CELT adaptive optics requirements and development program

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Outline

- CELT AO conceptual design
- AO observing modes
  - Multiconjugate AO (MCAO)
    - Performance targets
    - Scaling laws
    - Optical considerations
  - Emissivity-optimized AO (LOAO)
  - Extreme AO (ExAO)
  - Ground-layer AO (GLAO)
- Development program outline

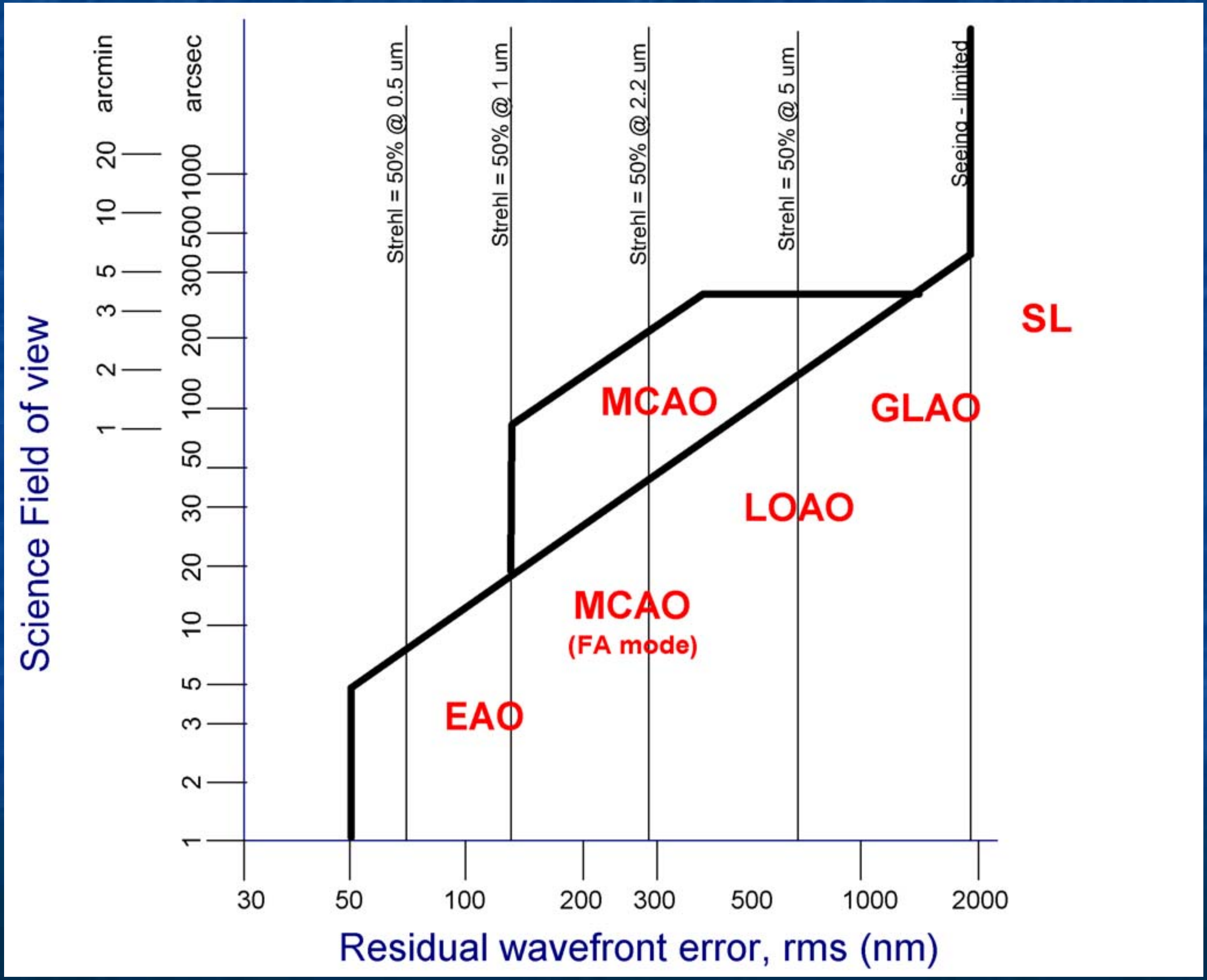
CELT AO conceptual design phase

- Goals
  - Demonstrate the feasibility of scientifically meritorious AO on a 30-m class telescope
  - Identify physical limitations
  - Identify key technology requirements
  - Prepare a development plan for the (following) preliminary design phase

CELT AO concept modes

- Baselined
  - Low-emissivity AO (aka Low-order AO)
  - Multiconjugate AO
    - Bauman and Dekany, "Multiple conjugate adaptive optics (MCAO) system for extremely large telescopes" SPIE 4840-06
    - Gavel, et. al., "Scaling laws for designing multiconjugate multi-guidestar adaptive optics" SPIE 4840-13
- Not baselined
  - Extreme AO
    - Macintosh, et. al., "'Extreme' adaptive optics for planet detection with extremely large telescopes" SPIE 4839-140
  - Ground-layer AO

Phase space for AO observing modes



Multiconjugate Adaptive Optics

CELT MCAO

- Scientific goal of 2′ FoV
- Study identified three performance levels based upon scientific priorities
  - Floor level: Minimum capability for diffraction-limited science goals
  - Requirement level: Performance that will be costed and to which project management shall be held accountable
    - Note, the CELT MCAO requirements are not established
  - Goal level: Desired performance without major modifications to other Observatory subsystems (i.e. sets telescope specifications)

CELT MCAO study performance levels

MCAO performance levels	floor	"requirement"	goal
rms wavefront error (nm)	248	180	133
FoV (arc min)	1	1	1
Sky coverage	30%	30%	50%
Strehl Ratio in J-band (1.25μm)	0.21	0.44	0.64
Strehl Ratio in H-band (1.65μm)	0.41	0.61	0.77
Strehl Ratio in K-band (2.2 μm)	0.61	0.77	0.87

- "Goal" performance also results in:
    - σ = 184 nm over 2 arcmin FoV
    - σ = 101 nm for a bright, on-axis natural guide star ($SR_{0.5\ um}$ = 0.20)

Sample error budgets
for three MCAO performance levels

(SPIE 4840-13 Gavel, et al., "Scaling laws for designing multiconjugate multi-guidestar adaptive optics")

Error term	248 nm	180 nm	133nm
Generalized anisoplanatism	181	116	86
Fitting	110	77	60
Residual primary figure	50	50	50
Measurement	80	70	40
Tomography	51	39	32
Bandwidth	50	35	25
Residual internal	20	15	10
Residual instrument	20	15	10
Equiv. Tip/tilt bandwidth (λ = 1μm)	20	15	10
Equiv. Tip/tilt anisoplanatism	26	26	26
Equiv. Tip/tilt measurement	12	12	6
Total RMS	248	180	133

CELT MCAO concept

- 4 deformable mirrors
  - Errors budgets dominated by generalized anisoplanatism
  - Optimized at 0 km, 3.0 km, 5.8 km, and 12.0 km conjugates
  - Possessing 7700, 7000, 4200, and 1780 actuators respectively
  - Total actuator count 20,600 (inscribed in metapupil)
- 9 sodium laser guide stars
  - 0.4 arcsec FWHM on sky
  - Return of 180 PDE/subap/frame
  - Measurement error falls slightly when constant flux is divided into more guide stars, $\sigma_{meas} \sim n_{gs}^{-0.07}$ (until read-noise fights back)
- 9 Shack-Hartmann WFS
- 3-5 NGS for tip/tilt anisoplanatism and asterism distortion correction

California Extremely Large Telescope

CELT MCAO optical design concept

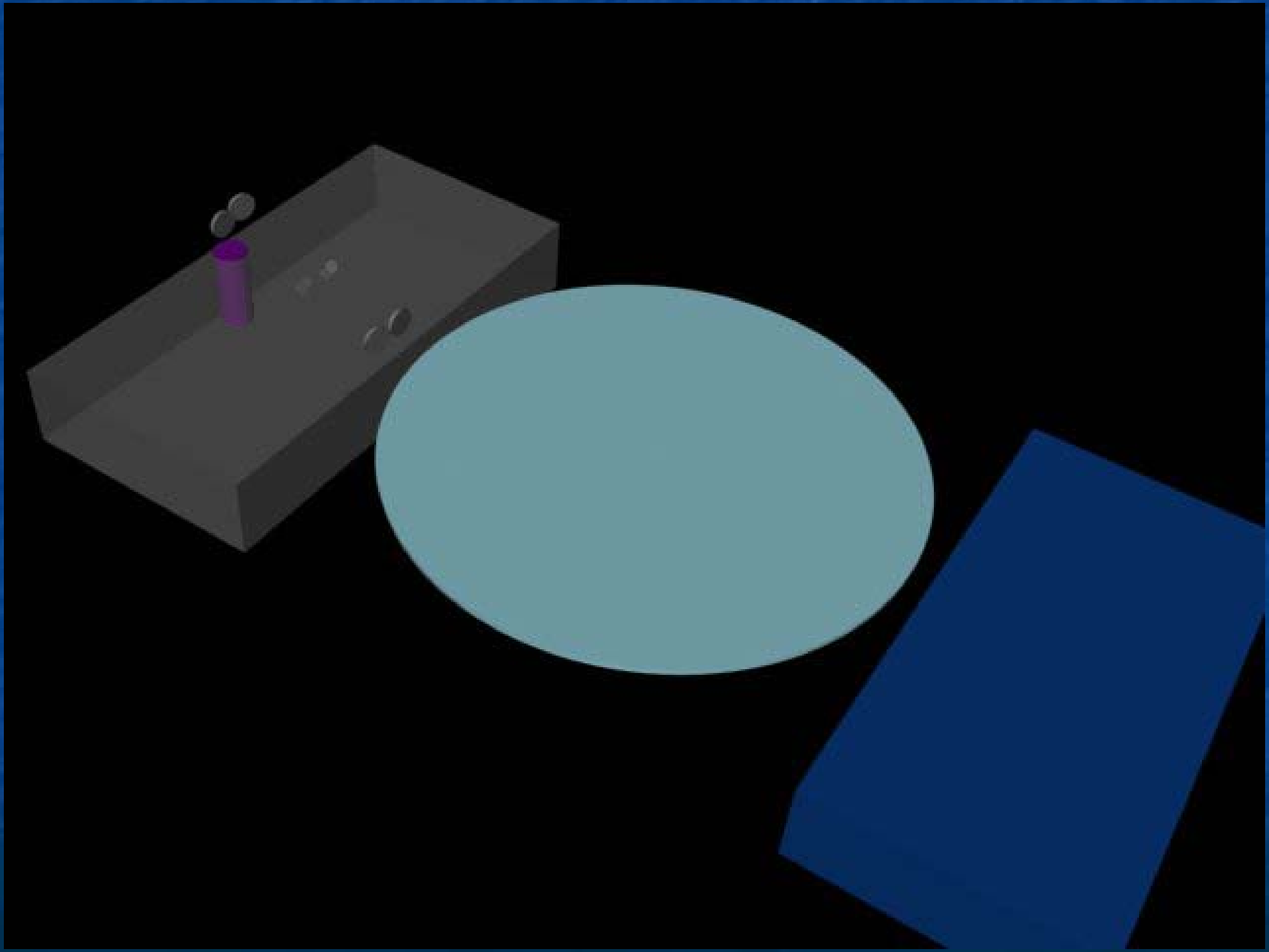
(Bauman and Dekany, SPIE 4840-06)

- Fixed Nasmyth AO relay
  - 4 deformable mirrors
    - For example, select 0, 4, 8, and 12 km
  - 6′ unvignetted FoV
    - Supports ground-layer AO operations
  - LGS passed through science relay using optical trombone
- LGS launches from 30m perimeter
  - Launch from behind secondary to be avoided
    - Launch through primary may be preferred – requires further structural and AO system engineering trades
- Image and pupil rotation
  - CELT instruments envisioned as vertical rotating drums
  - Rotating vertical WFS drum and rotating DM’s

California Extremely Large Telescope

MCAO layout relative to Nasmyth platform

(with instrument)



CELT study MCAO technology needs

Technology	Today	248 nm	180 nm	133 nm
Na guide star lasers	2W CW dye, 8W micropulse/ macropulse, 15-20 W stretched-pulse	5 each with Today's Technology	7 lasers, 15-25 W m/m pulsed	9 lasers, 15-25 W m/m pulsed, AO on uplink
Deformable mirrors	1 DM, 900 actuators	2 DMs, 2,500 total actuators	3 DMs, 9,000 actuators	4 DMs, 21,000 actuators
Visible WFS detectors	128 x 128 x 1 kHz	5 each with Today's	7 cameras, 256x256 x 1kHz	9 cameras 256x256 x 1kHz
Near IR WFS detectors	128x128 x 250Hz, 20e- rms read noise	3 each with Today's	3 cameras, 5e- rms	5 cameras, 5e- rms
Real-time computing	1 x 10^9 operations/sec	Today's	3x Today	10x Today

Low emissivity AO

Low emissivity AO for mid-IR science

- For $\lambda > 2.4$ μm, thermal background of AO system can substantially impact scientific use
- Still, mid-IR resolution considered scientifically more compelling than sensitivity (due to commanding advantage of NGST)
    - Residual rms wavefront error goal of 500 nm
    - Significant sky coverage using only single natural guide star
        - Based upon relatively loose wavefront error budget (500 nm rms), which allows for large subaperture wavefront sensing and large isoplanatic angle
        - Sky coverage at 500nm rms is > 30% (for guide stars up to 1′ off-axis)
            - For 5 and 10 μm work, excellent coverage; for 3.5 μm work, poor pole coverage
    - Diffraction limited at 3.5 μm and longer
        - ~ 500-1000 actuators, single conjugate DM
        - Wide-band and low-noise wavefront sensing

Low emissivity AO options

- Adaptive secondary mirror
  - CELT F/15 secondary is 4.2 m diameter
  - ASM state of the art is ~ 1 meter diameter, ~600 actuators (LBT)
    - Must either sacrifice FoV (by going to significantly slower F/#) or develop much larger diameter adaptive secondaries
  - Wind remains a design driver, so minimizing secondary complexity desirable
- Cryogenic AO system
  - Prime focus
    - Truly 'optimized' with total of 1 warm surface (primary mirror)
    - Has major impact on telescope and dome design
    - Thermal emission from atmosphere often dominates over that from telescope or AO system
  - Nasmyth
    - Cryo-analogue of existing AO systems (ie, Keck)
    - Sacrifice some science return
    - Easier implementation

Comparison of integration times for same SNR

(Following Lloyd-Hart, et. al., SPIE Proc 3353, 1998)

Integrated Wavelength Band	Relative integration time (T=275K, Cryo-prime focus = 1.0)	
	Cryo-Nasmyth or adaptive M2	Warm MCAO at Nasmyth
K (2.2 μ)	1.32	3.31
L (3.4 μ)	1.51	4.76
M (5.0 μ)	1.34	3.51
N (10.6 μ)	1.35	5.41

Low emissivity AO summary

- 4.2 m adaptive secondary considered unnecessary development risk
  - Faster primary may enable reconsideration of 2m-class adaptive secondary
- Prime cryo-AO system feasible, but has significant impact on telescope
  - Increases enclosure size
  - Increases wind cross-section of upper structure
  - Difficult to service
- Nasmyth cryo-AO appears to be the best alternative

- Outstanding issues
  - Appropriate deformable mirrors must be prototyped and proven
  - Chopping/counterchopping requires further system-level consideration
    - Preliminary estimate of 2-4 Hz chop of secondary made without detailed structural model
  - Vertical drum rotation

Extreme Adaptive Optics

High-contrast observations

- Fundamental photon limitations to wavefront sensing with NGS allow study of mature exo-Jupiters and possibly a few exo-Earths with CELT (Angel, 1994; Macintosh, 2000; Stapelfeldt, Dekany, et al., in preparation)
  - Challenge is technological and conceptual
  - Optimized classical systems require O(10^6) actuators, massive computation
- Space-variant AO techniques relax technology requirement
  - Correct whole PSF to very good Strehl
  - Only a portion of the PSF to extreme contrast ($<10^{-9}$)
    - Photon counting wavefront sensors
    - Dark hole algorithms (Malbet, 1994)
- Concentrate on study of exoplanets found by interferometer astrometry or small aperture space coronagraphs

Ground-layer Adaptive Optics

Ground-layer (GLAO) observing mode

- Perfect correction of ground-layer can theoretically reduce the seeing over a wide field of view (FoV)
  - For idealized 2-layer atmosphere resultant image size would be determined by r_0 of the high-altitude layer
    - Typically a factor 3 larger than the total r_0 value
    - 0.5″ arcsec seeing -> 0.167″ seeing (best case)
    - Goal is to improve 0.5″ seeing into 0.35″ seeing or better, over 5-6 arcmin FoV

  - Correction of ground-layer must be good at the desired wavelength (e.g. a first-order calculation indicates ~80% Strehl needed for 80% encircled energy)
  - High-altitude turbulence is partially converted into amplitude fluctuations
    - Still increases FWHM, but does not corrupt ground-layer phase determination

Correction potential

- Assuming 80% Strehl requirement, ask ‘how large a field can I correct?’
  - $80\% = \exp(-\theta/\theta_0)^{5/3} \rightarrow \theta_{\mathrm{partial}} = 0.406\ \theta_0$
  - $\theta_0 = 0.317\ r_0/h \rightarrow \theta_{\mathrm{partial}} = 0.13\ r_0/h$
  - $\mathrm{FoV}_{\mathrm{partial}} = 0.26\ r_0/h$

Layer height (modified CP profile)	Fraction of entire CP model C_n^2	r_0 (2.2 μm)	$\mathrm{FoV}_{\mathrm{partial}}$ (2.2 μm)	$\mathrm{FoV}_{\mathrm{partial}}$ (0.5 μm)
0	8%	0.94 m	◎	◎
50 m	18%	0.56 m	30 ‘	6′
200 m	29%	0.42 m	5.6′	1′
700 m	10%	0.79 m	3′	30″
1800 m	8%	0.91 m	1.3′	13″

- In fact, some acoustic sounding measurements show that half of all turbulence can occur within 100m of the ground.
- 80% Strehl requirement is likely *too strong* (example: 75″ off-axis correction of Pluto/Charon with PALAO gave 0.25″ FWHM)

Conclusions

- There are no fundamental reasons why 500 nm rms wavefront error with NGS, and 133 nm rms wavefront error with LGS, cannot be achieved
- 248 nm rms MCAO system possible with (nearly) today's technologies
  - Many error terms must be validated in the lab and on the sky
- Important, but incremental, component technologies are required to maximize science return
  - Deformable mirrors (larger diameters, more actuators)
  - Beacon lasers (more practical power, perhaps new pulse formats)
  - Low-noise detectors (e.g. IR WFS detectors)

ELT AO development

- AO development for ELT's broadly benefits existing national and private observatories
  - To ensure CELT-specific development goals are addressed a strong AO effort within the CELT project
  - However, significant resources available throughout the community (approximately multiplying CELT effort by 3x)
  - Actively coordinate CELT development with:
    - NSF (AO Roadmap, CfAO, NIO, Gemini, etc.), UCSC LAO, Caltech, JPL, LLNL, SOR, and elsewhere

CELT AO Development Program

(2003-2005)

- Analytical and semi-analytical models
  - Theoretical development (e.g. Cone effect in tomography)
  - Computer-based calculations (e.g. Covariance matrix analyses)
- Monte Carlo wave propagation models
  - End-to-end AO system models including laser, DM, and WFS details
- Component technology development
  - Build two alternative 4,000 element DMs with >~ 2 micron stroke
  - Build two sodium lasers (micropulse/macropulse; fiber laser) of power 10-20 W
  - Invest in low-noise IR WFS arrays for LOAO
- Testbed development
  - MCAO lab demonstrator within UCSC LAO
  - PALMAO testbed on the 5.1m Hale Telescope
    - 4-channel wavefront sensor
    - ~180nm WFE w/ LGS)