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Design considerations for CELT adaptive optics

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ABSTRACT

California Institute of Technology and University of California have begun conceptual design studies for a new telescope for astronomical research at visible and infrared wavelengths. The California Extremely Large Telescope (CELT) is currently envisioned as a filled–aperture, steerable, segmented telescope of approximately 30m diameter. The key to satisfying many of the science goals of this observatory is the availability of diffraction–limited wavefront control. We describe potential observing modes of CELT, including a discussion of the several major outstanding AO system architectural design issues to be resolved prior to the initiation of the detailed design of the adaptive optics capability.

Keywords: Extremely large telescopes, adaptive optics

1. INTRODUCTION

Of the technical challenges faced in the design of CELT[1–4], achieving diffraction–limited science in the near–infrared over significant fields is among the most challenging. CELT requires an unprecedented number of degrees of freedom for science wavefront control and unprecedented total wavefront sensor signal to measure these degrees of freedom. The cost and ultimate performance of the adaptive optics capability for CELT is intimately related to subsystem and site decisions that impact the design of the entire observatory. The interplay of the optical design issues for the primary mirror, secondary mirror, AO system(s), and instrumentation is particularly interdependent. An early understanding of the impact of fundamental design parameters such as primary mirror F/#, projected deformable mirror, wavefront sensing, and science detector technologies is essential to applying the appropriate early effort to minimize technical and cost risk.

Because of the systemic interrelationship of the AO capability with the observatory, the traditional approach to AO development, in which AO is considered an add–on module, to be developed independent of the telescope, must be questioned. Without a clear understanding of the role, the requirements, and the risk of adaptive optics in the scientific mission of this observatory, we cannot proceed to undertake the great engineering challenges of the telescope construction itself. Thus, we present in the remainder of this paper a series of issues that require resolution prior to the undertaking of a detailed design effort for CELT AO facilities.

While the detailed science requirements for the CELT observatory are still in formulation among Caltech and UC astronomers, several scientific themes for the role of any 30m class telescope have recently been considered in several workshops[5]. To be operated in the era of NGST and other great space observatories, CELT provides a unique scientific advantage attributable to its enormous collecting area and very high diffraction–limited imaging resolution. Imaging spectroscopy at high spatial and spectral resolution over large fields is one technology particularly well suited to enabling forefront CELT science.

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2. CELT OBSERVING MODES

Early science discussions lead us to consider three different adaptive optics observing modes for potential use with CELT. At mid–infrared wavelengths (20 μm down to 5 μm), natural guide stars provide sufficient flux to ensure diffraction–limited imaging over the 30m diameter for nearly full sky coverage over wide fields. Thus, a single–conjugate AO system (SCAO) utilizing only NGS's is suggested for this observing range. At near–infrared wavelengths (5 μm to 1 μm), the isoplanatic angle of the atmosphere prohibits wide correction with a single element, calling for a multi–conjugate AO (MCAO) approach. At visible observing wavelengths, rapidly increasing technology challenges lead us to consider a narrow–field, extreme AO (EAO) system, dedicated to very high levels of wavefront correction for bright guide stars only. Note also that for the longest wavelengths, a tip/tilt (TT) only system could obtained some reasonable Strehl ratio over the entire sky. Because CELT will almost certainly operate in a new regime where finite outer scale dramatically affects total atmospheric tip/tilt energy, we give the TT observing mode no further consideration here.

As currently envisioned, CELT AO capability for high–Strehl visible band observations remains a significant technical challenge. Although promising advanced adaptive optics technologies are under investigation within the UC Santa Cruz–headquartered Center for Adaptive Optics[6] and elsewhere, we recognize that technical progress in many areas is urgently needed to meet visible AO goals. While we recognize that CELT planning should provide for a continuous path to shorter wavelength diffraction–limited performance, the time scale over which the detailed design work is to be performed 4–5 years, will likely preclude the availability of visible AO at time of telescope commissioning. Having said that, by taking careful consideration of the site selection and enclosure design (both of which are critical to minimizing the AO complexity and cost), CELT will provide outstanding seeing–limited (SL) visible science capability from the start.

For the purposes of motivating this paper, we present in Table 1 an outline of the science–derived goals for the wavefront control performance of the CELT telescope in these adaptive optics modes. We note that at this early stage in the conceptual design of the observatory, this tabulation is not considered to convey requirements, but rather to provide us a framework in which to begin to consider the architectural and technological challenges inherent to the problem.

As an example, consider the various observing modes available for M–band (5μm) science. Using only a fast tip/tilt capability, approximately 2% Strehl could be achieved over an area limited by the static aberrations of the telescope. Employing a single–conjugate AO mode with NGS's only, 95% Strehl could be achieved over approximately 30% of the night sky, with an corrected field of view of 3' diameter, set by the anisoplanatic angle in $r_0 = 0.24$ m (at 0.5 μm) seeing. With a multi–conjugate AO system, 97% Strehl over 40% of the sky may be possible, with a 4' diameter corrected field. Finally, employing a very high actuator count extreme AO (EAO) system, Strehls > 98% over a small fraction of the sky, approximately 1% may be attainable, with a relatively narrow 20" diameter corrected field.

3. SINGLE CONJUGATE AO (SCAO)

At mid–infrared wavelengths, natural guide star (NGS) sky density is sufficient to provide full sky diffraction–limited capability for CELT. A graphical description of the potential design space for a SCAO system utilizing visible wavefront sensing is presented in Figure 1. The primary three curves in this chart describe the number of actuators needed, within the area of a 30 m filled aperture, to provide a fitting error term of three different Strehl ratios. For reference, the fitting error term used here can be described by,

$$\sigma_{fit} = \sqrt{0.28}\left(\frac{\lambda}{2\pi}\right)\left(\frac{d}{r_0}\right)^{\frac{5}{6}}[nm] \qquad (1)$$

where d is the actuator spacing of the correcting element, as projected back onto the entrance pupil. As an example of the interpretation of this chart, by first looking at the isoplanatic angle curve, we find that for L–band (3.5μm) observing, assuming $r_0 = 0.24$ (0.5 μm), effective height = 10 km, wind vel = 20 m/s, $\theta_0 \sim 45$ arcsec. Next, using the P(N>0) curve, we find that 20% of the sky is available for non–fitting Strehl ratios of 70%. This happens to require an mV = 17.5 NGS, but the measurement, isoplanatic, and bandwidth error terms have been optimally chosen to maximize sky coverage. Finally, we find that for Strehl ratios due to fitting error of 20%, 50%, and 80% requires a total actuator count of ~ 40, 100, and 400 respectively.

Band	Wavelength (μm)	Seeing Limited λ/r_0 (mas)	Diffraction Limited					
			1.22 λ/D (mas)	Strehl (%) / Sky Coverage (%)				DL FOV (dia.)
				TT	SCAO	MCAO	EAO	
V	0.55	422	4.61				20 / *	2"
R	0.70	402	5.87				30 / *	2"
I	0.90	382	7.55			10 / 30		40"
							50 / <<<1	2"
—	1.00	374	8.39		7 / <<<1			20"
						30 / 30		1'
							60 / <<<1	2"
J	1.25	358	10.49		10 / <<1			40"
						40 / 30		2'
							80 / <<1	4"
H	1.65	339	13.84		15 / < 1			60"
						60 / 30		3'
							90 / <<1	6"
K	2.2	320	18.45		20 / 5			80"
						80 / 30		4'
							95 / <1	8"
L	3.5	291	28.52		30 / 25			2'
						90 / 30		4'
							98 / 1	12"
M	5.0	271	41.9	2 / 100				**
					95 / 30			3'
						97 / 40		4'
							>98 / 1	20"
N	10.2	235	85.6	36 / 100				**
					>98 / 95			8'
						>98 / 40		4'
							> 98 / 5	1'

Table 1. Comparative performance goals for three modes of AO correction on CELT. Seeing limited image widths assume r_0 = 0.24 m at 0.5 μm wavelength. TT represents a fast tip/tilt system, only, assuming here an infinite outer scale. SCAO represents a single–conjugate AO system with one deformable element, possibly an adaptive secondary, which would provide a minimum emmissivity optical train. MCAO is a multi–conjugate AO system providing large corrected field of view (FOV). Note that we assume here that the MCAO system is limited to 4' diameter due to vignetting through the MCAO relay. EAO is a extreme–AO system providing very high Strehls on bright NGS only.

* Note, although EAO may utilize the optical train of the MCAO system, only NGS's are currently envisioned as providing sufficient flux to enable the very high order correction characteristic of the EAO system. The science program for this system would include dozens to hundreds of bright objects.

** Image quality will be limited over large fields by the static off–axis aberrations of the telescope.

We can further investigate the performance possibilities of a SCAO system throughout the infrared bands, by developing a detailed error budget for a given atmospheric model. Table 2 contains such a budget, which now includes residual error terms from the telescope that are not correctable by the adaptive optics capability. In this case, we assume a Mauna Kea model for the atmosphere[7]. For our purpose here, we have created an error budget for a plausible 700 actuator SCAO system, performing wavefront sensing in the near infrared. We choose to utilize wavefront error in nm rms as a metric, because it allows for simple scaling to various wavelengths. For some error terms, however, we recognize that the wavefront error itself would change, due to one wishing to take advantage of near–optimal observing techniques as appropriate. In Table 2, for example, we choose to integrate the wavefront sensor signal for a variable length time, depending on the science observation wavelength.

The extension of this error budget to faint guide stars is made in Table 3. In this table, we consider two sets of guide star magnitudes, and distribute the error budgets in order to maximize sky coverage for a given final Strehl ratio. For example, imaging at L–band, one finds a final Strehl ratio of 28% is obtainable over 25% of the sky, while final Strehl ratio of 65% is obtainable over 0.1% of the sky. This trade in sky coverage includes both the larger acceptable isoplanatic error, and the larger measurement error associated with guiding with a fainter guide star.

While this implementation of a SCAO system could occur through a traditional AO module residing on, say the Nasmyth platform of CELT, it is interesting to note the trade–offs between this and a more ambitious, adaptive secondary mirror approach.

During the past 5 years, adaptive secondary mirror (ASM) technology has matured to the point that several new observatories plan to rely on adaptive secondaries as their only secondary mirrors[8–10]. It is difficult to extrapolate the technological progress of large, powered, deformable mirrors over the design and construction lifetime of CELT. Because of the severe disadvantage in sensitivity of CELT relative to NGST in the mid–IR, the scientific advantage of a MIR SCAO system possessing only 3 warm surfaces (primary, secondary, and Nasymth fold), may not justify the cost of increasing the current 1m class ASMs to the 2–4m class ASMs required for CELT. Alternately, it is possible to reduce the diameter of M2 by decreasing the focal ratio of M1. This trade, however, carries potentially expensive repercussions in the fabrication, mounting, sensing, and actuation of the primary mirror. Furthermore, it is recognized that wind loading of the secondary support structure may one of the large contributors to the vibrational environment of CELT. An adaptive secondary, as currently conceived, would increase the mass and cross–section of this structure and the subsequent transfer of vibrations through the telescope. The optimum size and nature, static or adaptive, of the CELT secondary mirror, considering both technical and economic factors, will be the topic of future work.

4. MULTICONJUGATE AO (MCAO)

4.1 Guide star requirements

At near–infrared wavelengths, the challenge of providing diffraction–limited wavefront control over a significant fraction of the night sky over a wide corrected field of view, becomes considerably more difficult. Historically, the absence of sufficiently bright NGS's near any given science target has spurred the development of laser guide star (LGS) technologies, that are now beginning to show practical use on 3–10m diameter telescopes[11–14], but thus far, only for the longer wavelengths in this observing band. The technical challenges of laser guide star development are driven fundamentally by a strong dependence on required laser power to achieve a given Strehl, scaling as the – 18/5ths power of wavelength[15]. Thus, while the current state–of–the–art Na guide star lasers, for example, may provide 8W equivalent power at the sodium layer, sufficient for K–band correction, J–band correction requires a 7.6 * 8 = 61 W of power. Integral to the steep power dependence on wavelength, focal anisoplanatism for CELT LGS's is similarly an unprecedented problem.

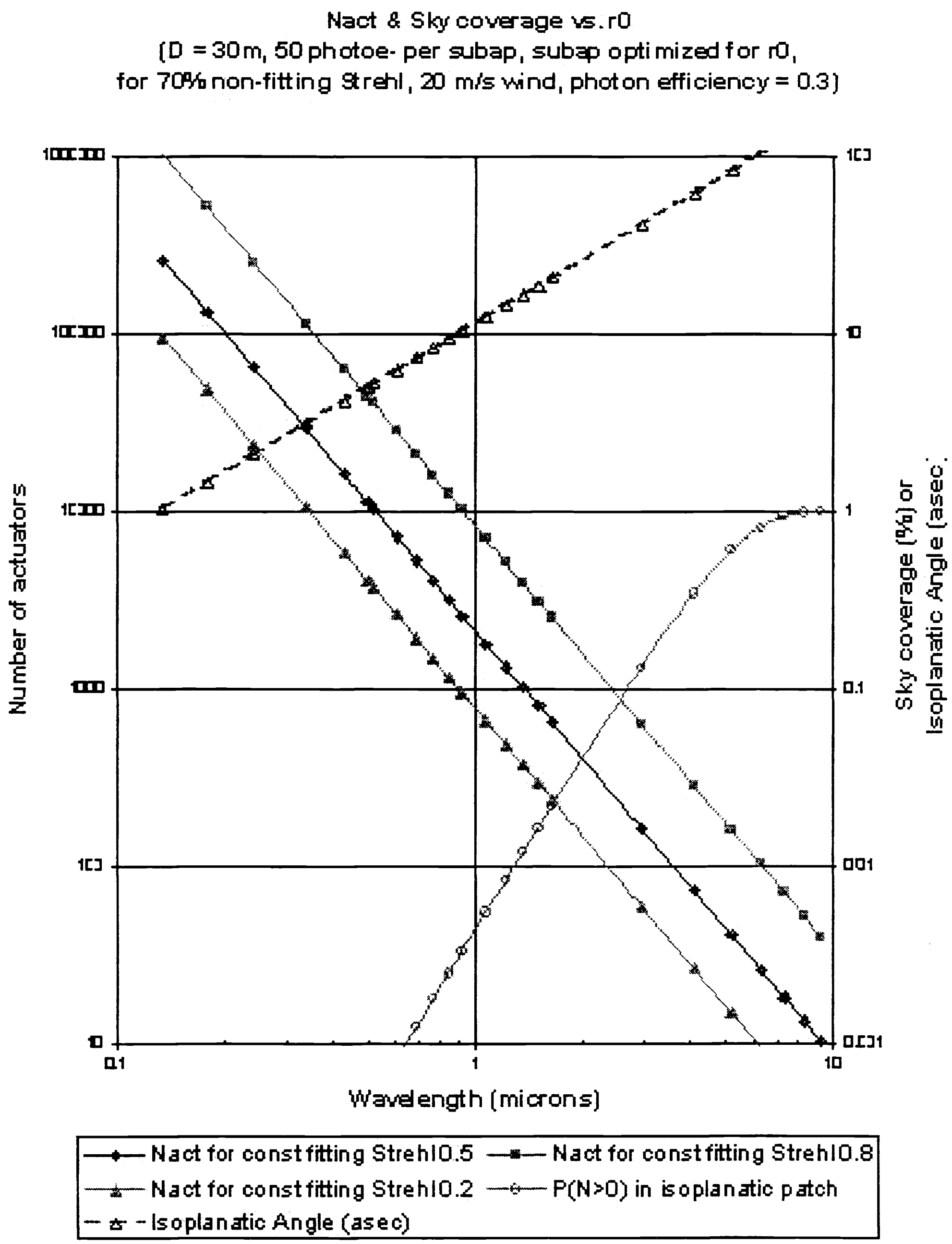

Figure 1. Number of actuators (left axis) needed for constant fitting error term (only) for various levels as a function of wavelength. Of course, many other error terms will decrease the total Strehl achievable. The system design will need to balance fitting error with other error terms. Also plotted (right axis) are the isoplanatic angle in arcsec and the probability of finding a NGS bright enough to provide 50 photodetections within the 0.84 Strehl isoplanatic area (assumes total photon efficiency of 0.5). These curves have been generated assuming $r_0 = 0.24$ ($0.5\mu m$), effective height = 10km, wind vel = 20 m/s, a constant bandwidth Strehl of 0.84, and constant isoplanatic Strehl of 0.84.

theta0 (arcsec)		5.26	13.55	23.66	83.38
subaperture diameter (m)		1	1	1.5	1.5
Greenwood (Hz)		15.75	6.12	3.5	0.99
Fundamental tilt tracking freq (Hz)		0.05	0.05	0.05	0.05
guide star magnitude (mV)		13	14	15	16
WFS SNR		5.59	3.62	4.21	4.2
GS/target separation (arcsec)		3.39	8.73	15.24	53.71
Telescope Residual Errors					
Segment fitting	60	0.87	0.97	0.99	1.00
Secondary fitting	60	0.87	0.97	0.99	1.00
ACS noise	30	0.97	0.99	1.00	1.00
Phasing	25	0.98	0.99	1.00	1.00
Vibration	50	0.91	0.98	0.99	1.00
Stacking	10	1.00	1.00	1.00	1.00
Wind buffetting	25	0.98	0.99	1.00	1.00
Focus	20	0.98	1.00	1.00	1.00
Total telescope	**111**	**0.61**	**0.90**	**0.96**	**1.00**
Atmospheric Residual Errors					
Fitting (Nacts =700)	140	0.46	0.85	0.94	0.99
High-order bandwidth	99/175/216/460	0.68	0.78	0.86	0.92
Tip/tilt bandwidth	73	0.81	0.96	0.98	1.00
Total atmospheric	**187/236/268/486**	**0.25**	**0.64**	**0.79**	**0.91**
Instrument Residual Errors					
PSF calibration	50	0.91	0.98	0.99	1.00
Fitting	25	0.98	0.99	1.00	1.00
Non-common	25	0.98	0.99	1.00	1.00
Total instrument	**61**	**0.86**	**0.97**	**0.99**	**1.00**
Total bright star Strehl	**226/267/297/502**	**0.13**	**0.56**	**0.75**	**0.91**

Table 2. Bright NGS error budget example for single conjugate AO capability with CELT. Telescope errors are estimates extrapolated from experience in the construction of the Keck Telescopes. The many necessary assumptions for this analysis are presented at the top of this table. For entries marked A/B/C/D, the four quantities are for 1, 2.2, 3.5, and 10 μm observing scenarios respectively. Extension of these results to faint guide stars is presented in Table 3.

Still using the MIRSCAO system, consider two 'acceptable Strehl' cases

GS/target separation (arcsec)			3.39	8.73	15.24	53.71
guide star magnitude (mV)			13	14	15	16
WFS SNR			5.59	3.62	4.21	4.2
Guide Star Residual Errors						
	Isoplanatic error	132/292/464/1325	0.50	0.50	0.50	0.50
	Measurement	65/220/301/863	0.85	0.67	0.75	0.75
	Total guide star	**148/365/553/1581**	**0.42**	**0.34**	**0.37**	**0.37**
	Total Strehl		**0.06**	**0.19**	**0.28**	**0.34**
	Sky coverage (for this SR, %)		**0.2**	**3**	**25**	**95**
GS/target separation (arcsec)			0.35	0.91	1.59	5.6
guide star magnitude (mV)			12	13	14	15
WFS SNR			11.24	7.7	8.8	8.77
Guide Star Residual Errors						
	Isoplanatic error	52/114/181/517	0.90	0.90	0.90	0.90
	Measurement	32/103/144/413	0.96	0.92	0.94	0.93
	Total guide star	**61/154/231/661**	**0.86**	**0.82**	**0.84**	**0.84**
	Total Strehl		**0.12**	**0.46**	**0.63**	**0.76**
	Sky coverage (for this SR, %)		**0.001**	**0.02**	**0.1**	**3**

Table 3. Performance prediction for faint NGS single–conjugate AO system for mid–IR observations with CELT, for two 'acceptable Strehl' levels. Continued from Table 2, the four columns represent observation conditions (from left to right) at 1, 2.2, 3.5, and 10 μm wavelength. GS/target separation is the angular distance between guide star and the science target on the sky.

4.2 Focal anisoplanatism

Because of CELTs large diameter, current thinking implies that even narrow field correction will require multiple LGS beacons to overcome focal anisoplanatism. For a telescope of diameter, D, the rms wavefront error due to focal anisoplanatism is given by[16],

$$\sigma_{FA} = \frac{\lambda}{2\pi}\left(\frac{D}{d_0}\right)^{\frac{5}{6}}[nm] \tag{2}$$

where d_0, which is a linear function of beacon height and scales as $\lambda^{6/5}$, may be considered the diameter over which this error is 1 radian of phase. Again, using the Mauna Kea model atmosphere, we find the following values of d_0, assuming 45 degree zenith angle,

$$d_0(10\text{ km, MK, 45 zen}) = 1.08\text{m}$$
$$d_0(92\text{ km, MK, 45 zen}) = 3.60\text{m}$$

which leads to, for 1 μm observing wavelength, D = 30 m,

$$\sigma_{FA}(10\text{km}) = 2540\text{ nm}$$
$$\sigma_{FA}(92\text{km}) = 931\text{ nm}$$

which are both obviously unacceptable wavefront errors.

In addition, the geometric elongation of any artificial guide star image, as viewed from an off–axis subaperture of the telescope, will significantly degrade the SNR of a centroid measurement along the direction of elongation. The challenge of multiple LGS is further compounded by the need to continue to sense multiple NGS's to eliminate non–detected modes that arise from tilt indeterminism. Through the use of multiple laser beacons, FA error can be greatly reduced, but at the cost of both laser technology development and system complexity. Because of these and many other issues, we feel that

CELT will benefit from a significant effort to consider what is the ultimate limitation of NGS wavefront sensing over wide fields. Clearly, where they meet the scientific objectives, NGS systems are simpler than LGS ones.

4.3 Wide field correction

To obtain a wide field of view correction in the NIR wavelength bands, the MCAO CELT capability will necessarily exploit multiple wavefront correctors located at several conjugate planes in the atmosphere[17–18]. Although recent studies are beginning to explore the nature of the multiconjugate correction problem for extremely large telescopes[19], several fundamental questions remain to be answered. Among these are how many wavefront correctors and how many guide stars are necessary to obtain a particular level of wavefront correction with a particular uniformity across a given field. Although recent work, assuming a 4m telescope and +– 28 arcsec FOV, has claimed no need for more than 3 correctors and 3 guide stars[20], we believe this issue requires further investigation. In general, we expect the field of view to be roughly proportional to the number of wavefront correctors.

4.4 "Tie–dye" error

There is another subtle, yet potentially crucial, issue to be aware of in the development of wide–field AO correction. Any tip/tilt correction made at an auxiliary tip/tilt mirror (as opposed to that made with telescope pointing), imposes a slight field rotation upon the corrected image. During a typical integration, the rapid succession of tip/tilt corrections of variable amplitude lead to a rotation–blurring of the science image. The blur amplitude is linearly proportional to the radial distance of the field point from the boresight of the telescope. The impression upon the corrected image, therefore, is that the field had been 'spun' during the integration, similar to the technique of coloring clothing popularized during the very early days of adaptive optics development.

Although existing AO system suffer this effect, they typically do not observe over a sufficiently large field to notice this effect, which remains small compared to the diffraction–limit of 4–10m telescopes. For CELT, however, this issue requires further investigation, and may lead to additional complications in the MCAO and or science instrumentation design. The finite outer scale benefits expected for CELT, however, should serve to reduce the magnitude of this error.

4.5 M2 conjugate location

One interesting possibility for a MCAO architecture is to exploit an adaptive secondary mirror, M2, which may be developed for the SCAO capability, as the first element in a MCAO system. The baseline CELT telescope design places M2 conjugate to a plane in object space approximately 300m below the primary mirror. Thus, the use of an adaptive M2 as a compensator for the ground layer in a MCAO system may restrict the size and/or uniformity of wide FOV correction. At J–band wavelengths, for example, assuming $r0(1.25\mu m) = 0.72m$, a ray traced through the center of a turbulence cell at the ground layer, would shear by $r_0 / 4$ at M2, for a field angle of 2'. The detailed impact of this error on MCAO isoplanatism is also a topic for further study.

While common assumptions for the locations for atmospheric conjugation include 0, 2 (or 4), and 8 km, we have to be careful about taking the correction layers too literally, since in practice, we will be tilting the telescope to some elevation angle. This will increase the apparent correction altitudes from h to $h / \cos(\xi)$, where ξ is the zenith angle of the observation.

4.6 Order of correction

An important issue in designing the optical system is whether or not the atmospheric layers need to be corrected in the reverse order in which they "happen", i.e., ground layer first, then the next layer up (say, 4km), then the next layer (say, 8km). The reason that this is important is that in the any optical space the conjugates of the layers will occur in the order 8km, 4km, 0km . Clearly, it is more convenient if the 8km correction can be done first, then the 4km, then the 0km, since that is the nominal order in which the correction heights will occur in the optical space following the telescope. It will probably require more optics to do the corrections in the order 0km–4km–8km, so this is an important issue in the design.

Hardy[21] asserts that since the light is perturbed in the order 8km–4km–0km, each layer's aberrations should be undone before going to the next one, i.e., the order of incidence needs to be star–8km–4km–0km–0km correction–4km correction–8km correction–image). While this is certainly true in order to obtain the maximum FOV*, the engineering–oriented question still remains: how bad is it to not do it in that order?

In most arguments made about MCAO performance, a geometrical propagation assumption (aka small perturbation approximation) is made, i.e.,

$$\phi_{\alpha}(\vec{r})=\sum_{j=1}^{N_{layers}} \phi_j(\vec{r}+h_j\alpha) \tag{3}$$

where α is the field angle, h_j's are the layer heights. This approximation and Hardy's assumption are inconsistent with each other since in the approximation, the order of summing does not matter and there is no crosstalk between neighboring points in the layers for any given field angle. Clearly, this inconsistency needs to be resolved.

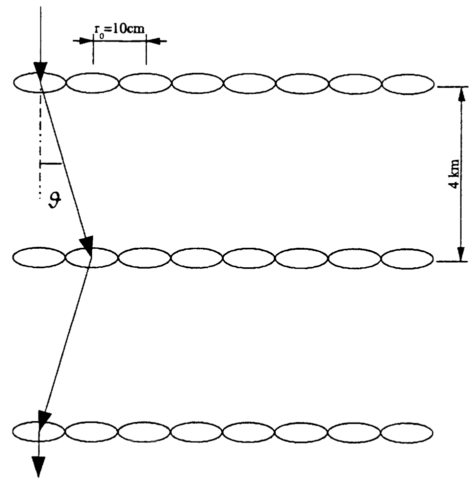

Figure 2. Schematic of ray propagation through various turbulent cells within various atmospheric layers.

A simple argument can be made that the order of correction is not important. Refer to figure 2. Assume that we have 3 layers of atmospheric turbulence at 0, 4, and 8 km. If we model the turbulence as a group of turbules of diameter r_0, then the order of correction will certainly matter if the ray deflection introduced by a turbule exceeds one turbule diameter (r_0) at the next layer. It is important to note that this is a differential tilt between turbules and the common mode does not affect performance since it serves only to shift where the turbules in the following layer are drawn. The differential tilt, then, in order to steer the beam by an r_0 is θ = 0.1m/4km = 25 μrad = 5 arcsec. That is larger than we expect to see.

*This can be seen with a geometrically–oriented argument in an operator type notation:

O = star
$Z_{\infty\rightarrow 8km}$ = propagation from star to 8 km layer
$Z_{8km\rightarrow 4km}$ = propagation from 8 km to 4 km layer
$Z_{4km\rightarrow 0km}$ = propagation from 4 km to 0 km layer
$Z_{0km\rightarrow image}$ = propagation from 0 km to image

W_{8km} = aberration due to 8 km layer
W_{4km} = aberration due to 4 km layer
W_{0km} = aberration due to 0 km layer

If the correction is done according to Hardy,

$$Z^{-1}_{\infty\rightarrow 8km} W^{-1}_{8km} Z^{-1}_{8km\rightarrow 4km} W^{-1}_{4km} Z^{-1}_{4km\rightarrow 0km} W^{-1}_{0km} Z^{-1}_{0km\rightarrow image} Z_{0km\rightarrow image} W_{0km} Z_{4km\rightarrow 0km} W_{4km} Z_{8km\rightarrow 4km} W_{8km} Z_{\infty\rightarrow 8km} O=O$$

It is apparent that this equality is not true in general if the correction is done differently, since the inverse of the aberration/propagation sequence is unique. However, to the extent that the Z operators are "diagonal matrices" (i.e., there is no crosstalk between subapertures), the order of correction will not matter.

However, the turbule does not need to steer over by a full r_0 in order to cause problems; a shift of 1/3 r_0 may be enough. That would be a tilt of 1.5 arcsec. This is still larger than we expect to see. Our estimate is probably pessimistic since r_0 will very likely be greater than 10 cm.

4.7 Multiple guide star sensing

The exploitation of NGS's, in particular, over a wide field of view leads to several interesting issues. Because of the need to optimize the equivalent subaperture diameter for each guide star, there may be advantages to variable aperture wavefront sensing approaches such as curvature sensing or shearing interferometry. Furthermore, there remains to be determined the trade offs between the use of open–loop wavefront information from brighter guide stars (that is, from guide stars outside the corrected FOV, but within the *technical field* provided by the telescope) versus closed–loop information from fainter guide stars. Additionally, is it possible to conceive of alternative wavefront sensing geometries that enhance the 3–dimension understanding of the instantaneous state of the science wavefront propagation path? Also, important will be the practical difficulty of sensing potentially many guide stars, using, for example, a field segmenting device such a segmented actuated mirror. All these issues require detailed consideration before we may proceed with a design of the CELT adaptive optics capability.

4.8 NIR MCAO Error Budget

To guide future discussions of the NIR MCAO system, we include an example wavefront control error budget in Table 4. Many of the terms in this table are based upon Keck Telescope and Palomar Adaptive Optics System experience. Noteworthy in this tabulation is the 100 nm of rms wavefront error distributed to tomographic reconstruction error. This includes all of the multiple wavefront sensing issues described above and is the most poorly understood of the error budget terms.

We consider in this error budget a system with 7000 actuators, which from Figure 1, can be seen to be sufficient to control fitting error for a 30m telescope in the near–infrared regime. We note that this does not imply that each adaptive element of the MCAO requires this actuator count, but at least one does. Rather, the detailed design trade offs of various actuator count correctors for the various atmosphere conjugates remains a topic for further study.

5. EXTREME AO (EAO)

Over the lifetime of the CELT observatory, we believe the wavefront control capability can and should continue to advance, encompassing both improved wavefront correction at NIR wavelengths and new diffraction–limited capability at visible wavelengths. It is difficult to predict the potential for LGS technical development over the, say, 50 year lifetime of CELT, so for our purposes here, we assume that an upgrade path to a V–band extreme AO (EAO) system is based upon wavefront information derived from only the brightest nearby NGS's. Obviously the extension of visible AO to wide fields and significant sky coverage for CELT would be an enormously rewarding technical and scientific milestone.

AO systems optimized for planet detection have been suggested by Angel[22–23]. A wavefront sensor with variable subaperture size, such as a zoom Shack–Hartmann, shearing interferometer or curvature sensor, would provide for a straightforward upgrade path toward a extreme AO (EAO) system for CELT, taking advantage of further increases in deformable mirror technology to provide very high actuator counts (> 25,000) at affordable cost.

For comparison, we include an example error budget for a V EAO capability in Table 5. In this table, we (very) conservatively assume only modest reduction in the residual telescope error, while invoking a dramatic decrease in the atmospheric residual errors. The implications of this error budget to the detailed design of a V EAO capability for CELT are left for further investigation.

NIR MCAO SYSTEM	Error (nm)	1 um 7000 act	2.2 um 7000 act	3.5 um 7000 act	10 um 7000 act
Telescope Residual Errors					
Segment fitting	40	0.94	0.99	0.99	1.00
Secondary fitting	30	0.97	0.99	1.00	1.00
ACS noise	30	0.97	0.99	1.00	1.00
Phasing	25	0.98	0.99	1.00	1.00
Vibration	50	0.91	0.98	0.99	1.00
Stacking	10	1.00	1.00	1.00	1.00
Wind buffetting	25	0.98	0.99	1.00	1.00
Focus	20	0.98	1.00	1.00	1.00
Total telescope	**87**	**0.74**	**0.94**	**0.98**	**1.00**
Atmospheric Residual Errors					
Fitting (Nact = 7000)	55	1.00	1.00	1.00	1.00
Tomographic reconstruction	100	0.67	0.92	0.97	1.00
Bandwidth	50	0.91	0.98	0.99	1.00
Measurement	50	0.91	0.98	0.99	1.00
Tip/tilt	50	0.91	0.98	0.99	1.00
Internal	50	0.91	0.98	0.99	1.00
Total atmosphere	**152**	**0.45**	**0.85**	**0.94**	**0.99**
Instrument Residual Errors					
PSF calibration	25	0.98	0.99	1.00	1.00
Fitting	25	0.98	0.99	1.00	1.00
Non–common	25	0.98	0.99	1.00	1.00
Total instrument	**43**	**0.93**	**0.98**	**0.99**	**1.00**
Total	**180**	**0.31**	**0.79**	**0.91**	**0.99**

Table 4. Example error budget for NIR MCAO capability for CELT.

6. SEEING LIMITED (SL) MODE

Although the primary scientific mission of CELT calls for diffraction–limited wavefront control at near and mid–infrared wavelengths, we include brief discussion of the seeing–limited observing mode. CELT provides a new challenge to maintaining even seeing limited observations. Because of the envisioned larger number of primary mirror segments, compared to the Keck telescope, and the simplification to the edge sensing scheme over that of Keck, the active control system (ACS) is expected to experience a higher noise propagation from sensor noise to wavefront error for low order spatial modes of the primary mirror[24]. Due to the envisioned edge sensor geometry, focus mode of the primary would additionally not be sensed.

Both of these effects motivate us to consider a full–sky, slow wavefront sensor that would be used to sense, perhaps, the 50 lowest spatial frequency modes of the telescope. We have seen from our discussion of natural guide star adaptive optics in Section 3 above, there are abundant guide stars of sufficient brightness to provide an external measure of these modes. While certain metrology schemes remain under consideration in lieu of wavefront sensing, these remain to be developed and tested for feasibility.

V EAO System	Error (nm)	0.4 um 25,000 act	0.7 um 25,000 act	1 um 25,000 act	2.2 um 25,000 act
Telescope Residual Errors					
Segment fitting	40	0.67	0.88	0.94	0.99
Secondary fitting	30	0.80	0.93	0.97	0.99
ACS noise	30	0.80	0.93	0.97	0.99
Phasing	25	0.86	0.95	0.98	0.99
Vibration	50	0.54	0.82	0.91	0.98
Stacking	10	0.98	0.99	1.00	1.00
Wind buffetting	25	0.86	0.95	0.98	0.99
Focus	20	0.91	0.97	0.98	1.00
Total telescope	**87**	**0.15**	**0.54**	**0.74**	**0.94**
Atmospheric Residual Errors					
Fitting (Nact = 25,000)	18	1.00	1.00	1.00	1.00
Bandwidth	25	0.98	0.99	1.00	1.00
Measurement	25	0.98	0.99	1.00	1.00
Tip/tilt	25	0.98	0.99	1.00	1.00
Total atmosphere	**47**	**0.93**	**0.98**	**0.99**	**1.00**
Instrument Residual Errors					
PSF calibration	10	1.00	1.00	1.00	1.00
Fitting	5	1.00	1.00	1.00	1.00
Non–common	10	1.00	1.00	1.00	1.00
Total instrument	**15**	**0.99**	**1.00**	**1.00**	**1.00**
Total	**100**	**0.14**	**0.53**	**0.73**	**0.94**

Table 5. Example error budget for V EAO capability for CELT. Note that here we conservatively assume only modest improvement to the residual telescope errors.

7. SCIENCE INSTRUMENTATION CONCEPTS

As important to the CELT science mission as the enormous collecting area and the precision wavefront control capability, is the science instrumentation complement. These will have unique technical challenges. In order to exploit the wavefront correction lifecycle of the observatory, we envision a set of early and a set of later instruments that are matched to particular observing modes. An early conceptualization of this instrument compliment is presented in Table 6. Although there clearly can be several papers written detailing the complex technical issues unique to each instrument, we choose here to concentrate on two aspects that may be common to all instruments exploiting diffraction–limited wavefronts.

AO Mode	*Early Instruments*	*Later Instruments*
SL	VIS MOS VIS Fiber feed to HIRES	TBD
SCAO	MIR Imager	MIR IF Spectrograph (R>>2,000)
MCAO	NIR Imager NIR Deployable IF Spectrograph	NIR M–slit Spectrograph (R~5,000)
EAO	VIS Spectrometer (R~80,000)	TBD

Table 6. Early conceptualization of an instrument suite designed to exploit the wavefront correction capability of CELT (IF = integral field).

The suite of early instruments includes, for seeing limited observations, a visible multi–fiber multi–object–spectrograph and a fiber feed to a visible HIRES–like spectrograph, which would enable spectral resolution R ~ 80,000. This same spectrograph is envisioned as potentially providing diffraction–limited science later with the EAO observing mode. For diffraction–limited observations in the mid–infrared an imager would be followed later by an integral field spectrograph of R >> 2,000. For diffraction–limited near–infrared observations, an imager and integral field spectrograph would be followed by a multislit spectrograph of R ~ 5,000.

7.1 Slow wavefront sensing

The calibration requirement for the delivered wavefront for CELT instrumentation is uniquely challenging. We envision that each instrument may be required to actively participate in the efficient calibration of the various adaptive optics observing modes by providing slow wavefront sensing of the non–common path errors between the science detector and the wavefront sensor detector. The determination of the need for this capability will be made once better understanding of the local turbulence and mechanical vibration environment of the science instrumentation is obtained.

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