Exploration of a 14-meter, 1.5-degree field of view, quad-mirror anastigmatic telescope concept for wide-field spectroscopy and imaging

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ABSTRACT

Three mirror anastigmatic telescope designs offer excellent imaging performance in a compact optical structure. The introduction of a fourth, fold mirror allows straightforward access to the image surface of the telescope at a Nasmyth position where instrumentation can be located and easily exchanged. The design presented here is of a 14-meter diameter primary providing a 1.5 square degree field of view with an f/4 focus to a pupilcentric image surface. Two fused silica lenses serve as an atmospheric dispersion compensator, a third field lens forms a large radius pupilcentric image. The optical design gives polychromatic (360-1800 nm) encircled energy diameters (EED) of greater than 80% within 0.25 arc-second diameters across the full field at Zenith. Excellent monochromatic image performance extends through and redward of the K-band (2320 nm). The flat fold mirror, located at a pupil, could be upgraded to an adaptive mirror for image correction and/or GLAO. Image performance is given. We believe that this design offers a very powerful, versatile, and scientifically viable facility suitable for the next generation of ground-based facilities for fiber spectroscopy (~18,000 probes), multi-slit spectroscopy, IFU spectroscopy, and imaging.

Keywords: Massively multiplexed spectroscopic surveys, 10m-class telescopes, optical ghosts, anastigmatic telescopes, telescope design

1. INTRODUCTION

Massively multiplexed spectroscopic facilities have recently been or will soon be implemented on a variety of 4-meter class telescopes (e.g., WEAVE[1], DESI[2], 4MOST[3]). These facilities will enable extensive scientific surveys exploring such questions as the nature of Dark Energy and the structure of the Milky Way galaxy; however, they will remain somewhat limited in the depth of those surveys due to the aperture of their telescopes. Imaging surveys already produce targets fainter than what these spectroscopic facilities can easily observe. The 8-meter class Simonyi Survey Telescope (LSST) of the Vera C Rubin Observatory[4] will also soon flood the field with targets 6 to 7 magnitudes fainter than the background sky. As such, there remains a need for larger aperture facilities for proper spectroscopic follow-up of the targets coming from these surveys.

Although classical Prime Focus and Cassegrain telescope concepts provide good baselines for larger facilities, they risk suffering from optical ghosting with the significant number of transmissive lenses required for aberration correction.[5] Such ghosting may limit the observations of targets significantly fainter than the sky unless the correcting optics are carefully designed to diffuse any optical ghosts generated by the brighter stars imaged within the telescope field of view.

Paul-Baker 3-mirror anastigmatic telescopes[6] offer alternative solutions where the number of transmissive lenses can be significantly reduced. The Simonyi Survey Telescope of the Rubin Observatory[7] is one such anastigmatic telescope. However, for spectroscopic applications, the embedded focus of that design makes spectroscopic instrumentation difficult.

In this paper, we describe a modified Paul-Baker with the secondary (M2) producing an internal focus rather than a collimated beam (as in the Simonyi Survey Telescope design). The tertiary mirror (M3) forms a pupil image back on top of the internal focus where the quaternary mirror (M4) is placed. The flat M4 can be angled to fold the light towards the side and outside of the telescope for spectroscopic instrumentation. This concept is an evolved design of a previously presented concept[8,9] that was initially provided as a possible 1-degree field of view 30-meter telescope. The current

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paper discusses a reduced aperture size with an increased field of view (1.5 degree squared) located at the elevation axis to provide a Nasmyth configuration. We refer to this design as the Quad Mirror or QM design.

2. DESIGN

This design is based upon a 14-meter primary. A version with a 12.5-meter primary is being explored in detail as a viable option for the Maunakea Spectroscopic Explorer (MSE)[10] in which the ADC lens production is more feasible than that presented here. A raytrace schematic of the 14-meter design is shown in Figure 1.

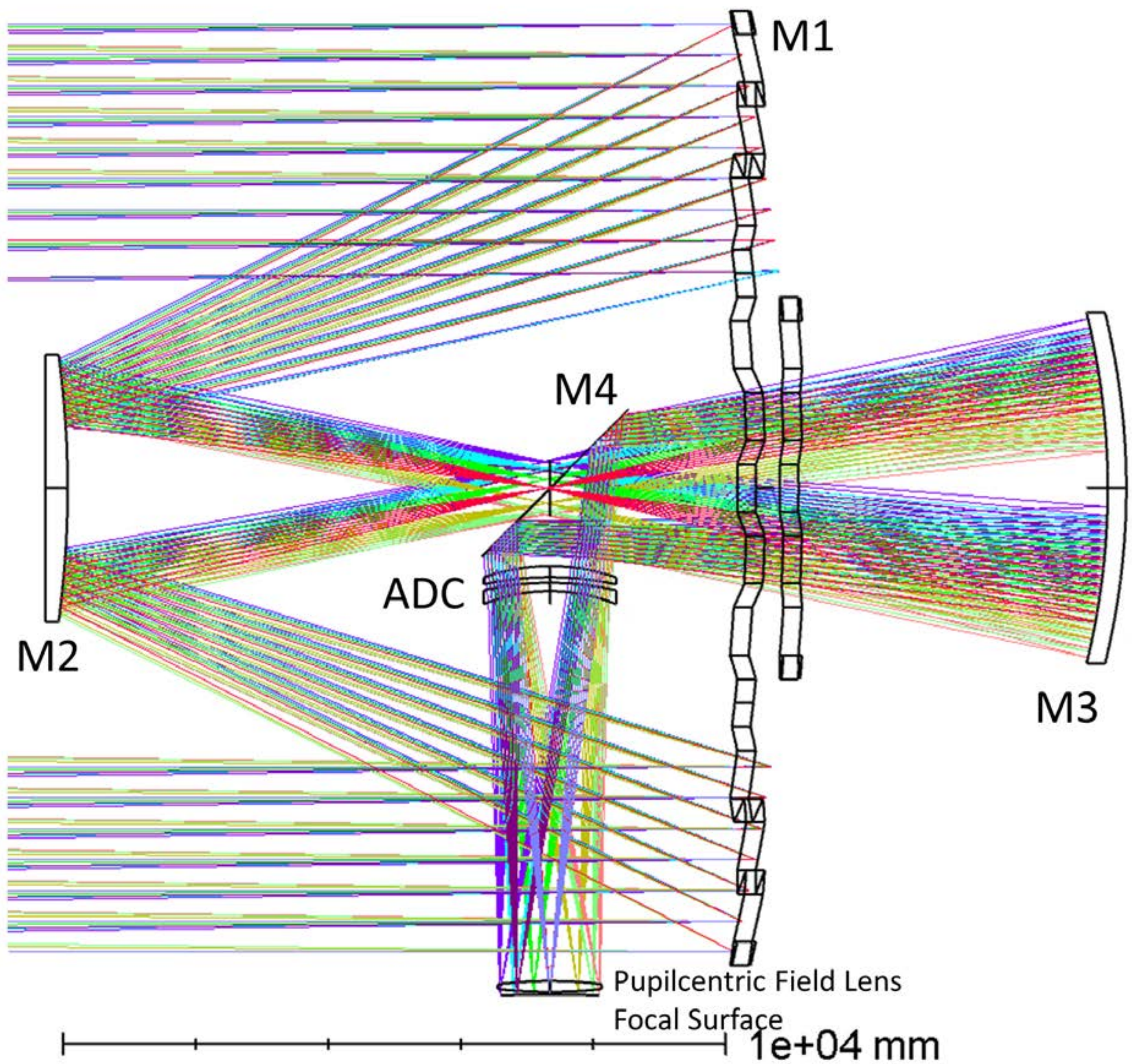

Figure 1. Raytrace schematic of telescope concept showing the four mirrors (M1, M2, M3, and M4), the ADC lenses, and the Pupilcentric Field Lens near the Focal Surface.

The salient features of the 4 mirror, Nasmyth focus are the added versatility of the telescope from the following:

- A Nasmyth focus relaxes gravitational constraints on instruments and allows potential gravitational invariant implementations with an image derotator.

- If the M4 assembly can be rotated, then other instrument ports can be implemented, such as the opposite Nasmyth or possibly ports mounted around the telescope. This could allow contemporaneous access to imaging and IFU style instruments.
- Aberration correction from the mirrors along with minimal fused silica lenses allows the possibility of a very broad wavelength range (330 nm to 2.5 microns).

When freely optimizing the design, the M4 and foci tend to be closer to M2 than M1. While this is good for minimizing the central obstruction, which in this case is set by the field of view, it would make the design unbalanced if the elevation axis were to be aligned with M4 and the focal surface. The designs here were constrained to have the internal focus closer to M1 than M2 which allows a more balanced telescope with the external focus aligned with the elevation axis.

Additional constraints were imposed to keep both the M2 and M4 mirrors smaller than a specified diameter. In this case, the 12.5-meter MSE version imposed a maximum diameter of 4.6 meters for either of the two mirrors. This is due to the need to make these mirrors monolithic rather than segmented due to constraints of asphericity for possible mirror segments. Handling constraints within the proposed MSE facility imposed the diameter constraints without the facility exceeding design objectives for repurposing the Canada France Hawaii Telescope (CFHT) building on Maunakea.

The TMT/ELT mirror segment technology imposed further constraints on the design. Peak to valley (PV) asphericity for a given segment is limited by the testing process and is restricted to of order 400 microns for interferometric testing. This imposed constraints on both the radius of curvature and the conic/aspheric values for the M1 primary mirror. Additionally, current segment mounting designs place an additional constraint that the radius of curvature must be greater than approximately 23 meters.

Other constraints are imposed by the diameters of the ADC lenses and field lens. The sizes required limit glass options to fused silica and/or BK7 glass types. Fused silica was selected given its broad spectral transmission window compared to BK7.

The final focal ratio is another constraint necessary to keep the focal surface and optical sizes minimal, but also to provide a reasonable value to keep fiber optic focal ratio degradation at an acceptable minimum. Too fast of a focal ratio will increase lens sizes and will want to pull the focus inside the incoming telescope beam. Too slow and the field lens grows too large.

The 14-meter diameter design pushed against all these constraints. Although it produces great images, the monolithic mirrors were too large. Hence the need to shrink the overall telescope to a ~12.5-meter primary for MSE consideration. In this case, the telescope parameters met all the imposed constraints while maintaining the same level of image quality.

Conic Options for M2

This family of anastigmats has solutions in which the secondary (M2) is hyperbolic ($k \approx -6.0$) and has solutions where it can be spherical ($k = 0$). For the hyperbolic solution, M1 tends to be nearly parabolic with k in the range of -0.8 to -1.0 and M3 at $k \approx -0.35$. The spherical M2 solution lowers M1 to about $k \approx -0.6$ and raises M3 to a $k \approx -.45$. The spherical solution also preferentially pushes the internal focus towards M1. Unfortunately, the aberration correction is not quite as exquisite from balancing the three mirrors. Inclusion of the ADC and field lens optics appear to require aspheric surfaces on some of the lenses to bring the image quality in line with the hyperbolic M2 design. Inclusion of these aspheric surfaces actually provides markedly better images than from the hyperbolic design, even if aspheric surfaces are included in the hyperbolic design.

A spherical M2 is likely much easier to produce than the hyperbolic secondary, but the hyperbolic solution is currently viewed as the preferred solution since quite good images are achieved with the spherical ADC and field lenses.

The other drawback of the spherical M2 arises from the design preferring a faster focal ratio that increases the diameter of the ADC optics by around 20%.

There also appears to be possible solutions with M2 as an oblate ellipsoid with conic values around +6.0. This design family has not been explored.

Table 1 gives the parameters for representative designs of both the hyperbolic and the spherical secondary options.

Table 2. Optical parameters for the QM designs. Both hyperbolic and spherical designs are given. The aspheric column shows the level of even aspheric terms used for the back surfaces of both ADC lenses in the spherical design in addition to non-zero conic terms.

		Hyperbolic M2				**Spherical M2**			
Component	**Material**	**Diameter (meters)**	**Radius (meters)**	**Conic**		**Diameter (meters)**	**Radius (meters)**	**Conic**	**Asphere**
M1 Primary		14.0	29.1	-0.88		14.0	29.1	-0.59	
M2 Secondary		4.0	14.5	-6.29		5.0	31.3	0.00	
Internal Focus		0.9				0.7			
M3 Tertiary		5.4	11.0	-0.37		6.0	10.2	-0.44	
M4 Quaternary		2.1 x 3.1	Plano	0		2.7 x 4.2	Plano	0	
ADC Lens 1	Fused Silica	2.0	3.1/4.7	0		2.4	3.0/2.7	-0.06	10th order
ADC Lens 2	Fused Silica	2.0	4.1/2.6	0		2.4	2.7/2.9	0.03	10th order
Pupilcentric Field Lens	Fused Silica	1.6	6.6/-6.8	0		1.3	3.3/2.7	0	
Focal Surface		1.5	34.7			1.1	4.5		
Focal Ratio / Plate Scale		f/4.0 / 272 μm/arc-second				f/3.1 / 208 μm/arc-second			

3. PERFORMANCE

Both designs provide excellent image quality for fiber fed spectroscopy with greater than 85% polychromatic (lambda 0.36 to 1.8 μm) encircled energy within 0.25 arc-seconds diameter at zenith across the full 1.52-degree linear field of view. The spherical M2 with high order aspherics on the back side of the two ADC lenses gives somewhat better concentration with 90% polychromatic encircled energy within 0.25 arc-seconds.

The polychromatic encircled energy plots are shown for both designs in Figures 2 and 3. Included in those figures are the spot diagrams as a function of field position (0 to 0.76 degrees radial location) and Zenith Distance (0 to 70 degrees).

The ADC performance is quite good given that the only material in use is Fused Silica. The ADC lenses are slightly wedged and counter rotated to perform the correction. Figure 4 shows the encircled energy and spot diagrams for the extended wavelength range of 0.33 to 2.32 μm.

Alignment of the pupil to the normal of the curved focal surface is excellent in both cases as well. The spherical M2 design gives optimum performance at a much shorter radius of curvature for the focal surface. This makes the hyperbolic M2 slightly more advantageous.

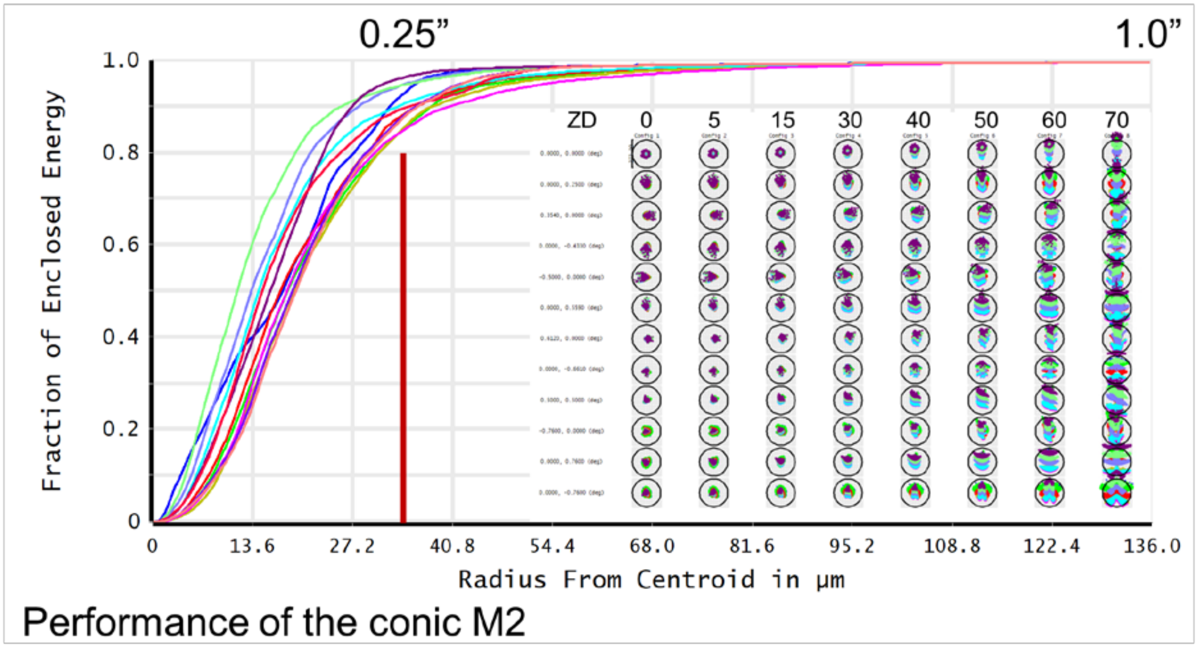

Figure 2. Hyperbolic polychromatic encircled energy versus image radius at range of field angles for Zenith Distance of 0 degrees plus Spot Diagrams versus field angle and Zenith Distance for 360-1800 nm wavelength.

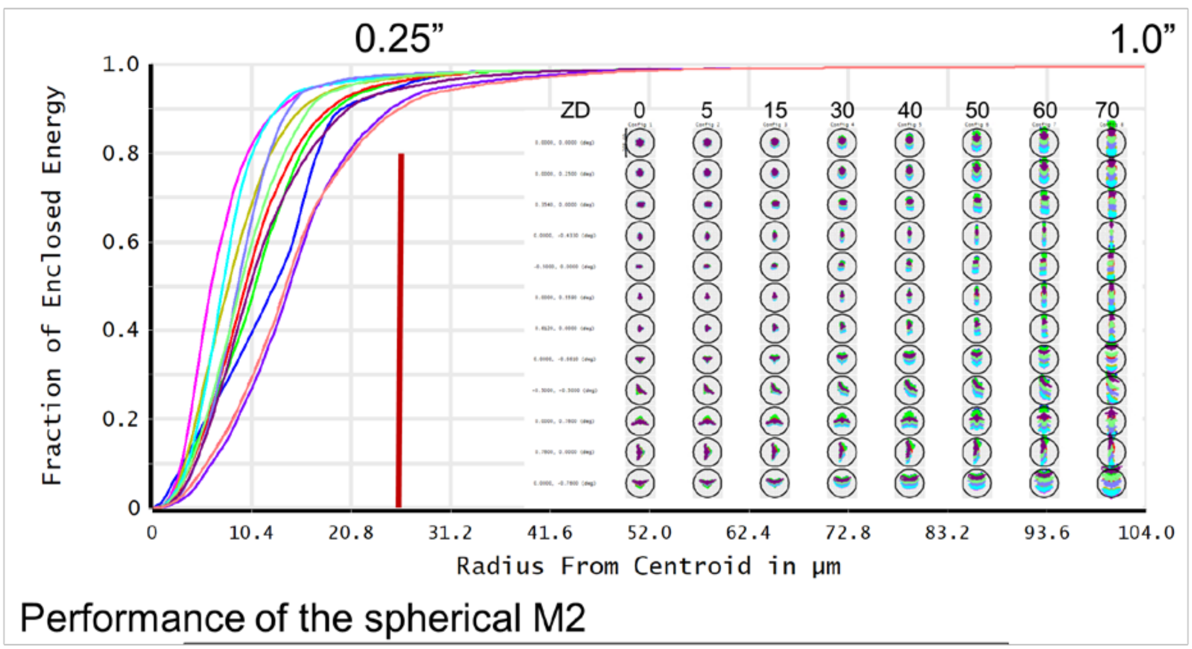

Figure 3. Spherical M2 polychromatic encircled energy versus image radius at range of field angles for Zenith Distance of 0 degrees plus Spot Diagrams versus field angle and Zenith Distance for 360-1800 nm wavelength.

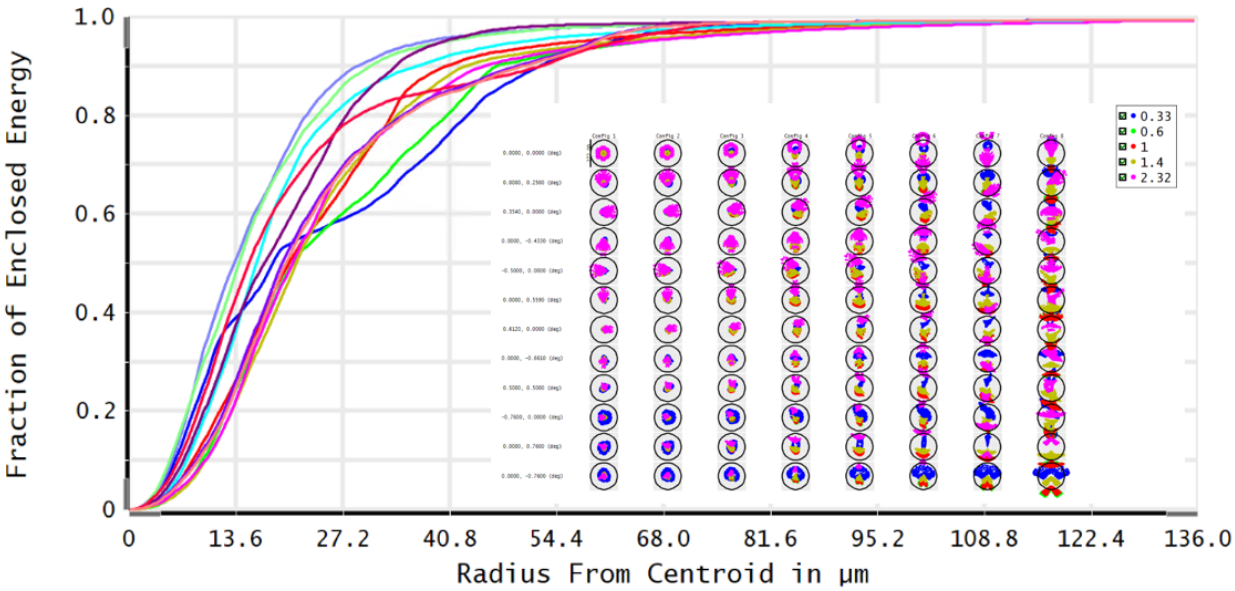

Figure 4. Hyperbolic M2 polychromatic encircled energy versus image radius at range of field angles for Zenith Distance of 0 degrees plus Spot Diagrams versus field angle and Zenith Distance for 330-2320 nm wavelength. Note that the design was not optimized for this broadened wavelength span.

4. CONCLUDING COMMENTS

This QM concept, a 3-mirror anastigmat with a fold mirror, can provide a relatively large field of view located at a Nasmyth with excellent image quality suitable for seeing limited instrumentation. Some of the positives and negatives of this concept are summarized here:

+ Excellent chromatic imagery requiring only transmissive lenses for atmospheric dispersion correction and alignment of the pupil with the final focal surface.
+ The spectral window could extend from the UV through the K-band in the infrared and further if the ADC is not required.
+ Instruments can be located off the telescope with only a radial variation in gravitational loading or where a field derotator can be implemented to fully fix the instrument with respect to gravity.
+ The fold mirror can be rotated to direct the light to other instrument ports (a second Nasmyth plus small ports mounted to the telescope) for easy instrument exchange and increased versatility of the telescope facility.
+ High order, non-conic aspheric surfaces can be avoided.
+ The folded design makes the concept shorter than a prime focus configuration, allowing the enclosure to be smaller.
+ The presence of a flat fold mirror located at a pupil opens the prospect for ground layer adaptive optics.
+ The presence of the internal focus allows additional locations for optical alignment and test/calibration equipment.
+ If high performance, UV enhanced silver coatings can be applied to the large monolithic mirrors, or if those mirrors could also be segmented, the efficiency of the telescope can be greatly improved to be competitive with telescopes containing fewer mirrors.
+ Fiber fed instruments likely have shorter fiber runs from Nasmyth than from either Prime Focus or Cassegrain telescope mounted instruments. This is important for the blue performance and could recoup losses in the blue due to the larger number of mirrors in the QM design.
+ The orientation of the large ADC and field optics is such that for Nasmyth instruments, the lenses only encounter radial gravitational loading, not axial. This likely eases risk with such large optics. Additionally, a

central shadow in the light beam resides at the ADC lenses where axial supports could be provided at the lens centers.

Negative aspects are:

- The design utilizes four mirrors compared to one for a Prime Focus configuration and two for a Cassegrain configuration. This could reduce efficiency.
- The field of view dominates the central obstruction and ultimately limits the size of the workable field of view without increasing vignetting losses.
- The natural design solution tends towards rather large M2 and M3 mirrors.
- The design may be more massive than a Prime or Cassegrain telescope given the additional mirror optics.
- The ADC and field lenses are large.

All in all, we believe that the QM concept offers significant advantages over a prime focus telescope and over Cassegrain telescopes primarily due to the ability to locate the instruments at the elevation axis. It is limited in the potential field of view, however, the focal ratio provides a larger plate scale that allows a denser population of spectroscopic slits or probes than f/2 telescopes. The large aperture could make for a facility that can reach to further depths in target brightness.

5. ACKNOWLEDGEMENTS

This study arose from an exploration of alternative telescope concepts for the Maunakea Spectroscopic Explorer (MSE) Project.

About the Maunakea Spectroscopic Explorer Project

The mission of the MSE Project is to realize a dedicated facility that enables a diverse suite of large-scale spectroscopic surveys of millions of astrophysical objects at a range of wavelengths, spectral resolutions, redshifts, and spatial scales.

MSE is the first planned project among the future generation of massively multiplexed spectroscopic facilities. MSE is designed to enable transformative science, being completely dedicated to large-scale multi-object spectroscopic surveys, each studying thousands to millions of astrophysical objects. At a minimum, MSE will use an 11.25 m aperture telescope to feed 4,332 fibers over a wide 1.52 square degree field of view. It will have the capabilities to observe at a range of spectral resolutions, from R~3,000 to R~40,000, with all spectral resolutions available at all times across the entire field. Alternate facility architectures are under evaluation with insight from participants' national strategic planning priorities along with technical feasibility. Engineering development is supported by a culturally and geographically diverse design team that is centrally coordinated and managed by the Project Office. We are cognizant that the decisions we make today are intertwined with the future of Maunakea and its cherished summit. The MSE Project deeply respects its cultural importance and storied past.

The MSE Project is hosted by the Canada-France- Hawaii Telescope Corporation, and supported by contributing organizations in Canada, France, Hawaii, Australia, China, India, South Korea, Texas, the UK, and the US. The MSE collaboration recognizes the cultural importance of the Maunakea summit to a broad cross-section of the Native Hawaiian community, and is committed to equity, diversity, and inclusion.

Statements of MSE's mission, cultural respect, and equity, diversity and inclusion are available on https://mse.cfht.hawaii.edu.

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