

Wide field telescope using spherical mirrors

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ABSTRACT

A new class of optical telescope is required to obtain high resolution spectra of many faint, distant galaxies. These dim objects require apertures approaching 30 meters in addition to many hours of integration per object, and simultaneous observation of as many galaxies as possible. Several astronomical telescopes of 20, 30, 50, even 100 meters are being proposed for general purpose astronomy. We present a different concept here with a 30-m telescope optimized for wide field, multi-object spectroscopy. The optical design uses a fully steerable, quasi-Cassegrain telescope in which the primary and secondary mirrors are parts of concentric spheres, imaging a 3° field of view onto a spherical surface. The spherical aberration from the mirrors is large (about 2 arc minutes) but it is constant across the field. Our system design uses numerous correctors, placed at the Cassegrain focus, each of which corrects over a small field of a few arc seconds. These can be used for integral field spectroscopy or for direct imaging using adaptive optics. Hundreds of these units could be placed on the focal surface during the day to allow all-night exposures of the desired regions. We believe that this design offers an economical system that can be dedicated for several important types of astronomical observation.

Keywords: telescope, optical design, astronomical optics

1. INTRODUCTION

The optical design of the Schmidt telescope is well known to provide excellent images over a large field of view by using a spherical primary mirror and a corrector located at the stop of the telescope at the center of curvature of the primary mirror. By symmetry the images from the primary mirror do not change with field angle – the spherical primary looks the same everywhere. The spherical aberration is corrected with the aspheric corrector at the stop. A Cassegrain type variation of the Schmidt design uses the same spherical symmetry, but also includes a concentric secondary mirror.

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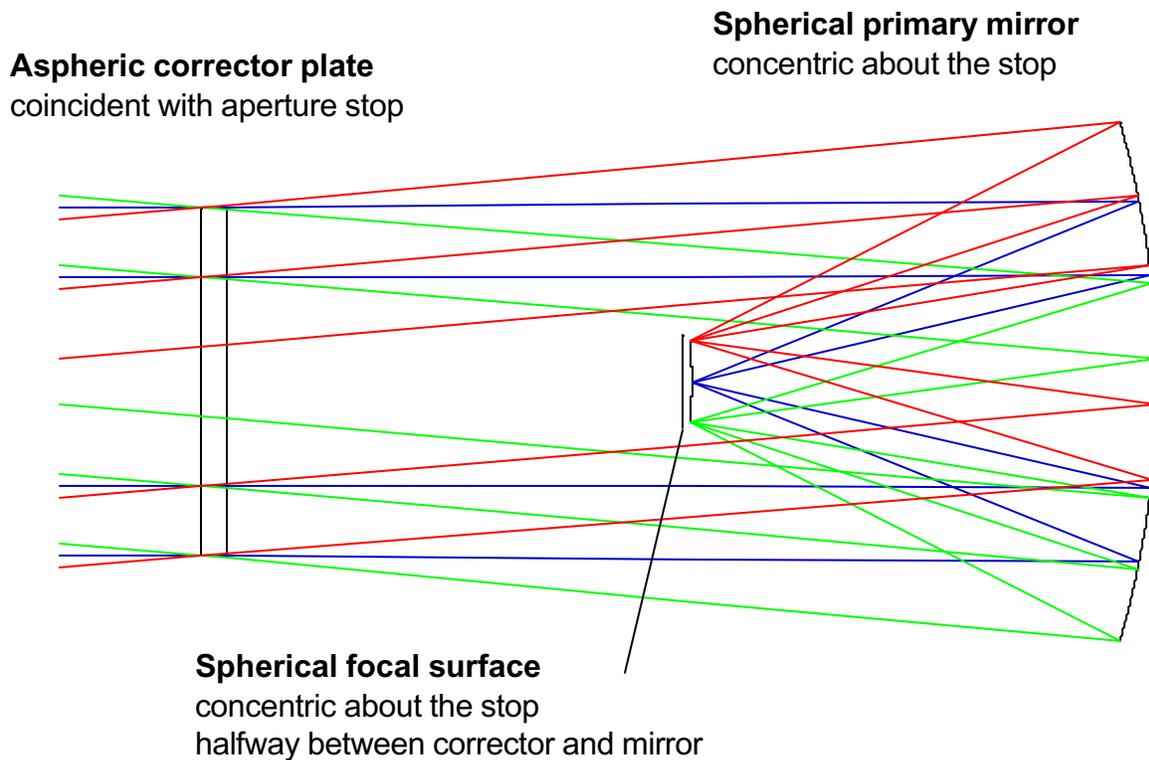


Figure 1. The Schmidt telescope achieves a wide field of view using spherical symmetry. The spherical primary mirror is concentric about the stop. The spherical aberration is corrected with an aspheric corrector placed at the stop.

The Schmidt telescope achieves wide field of view with spherical mirrors, but it is difficult to scale up because of the corrector plate and because of the required length. Transmissive (glass) correctors suffer from chromatic effects and limitations from self-weight deflection. Reflective designs can be scaled up, but the large reflective corrector is extremely difficult to manufacture. Currently, the LAMOST project in China is attempting to solve these problems.¹

The designs for the 11-m Hobby Eberly Telescope² and the proposed 100 meter Overwhelmingly Large (OWL) Telescopes³ use spherical primary mirrors in combination with several large mirrors that correct the spherical aberration and field aberrations. These telescopes violate the spherical symmetry that provides the huge field of view, but they retain the cost and complexity advantages of using primary mirrors with spherical shapes.

The spherical aberration from a Schmidt type telescope can also be corrected by relaying an image of the center of curvature to a smaller, aspheric corrector that is located in a more convenient place.⁴ This is in fact the same principle that was applied for the correction of spherical aberration in the Hubble Space Telescope.⁵ The HST correction was performed for each instrument using an aspheric corrector located at an image of the aberrated primary mirror. This same concept was proposed by Wang and Su², and analyzed by Meinel and Meinel⁶ for the case of a telescope that uses a single spherical primary mirror. An array of small correctors populates the field of the telescope, and each corrector provides a small sub-field for imaging or spectroscopy.

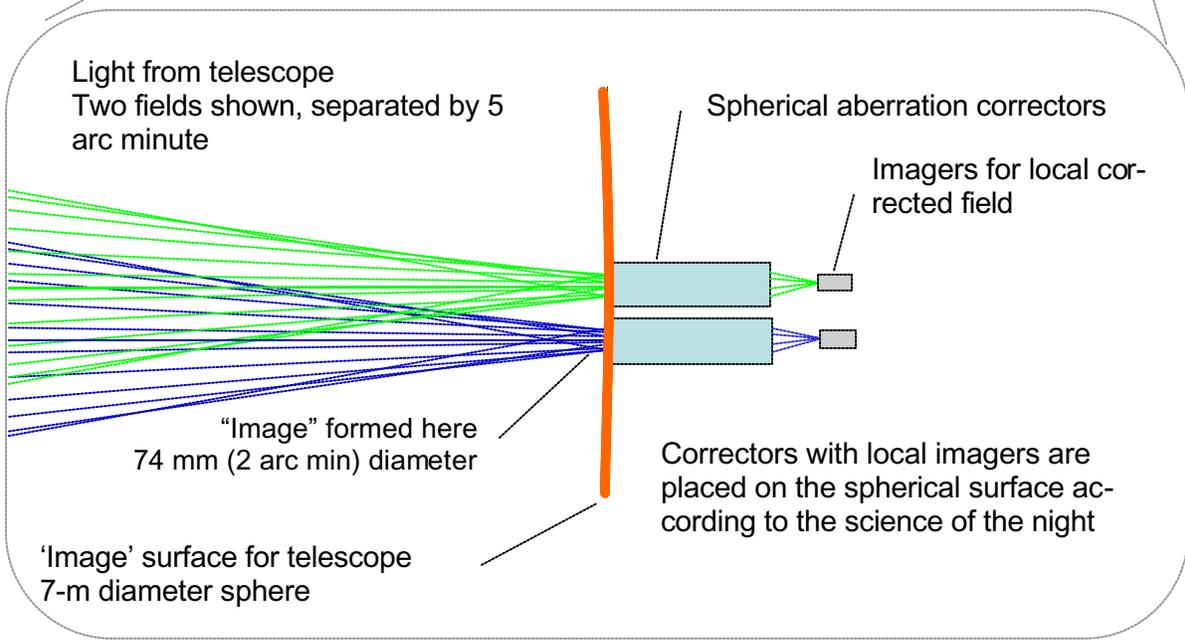
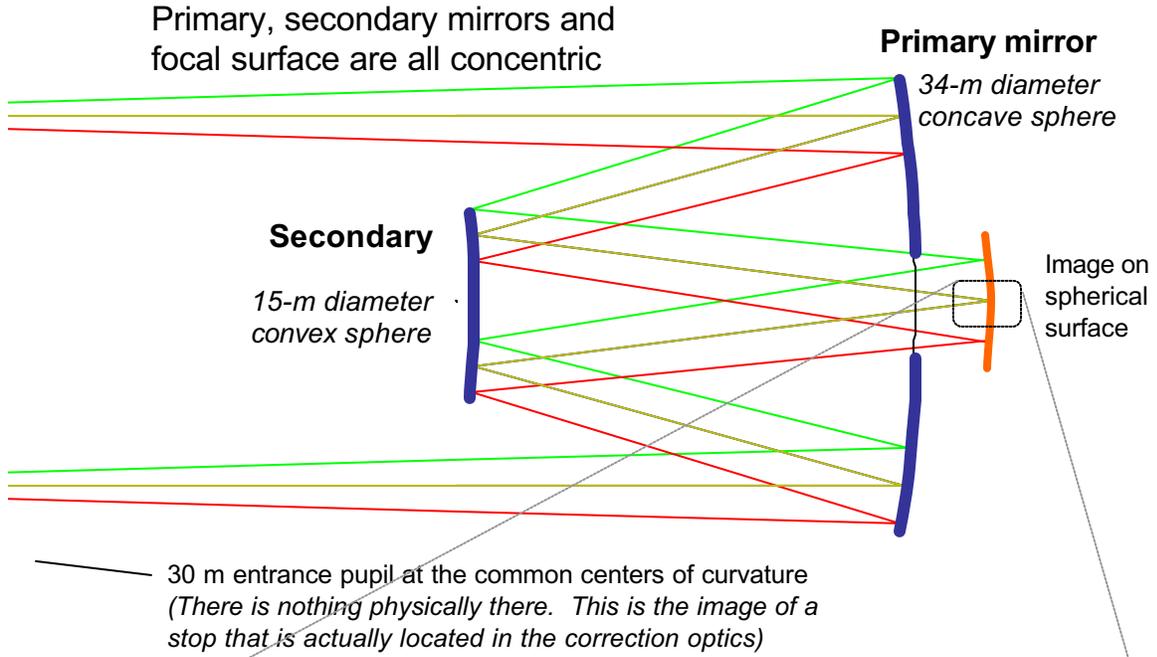


Figure 2. Telescope design for 30-m aperture and 3 degree field of view. The two mirrors create images with 2 arc minute diameter spherical aberration on a 7-m spherical surface. The correctors, shown in the inset, are placed onto the 7-m spherical 'image' surface, and each corrects a field of a few arc seconds.

We now build on this idea to present a much more compact telescope that uses a concentric spherical primary and convex secondary mirror.^{7,8} This combination reduces the overall length of the telescope, moves the focal surface to a more accessible location, and reduces the spherical aberration. This concept is shown in Fig. 2.

In this paper, we present the optical design of a version of this telescope that has a 30 meter aperture. We show a possible application of this telescope for integral field spectroscopy at the seeing limit. We also discuss the use of natural guide star adaptive optics for direct imaging at the diffraction limit

2. OPTICAL DESIGN OF TELESCOPE AND CORRECTORS

The optical design for this system is divided into two sections – the two-mirror telescope and the correctors. We choose the telescope to provide the geometry required. We desire a 3 degree field with blur size of the spherical aberration to be only a few arc minutes. The resulting design shown meets our constraints, but we have not optimized the overall system, including the mounting and building. A more global design approach is likely to change the telescope design. The correctors were chosen to use elements that are about the same size as the spherical aberration blur. This allows close packing of the sub-fields. Again, optimization of the complete telescope system is likely to change these. We present here a starting point.

2.1 Telescope design

The two-mirror system is used to reduce the overall size of the telescope and to balance some of the spherical aberration. The Seidel spherical aberration from the primary mirror alone, W_4 , is calculated as

$$W_4 = \frac{D_p}{512F_p^3} \quad (\text{Eq. 1})$$

Where

F_p = focal ratio of the primary mirror (focal length/aperture diameter)

D_p = primary mirror aperture diameter

The telescope presented here uses a primary mirror with 30-m aperture at $f/2$, so the Seidel spherical aberration from the primary alone is 7.3 mm. With the secondary mirror, the system focal ratio is $f/4.2$.

The spherical aberration for the system is reduced when the spherical secondary mirror is used. The Seidel spherical aberration in the wavefront for the 2-mirror system is

$$W_4 = \frac{D_p}{512F_p^3} \left\{ 1 - \frac{k^4}{\beta^3} \left(\frac{m+1}{m-1} \right)^2 \right\} \quad (\text{Eq. 2})$$

Where

m = magnification of secondary ($=F_{\text{sys}}/F_p$) = $4.2/2 = 2.1$ for the system shown here

$k = D_s'/D_p' = 10.7\text{m} / 30\text{m} = 0.36$

D_s', D_p' = diameter of beamprint on secondary and primary mirror

$\beta = R_s/R_p = 82\text{m} / 120\text{m} = 0.68$

R_s, R_p = radius of curvature of the spherical secondary and primary mirror

So the Seidel spherical aberration from the 2-mirror system is 4.2 mm. This is significantly less than that from the primary itself, but it is still large. This must be compensated by the corrector.

The diameter of the spherical aberration, ϵ , is found by differentiating the wavefront, and is given as

$$\epsilon = 4W_4 F_{sys} \quad (\text{Eq. 3})$$

So the 30-m telescope shown here produces “images” with about 70 mm diameter spherical aberration. Since the system focal length is 126 meters, the spherical aberration corresponds to about 2 arc minutes in object space.

The primary and secondary mirrors are both spherical so the fabrication costs will not be extreme. The issue of segmentation for these mirrors becomes important. If the segments are made large enough, they do not need to be phased for seeing limited observations. This provides a significant relaxation for the system. For the adaptive optics application, the segments will need to be phased.

2.2 Corrector design

For a previous version of this design, we used aspheric refractive correctors. These prove to be extremely difficult to achromatize. So we have adopted a simple 2-mirror corrector, shown in Fig 2. The design of the correctors is straightforward. The first concave mirror (M3) is placed at the telescope focus to create an image of the entrance pupil (the common centers of curvature for the two mirrors) onto the corrector mirror M4. The power for M3 and the spacing between the elements is chosen to make M4 about the same size as M3. The aspheric shape of M3 is optimized to provide a good pupil image onto M4 to maintain the Abbe sine condition. The aspheric shape of M4 is the adjusted to bring light to focus at $f/4.2$. The tilts of the two mirrors allow a clear path for the rays.

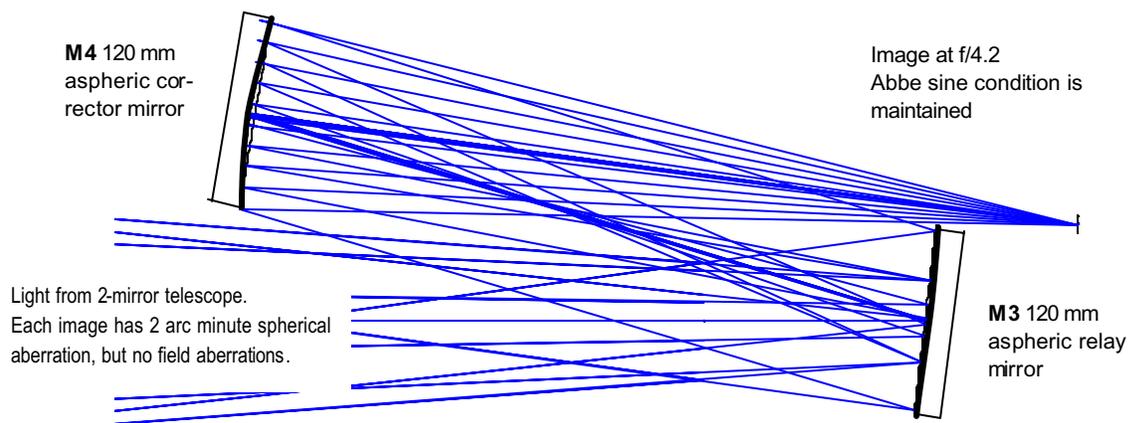


Figure 3. Two- element corrector located at the image of the telescope. Each mirror is about 100 mm in diameter, so the corrector uses an area of the focal plane equal to 3.2×6.4 arc minute.

The design of the correctors uses two aspheric surfaces to simultaneously correct spherical aberration and satisfy the Abbe sine condition, requiring only on-axis rays to be traced.⁹ The first corrector mirror M3 images the entrance pupil (which is at the center of curvature of the primary and secondary mirrors) onto the second corrector mirror M4. M4 is designed to be the aperture stop, so the entrance pupil is imaged to the centers of curvature

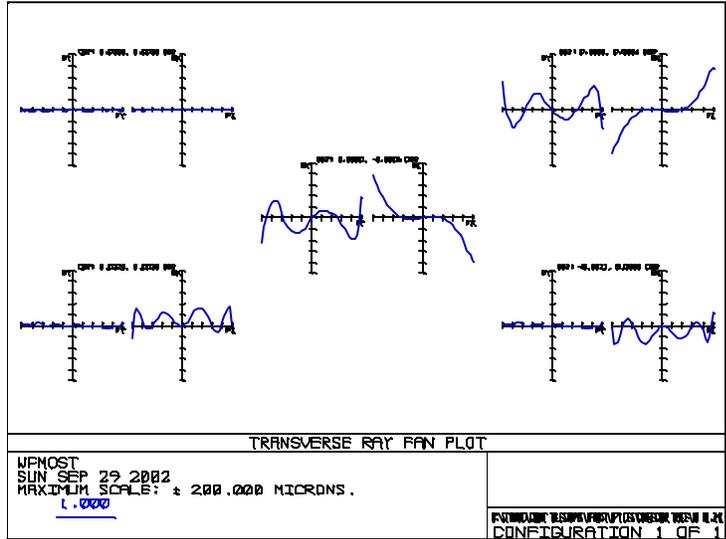


Figure 6. Ray fans for the system showing the limiting image quality in the two directions for the optical system shown above. .

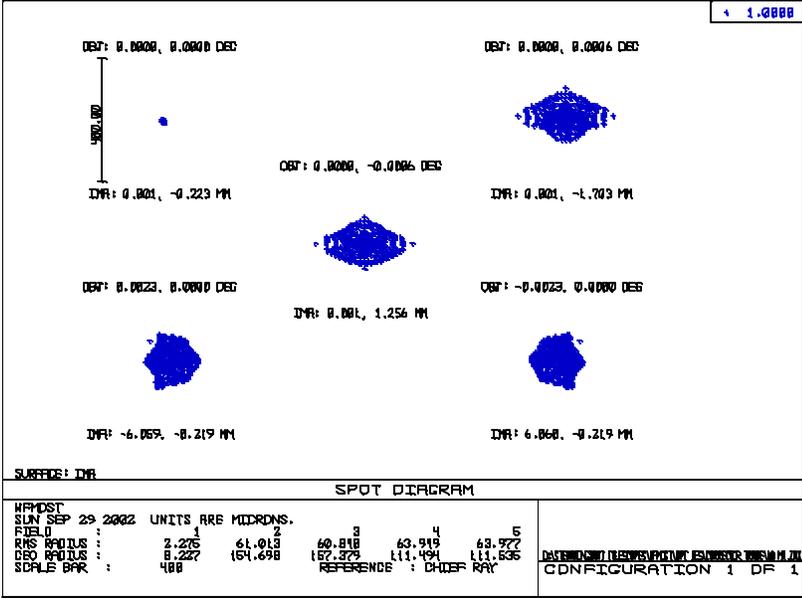


Figure 7. Spot diagrams for the system showing the limiting image quality in the two directions for the optical system shown above. .

The optical performance of the system can be improved by making the mirrors larger. This also has the unwanted effect of limiting the packing for the sub-fields, so this was not chosen. The corrector systems have a footprint of about 240 x 120 mm in the focal plane of the 2-mirror telescope. This means that each corrector uses a local field of view of about 7 x 3.5 arc minute. As shown above, the field of view with excellent correction is 4 x 16 arc second.

3. INTEGRAL FIELD SPECTROSCOPY

Multi-object, integral field spectroscopy is a natural application of this telescope. Each of the sub-fields that are well corrected can be sliced up using mirrors or fibers to feed a spectrograph. Figure 8 below shows how such a system may look using lenslets and fibers. The basic idea here is that each spatial pixel is sent to a spectrograph. Since the system can integrate many hours, high resolution spectra can be obtained.

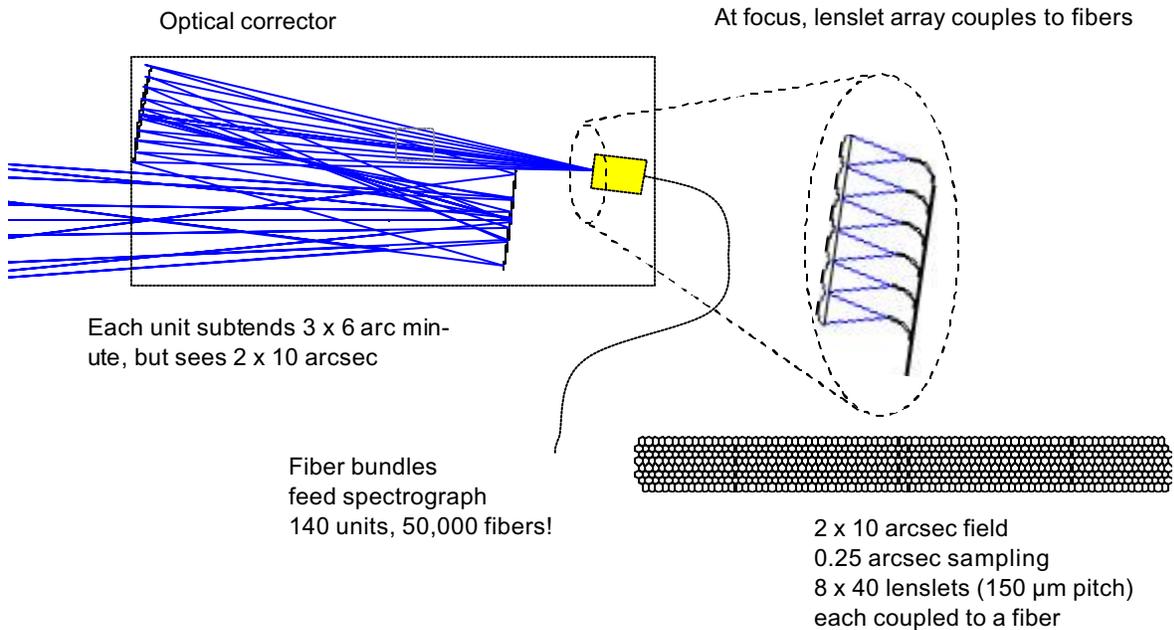


Figure 8. Layout for correctors that use integral field spectroscopy.

Numerous corrector units could populate the focal plane of the telescope, limited only by the need to develop a set of spectrographs capable of handling the potentially huge data throughput.

A single tracking system would maintain the tracking for all of the units at once. The telescope could use a conventional alt-azimuth system for large motions. Small motions for fine guiding could be made by rotating the focal plane about its center of curvature.

4. NATURAL GUIDE STAR ADAPTIVE OPTICS

The telescope design also readily lends itself to making deep imaging observations using adaptive optics at numerous correctors. The correction mirror in the design shown in Section 3 is conjugate to a plane 120 meters above the telescope. If this static mirror is replaced by a deformable mirror, most of the atmospheric aberration can be corrected using adaptive optics. This relies on a bright natural guide star at the center of the sub-field. The limitation on the number of objects that can be imaged is offset by the ability of this telescope to make dozens of simultaneous such observations with many hour exposures.

A preliminary optical design for such a system is shown in Figure 9. This uses a 30 cm deformable mirror, imaged to the common centers of curvature 120 m above the primary mirror

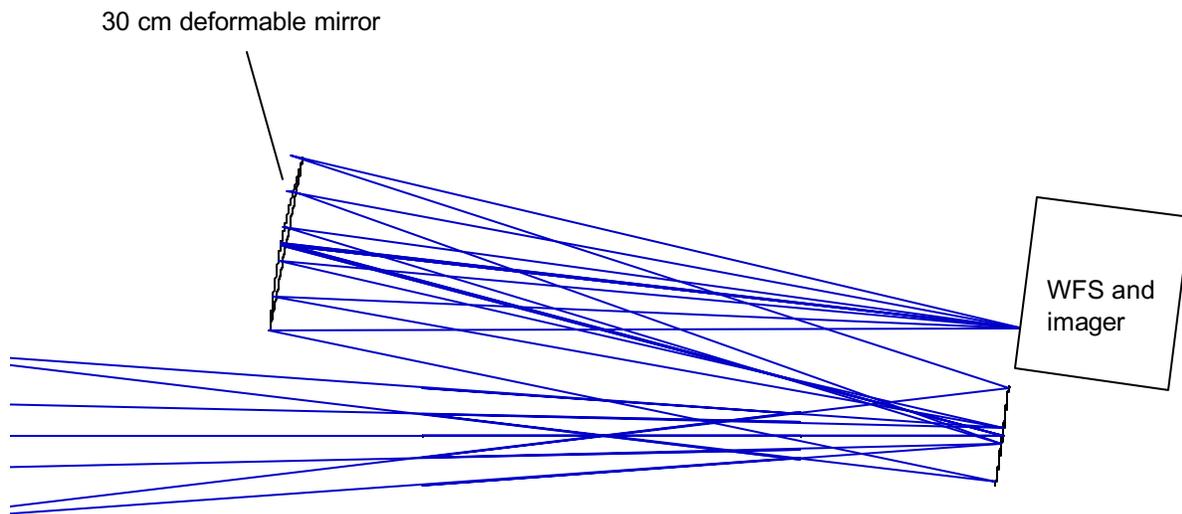


Figure 9. Layout for correctors that use adaptive optics. This allows the system to Look under natural guide star ‘lampposts’ over small corrected field an arc second field with 3 milli-arc second resolution. Again, numerous units can operate simultaneously.

Since even at the galactic poles the 3 degree field contains ~ 4000 stars of 16th magnitude or brighter, the total field area accessible for near infrared diffraction limited imaging is ≥ 0.2 square degrees. The wavefront reference star would be placed at the on-axis “sweet spot” free of residual aberration, and the residual errors of the off axis target object must be corrected by other optics.

The capability to look under many natural “lampposts” at the same time promises a cost effective and reliable way to realize the extraordinary diffraction limited resolution and light grasp of a 30 m aperture. To maximize the scientific return, the 3% of the sky accessible in this way would first be surveyed with smaller wide field telescopes, such as LSST.

5. CONCLUSION

We present a concept for a fully steerable, quasi-Cassegrain telescope, which uses concentric spherical surfaces for the primary mirror, secondary mirror, and focal surface. By symmetry, there are no field aberrations, only spherical aberration which is constant in the field. We correct the spherical aberration over small local fields using correctors. Numerous correctors can populate the focal surface. To achieve a 30-m aperture we use a telescope with 36-m primary mirror and 15-m secondary mirror. The 3° field of view extends over a 7 meter focal surface. The spherical aberration from this system is large (about 2 arc minutes), but many small fields are fully corrected locally using pairs of off-axis mirrors, each are 120 mm diameter.

The corrector concept, which evolved from a Schmidt camera, was first suggested by Aden Meinel. Multiple small units are placed in the focal surface at regions of interest. Each has an optical relay with two aspheric mirror mirrors. The first mirror (M3 in the layout) creates an image of the center of curvature, where the second (M4) is placed conjugate to a classic 30 m Schmidt plate. This surface defines the aperture stop and corrects the spherical aberration. Each corrector set has a 120 x 240 mm footprint (3 x 6 arc minute), 1/1400 of the 3° field, and provides a 0.2 arc second correction over a limited field of 4 x 16 arc seconds.

The system is optimal for integral field spectroscopy, where correctors can be placed corresponding to interesting objects and deep spectra can be obtained with seeing limited spatial resolution. The same telescope can take advantage of adaptive optics if some of the corrector units incorporate a deformable mirror and natural star wavefront sensor. These systems allow simultaneous imaging over small fields of view to the diffraction limit of the 30 m aperture.

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