

# Optical issues for giant telescopes with extremely fast primary mirrors

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## ABSTRACT

Existing design rules break down as we plan for a new generation of giant optical telescopes of 20, 30, 50, even 100 meters in diameter. One might expect these telescopes to converge on the design universally accepted for similarly sized radio telescopes, with their highly aspheric,  $\sim f/0.4$ , primary dish. But most of the optical design concepts now under consideration have favored spherical or relatively slow paraboloidal surfaces, leading to a much larger telescope, more subject to wind buffeting, and requiring gargantuan enclosures for protection. This paper explores issues and limitations for building and operating telescopes as the primary focal ratio is reduced to a value as small as  $f/0.4$ . Such compactness will be particularly important for mechanical stability, cost control and for large telescopes that must move continuously on a track, as in the 20/20 concept. We find that fabrication and alignment methods for telescopes using numerous small (1-m class) segments are driven to long focal ratios, while those using few large, actively controlled segments can be made as fast as  $f/0.5$ .

**Keywords:** Telescope, astronomical optics, optical fabrication

## 1. INTRODUCTION

Throughout the 1980's, many groups around the world were planning, designing, and starting to build a new class of large telescope, with apertures from 6 to 10 meters. In the 1990's a dozen of these were completed and are now operational. These new telescopes allow measurements with sensitivity that was not possible a few years ago with smaller telescopes. Also very high resolution is obtained when the atmospheric effects are corrected in these telescopes using adaptive optics. Some of these large telescopes are now combined as interferometers, achieving higher resolution yet.

### *Enter the era of the really giant telescopes!*

The groups of astronomers and engineers who recently solved the difficult problems for 6 to 10 meter telescopes are now applying their talents and resources to the design of new types of telescopes that increase the collecting area by an order of magnitude with 20, 30, 50, even 100 meter apertures. It is interesting how different groups have approached the design problem for giant telescopes. For sizes larger than 8 meters, the primary mirror must be segmented, *i.e.* the mirror must be constructed from a mosaic of smaller mirrors, all co-pointing and co-phased. The details of the segmentation and the optical design vary widely according to the groups' experience and engineering choices.

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The focal ratio of the primary mirror is a single degree of freedom for any telescope that must be chosen carefully. This focal ratio, defined as the focal length of the primary mirror (half of the radius of curvature) divided by its diameter, determines the overall length of the telescope. It is not the intent of this paper to discuss the merits or drawbacks for any particular design, nor is it the intent to elaborate on all of the issues that must be traded when optimizing the focal ratio. This paper focuses on the optical issues that must be considered for designs that use extremely fast primary mirrors.

### 1.1 The drive for faster primary mirrors

The primary motivation for using fast primary mirrors for giant telescopes comes from the desire to minimize the volume of the enclosure and the need to minimize the exposure of the secondary mirror to the effects of the wind. This follows the historical trend of decreasing the telescope focal ratio as the apertures are made larger. Thirty years ago, most telescopes used primary mirrors with focal ratios longer than  $f/3$ . The telescope boom of the 1970's saw this reduced to nearly  $f/2$ . The 8-m telescope boom of the 1990's saw a steady decrease from a conservative focal ratio of  $f/1.8$ <sup>1,2,3,4</sup> to  $f/1.25$ <sup>5,6</sup> and even  $f/1.14$ .<sup>7</sup>

The length of a telescope with given aperture is obviously linearly proportional to the primary focal ratio. This means that the volume defined by the swing of this telescope goes as the cube of the focal ratio for a dome type enclosure and the square of the focal ratio for a co-rotating building. The cost of larger enclosures certainly increases steeply with the size of the building. The dramatic change in system size is illustrated for the two 30 meter telescope designs shown below, one with  $f/1.5$  primary and the other at  $f/0.5$ .



**Figure 1.** The difference between a telescope with  $f/1.5$  primary and  $f/0.5$  primary is easy to see in these two designs of 30-m telescopes.

The telescope is easier to control if the primary mirror is made to be fast and the secondary is close to the primary. This is due to two different effects. The moment of inertia for the moving mass is increased as the secondary moves farther from the primary mirror. This makes the pointing control system more difficult. Also, the secondary mirror located many stories from the primary mirror is susceptible to forces from the unblocked wind and its lever arm is longer, so it exerts more torque onto the telescope. A long telescope may require wind baffles, which cause local seeing effects, degrading the image quality.

There is another motivation for fast primary mirrors, which allow the telescope to use a Gregorian design without becoming excessively long. The Gregorian design has several unique advantages over the classical Cassegrain. Since the secondary mirror is concave, it is more easily tested and manufactured. More importantly, the use of the secondary mirror as the adaptive element in the telescope is more readily accomplished with a concave mirror. The system can be tested by placing a point source at the near conjugate of the ellipsoidal surface. It requires a complicated optical system to test the adaptive control using a convex secondary mirror. Also, the field curvature from the Gregorian design has the opposite sign as that from the Cassegrain, and is more easily mated to a refractive collimator for a spectrograph<sup>8</sup>. The Large Binocular Telescope and Magellan Telescopes have taken advantage of their relatively fast primary focal ratios and have adopted Gregorian designs.

It is interesting to compare the giant optical telescopes with their cousins used for radio observations. Radio telescopes of 30 meters are not uncommon and have been made as steerable systems to 100 meters and with fixed primary to 300 meters. These telescopes all use the fastest practical primary mirror, typically  $f/0.4$ .

### **1.2 The tendency to maintain long focal ratios**

What prevents optical telescopes from adopting the steep  $f/0.4$  focal ratio that is used by radio telescopes? The telescope optics become more difficult to manufacture as the primary mirror becomes steeper. The optical surfaces become more aspheric, thus become harder to polish and measure. The coupling of alignment error to image degradation is more severe for faster systems. These issues are addressed below.

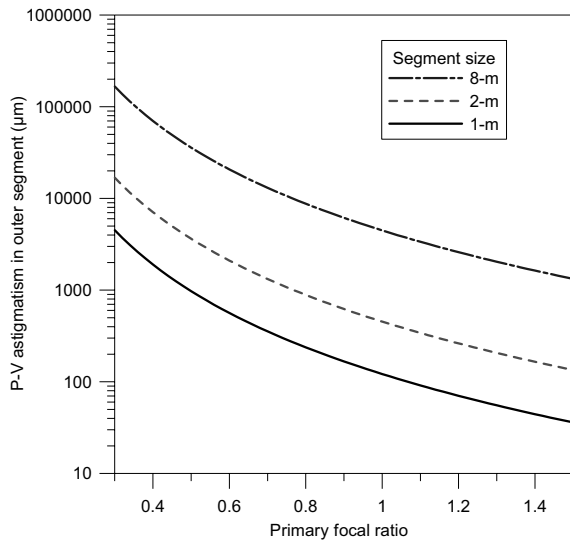
### **1.3 Active optics**

It is important to understand that any large telescope will be operated using active optics – meaning that the shape of the mirrors will be adjusted periodically based on wavefront measurements. This is distinct from *adaptive optics* where a deformable mirror in the system is controlled to compensate wavefront aberrations induced by the atmosphere at millisecond rates. Active optics uses actuators to maintain the correct shape of the mirrors, as defined by integrations that are very long compared to the atmospheric effects. All current large telescopes rely on active optics to maintain the shape of the primary mirror in the presence of thermal, wind, and gravity induced deflections of the support system.

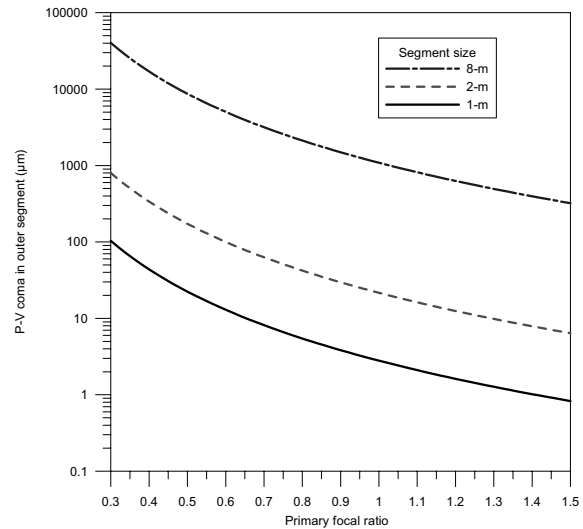
The use of active optics allows the fabricator to relax all of the degrees of freedom that will be controlled at the telescope. This clearly includes the phasing and pointing for each segment, but it also includes the low order bending modes for any large mirror. For example, the lowest 14 modes of the stiff honeycomb borosilicate mirrors are controlled in the telescope. Even if the mirrors were made absolutely perfectly in the shop, the shape of these modes *in the operational telescope* will be determined by the active optics system. This means that there is no premium for polishing or testing these modes perfectly and the fabricators can apply their efforts to the smaller scale errors that are not actively controlled. There is a limit to the magnitude of the low order errors that are bent out with the active optics system, but this is large compared to the operational requirement.

## **2. FABRICATION AND TESTING**

Telescopes with faster primary mirrors require more severe aspheric surfaces. The fabrication and testing of these surfaces can drive the overall cost and must be considered carefully. Figures 2 and 3 show the dramatic increase in aspheric departure for primary mirror segments as the focal ratio is driven shorter. However, depending on the fabrication technique, the aspheric departure may not be the correct figure of merit. As shown below in section 2.1, the fabrication of 8-m segments from an  $f/0.65$  parent is no more difficult than the mirrors that have already been made!



**Figure 2.** Astigmatic aspheric departure for segments of a 30-m primary mirror.



**Figure 3.** Comatic aspheric departure for segments of a 30-m primary mirror.

## 2.1 Fabrication considerations for large segments

Size and asphericity are the factors that challenge our ability to make larger and faster mirrors for giant telescopes. Size drives the requirement for greater efficiency in manufacturing the optics. While no one is proposing to make individual segments larger than the 8 m class mirrors for which facilities already exist, the new telescopes will have collecting areas of hundreds or even thousands of square meters. Producing  $700 \text{ m}^2$  of mirror surface for a 30 m telescope in less than a decade calls for a significantly higher throughput than has been developed for large telescope projects to date. To some extent this will be achieved through expanded facilities, but there is strong financial incentive to make these optics more efficiently. All steps of the process, from creation of mirror blanks through generating and figuring, need to be streamlined. For the early stages of finishing, rapid but controlled removal of glass is needed, calling for lapping tools that cover as large a fraction of the surface as possible. For the later stages where accuracy is most critical, the greatest gains in efficiency will be made by making the figuring process more predictable, thus reducing the number of iterations of figuring and measuring.

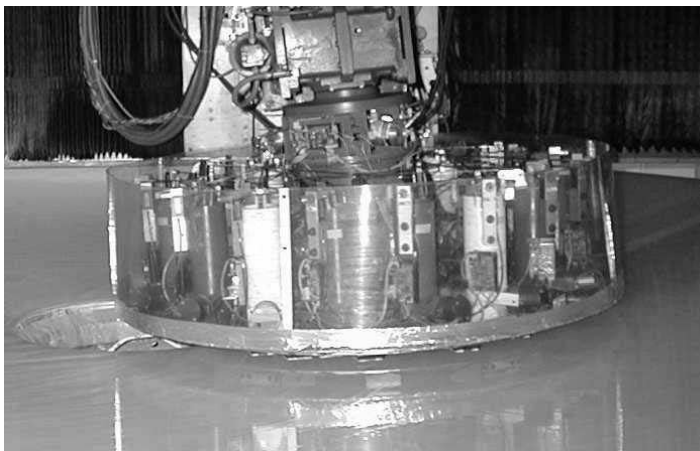
Asphericity presents a more fundamental challenge than size. Our ability to produce surfaces sufficiently accurate for astronomical telescopes limits the focal ratio. This is a limitation for lapping processes only. We can generate, or machine, glass to the desired accuracy on the order of  $10 \text{ }\mu\text{m}$ , independent of the focal ratio. Likewise, certain local figuring processes such as ion figuring and, to some extent, small-tool computer-controlled polishing, can improve the figure independent of the focal ratio. But a large-scale lapping process has always been, and will probably continue to be, an essential part of the manufacture of large mirrors. We rely on it to control large-scale figure errors and to smooth out small-scale structure.

### 2.1.1 Polishing large segments

Asphericity causes problems for lapping processes because it implies a change of curvature from point to point on the mirror surface. A polishing lap must match the shape of the mirror surface to high accuracy—on the order of microns—in order to achieve surfaces that are smooth at the  $10 \text{ nm}$  level. The lap must be stroked in order to remove glass and smooth the surface. A lap that matches the shape of an aspheric mirror surface at one position will experience a significant mismatch when it has moved a sufficient distance. This misfit can be minimized by using a small lap or a flexible lap, but both of these reduce the lap's natural tendency to smooth out small-scale structure.

One can easily work out the degree of misfit as a function of mirror shape, lap size and stroke distance. As an example, a 1 m diameter lap experiences a 15 μm misfit when it is stroked by 40 mm near the edge of an 8 m f/1 parabolic mirror. Of course the same misfit occurs for the same lap and stroke on the edge segment of an 8 m f/1 parent.

One lapping system that has been designed to overcome the challenge of aspheric surfaces is the stressed-lap system used at the Steward Observatory Mirror Lab. The lap's shape is controlled by actuators that bend it elastically and continuously as it is stroked over the mirror. A relatively large and stiff lap can be used with no restriction on its motion, thus maintaining a strong passive smoothing action. Figure 4 shows a 1.2 m diameter lap being used to polish a 6.5 m f/1.25 mirror. The lap plate is 50 mm thick aluminum, which gives strong smoothing of structure with periods less than about half a meter. For this system, the limitation is the lap's ability to bend accurately. A more aspheric mirror requires more bending and therefore better relative accuracy of bending.



**Figure 4.** 1.2 m diameter stressed-lap polishing tool, shown polishing a 6.5 m f/1.25 mirror.

If we are interested in making faster, more aspheric mirrors for larger telescopes, we need a quantitative measure of difficulty that contains a precise dependence on focal ratio and diameter. Knowing that metric would give us a better idea how fast a primary mirror is practical as far as polishing is concerned. The degree of difficulty depends on spatial changes in curvature: a rigid passive lap experiences misfit, and a stressed lap must bend, in proportion to the change in curvature it sees as it moves from point to point. For fixed stroke length, this change is proportional to the first spatial derivative of the curvature and the third derivative of the mirror surface. For given amplitude of asphericity, this quantity is a strong function of mirror diameter, with larger mirrors having much smaller curvature changes.

To quantify this argument, we can work out the first derivative of curvature for a parabolic mirror and see how it depends on diameter  $D$  and focal ratio  $f$ . The aspheric departure is

$$z = \frac{1}{48R^3} (6r^4 - 6r_m^2 r^2 + r_m^4) \tag{1}$$

where  $R$  is the vertex radius of curvature,  $r_m = D/2$ , and  $r$  is the radial coordinate on the surface. The first derivative of curvature in the radial direction is

$$z''' = \frac{3r}{R^3} \tag{2}$$

and reaches a maximum, at  $r = r_m$ , of  $\frac{3D}{2R^3} = \frac{3}{16} f^{-3} D^{-2}$ .

Using this metric, in order to maintain constant difficulty as we consider larger mirrors, the quantity  $f^{-3}D^{-2}$  must remain constant, *i. e.*,  $f \propto D^{-2/3}$ . An 8 m f/1 primary mirror is roughly the state of the art with the stressed lap polishing system used at the Mirror Lab. This mirror has the same difficulty as a 20 m f/0.54 or a 30 m f/0.41 primary mirror. More precisely, for a fixed stroke length, a stressed lap must bend by the same amount (or a rigid passive lap would misfit by the same amount) for these mirrors. Based on these lapping considerations alone, we can decrease the focal ratio dramatically as we go to larger mirrors.

The above argument applies for a fixed stroke length. This is appropriate if we increase the mirror diameter by using a larger number of segments of similar size. If we choose to use larger segments or a monolithic mirror (not likely for telescopes larger than 8 m), it is desirable to let the stroke length increase with mirror diameter. One could conceivably use a series of laps each with a short stroke—what counts is the stroke in the radial direction relative to the vertex of the parent—but a simpler lapping system would let one lap cover the entire mirror or segment. In this case the metric for difficulty is the total change in curvature over the mirror, obtained from the curvature of the aspheric departure,

$$z'' = \frac{1}{4R^3} (6r^2 - r_m^2). \tag{3}$$

The total change in curvature is  $\frac{3D^2}{8R^3} = \frac{3}{64} f^{-3} D^{-1}$ . Using this metric, we maintain constant difficulty by making  $f \propto D^{-1/3}$ . Thus an 8 m f/1 mirror has the same difficulty as a 20 m f/0.74 or a 30 m f/0.64 mirror. Even with this milder scaling, lapping considerations allow telescopes of 20-30 m diameter to be much faster than an 8 m telescope. Martin *et al.*<sup>9</sup> give an illustration of these scaling laws for the case of 8.4 m segments of a 23 m f/0.65 parent.

### 2.1.1 Optical testing for large segments

Large segments can economically be measured interferometrically from the center of curvature through a null corrector. The large, fast segments require a difficult class of null corrector that does not use axisymmetry. The null corrector alignment, and high order wavefront correction can be accurately provided using computer generated holograms (CGHs).<sup>10</sup> These CGHs use multiple patterns that are simultaneously fabricated onto a single substrate, which assures their registration. The optical tests can be made to high accuracy, but the active optics system will compensate for large scale errors, especially astigmatism. This provides some relaxation in the specifications for the test optics.

Figure 5 shows a null corrector designed for an 8-m segment of a 23-m f/0.65 primary mirror. This system uses two concave spherical mirrors to correct the aspheric departure of the segment. A CGH will compensate higher order residuals and provide an alignment reference.

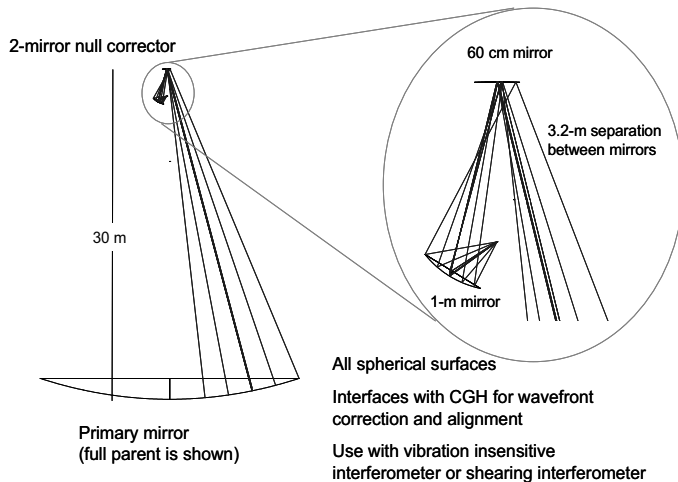


Figure 5. Two-element null corrector for measuring an 8-m segment of a 23-m f/0.65 primary mirror.

## 2.2 Fabrication considerations for small segments

The issues are different for smaller segments because the controls for fabrication and operation are not the same. Other polishing methods have more stringent limitations for the aspheric departure that they can handle. Also, depending on the control system, the low order errors in the segments may not be controlled based on wavefront measurements, especially for the case of many hundreds of small segments. So the optical shop testing of these mirrors must be absolutely accurate to hit the low order errors as well as the smaller scale figure.

The choice of the method for fabricating the segments may place hard limits on the aspheric shape, such as stressed mirror polishing.<sup>11</sup> This fabrication method does not use a stressed polishing tool, but rather a stressed optic. The mirror segments are bent and polished spherical, then relaxed so when they spring back, they take on the desired aspherical shape. The mirror segments for the Keck Telescope were polished this way. Since this technique requires the glass to be stressed, the strength of the glass imposes a limitation on the applied stress. For a given diameter and thickness blank, this in turn presents a limitation for the aspheric departure of the segments, thus the primary focal ratio. If the blanks are made too thin, then they become overly sensitive to small errors in the attachment, wind effects, and self-weight deflection. This issue has been studied carefully for the 30-m CELT telescope.<sup>12</sup>

The measurement of small segments can be performed using a test plate, with correction from a CGH.<sup>13</sup> This allows all of the degrees of freedom to be easily constrained, and it has been carefully evaluated for segments from a 30 meter, f/1 primary mirror.<sup>14</sup> The difficulty of this test increases roughly with the aspheric departure, shown in Fig. 2.

## 2.3 Fabrication considerations for the secondary mirror

The secondary mirror certainly becomes more difficult if it is larger or more aspheric. Figures 6 and 7 show the size and aspheric departure secondary mirrors for a 30-m telescope. A back focal distance of 18 meters was assumed, to allow access to a Nasmyth focus.

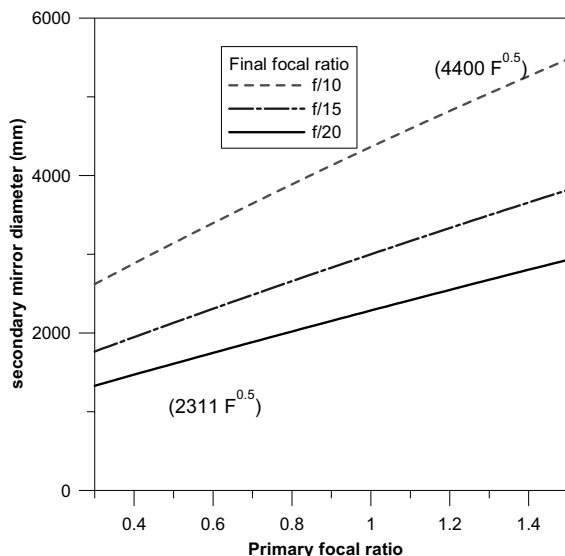


Figure 6. Secondary mirror for 30-m telescope size as function of primary mirror focal ratio.

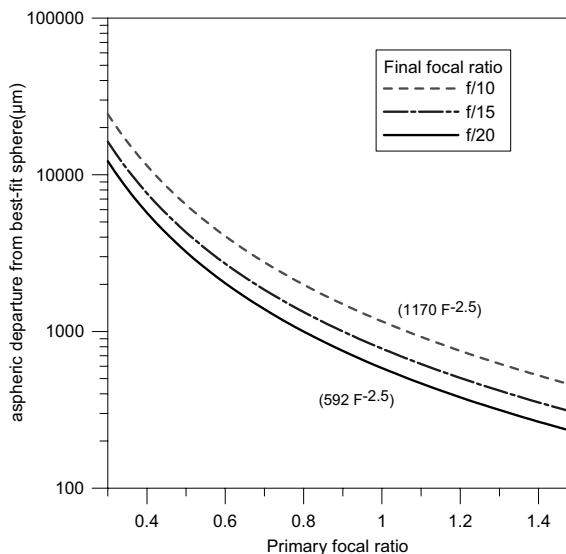


Figure 7. Secondary mirror aspheric departure for 30-m telescope size as function of primary mirror focal ratio.

Although the size of the secondary mirrors is smaller when a fast primary mirror is used, the aspheric departure increases dramatically. The difficulty of polishing and testing the secondary mirror will scale with the mirror area and the aspheric departure. In this case, the secondary mirrors for the faster telescope are significantly more difficult to make than those from the 8-m telescopes. Before driving the entire telescope length based on the secondary mirror, two important points must be considered:

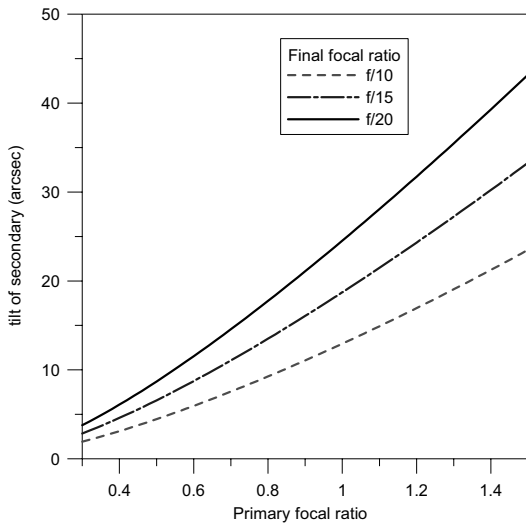
1. There is only one relatively small secondary per telescope, so the cost per square meter of this mirror should not be compared with that of the primary.
2. Many telescope schemes use the secondary mirror as the adaptive element in the telescope, and can thus accommodate significant shape error.

### 3. ALIGNMENT SENSITIVITY

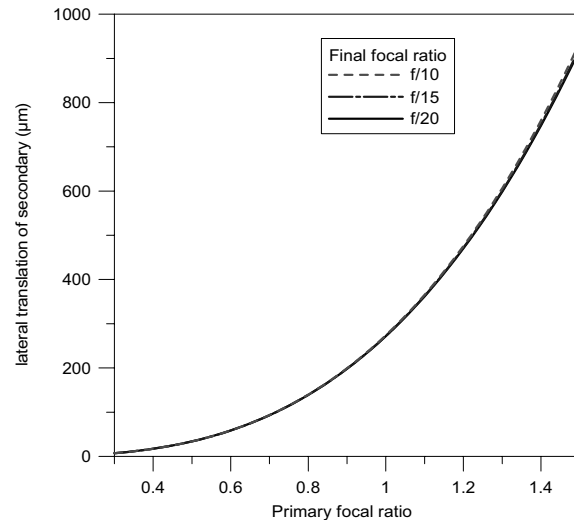
The fast telescopes are sensitive to alignment of the primary mirror segments and the secondary mirror. The first order effects of phasing and pointing the segments are independent of primary mirror focal ratio. The sensitivity to lateral segment position and in-plane rotation is proportional to the aspheric departure of the segment. (Spherical segments are completely insensitive to these errors.) These errors cause astigmatism in the individual segments. Rigid segments must be controlled accurately enough that this astigmatism is acceptably small. Actively controlled segments can be driven to compensate by a bending.

Fast telescopes are especially sensitive to alignment of the secondary mirror. The sensitivities are quantified in the plots below, given for the case of a 30-m Cassegrain telescope with 18-m back focal length. Simulations of the telescopes were made as a function of the primary focal ratio for system focal ratios of  $f/10$ ,  $f/15$ , and  $f/20$ .

The effect of secondary mirror alignment error is coma, which is constant across the field. The tolerances for the secondary mirror tilt and lateral translation are given below in Figures 8 and 9, allowing  $1\ \mu\text{m}$  rms coma in the wavefront from each. As long as this coma is measured, the secondary mirror position or shape can be adjusted to correct this. Figure 10 shows a related quantity, which is the amount of fine steering that can be accommodated by tilting the secondary about its vertex before it induces  $1\ \mu\text{m}$  rms coma in the wavefront.



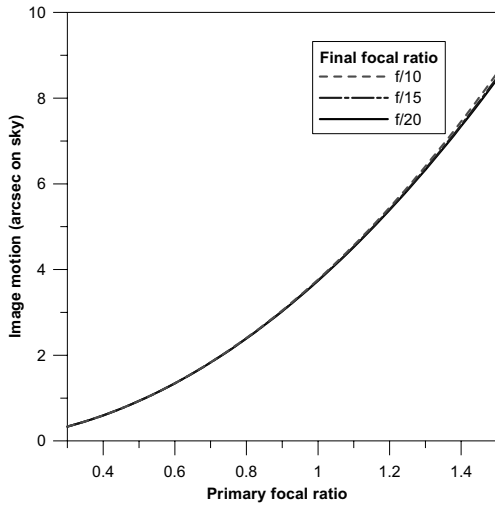
**Figure 8.** Tolerance for secondary mirror tilt, corresponding to  $1\ \mu\text{m}$  rms coma in the wavefront.



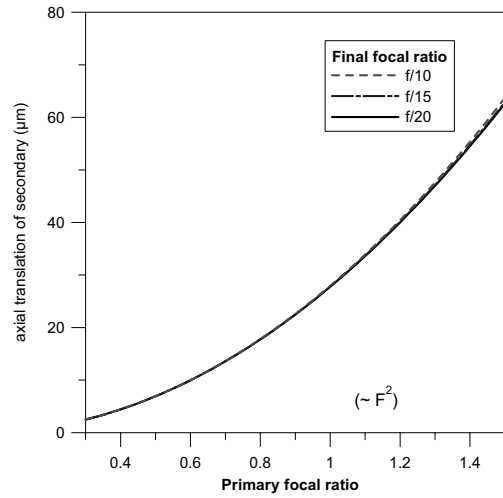
**Figure 9.** Tolerance for secondary mirror translation, corresponding to  $1\ \mu\text{m}$  rms coma in the wavefront.

Fast telescopes are sensitive to axial translation of the secondary mirror as well. The tolerance for this motion is shown in Figure 11. Again, this error can be measured in the system and used for closed loop control. Active control of secondary mirror alignment is based on wavefront measurement rather than position measurement. Sensitivity to position is largely irrelevant as long as the wavefront measurements have sufficient accuracy and the positioning system has adequate resolution.





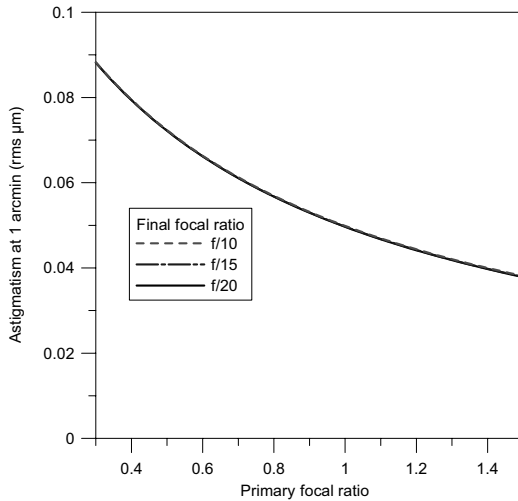
**Figure 10.** Amount of fine steering that can be accommodated by tilting the secondary about its vertex, while limiting the induced coma to  $1 \mu\text{m}$  rms wavefront.



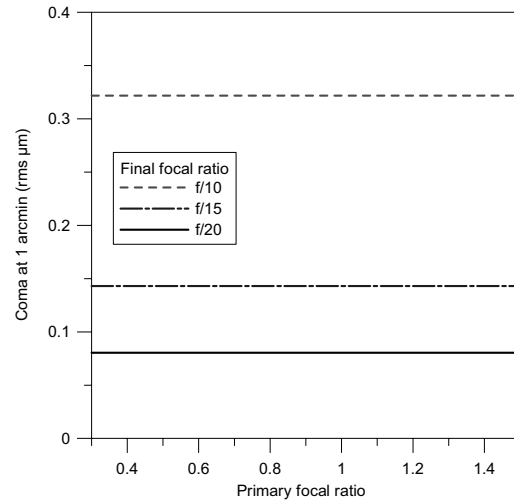
**Figure 11.** Tolerance for axial motion of the secondary mirror, limited by  $1 \mu\text{m}$  rms wavefront error in the form of power.

#### 4. FIELD OF VIEW

The telescope field of view is also affected by the primary mirror focal ratio, but this is not a driving factor for large telescopes. Figures 12 - 13 show how the aberrations of coma, astigmatism, and field curvature depend on the primary focal ratio for a 30-m Cassegrain telescope. The aberrations for a Gregorian type of system are nearly the same, but the field curvature changes sign, changing the focal surface from bowl shaped to dome shaped. This may have advantages for mating to collimators for multi-object spectrographs.



**Figure 12.** Field astigmatism for 30-m Cassegrain telescope at 1 arcminute. This scales with the square of the field.



**Figure 13** Field coma for 30-m Cassegrain telescope at 1 arcminute. (This can be set to zero using a Ritchey-Cretien design.) The magnitude scales linearly with the field.

The field curvature, as shown in Fig. 14, can usually be accommodated by placing the detectors on a curved surface. Otherwise, a set of field lenses can compensate this effect.

The field of view for a large telescope is most likely to be limited by the ability to fill the focal plane with glass and detectors, rather than any limitation from the optical design. We have developed optical designs for fast telescopes, including a 30-m telescope with  $f/0.5$  primary. This Ritchey-Chretien type telescope achieves a huge 10 arcminute field of view with 0.2 arcsecond diameter images with no corrective lenses. This is shown in Fig. 15. By adding three 1.6-m fused silica lenses, the field is corrected over 20 arcminutes to 0.04 arcseconds, and the rays come to focus normal to the curved focal surface. At  $f/8$ , the area of this corrected focal plane is about 18,000 cm<sup>2</sup>. It seems that the cost of placing useful detectors will provide a practical limit to the field of view, rather than limitations in the optical system.

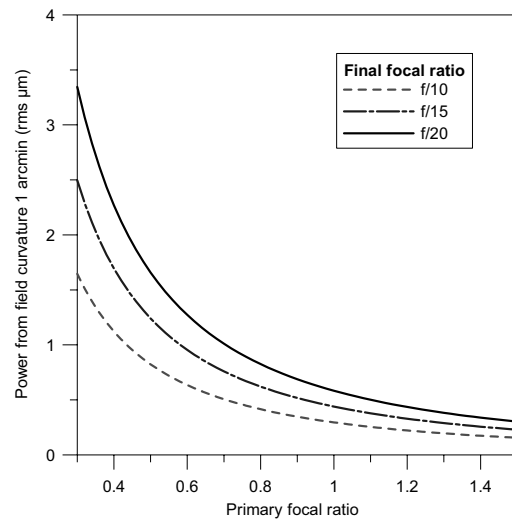


Figure 14. Field curvature for 30-m Cassegrain telescope at 1 arcminute. This scales with the square of the field. The field curvature can always be compensated using a curved focal plane.

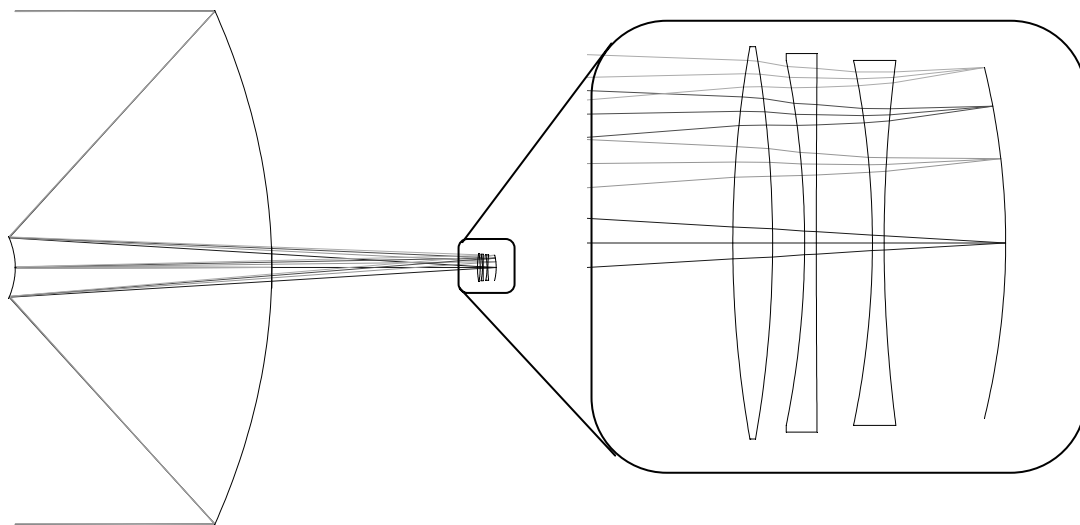


Figure 15. A wide field corrector for a 30-m telescope that has an extremely fast  $f/0.5$  primary mirror. The 20-arcminute field of view is fully corrected to 0.04 arcseconds from 0.38 – 1.3 μm and the rays come to focus normal to the focal surface.

## 5. COATING EFFECTS

It is important to consider possible sensitivity to coating effects for steep telescopes. The mirror coatings in general have a complex refractive index, which gives a different phase shift for the *S* and the *P* polarizations. This causes a polarization sensitive wavefront aberration that is impossible to compensate. These effects were studied for aluminum coatings and were found to be insignificant for the geometries considered. Figure 16 shows the phase shift for *P* and *S* reflection as a function of incident angle for an aluminized surface. The magnitude of the resulting wavefront aberration is shown as a function of primary mirror focal ratio in Figure 17.

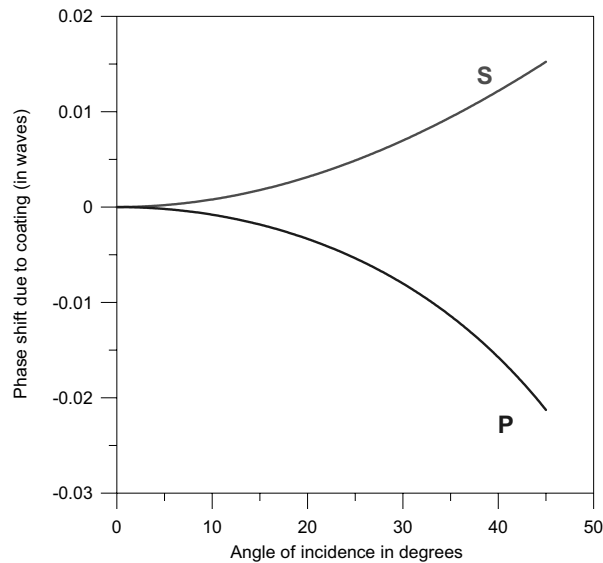


Figure 16. Phase shift from reflection from an aluminized surface.

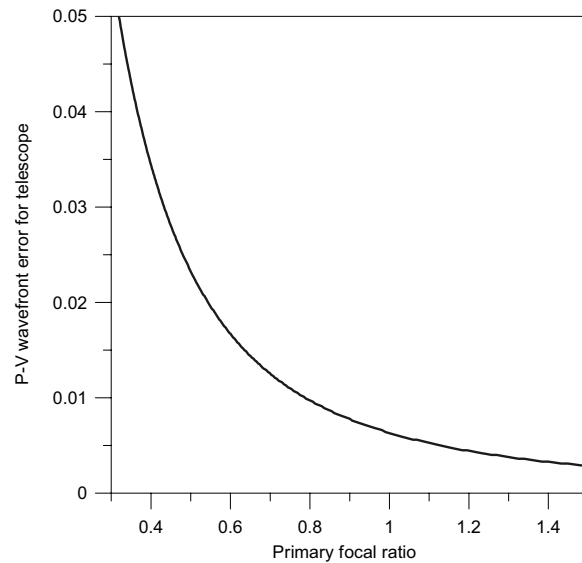


Figure 17. Wavefront aberration caused by polarization phase shift from the aluminized mirrors.

## 6. CONCLUSION

The choice of the primary focal ratio for a giant telescope involves a complicated set of tradeoffs, including the optical fabrication and testing, alignment, operational philosophy, enclosure, and dynamic requirements. However, based on the work presented here there seem to be two different design spaces that both have their merits:

- Several large segments, with active control of phasing, pointing, and shape  
The primary focal ratio for this type of mirror can be pushed to be very fast ( $<f/0.7$ ), thus the telescopes can be short. With only a few of these large segments, each can be polished and measured using the same basic methods as the current 8-m mirrors. The shape is actively controlled, which accommodates fabrication and alignment errors. For a 30-m primary with about 20 eight meter segments, a total of about 400 degrees of freedom require real time control (tip, tilt, piston, and 17 bending modes).
- Numerous small segments, controlled only in pointing and piston  
It is more difficult to push the primary mirror very fast with this type of design. With so many segments, they must be mass produced, which is difficult or prohibitive for the highly aspheric shapes required by very fast mirrors. Also, the control system for such mirror with about 1000 segments has 3000 degrees of freedom just to control the phasing and pointing of the segments, and cannot readily compensate fabrication or alignment errors.

So designers of giant telescopes must make a choice. If they adopt the successful type of design and fabrication methods used for the Keck Telescope, they are driven to a slow focal ratio and must deal with a long telescope and large enclosure. If they adopt the mirror designs using 8-m actively controlled large segments, then they can enjoy the benefits of a faster primary mirror and a smaller telescope.

## REFERENCES

- 1 J. Nelson , "The Keck Telescope", American Scientist, Vol. 77, (1989),
- 2 C. M. Mountain, R. Kurz, J. Oschmann, "Gemini 8-m telescopes project," Proc. SPIE **2199** (1994).
- 3 P. M. Gray, "Assembly and integration to First Light of the Four VLT Telescopes," Proc. SPIE **4004** (2000).
- 4 N. Kaifu, " Status and perspective of the Subaru Telescope Project," Proc. SPIE **2871** (1996)
- 5 S. C. West, et al, "Toward first light for the 6.5-m MMT telescope" Proc. SPIE **2871** (1996).
- 6 S. A. Shectman, "The Magellan Project," Proc. SPIE **4004**, (2000).
- 7 J. M. Hill and P. Salinari, "The Large Binocular Telescope Project," Proc. SPIE **4004**, (2000).
- 8 B. C. Bigelow, A. M. Dressler, S. A. Schectman, H. W. Epps, "IMACS: The multi-object spectrograph and imager for the Magellan I Telescope," Proc. SPIE **3355**, (1998).
- 9 H. M. Martin, J. R. P. Angel, J. H. Burge, S. M. Miller, J. M. Sasian and P. A. Strittmatter, "Optics for the 20/20 telescope", in these proceedings.
- 10 J. Burge, P. Koudelka, "Optical test alignment using computer generated holograms" in *Optical Fabrication and Testing*, (Optical Society of America, Washington DC, 2002) pp. 105-107.
- 11 J. Lubliner and J. E. Nelson, "Stressed mirror polishing. 1: A technique for producing nonaxisymmetric mirrors," Applied Optics 19, 2332-2340 (1980).
- 12 J. Nelson and T. Mast, ed. *Conceptual Design for a 30-Meter Telescope* (Celt Report #34, University of California, June 2002)
- 13 F. Pan and J. Burge, "Efficient testing of segmented aspherical mirrors using a reference plate and computer-generated holograms. 1: theory and system optimization," to be submitted to Applied Optics, (2002)
- 14 F. Pan, J. Burge, D. Anderson and A. Poleshchuk, "Efficient testing of segmented aspherical mirrors using a reference plate and computer-generated holograms. 2: experiment validation, case study and error analysis," to be submitted to Applied Optics, (2002).