 10 years.

Of course our task as telescope builders is not to follow history but to make it, so we should be inventive and bold, but not ignorant of the history of our field.

Predicting the Future

During the late 1970's an engineering group at Kitt Peak National Observatory carried out a series of design studies for a 25 m telescope, and worked out many engineering details for these designs. (NGT Reports,1977) They concluded that several designs were feasible and within their technological reach. Their studies included a steerable dish, a multi-telescope telescope (like the MMT built in the 1970's), a spherical primary (the "shoe"), a protected and gravity-invariant parabolic primary fed by a steerable flat mirror (the mailbox), and singles arrays of 6x10 m telescopes and 100x2.5 m telescopes. However, they were not within our cost reach or astronomical imperative, and lack of astronomical support brought this effort to an end. Most of these designs involved segmented optics that were then considered risky and untested.

Today we see an extremely ambitious space telescope, NGST, (Seery & Smith,1998) being designed by NASA and planned for launch in 2007. This 8 m, cooled (40°K) telescope is to be placed at the L2 Lagrangian point in orbit around the sun. When completed this telescope will work in the 1-5 μm range and with its diffraction-limited image quality and very low thermal background, be a truly formidable telescope. Potential ground-based telescopes are now forced to compete against this project. Thus the history suggesting a 20 m telescope as a suitable next step is challenged. Although this telescope does not exist, NASA is proceeding in a very serious way, identifying potential technical and cost problems and attacking and solving them in impressive fashion. Size increase, cryogenic operation, deployment into an orbit 10^6 km from Earth, extremely demanding IR detectors, are all being addressed in an impressive fashion. A ground-based telescope designer must not ignore the future potential of the NGST in justifying a large ground-based telescope.

In the last 1-2 years an ambitious and imaginative group at ESO has suggested that a 100 m ground-based telescope can be built (Gilmozzi etal, 1998). This potential future telescope also has the effect of tilting the playing field towards extremely large telescopes. Such a telescope will require significant improvements and innovations in mass production of segments, possibly exotic optical configurations with a spherical primary, structural design, active control systems, and enclosure/weather protection, to say nothing of truly enormous steps in adaptive optics.

History and experience suggest that such large steps bring significant risks and/or excess costs. Somewhat smaller steps on the ground may lead to much shorter completion times, and much more economical telescopes, as lessons learned on one scale are applied to the next. As an example, using the empirical scaling law that for a given design family the telescope cost varies as $D^{2.5}$, one concludes that a 100 m telescope could be built for \$1B and a 25 m telescope could be build for \$30M. Since it could surely be built much more quickly than a 100 m, such an intermediate step at worst costs a negligible fraction of a 100 m and causes a modest increase in overall schedule. On the positive side, such an intermediate telescope will probably lead to design and fabrication improvements that will significantly reduce the cost and risk of a 100 m telescope. It will also brings an extremely powerful telescope into the hands of astronomers at an early date, and provides very useful experience in assessing the astronomical problems such monsters are suited for and what instruments should be built for them.

Scaling Laws

It is interesting to understand, at least crudely, the impact of changes in size on various aspects of the performance of a telescope structure. We define the scale size by S. We simply summarize a few results without deriving them.

Deflections due to gravity driven by self weight scale $\delta \sim S^2$. We assume that all dimensions have been scaled by S. Deflections driven by a fixed load/m^2 on a structure, such as thin mirror segments scale $\delta \sim S$.

Angular changes due to self weight deflections scale $\theta \sim \delta/L \sim S$. Angular changes due to a fixed load/m^2 on a structure scale $\theta \sim \delta/L \sim S^0$.

Mass of a structure ~ S^3. This extremely rapid scaling often drives the designer to design changes as the structure scales, thus often negating the accuracy of these scaling laws. Examples include the Keck 10 m telescope which has a total moving weight (including instruments, etc) of 250 tons. The Green Bank Telescope (GBT), a 100 m radio telescope weighs 8000 tons. Simple scaling would predict 250,000 tons. Many issues drive the structural design, including live loads such as mirror mass, wind loads, snow loads, and various geometrical constraints.

Stiffness, or equivalently, the spring constant of a structure $k \sim F/\delta \sim Mg/\delta \sim S^3/S^2 \sim S$.

Resonant frequency $f \sim \delta^{-1/2} \sim S^{-1}$.

Stress $\sigma \sim$ Force/Area $\sim S$.

Wind related effects are important and rather complex, but some crude scaling laws may have some value. The characteristic frequency of wind eddies caused by the interaction of the wind with the structure scale $\sim v_{wind}/L \sim S^{-1}$. This is interesting in that the structure resonant frequency is decreasing the same way, hence dynamic effects of wind on a structure will not grow with increasing size. Deflections caused by the wind $\delta_{wind} \sim F/k \sim S^2/S \sim S$. For such a system, angular changes due to wind scale $\theta \sim \delta_{wind}/L \sim S/S \sim S^0$.

Performance Parameters

The point source sensitivity is one simple and important way to describe the performance of a telescope. The light gathering power obviously influences the sensitivity, but for diffraction-limited images, the background flux under the diffraction limited image is decreasing as the image size shrinks. We tabulate below the stellar magnitude that delivers 1 photon/s to the telescope, and also the noise equivalent background. The background is usually given in magnitudes/arc second^2. The noise equivalent background is the unit background times the equivalent background area. This is the equivalent background area one implicitly includes when optimally fitting to a point source. For a diffraction-limited point source this is $2\pi\ (\lambda/D)^2$ (King, 1983). We assume the measured backgrounds for Mauna Kea.

	Magnitude yielding 1 photon/sec			Noise Equivalent Area background (mag)		
Diameter	J 1.25 µm	H 1.68 µm	K 2.2 µm	J 1.25 µm	H 1.68 µm	K 2.2 µm
10 m	29.0	28.4	27.8	21.8	18.7	18.7
25 m	31.0	30.4	29.8	23.8	20.7	20.7
50 m	32.5	31.9	31.3	25.3	22.2	22.2
100m	34.0	33.4	32.8	26.8	23.7	23.7

The angular resolution is usually very significant. When the telescope is diffraction limited, the image size (FWHM) is approximately given by λ/D. When the atmosphere limits the angular resolution (seeing limited) the image quality varies with wavelength. For Kolmogorov turbulence, the seeing FWHM ~ $\lambda^{-1/5}$. Figure 2 shows image size vs wavelength for several telescope sizes and for both diffraction-limited and seeing-limited conditions.

Another important parameter in defining a telescope is the field of view that achieves some specified image quality. Optical configurations exist with widely different fields of view.

Finally, the operating wavelength range is also needed to define a telescope system.

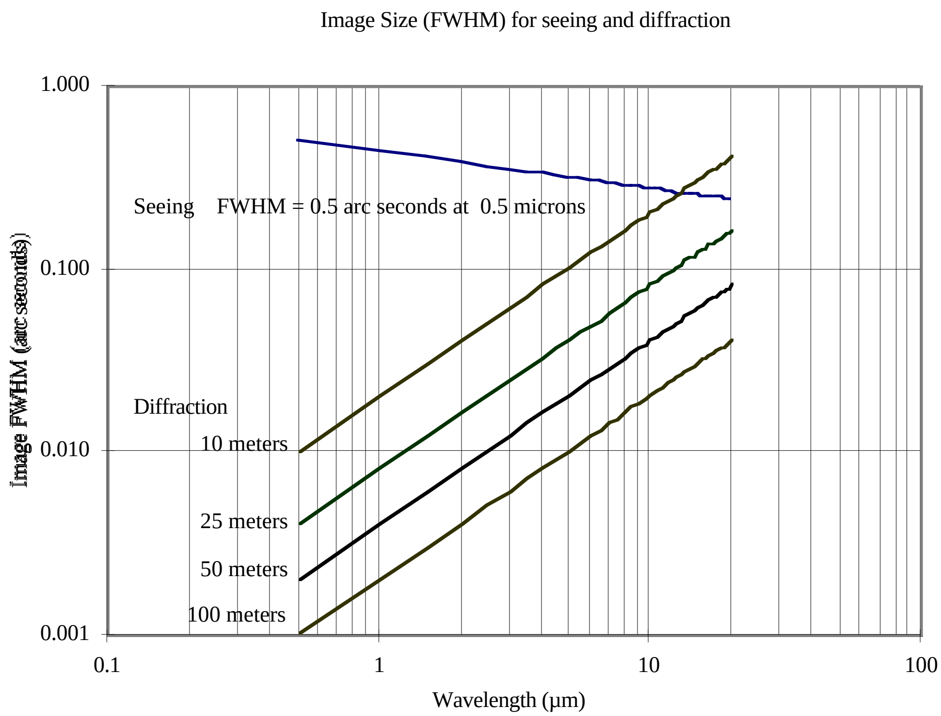

Figure 2.

Resource Drivers

In planning a telescope project, there are several resource drivers that should be kept in mind.

How much money will be available to the Project?

How quickly must the Project be completed? The Keck telescope took about 16 years from inception to completion (1977-1993). The ESO VLT took about 18 years (1983-2001). The Subaru telescope took about 16 years (1984-2000). It seems likely that even larger telescopes will take longer, given the increased difficulty in making such telescopes. If shorter times are sought, clearly special effort must be taken to achieve this.

What human resources can be made available? For large projects, there may be several institutions and countries involved. Further, available individuals or institutions may have special areas of expertise or special interests that assist or modify the path of a project.

Implementation Issues

There are a number of basic issues that need to be understood and decisions made in proceeding on a telescope project. Typically deciding these issues is difficult as they interact with each other. Thus several point designs may need to be studied in some detail in order to make the choices.

First, the telescope size needs to be chosen. What size telescope is needed to carry out the desired science? How much money is available? Next, the optical configuration needs to be selected. Typically the issue will include whether the primary mirror should be spherical or hyperbolic. This will drive the size, surface shapes, and number of auxiliary elements needed. Which site will be selected? One probably wants the best possible site. Candidates may include Mauna Kea in Hawaii and Chajnantor in Chile. The site will define important characteristics such as seeing image quality, water vapor, wind and weather conditions under which the telescope should operate and survive. Is an enclosure needed? The site conditions and the durability of the telescope and optics will dictate this. What adaptive optics will be used with the telescope? This may influence the optical design and site selection, and for very large telescopes be a very major design and cost issue for the telescope. We will discuss this further in the next section. Motion controls for the telescope must also be selected. Should the telescope have a two-axis drive system (conventional altitude-azimuth) or can a one-axis system be used as in the Hobby Eberly Telescope (HET). The latter has sky coverage limitations.

Adaptive Optics Scaling Laws

Because adaptive optics (AO) is so appealing, all modern large ground-based telescopes have, or are planning to have, some form of AO to reduce the blurring effects of the atmosphere. Because AO is so difficult, none of the systems is even close to ideal. Thus it is important to understand how AO systems will scale for even larger telescopes. We assume that the Kolmogorov turbulence models of the atmosphere are valid and describe the scaling laws with telescope diameter and wavelength. At least at Keck there is strong evidence that the outer scale of turbulence is not infinite, but comparable to the mirror size. This modifies the scaling laws, particularly for the lowest spatial frequency errors such as tip-tilt. The most important parameter to define the atmosphere properties is r_0. This is the diameter for which the telescope is essentially diffraction limited (wavefront errors of one radian).

$r_0 \sim \lambda^{6/5}$.

For an AO system, there must be some form of wavefront correction, and we characterize the complexity by the number of controlled degrees of freedom (dof) or actuators. We will speak of the correction element as a deformable mirror (DM), although there are several kinds of devices to correct wavefronts.

$$N_{dof} = N_{act} \sim (D/r_0)^2 \sim D^2 \lambda^{-12/5}.$$

The wavefront errors must be sampled at approximately this density, so $N_w \sim N_{act}$.

The wavefront errors of the atmosphere change with time, and conventional wisdom is that the actual turbulence in the atmosphere changes slowly compared to the speed at which the wind driven turbulence moves across the telescope (Taylor frozen turbulence hypothesis). Thus the atmospheric time constant scales as

$$\tau_0 \sim r_0/v_{wind} \sim \lambda^{6/5}.$$

Computation speed is a key issue, and in the simplest models where a measured wavefront error vector (sensor signals) is multiplied by a correction matrix to yield the command vector for the DM. In this case, the rate of computation varies as

$$R \sim N_{act}^2/\tau_0 \sim D^4 \lambda^{-18/5}.$$

This rapid scaling indicates that even with the expected advances in computing speed, computation speed will be a key issue for future advanced AO systems. For a simple atmosphere that has only a single layer of turbulence at height h, the wavefront error seen at the telescope will vary with field angle. The angle which has a one-radian difference is the isoplanatic angle

$$\theta_0 \sim r_0/h \sim \lambda^{6/5}.$$

Real atmospheres are likely have a much more complex vertical distribution of turbulence, but the net effect can still be characterized by an isoplanatic angle. Natural guide stars are the best light sources to estimate the atmosphere-induced wavefront errors; but sufficiently bright stars are scarce. The required star flux (natural or laser beacon) does not depend on telescope size, however, it does depend on wavelength as

$$\text{Flux} \sim 1/r_0^2\ \tau_0 \sim \lambda^{-18/5}.$$

For a wide range of star brightness (5-18 magnitude), it is approximately true that the increasing density of stars with increasing faintness yields an accessible sky solid angle with natural stars

$$\Omega \sim \lambda^5.$$

Thus, natural guide stars are adequately dense for full sky coverage at 10 μm but only cover 1-2% of the sky at 2 μm, and an even smaller solid angle at shorter wavelengths. It is this fact that drives us to consider artificial beacons (laser guide stars) for shorter wavelength AO.

A useful measure of the degree of correction with AO is the Strehl ratio (actual central peak intensity/theoretical maximum peak intensity). If one wants to achieve a Strehl ratio of 0.5 at 1 μm, one needs an rms wavefront error of 132 nm.

$$S = \exp(-(2\pi\sigma/\lambda)^2)$$

Figure 3 shows the Strehl ratio as a function of wavelength for several assumed values of the rms wavefront error.

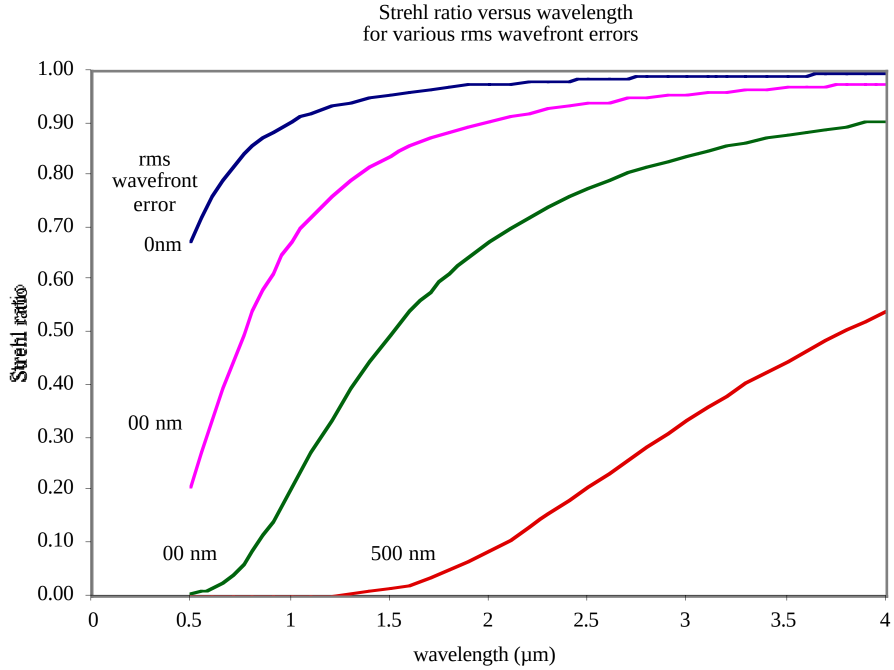

Figure 3.

A Point Design

We are not ready to provide a full design, but here we suggest a few ideas for a segmented-mirror design that may be interesting to pursue for a 25 m class telescope. Many of the features are based on known challenges for the Keck telescopes, that we hope to simplify with this design.

Optical Design

We assume the telescope primary is 25 m in diameter and is a roughly circular filled aperture. Further, we assume a hyperbolic primary that is f/1.5 (f=37.5 m). Ritchey-Chretien two-mirror design is simple and powerful with images having θ_{100} = 0.005 arc seconds over a 2 arc minute FOV, θ_{100} = 0.13 arc second over a 10 arc minute FOV and θ_{100} = 0.5 arc second over a 20 arc minute FOV. This is in strong contrast to spherical primary designs with 5-6 mirrors causing significant light loss and delivering a much smaller field of view. Of course spherical segments are surely the least expensive to produce, so a key issue for the above design is the economical fabrication of the mirror segments.

Segment Size

Segment size is a key aspect of a segmented mirror telescope. Larger segments are more difficult to support against gravity, are generally thicker and thus require more (very expensive) material. They deviate more from a sphere and thus are more difficult to polish and require more accurate alignment in the telescope. Handling is are also more difficult requiring larger handling equipment and cranes and bigger coating facilities. All these factors argue for smaller segments. On the other hand, smaller segments require more position actuators (3 per segment) more edge sensors (if used) and a more complex alignment and calibration camera. The active control system must compute and control more degrees of freedom and a more complex network of cables is needed. More segments must be handled regularly for re-coating, thus increasing the risk of damage. Simply keeping track of more segments becomes an issue. Finding the optimum segment size is an extremely difficult task.

Our experience at Keck is that our choice of 1.8 m diameter segments led to several difficult issues that will be ameliorated by using smaller segments. The optimum is not at all clear, but we think with today’s technology, overall, smaller segments are preferred.

We somewhat arbitrarily select segments 1.0 m in diameter (0.5 m side length, Keck was 0.9 m). For the 25 m telescope this implies we will have 756 segments and the pattern is shown in Figure 4. This makes for a more circular overall shape than Keck and this is an advantage for the design of scientific instruments, particularly for an altitude-azimuth mount that exhibits field or pupil rotation.

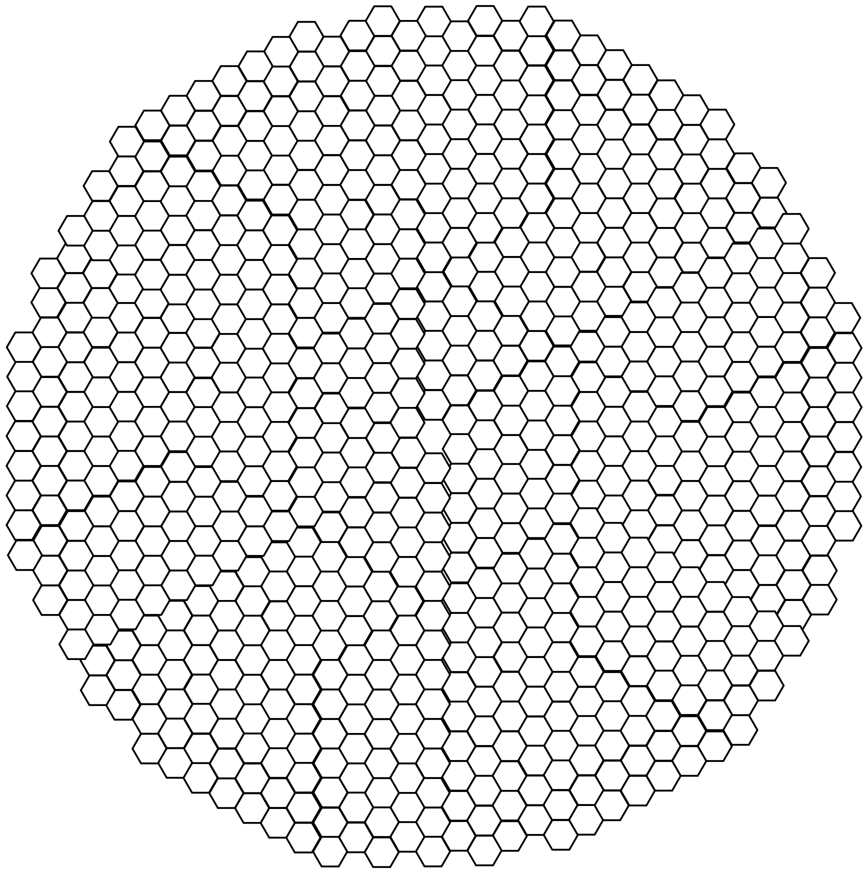

Figure 4.

For a given support system, the total mass of the primary mirror will vary inversely as the number of segments. This is because smaller segments can be made thinner for a given support system. Thus smaller segments cause significant savings in the cost of the mirror material, as well as reducing the entire mass of the telescope (defined largely by the need to support the primary mirror). For this design, the primary will have a mass of 55 tons (Keck is 15 tons).

Segment Fabrication

We suggest polishing these segments with planetary polishers. This allows multiple mirrors to be polished simultaneously and is by far the most efficient and least expensive industrial polishing method. This method works on spheres only. We will turn our polishing problem into that of polishing spheres by deforming the mirror blanks with a simplified stressing fixture during polishing. After polishing the mirrors should be cut into hexagons and then final figure established with ion figuring. We believe this will reduce the polishing problem to nearly that of polishing spheres. The HET used planetary polishing and ion figuring to make its spherical segments, and these were accomplished extremely economically.

The major challenge of segment fabrication is measured by the degree of asphericity of the segments. This asphericity is dominated by astigmatism, which, with small amounts of coma, allows a virtually complete description of the asphericity. It has been shown (Lubliner and Nelson, 1980, Nelson and Temple-Raston 1982) that the astigmatic amplitude for a segment of radius a, an off axis distance R, and a global radius of curvature k is given by the Zernike coefficient .

$$C_{22} = a^2 R^2/4k^3$$

For a = 0.5 m, R = 12 m, k = 75 m, C_{22} = 21 µm, about 5 times smaller than Keck segments. Figure 5 shows the rms asphericity as a function of segment type and shows the residual when only astigmatism is removed. This great reduction in asphericity allows a simpler and more efficient polishing technique than the gravity-driven stressed mirror polishing (SMP) used for the Keck segments (Nelson etal, 1980). We will use the basic idea of SMP. For a purely astigmatic shape change, one must apply pure bending moments around the perimeter of a circular mirror, with a cos2θ pattern. We suggest using

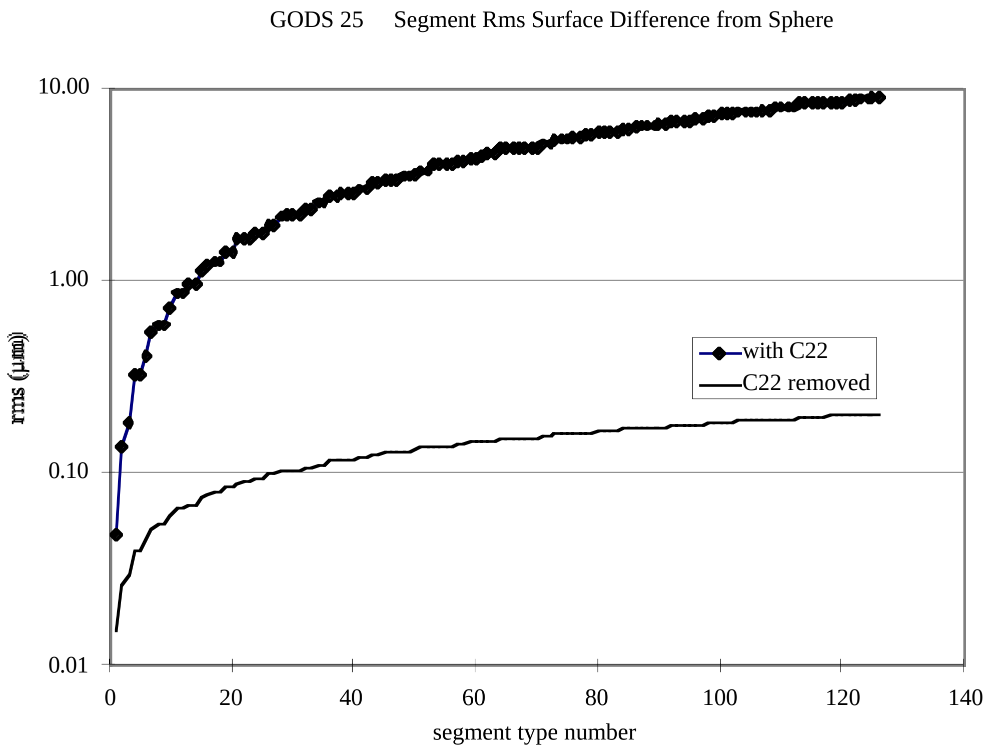

Figure 5.

springs arranged as shown in Figure 6 to apply these moments. Coma is only slightly more complex to remove with SMP, and future studies will establish whether this is advantageous. When these loads are applied, the stressed mirror blank can be placed on a planetary polisher and multiple segments can be polished at one time, polishing a sphere into all of the stressed mirrors. A 1% warping accuracy should be straightforward, based on Keck experience. The polishing will achieve the correct shape to within about 0.2 µm, close enough that a single short cycle of ion figuring should complete the mirror. Here we suggest cutting after the planetary polishing, and our Keck experience is that the warping from cutting should be well within the 0.2 µm amplitude for these size segments.

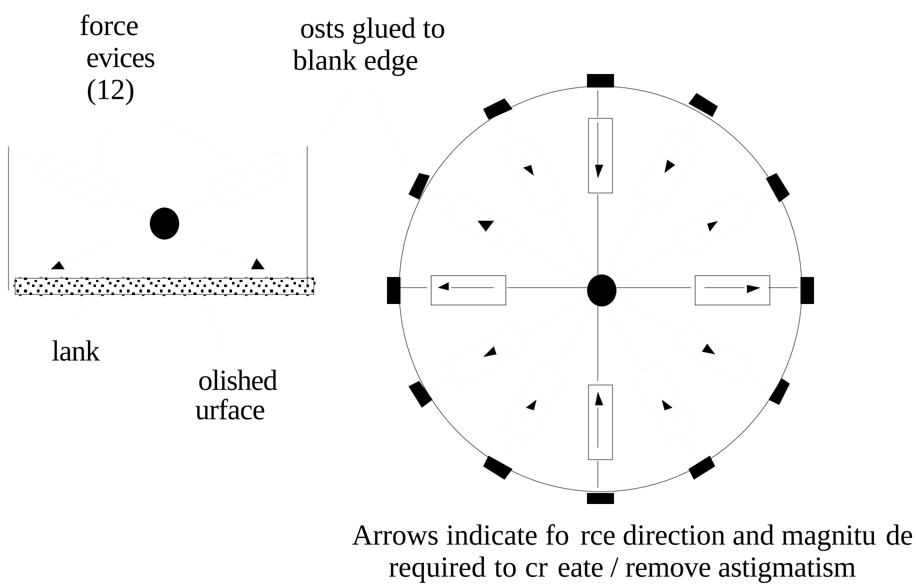

Figure 6

Optical testing was also an extremely expensive part of Keck segment fabrication. We suggest that holographic testing of the segments, as has been proposed by Burge (1996), can greatly reduce the testing cost.

We tentatively assume a low expansion glass for the segment material, but some years ago ESO carried out a successful engineering effort to develop stable aluminum mirrors. It may be worthwhile revisiting this alternative.

Segment Support

Mirror support was also challenging for the Keck segments. The segment size and thickness proposed here (h = 45 mm, Keck was 75 mm) allows the mirrors to be supported on 18 points (Keck was 36) which should lead to a significant simplification of the whiffletrees. Further, we anticipate that the axial and lateral supports can function without drilling the many holes into the mirror material that were done for Keck.

Active Segment Control

We assume that edge sensing to stabilize segment piston-tip-tilt against their neighbors is still an appropriate solution to providing a stiff and aligned mirror. It may be that the more direct wavefront sensing systems used on Gemini and VLT will suffice, but this is a subject for future study.

Keck edge sensors were very accurately made (and hence expensive) and interlocked with neighboring segments, thus making segment exchange complex. We suggest here a much simpler sensor geometry. Here the sensor is basically a film attached to the segment edge. A differential capacitor system is shown in Figure 7. Inductive sensors may also work well with the same geometry. Thus a much less expensive and physically awkward sensor seems quite plausible. About 4000 edge sensors are needed

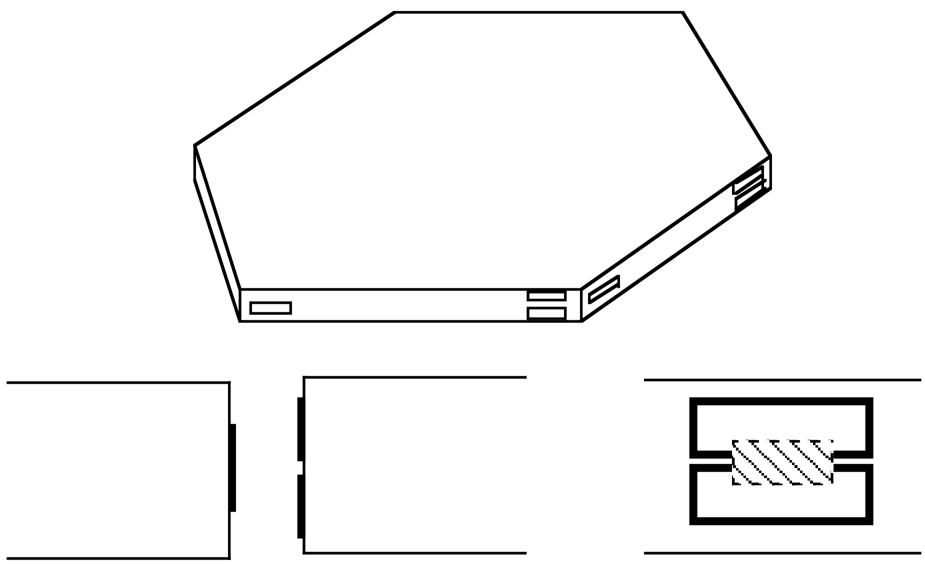

Figure 7.

Error propagation with smaller segments and a greater number of segments is a key issue. Simulations and simple geometric models suggest that the rms surface error resulting from random sensor noise is given by

$$\sigma_{surface} = 4.2\ (\text{Nsegment}/36)^{1/2}\ \sigma_{sensor}.$$

At Keck our experience is that random sensor noise is small , so increasing it by a factor of 4.5 will probably not be a problem.

The design discussed above has a key limitation caused by the lack of a sensor mechanical offset. One specific modal shape is not sensed. This mode is called focus mode and is characterized by all segments tilting by the same dihedral angle with respect to their adjacent neighbors. We believe that this mode will change slowly and can easily be sensed and controlled by a low order wavefront sensor as is used on recent 8 m telescopes.

About 2200 actuators are needed and efforts should be made to find a less expensive solution than the Keck actuators.

Edge sensors require calibration. At Keck this is done using starlight, and is done about once a month. The purpose is to establish the sensor readings that hold the mirror in its desired shape, with segment tilts perfect and segment pistons set so the mirrors are phased. With more segments, one must re-think through the calibration process. Chanan etal, (1998) has developed an elegant technique using a variant of curvature sensing to phase the segments. Techniques like this may be suitable for aligning a large number of segments.

Adaptive Optics

Achieving diffraction-limited imaging is a critical objective for such a telescope. Image quality is shown in Figure 2. Adaptive optics is sufficiently difficult that it is probably the largest challenge to be met in building a 25 m telescope. Of course a key parameter is the wavelength at which the telescope is diffraction limited. If we set as a goal a Strehl ratio of 0.5 at 1 μm, we will need roughly 5000 degrees of freedom DM's and also multiple laser beacons to overcome cone effect. This exciting and difficult subject is discussed by Rigaut in these proceedings. (Rigaut, 1999)

Other Issues

The site is clearly important, and selecting the best one possible is clearly appropriate, particularly if AO is planned for the telescope. Thus sites such as Mauna Kea or Chajnantor in Chile are very interesting. Many other aspects of the observatory, such as the telescope and the enclosure require significant study in order to develop a reasonable plan for a 25 m telescope.

Initial Process

How do we begin a giant telescope project? It is clearly important to define the resource drivers. How much can one afford, when is it needed, who will do it. The critical science objectives must be thought through. Without wide community support it is unlikely that a giant telescope can be built, so the science goals and the telescope capabilities must be carefully organized. The overall performance parameters (image quality, field of view, etc) of the telescope must also be clearly defined and be supported by a significant fraction of the community. In order to predict the performance with any accuracy or to bring the costs down to some acceptable level will require appreciable technology developments. These must be clearly defined and key tests carried out. This will surely involve segment fabrication, active control systems, adaptive optics, etc. Many of the decisions and choices leading to a design are likely to be challenged as development activities take place. Thus the actual process is extremely rich and non linear. With skill, perseverance, and perhaps a bit of luck, we will enter into the next generation of truly enormous telescopes.

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