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ABSTRACT

We aim to build a new tertiary mirror (M3) and its mount for the 10 m Keck I (K1) telescope at the W. M. Keck Observatory (WMKO) to make its full observational capabilities available for time-sensitive scientific programs.. In contrast to the existing tertiary mirror and mount, the device will rapidly deploy and rotate the mirror to any instrument at a Nasmyth focus or, as desired, stow the mirror out of the light path to permit observations at the Cassegrain focus. In this manner, the K1 deployable tertiary mirror (K1DM3) will enable observations with any of the K1 instruments on any given night, and at any given time. The K1DM3 device will be integrated within the K1 telescope control system and WMKO has committed to a new operations model that takes full advantage of this new capability.

Keywords: Time domain, Keck telescope, tertiary mirror

1. INTRODUCTION

A major thrust of astronomy in the 21st century is to study, observationally and with theoretical inquiry, time-variable phenomena in the night sky. This area is broadly referred to as time domain astronomy (TDA) and its high scientific priority was established by the Astro2010 report (National Research Council, 2010). Their highest recommendation for large telescope ground-based observing, for example, is to build the Large Synoptic Survey Telescope (LSST). In advance of that ambitious project, several projects are using wide-field cameras to image large areas of the sky at high cadence. This includes the Palomar Transient Factory (PTF) and the Pan-STARRS surveys which repeatedly image the full northern sky, finding hundreds of new transient phenomena on every clear night. These surveys are discovering *thousands* of supernovae, immense samples of asteroids and near-Earth objects, variable stars of diverse nature, flaring phenomena, and other exotic sources. These advances in TDA observing at optical wavelengths follow decades of TDA science performed at higher energies from space. Indeed, the first astronomical sources detected with γ-rays were themselves transient phenomena: the so-called γ-ray bursts (GRBs; Klebesadal et al., 1973). Satellites like *Swift* and *Fermi* monitor ≈π steradians of the sky, scanning for transient and variable high-energy events.

The focus of most previous and on-going TDA projects has been wide-field imaging of the sky in search of infrequent and new classes of events. In part, this is because the phenomena are relatively rare. To fully explore and exploit the astrophysics of newly discovered sources, however, one must establish the redshift and/or the type of star responsible. Optical and infrared wavelengths remain the most powerful and efficient passbands to perform the spectroscopy. This is the primary role of large, ground-based observatories in TDA science. Recognizing their value, several 8 m-class observatories have established very effective observing strategies (generally at great expense) to perform such science. Both the Gemini and European Southern Observatories (ESO) designed their largest telescopes with systems that could rapidly feed any of the available foci. Furthermore, they have designed queue operations to enable rapid responses to targets-of-opportunity (ToOs) and programs that repeatedly observe a source for short intervals at high cadence. Successes of this model include time-resolved spectroscopy of varying absorption lines from a GRB afterglow on minute time-scales (Vreeswijk et al., 2007) and high-cadence monitoring of the Galactic center to recover high fidelity orbital parameters (e.g. Gillessen et al., 2011).

The W.M. Keck Observatory (WMKO) boasts twin 10 m telescopes, currently the largest aperture, fully-operational optical/IR telescopes. Over the course of the past ~20 years, WMKO has successfully instrumented each telescope with high-throughput imagers and spectrometers spanning wavelengths from the atmospheric cutoff to several microns. The Keck I (K1) telescope hosts the Nasmyth mounted HIRES spectrograph (Vogt et al., 1994), one of the primary tools for obtaining high resolution visible wavelength spectra from TDA observations. K1 also hosts the Nasmyth mounted Keck I adaptive optics (AO) system which is receiving a laser guide star (LGS) upgrade and will soon host the near-IR integral field spectrograph OSIRIS (Larkin et al., 2006), a key tool for synoptic observations of the Galactic center. At

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Cassegrain, K1 hosts both the LRIS multi-object visible wavelength spectrograph (Oke et al., 1995), and is now home to the near-IR multi-object spectrograph and imager MOSFIRE (McLean et al., 2010). This is a unique instrument suite, especially within the US community: the HIRES spectrometer is the only echelle spectrometer on a large aperture telescope of the northern hemisphere; LRIS provides extremely sensitive spectroscopy especially at blue (<4000A) and red (>8000A) wavelengths, and MOSFIRE represents a unique capability of multi-slit, near-IR spectroscopy for the US community in the northern hemisphere.

Presently, K1 cannot switch rapidly between instruments, especially between Nasmyth and Cassegrain focal stations which requires the installation (or removal) of the tertiary mirror module. This limits any TDA investigation to a single instrument on a given night. Furthermore, it is essentially impossible to design an observing campaign to study a set of objects at high cadence (e.g., relatively short observations every night). The K1 deployable tertiary (K1DM3) will directly address these shortcomings, enabling Keck to fully and vigorously participate in TDA science with its unique set of instruments. This is especially critical in a regime when other facilities are being overwhelmed by the rate of transients discovered from imaging surveys.

2. SCIENCE MOTIVATION

2.1 Targets of Opportunity (ToOs)

There are a small but extremely valuable set of astrophysical phenomena that appear and then disappear on time-scales of hours to days. These transient events include the deaths of massive stars (GRBs), the flares from tidally disrupted stars, and the chirps of merging compact objects. These sources are random both in time and position on the sky and therefore require one to interrupt any planned observations to capture their fleeting light. Therefore, one needs the flexibility to match the proper instrumentation with the event to fully reap the science. We now discuss a few examples.

GRBs: The most active area of ToO science at present is the study of gamma-ray bursts (GRBs). In addition to the brief emission of γ-rays that announce these events, the majority of GRBs exhibit afterglows of longer wavelength emission. In the optical (typically the rest-frame UV for the GRB), the afterglows have peak apparent magnitudes of ~16(20) mag for the long (short)-duration events at t ~10 min fading rapidly (Figure 1). It is critical, therefore, to observe these events during the same night that they are discovered.

At WMKO, the primary ToO activity for GRBs is to obtain high-fidelity spectra of these afterglows. Indeed, the spectrum that first and firmly established that long-duration GRBs are extragalactic sources came from Keck/LRIS (Metzger et al., 1997). Modern programs of GRBs pursue a wide range of scientific goals that include (i) constraining the physical properties of the gas within the high z, star-forming galaxies that host the events (e.g. Prochaska et al., 2007, 2008; Fynbo et al., 2009); (ii) analyzing the intergalactic medium in a complementary manner to traditional quasar spectroscopy (e.g. Prochter et al., 2006); (iii) exploring the epoch of reionization (the z>7 universe; Kawai et al., 2006; Tanvir et al., 2009); and (iv) establishing the energetics of the GRB population (e.g. Butler, Bloom, & Poznanski 2010). For the short-duration GRBs, the community still awaits the first optical spectrum that would likely confirm their extragalactic nature and hopefully give fresh insight into their origin.

The principle gain of K1DM3 to GRB ToO observations would be to match the afterglow brightness and color with the appropriate instrumentation on K1. Ideally, one would observe V<18mag sources with Keck/HIRES to optimally resolve the many absorption lines associated with the GRB host galaxy. For sources at z>6 (or highly reddened events), near-IR spectroscopy is essential and MOSFIRE is the preferred instrument. Lastly, the faintest optical sources (R~23) demand the high throughput of LRIS. With K1DM3, one would optimally match the properties of any ToO to the instrument suite, perform the ToO, and then quickly return to the original observing plan for that night. Together with the existing programs on the Gemini telescopes, the combined activities would enable the US community compete successfully with the VLT in this field and provide complementary time coverage on key sources.

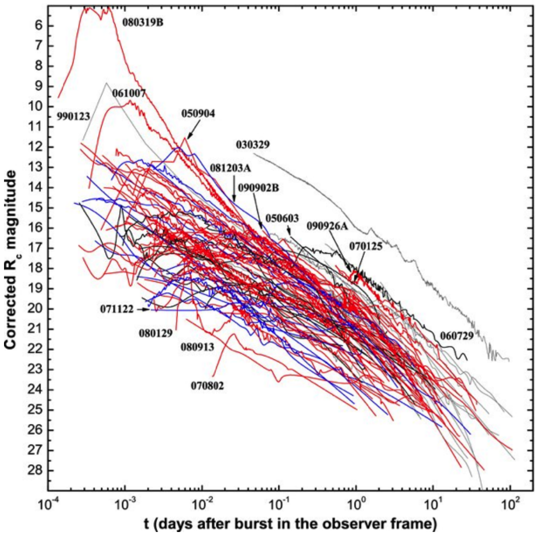

Figure 1. GRB light curves in the optical demonstrating the extreme brightness of these events and their rapid decay times (from Kann et al., 2011).

Tidal Disruption Flares: In the past few years, astronomers have detected flares believed to arise from stars that were tidally disrupted by a massive black hole (MBH) at the center of nearby galaxies (Figure 2). In these events, the emission is dominated by the UV/optical light arising from the fallback accretion of the stellar bound debris (Gezari et al, 2009). Ongoing optical and high-energy experiments and future radio observations are predicted to discover 10 to 100 such events per year, each fading on timescales of days to weeks (e.g. Strubbe & Quataert 2009). Follow-up observations with the suite of K1 instruments would precisely establish the position of the source and provide spectral diagnostics of the emission, which helps elucidate the demography of massive black holes in the local Universe (Rees 1988). These observations further test Einstein's theory in the strong field regime.

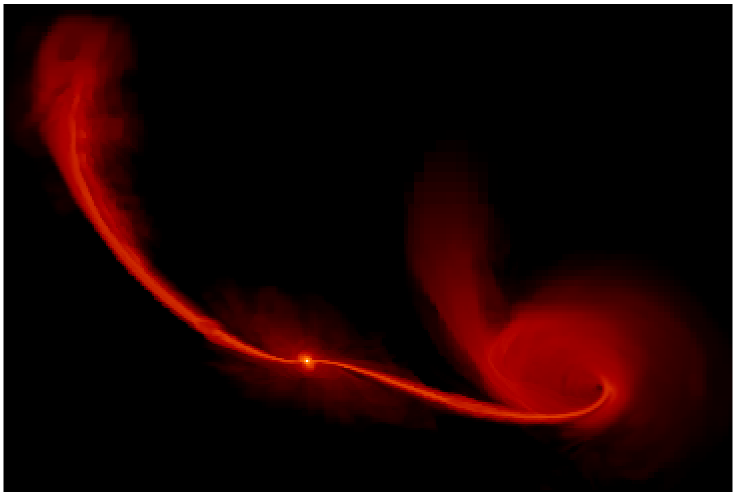

Figure 2. Disruption of a solar-mass star by a 10^6 M_{Sun} black hole where the star survives the encounter. In the tidal disruption of a star by a black hole, roughly half of the ejected stellar mass becomes bound and falls into the black hole, while the other half is ejected at high velocity. The emergent radiation may have a strong dependence on the structure and orientation of the accreted bound debris.

Gravitational Waves (GWs): If the merger described above had involved two stellar mass black holes, the primary emission would have been gravitational waves. Indeed, funded upgrades to the LIGO experiment should achieve sufficient sensitivity to provide direct detections of such events by the year 2018. The discovery and exploration of the electromagnetic (EM) counterparts to GW events would represent a crown jewel for the US community, one that would follow on over $1B of NSF investment.

Given its tremendous scientific import, there will be a significant investment of Keck users in pursuing the GW-EM connection. Starting in 2015 (culminating with full sensitivity in 2018), GW events from the merger of stellar mass remnants are expected to be readily detectable by Advanced LIGO (funded by the NSF), and upgraded VIRGO, and the Japanese LCGT. At advanced sensitivities for a three detector LIGO-Virgo network, predicted "realistic" event rates range from several tens to hundreds of sources per year (Abadie et al. 2010). Because the localizations of such events will be poor (20-100 square degrees at 90% confidence; Fairhurst 2011), wide-field imaging surveys (e.g. PTF2, SkyMapper, LSST) will be used to identify potentially dozens of possible optical candidates and spectroscopic follow-up with large-aperture telescopes will be critical to confirm candidates. K1DM3, on the K1 telescope, will enable such ToO activity on any clear night, most likely with the low-dispersion LRIS or MOSFIRE spectrometer.

Identifying the precise position via an EM counterpart is critical for breaking degeneracies inherent in the chirp signal (Nissanke et al. 2011) and understanding the nature of the progenitors/surroundings of the event. Importantly, since GW signatures encode luminosity distance but not redshift, an EM counterpart enables the use of such events as precision standard sirens (Schutz 1986, Holz et al. 2005, Dalal et al. 2006). Independent of the cosmological distance ladder and other systematics that plague traditional standard candles, the possibility of measuring H_0 to a few percent accuracy, with only an appeal that General Relativity correctly describes the GW emission and evolution, is a compelling impetus. Precisely *what* will be seen in the EM sector is not known for sure. GW event rates are informed by a potential connection to short-hard gamma-ray bursts (SHBs; see Bloom et al. 2006) which implies a coincident afterglow event. Such afterglows within the LIGO volume would be bright initially (R~18 mag for the first 10 minutes) but then fade rapidly as t^{-1} to t^{-2}.

Microlensed Stellar Spectroscopy: The OGLE and MOA surveys monitor more than 100 million stars in the Galactic bulge. Together they issue about 800 alerts for microlensing events a year. A small fraction of these (roughly 10 events/year) have maximum magnification (brightness amplification) factors in excess of 100, which boosts the brightness of a normal bulge dwarf into the range accessible to high dispersion observations with the Keck Telescopes. This offers us a new window into the Galactic bulge stellar population in which one trades the high magnification factors making the bulge stars temporarily much brighter against the difficulties of carrying out ToO observations.

These ToO programs provide very high S/N echelle spectra on sources that would otherwise be too faint for analysis (e.g. Cavallo et al., 2003; Johnson et al., 2007; Cohen et al., 2008). Efforts to date have focused on dwarf and subgiant stars of the Galactic bulge, with intriguing new results demonstrating (1) the abundance ratios of the bulge dwarfs follow closely those of the Galactic disk and (2) a surprising double-peaked metallicity distribution function, including an apparent correlation between metallicity and microlensing magnification (Cohen et al. 2010; Bensby et al. 2011).

Although the first measurements were made with HIRES on K1, the field is now dominated by the VLT owing to its well-established support of TDA observations. The installation of K1DM3 would bring Keck back into the fore-front of this research and the US community would be poised to further leverage upcoming high-cadence, wide-field imaging surveys. ToO programs could expand from analysis of Galactic bulge stars to stars throughout the Galaxy or even to other galaxies of the Local Group.

2.2 Cadence Observing

Traditional scheduling of time at WMKO is in increments of one-half to a whole night on each of the telescopes. For the standard allocation of a given PI, this implies only a handful of opportunities to observe a given object each year. However, for some sources there is tremendous scientific value in taking a series of observations across a short time-scale (days to months). Such high cadence observations are nearly impossible with K1, in part because classically scheduled observing demands that the instruments are changed weekly.

Galactic Center (GC): In 2018, the brightest star (SO-2) known to orbit the $\sim 10^6$ solar mass MBH at the Galactic center will reach pericenter (Ghez et al. 2008). During the few months when the star swings around the MBH, it will offer a tremendous opportunity to empirically constrain properties of the black hole and our galaxy (e.g. our Sun's distance to the center), and to test GR in a unique portion of parameter space. At that time, OSIRIS on K1 will be the premier instrument to perform the experiment. Using K1DM3, astronomers could observe on every clear night that the GC is available during the critical periapse, when the star's radial velocities are expected to change by over 10,000 km/s in the course of only a few months.

Exoplanet research: Extrasolar planets present another class of extremely exciting opportunities for the K1DM3. Of particular importance are high-resolution spectroscopic observations taken during the rare, precisely timed transits of eccentric long-period planets. By measuring the so-called Rossiter-McLaughlin effect (Figure 3), one can infer the projected degree of misalignment between the planetary orbital angular momentum vector and the spin pole of the star -- information that provides vital clues to these systems' intriguing dynamical histories. Furthermore, there are a number of key multiple-planet systems (such as those orbiting the nearby M-dwarfs Gliese 436, Gliese 581, and Gliese 876) whose characterization and orbital phase coverage can be dramatically improved by Doppler velocity measurements obtained at optimal, pre-determined, and highly specific times. With K1DM3, the HIRES spectrograph on Keck can be made available for these time-critical measurements when the need arises.

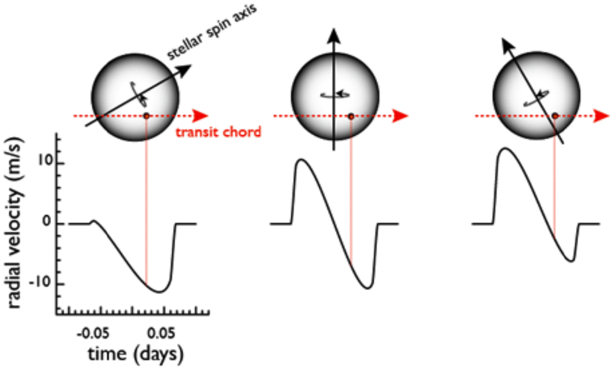

Figure 3. Schematic diagram that illustrates the Rossiter-McLaughlin (RM) effect. RM observations during planetary transits are currently generating a great deal of excitement in the exoplanet community because they give unique information regarding the dynamical configuration of the star-planet system. Precise scheduling of the HIRES spectrograph is required in order to obtain these measurements.

The current data also suffer from serious aliasing problems caused by the lunar synodic frequency, which makes it particularly difficult to pin down periods near 1 month or integral multiples of a month. These periods are especially important as they are similar to the periods of potentially habitable planets in habitable zone orbits around M-type stars. There are several exciting (unpublished) systems whose orbits beat awkwardly with the synodic lunar period, making it difficult to achieve complete phase coverage. With occasional access to phases at other times of the lunar month, it would be straightforward to confirm these orbits, and with much less overall Keck observing time. A simple 10 minute observation a few times/year at times other than bright of the moon would suffice.

Finally, even for candidates with non-aliased, low-eccentricity orbits, it would be a great benefit to spot-check the predicted orbits when particularly interesting or low-mass solutions emerge. With occasional access to 10 or 20 minutes/night, one could select the highest priority, most promising cases and quickly verify their nascent orbital solutions. If confirmed, then regularly scheduled time can be efficiently used to constrain the solution with increased observing cadence. If not, the star could be dropped in priority until a better solution arose. In short, "cadence" observations with K1DM3 would enable the detection of fascinating new planets with orbits that challenge traditional scheduling and greatly improve the efficiency of detection and follow-up analysis.

Monitoring Variability in SNe Spectroscopy: Despite the remarkable progress made to date in utilizing SNe Ia to constrain the cosmological model of the Universe, there is still no single satisfactory theory for their progenitor systems. SNe Ia are thought to arise via the thermonuclear explosion of a CO white dwarf (WD) which approaches the Chandrasekhar mass limit as it accretes material in a binary system. But the accretion mechanism is as unclear as the nature of the explosion (Hillebrandt et al. 2000). The merging of two WDs may better reproduce the observed SN Ia rates (Pakmor et al. 2010; Fink et al. 2010), but apparently some SNe Ia explode with masses significantly above the Chandrasekhar limit (Howell et al. 2006; Silverman et al. 2011). Quite possibly there are several routes to the production of a SN Ia event. Understanding the various channels and their dependence on the local environment is key not only to our physical understanding of stellar evolution, but also to our confidence in calibrating the use of SNe Ia in cosmology.

Even in the case of the SN2011fe, the closest SN Ia in decades, the progenitor system of these explosions continue to elude detection, despite sensitive, multi-color pre-explosion images from HST (Li et al., 2011). Instead, future progress appears to require an indirect approach, in particular by studying how the supernova interacts with the circumstellar environment. High-resolution optical spectroscopy of several recent nearby SNe Ia has revealed variability in the absorption profile of the Na D line, likely due to photoionization (and subsequent decay) of material ejected from the companion star via a wind (Patat et al. 2007). Based on the relatively low expansion velocity (coupled with the lack of X-ray and radio detections), these authors inferred that the companion star must be a red giant to account for the dense circumstellar environment.

Such high-resolution studies, however, have only been reported for a small handful of SNe Ia, and most were selected in large part due to their high line-of-sight extinction. A proper survey would examine a large sample (~ 20) of nearby SNe Ia, including SNe Ia from many different environments (ellipticals vs. spirals, extinguished vs. nonextinguished, intrinsically bright vs. faint). At present, the single dominant factor limiting our progress is the lack of regularly available access to HIRES. Ideally one would obtain spectra on a ~ weekly basis but the current operation leaves large (several week) gaps in coverage when the variability evolution is expected to be strongest. Installation of K1DM3 would enable an optimized experiment.

2.3 Flexible Observing (and Scheduling)

Time-Critical Observations: There is already a diverse set of programs being carried out at WMKO that are time-critical, i.e. require observations on a specific night, often to the precise minute. These include imaging and spectra of `once-in-a-lifetime' Solar system events (de Pater et al., 2008), planetary transits, and programs coordinated with coeval observations from ground and space (Eckart et al., 2009). With K1DM3, these time-critical events could be captured on any night with the instruments at any of the K1 foci.

Low-Elevation Targets: There are a number of valuable targets and fields that lie just at the edge of WMKO's grasp, e.g. the Galactic Bulge, GOODS-S. Because these can be viewed for only a few hours per night, programs that study them are either artificially expanded to include other targets or share the nights with other teams. Again, K1DM3 would provide flexibility to schedule and perform such observations throughout each semester.

Optimizing to Observing Conditions: Another common usage of K1DM3 would be to maximize observing efficiency by matching programs to the current observing conditions. WMKO would not transition toward a full-queue scheduling -- there is neither the funding nor sufficient community interest -- but we would establish a poor weather/seeing queue that observers could turn to on challenging nights (e.g. RV spectroscopy of bright stars with HIRES). By the same token, one could schedule AO observations that took advantage of the most stable nights with high-quality seeing. These are only some of the logistical 'use cases' -- coherent and cost-effective strategies will be generated by WMKO and its partners to make best use of this added capability.

3. INSTRUMENT REQUIREMENTS AND DESIGN

3.1 Conceptual Design

Motivated by the observational demands of TDA science, we have investigated the design and operation of a new tertiary mirror system on K1 that would permit observations at any of the foci on any given night and at any time. From this investigation we have developed the following top-level requirements:

1. The new tertiary mirror must be sufficiently large to satisfy the field of view (FOV) requirement for each of the existing and planned instruments at the Nasmyth platform of K1. It must have a high reflectance, bare Al coating.
2. Errors in the tertiary surface and its placement must not contribute to measurable image degradation.
3. When stowed, the device must not vignette the FOV of any existing or planned Cassegrain instrument for K1.
4. The device must be able to redirect the beam between Nasmyth foci in under 5 minutes.
5. The device must be able to be fully deployed/stowed in under 5 minutes.

The first two requirements constrain the dimensions and support structure of the tertiary mirror. Requirement 3 restricts the placement and dimensions of the full device while the last two requirements drive the mechanical design of the mount and deployment mechanism.

3.2 Design and Support of the Tertiary Mirror

Geometry of the tertiary: The existing and planned instruments at the Nasmyth foci of K1 include the HIRES spectrometer (Vogt et al., 1994) and the OSIRIS instrument (Larkin et al., 2006). Of these, HIRES requires the largest FOV, dominated by the MAGIQ guider system. The current design needs approximately a 4' FOV; to be conservative we will meet the requirement of a 5' FOV as even this field implies a relatively modest mirror.

The tertiary mirror has the shape of the intersection of a cone with a plane: an ellipse. The center of the ellipse does not intersect the optical axis of the telescope, but is somewhat offset. We calculate that a 5' FOV requires a mirror with a semi-major axis a = 0.673 m and semi-minor axis b = 0.476 m.

Support of the tertiary: The tertiary needs to be supported adequately against gravity. One pathway would be a whiffletree for the axial support and a central diaphragm for the lateral support. This is analogous to the support philosophy used for the full-sized Keck tertiary. The current, full-sized Keck tertiary (providing a 20' FOV) is an ellipse with major and minor diameters of 1.439 x 1.068 m with a thickness of 0.125 m and is axially supported by an 18-point whiffletree system.

We discuss briefly the axial support and the resulting thickness of the tertiary. The optic is elliptical, so it has four equal quadrants. Since we want to support the mirror axially in a kinematic fashion, there are three axial constraints. Thus the simplest support system for a thin and relatively flexible tertiary will be a 12-point support system. Figure 4 shows the axial support locations and interconnections to carry the load down to three points. Not shown is the lateral support system which could be a single diaphragm in the midplane of the mirror that would carry in plane loads and provide the three in-plane constraints. The axial support system would provide the other three constraints. We expect that the axial and lateral loads will be connected at the three defining points indicated in the figure by red dots.

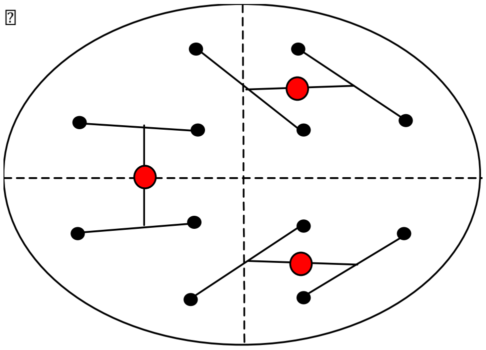

Figure 4. This schematic shows approximately the locations of a 12 point axial support system and how they might be combined with whiffletrees to three location points that would form the attachment locations to the outside world.

We can estimate the gravity deflections of such a 12 point support as a function of the thickness of the mirror. This can be done relatively easily using "analytic" expressions. The minimum rms gravity deflections of a mirror on an N point support are given by $\sigma_N=\gamma_N\ (q/D)\ (A/N)^2$ where σ is the rms surface error under full axial gravity loading, γ_N is the support point efficiency (TMT report #74), q is the gravity load/area, D is the "bending", and A is the mirror area. Taking N=12 and assuing the properties for Zerodur glass, we derive $\sigma_{12}= 4.09\mathrm{x}10^{-11}\ (\pi ab/h)^2$. For the dimensions required to provide a 5' FOV for M3 and with h = 0.050 m, we get $\sigma_{12}= 3.03\mathrm{x}10^{-9}$ m, and the mirror has a mass M = 54.5 kg.

In practice we need to find the optimum support point locations and forces in order to actually achieve this performance. Towards this goal we have done a preliminary finite element analysis (FEA) of this elliptical flat plate. For simplicity we modeled it as a shell, so the run time was negligible, allowing us to visually inspect the results and modify the inputs. We varied the positions of the support points (6 parameters) and forced the vertical deflections to be zero at these points. We minimized the peak to valley deflections and found a minimum of about $2.0\mathrm{x}10^{-9}$ m, quite consistent with the estimated rms of $3.03\mathrm{x}10^{-9}$ m. The map of the achieved surface deflections is shown in Figure 5. More generally, one can use FEA to vary the 8 independent parameters (6 positions and 2 force ratios) to minimize the surface error.

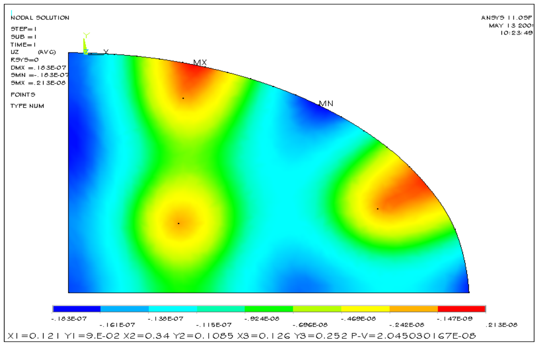

Figure 5. This color contour map shows the deflections of the FEA model for full gravity load perpendicular to the surface with a 12 point axial support. The support locations are indicated by the three small black dots. At these locations the vertical deflections were constrained to be zero. The peak to valley deflection is about 20 nm.

Image Blur: The geometric image blur follows from the slope errors on the tertiary, not the rms surface errors. More support points will reduce the deflections, but increase the spatial frequency of the undulations. Since the tertiary is close to the final focal plane, the slope errors have a smaller impact than if they arose on the primary mirror, by the ratio of the distances to the focal plane. If we assume the surface errors are sinusoidal, then the peak slope error is given approximately by $s_{max}=2\sqrt{2}\pi\sigma\sqrt{(N/A)}$. The image diameter is four times the slope, scaled by the distance to the focal plane. So the 100% enclosed energy diameter for the Keck geometry is given by $\theta_{100} = 4s_{max}(6.5m/150m)$. Continuing with the above example, we obtain $s_{max} = 1.42\text{x}10^{-7}$ radians θ_1□$2.46\text{x}10^{-8}$ radians = 0.005 arcsec.

We conclude from this that the surface deflections are sufficiently small, and resulting geometric image blur is negligible. An M3 with this surface quality is sufficiently good for both adaptive optics and seeing limited astronomy. Such a mirror is straightforward to fabricate, polish, and coat (e.g. in the UCO coatings lab).

3.3 The Mount

K1DM3 Mechanical design concept: As described in the top-level requirements, the mount for the tertiary must be designed to rotate rapidly to any of the Nasmyth foci. Furthermore, it must be positionable to a tolerance of 1 arcescond to preclude image degradation. Our conceptual design (Figure 6) envisions a "tub" which mounts the tertiary and deployment system. The tertiary mirror and deployment system is mounted on a custom bearing with inner diameter of 1.10 m and outer diameter of 1.23 m. A bearing meeting our requirements requires custom design and fabrication. In principle this is a source of great risk to the project. To address this key risk, we identified in the fall of 2011 two vendors who will commit to its fabrication at a reasonable cost. The bearing carrying the tertiary mirror and deployment system is caused to rotate by a servo motor and encoder system that drives a ring gear mounted on the bearing.

Instruments and equipment designed for the tertiary tower must travel on a two-rail system. All current designs rely on two pair of rollers, one set at either end of the structure. The tub provides some structural length to accommodate these rollers. The alternative (not yet considered) would be to have K1DM3 attached to an insertion device that is removed once the unit is connected to the kinematic mounts. If necessary two bearings spaced apart along the tub could be used to better resist the moment load of the tertiary. However, a single bearing meeting our requirements is capable of handling the moment loads on its own. The tub will also help protect the motors, encoders, and other related equipment.

Direct support of the mirror will employ uncoupled axial and lateral support systems. The design of these systems will be similar to the technology used on the primary segments and will also rely on recent studies for the support of the TMT tertiary mirror. The deployment system will consist of a linear actuator and a linkage system. Secondary actuators will also be used to lock the mirror in both deployed and stowed configurations. The deployed orientation needs to be as rigid as possible to ensure repeatability and stable imaging. The stowed position, although not as critical, needs similar reliability from an off-line and safety perspective.

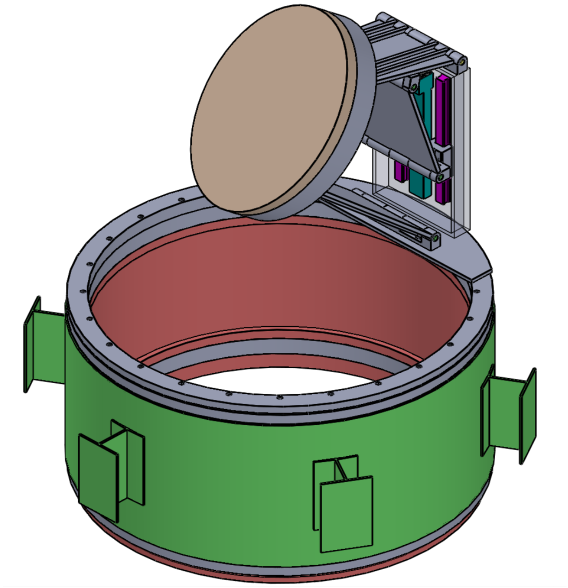

Figure 6. The K1DM3 “tub” which serves as the mount for the deployable tertiary. Aside from the custom bearing, all parts shown are standard, off-the-shelf items.

Deployment system: The system is not yet fully vetted but is a great milestone in the conceptual design. It works as a single travel motion device without the need of any telescoping elements. It consists of a ball screw driven carriage that is guided by two linear bearings. The locking mechanism requires further design work. It may also consist of a linear stage. This will help to orient the deployed configuration for optimum stiffness and rigidity.

The mirror assembly will have a rigid third support attached which is presently conceived has an armature with a ball at its end. The deployment system will direct this ball to a socket fixed on the ring. A secondary actuator will then lock this connection to maintain rigidity. A similar arrangement will be employed for the stowed configuration as well although the same ball mirror assembly may not be involved due to its alignment with the primary linear drive.

Vignetting: The major advance of K1DM3 over the existing tertiary is the ability to permit both Nasmyth and Cassegrain observations on K1 in the same observing night. For Cassegrain instruments, the tertiary mirror is stowed out of the light path, and for Nasmyth instruments the tertiary mirror is deployed and rotated to direct the light to one of the two Nasmyth focal stations.

Cassegrain instruments are mounted in rotator modules that allow the instrument to rotate about the telescope optical axis to compensate for the field rotation introduced by the altitude-azimuth mount of the K1 telescope. This requires that the tertiary mirror be stowed out of the FOVs of these instruments and kept in a position that does not vignette their FOVs as they rotate about the optical axis. Presently there is one Cassegrain instrument for K1 (LRIS; Oke et al., 1995) and one undergoing commissioning in 2012 (MOSFIRE; McLean et al., 2010).

Figure 7 shows a top view of the tertiary tower and K1DM3 in its stowed position. Overplotted on the figure are estimated sizes for the unobstructed FOV’s of LRIS and MOSFIRE at the top of the K1DM3 mount. These estimates have been informed by a full Zemax (optical design software) analysis using the existing “as-built” optical designs for K1, LRIS, MOSFIRE, and the atmospheric dispersion corrector (ADC) installed on K1. It is evident from the figure that MOSFIRE is easily avoided. Our Zemax analysis of the full system indicates that there is no vignetting of LRIS for elevation angles $\theta < 50°$ and that there is only ~1% vignetting at the extreme corners of the LRIS detector and for a subset of rotator angles at $\theta > 60°$. This is unlikely to ever impact scientific observations.

Stray light: Another concern is the possibility of stray light when the M3 mirror is stowed. A full stray light analysis and mitigation plan will be considered in the preliminary design phase.

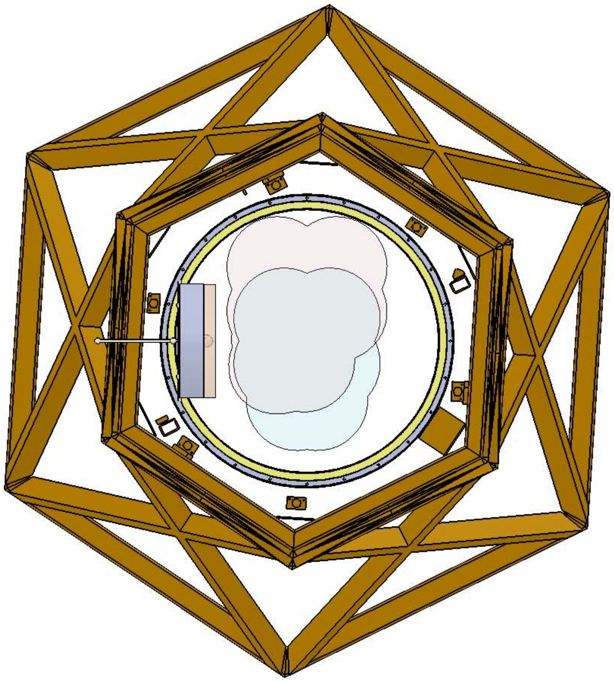

Figure 7. Top-view of K1DM3. FOV's for LRIS (pink) and MOSFIRE (blue) are indicated as estimated at the position of the top of the mount.

3.4 Development Plan

Work has been done previously to establish the basic modes of operation and the requirements, the space for the module and optics, and a concept design of the deployable tertiary mirror mechanisms including the rotation bearing. When funded the next phase will be the Preliminary Design (PD) that will finalize the overall design and fabricate and mount an envelope prototype on K1. Following the PD phase will be the Detailed Design (DD) phase in which the design will be completed and the fabrication drawings produced. At the end of the PD and DD phases a peer review will be conducted by WMKO. After the DD review, the Full Scale Development (FSD) phase will begin in which we will fabricate, integrate and test the K1DM3. Testing will include documentation of the compliance of the mechanism to the requirements. When testing is completed WMKO will conduct a pre-ship review. After that review, the K1MD3 will be shipped to WMKO, installed on K1, and commissioned over several nights on the sky.

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