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California Extremely Large Telescope (CELT) Performance Requirements

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In this report we describe the performance requirements for CELT. The emphasis is on the scientific drivers rather than the engineering details. We will describe the requirements at a high level, then describe more quantitatively the implications. In the notes for each requirement a more detailed discussion will explain the basis for the requirement and the potential engineering implications.

1. Telescope

1.0 Image Quality: The aim of the telescope is to gather light and produce image quality limited by the intrinsic site qualities or by diffraction. Further, the design of the telescope should not preclude effective use of adaptive optical systems aimed at delivering diffraction limited images to scientific instruments. These general objectives should be met for the wavelength range specified below.

Quantitatively, when the atmospheric seeing allows 0.30 arcsecond images FWHM (10%ile for Mauna Kea), the telescope imperfections should degrade these to no more than 0.33 arcsecond. This is defined for wavelengths of 0.5 μm.

1.1 Collecting area (Note 1)

1.1.1 Gross collecting area	707 m^{2-}
1.1.2 Area of central obstruction	12.34 m^2
1.1.3 Non-imaging or blocked surface area	<10%
1.1.4 Diffractive effects of blockages on PSF	less than atmosphere (Note 2)
1.1.5 Nominal surface shape	k = 90 m RC hyperbola (Note 3)

1.2 Optical Foci (Note 4)

1.2.1 Prime focus	none
1.2.2 Cassegrain focus	none
1.2.3 Nasmyth focus	two platforms (450m^2 each) Minimize polarization, unpredictability

1.3 Optical configuration (Note 5)

1.3.1 f/15 Secondary mirror	interchangeable
1.3.1.1 size	unvignetted for 20 arc min FOV
1.3.1.2 motion control	5 axis control
1.3.1.3 tip-tilt closed loop control	bandwidth of 2 Hz
1.3.1.4 active control range	suitable range for all needs
1.3.1.5 active control smoothness	less than 0.02 arcsec rms image motion
1.3.2 adaptive secondary mirror	
1.3.2.1 size	undersized for thermal IR
1.3.2.2 motion control	5 axis control

1.3.2.3 tip-tilt closed loop control	bandwidth of 5 Hz
1.3.2.4 active control range	suitable range for all needs
1.3.2.5 active control smoothness	less than 0.02 arcsec rms image motion
1.3.2.6 adaptive control	Strehl ≥ 0.9 at 5 μm (~ 500 dof)
1.3.3 Tertiary mirror	
1.3.3.1 Size	unvignetted for 20 arcminute FOV
1.3.3.2 Motion control	2 axis (tip-tilt)
1.3.3.3 Active control range	send beam to all positions of both Nas.
1.3.3.4 active control smoothness	less than 0.02 arcsec rms image motion

1.4 Wavelength range (Note 7) 0.4 – 30 μm (0.3μm goal)

1.5 Emissivity (Note 6) The design of the telescope shall allow low-emissivity observations in the thermal infrared. A system emissivity of 4% should not be precluded for well-designed instruments at 10 μm wavelength.

1.6 Throughput (Note 7) The telescope optics shall be coated with a high reflectivity coating (goal: as good as the better of Ag and Al over 0.3-30 μm).

1.7 Telescope instruments The telescope shall accommodate a variety of instruments on the Nasmyth platforms. (Note 8)

1.8 Environmental conditions for which the telescope shall meet specifications (Note 9)

1.8.1 Wind	<14m/s
1.8.2 Temperature	2±4 °C
1.8.3 Humidity	up to 100%

1.9 Telescope Motion (Note 10).

1.9.1 Pointing, tracking, guiding		
1.9.1.1 Pointing	within 1 arcsecond rms over all sky	
1.9.1.2 Tracking (open loop)	0.02 arcsecond rms in 10 s	
	0.1 arcsecond rms in 10 minutes	
	0.5 arcsecond rms in 1 hr	
1.9.1.3 Guiding (closed loop, AO off)	within 0.02 arcsecond rms over 10 min.	
	Within 0.05 arcsecond rms over 1 hr	
	Focus within 0.02 arcsecond (80%)	
1.9.2 Slewing	360° azimuth, 65° elevation in 5 minutes	
	1 arcsecond on sky	1 s
	10 arcsecond on sky	3 s
	100 arcsecond on sky	10 s
	1000 arcsecond on sky	30 s
	slewing **goals** are 50% of above values	
1.9.3 Sky coverage	Unvignetted above 25°, 75% of az range	
	<2° zenith blind spot diameter	
1.9.4 Observing range		
1.9.4.1 Azimuth	100.5° ±220.5°	

1.9.4.2 Elevation 25°-89°

1.10 Earthquakes facility shall survive 100 yr quake.

2. Adaptive Optics. (Note 11)

2.0 The telescope is expected to have an AO system that can deliver images at 1 μm with a Strehl of 0.5 for median seeing conditions (r_{00} = 0.2m). This corresponds to an rms wavefront error of 133 nm. The telescope design should not significantly increase the difficulty of achieving this objective.

2.1 Further, the telescope design should not significantly increase the difficulty of a future AO system from reaching a Strehl of 0.5 at 0.5 μm. This corresponds to an rms wavefront error of 67 nm.

2.2 The telescope should have an AO system that delivers wavefront errors of under 133 nm in median seeing conditions.

2.3 The AO system should have all sky coverage, which will require artificial beacons.

2.4 The AO field of view should be at least 2 arcminute at 2 μm and scale with wavelength as $\lambda^{6/5}$. The rms wfe over this FOV should be ≤ 133 nm.

2.5 The system should be optimized for work in the 1-2μm region, but be capable of working at longer wavelengths.

2.6 The telescope design should not preclude future AO systems with greater capabilities.

3. Enclosure. There shall be a telescope enclosure (dome) (note 12)

3.0 Protect telescope against inclement weather, wind, snow, rain, dust at site for up to 100 year storms

3.1 Protect the telescope against wind during normal observing. A minimal opening in the dome is acceptable (32.5m diameter).

3.2 Control the daytime temperature of the telescope environment to match the expected nighttime observing temperature.

3.3 Provide a benign nighttime environment for the telescope that preserves the seeing of the site. This means the temperature of the inside air should be no more than 0.5 °C warmer than the outside ambient temperature at night.

3.4 Motion of the dome opening should be at least as fast as the telescope slewing, so the dome motion does not restrict observing.

3.5 Range of motion of the dome opening should match the telescope.

3.6 Provide suitable handling equipment to support the construction of the telescope and routine maintenance of the telescope and its optics.

3.7 Provide suitable handling equipment to support the scientific and engineering instruments.

4. Support facilities

4.0 Local and remote facilities to provide suitable support for all

4.0.1 Observing, summit, local and remote

4.0.2 Maintenance of all telescope and instrument subsystems

4.0.3 Repair of all telescope and instrument subsystems

4.1 Safe Storage

4.1.1 180 spare segments

4.1.2 Other spares
4.1.3 Handling equipment
4.2 Coating and periodically re-coating optics
4.3 Periodic cleaning of optics
4.4 Provide safety and comfort for personnel
4.5 Support computer, networking, and backup hardware
4.6 Support software for system administration, networking, and observatory operations
4.7 Support communication hardware and software for communication to California

5. Reliability and Operations

5.0 The observatory reliability should be very high to minimize the operations cost and to maximize the time available for scientific observations.
5.1 The annual cost of operations should be under 5% of the cost of construction.
5.2 Nights available for science observing >90%
5.3 Lifetime >50 years

6. Site Requirements

7. Initial instrument investment should be 10% of the cost of the facility

8. Annual instrument investment should be 5% of the cost of the facility

Notes

Note 1: The telescope aperture is the equivalent of a 30-m diameter telescope. This has an area of 706.9m^2. The actual telescope will be segmented and not perfectly circular. In addition the diffraction-limited angular resolution of a 30-m telescope is desired. The actual segmented aperture should have at least this angular resolution.

Telescopes of a given diameter have various constraints that reduce the effective area below that of a circular disk. The secondary mirror usually obstructs part of the primary. In addition baffles that shield the focal plane from wide-angle light sources are often used and further reduce the effective area. Segmented-mirror telescopes have edge effects from the segments that reduce the useful area. Finally, the support for the secondary mirror blocks additional area.

For CELT we wish to keep all of these losses to a minimum and require that the net reduction is no more than 10% of the gross area, or 70.7m^2.

The present design has 1080 hexagonal segments composing the primary, with the central 19 segments of a regular array missing. The inscribed circle of the primary mirror has a diameter of 14.603m while the circumscribing circle has a radius of 15.524m. With segments having a nominal 0.5m edge length the gross glass area is 701.5m^2. In practice segment gaps of 2mm are needed for handling and safety, thus the real segments will be slightly smaller. Accounting for 1080 segments with 6 edges, one gets a net reduction in area due to gaps of 3.24m^2. The segment edges will be beveled for safety, with a projected width of 1 mm. This leads to an additional loss of 3.24m^2.

Note 2: Since angular resolution for CELT is important, the diffractive effects of the blockages should not have an objectionable effect on the PSF of the telescope. Diffractive effects are complex and will depend on the detailed shape of any blockages or apertures that define the net aperture of the telescope. At large angles the atmospheric PSF falls like $\theta^{-11/3}$ while diffraction from a circular aperture falls as θ^{-3}. Hence for large angles the diffraction effects of the aperture itself will define the mean strength of the PSF rather than the atmosphere. Figure 1 shows the PSF for the atmosphere and for a circular 30m aperture.

Note 3: The desire for a relatively large field of view and a simple optical system with minimal optical elements (mirrors) makes the choice of a Ritchey-Chretien optical system natural. This provides a coma-free field of view at the cassegrain/Nasmyth focus. This forces the primary and secondary to be matched hyperbolas. For the design space of interest the primary will be rather close to being parabolic. The current design has a primary mirror focal length of 45m, a secondary mirror focal length of –6.06m, and a back focal distance of 15m.

Note 4: Prime focus is a traditional location for wide-field-of-view cameras. For CELT the utility of prime focus is expected to be marginal because of the difficulty and cost of providing an adequate optical corrector (prime focus suffers spherical aberration and coma). Since the primary is segmented, its shape can be approximately changed to a parabola. This change requires 24µm of additional actuator stroke, a minor change. The individual segments will then have the wrong shape by about C22 = 50 nm (outermost segment) with a resulting worst case image blur of roughly 0.3 arcsecond. At prime focus, coma (growing linearly with field angle) reaches 1 arcsecond when 12 arcsecond off axis. The rms wavefront error there is 2.86 μm. Thus the bare prime focus provides seeing limited images over roughly 20 arcsecond FOV. In addition it is likely that a prime focus will increase the size and cost of the dome. Hence it will not be available.

Similarly, the cassegrain focus is attractive because it only requires two mirrors before focus, instead of the three needed for the Nasmyth. However, the added cost and complexity for a cassegrain focus (complexity in the mirror cell design and instrument handling implications) does not appear worthwhile. Special efforts should be made to provide high reflectivity mirrors to minimize this loss.

The Nasmyth foci will accommodate all scientific and engineering instruments. There will be Nasmyth platforms on either side of the primary. Each will be approximately 15m x30m in size. The level of the platforms will be about 4 m below the elevation axis. The platforms will also accommodate instruments with vertical rotation axis where the instrument may be largely below the main platform. A lower platform to provide support and servicing will be 10m below the upper platform.

The platforms can accommodate up to 150-ton loads.

Note 5: The R-C configuration will have a back focal distance of 15 m and a final focal length of 450 m. The secondary mirror will be sized to capture all of the light from the primary on-axis only. It will not be oversized. The vignetting is approximately proportional to the field angle and at 10 arcminutes the loss is 3%.

The tertiary mirror will be articulated to allow it to direct the optical beam towards any instrument on the Nasmyth platform. This allows essentially all instruments to be fed through only 3 reflections. Only when the optical axis lies along the elevation axis can the tertiary mirror be stationary while the telescope is tracking stars.

The elliptical tertiary mirror will be sized for a 20 arcminute FOV and has a size 3 m x 4.3 m.

Note 6: The system emissivity is likely to be a major source of background for wavelengths beyond about 2.5 μm. The emissive contribution of some sources can be controlled by making cold masks inside the scientific instrument. More diffuse sources such as the surfaces of mirrors are more difficult to control. As a practical matter, it is probably difficult to achieve less than 1% emissivity for room temperature, atmosphere exposed optics. Hence this 3-mirror telescope will likely have at least a 3% emissivity. It is also likely that segment cracks and bevels will account for another 0.8%, hence a performance better than 4% is unlikely, even with significant effort.

Note 7: High reflectivity mirror coatings are desired. At this time it is not clear that coatings can be made that provide good reflectivity in the ultraviolet and excellent reflectivity in the infrared simultaneously. In particular, the region where Al is better than Ag is ≤ 370 nm. ≥ 370 nm it is probable that protected Ag will be available. Improving reflectivity below 370 nm appears to require complex High-Low interference stacks that may in turn reduce reflectivity in the IR near 10 µm. It is also not clear that such complex coatings will work well on the 45° fold flat. Thus, good response ≥ 370 nm is likely, but quite uncertain ≤ 370 nm.

Note 8: The Nasmyth platforms are the location for scientific instruments. Normal facilities shall be available to support instruments here. This includes, handling equipment, cooling capabilities, clean electrical power, support of cryocooling systems, and guiding systems.

Field rotation is a natural phenomenon with altitude-azimuth telescopes. Field de-rotation will be available for small field-of-view instruments (FOV < 120 arcsecond). Larger field of view instruments must rotate or handle field rotation in some otherwise acceptable fashion.

Atmospheric dispersion compensation is the responsibility of the scientific instrument.

Note 9: On Mauna Kea at the Keck site the wind is under 14 m/s 95% of the time. The nighttime temperature is within 2±4 °C 90% of the time (Keck Report 90). Other sites may require different environmental ranges.

Note 10: The telescope is expected to be an altitude-azimuth design, with reasonable access to most of the sky at any time.

Unless otherwise stated, angles are angles on the sky.

Slewing requirements are three times slower than for Keck. It is not yet known whether these are practical objectives.

Since the telescope cannot reach the horizon, it is likely that some fixed platform will be needed to service, and possibly change secondary mirrors. This fixed platform will block some part of the sky. East or west directions will be inconvenient, but will not introduce fundamental losses in sky coverage. North or south directions will cause fundamental loss of sky coverage.

Observing range defines the range of observing and implicitly the range requirements for cable wraps or other similar devices.

Note 11: Since the AO system must contend with the aberrations of the atmosphere, the most straightforward interpretation of this requirement is that the telescope should not introduce power in its wavefront structure function that exceeds that of the atmosphere. This should apply over the range of structure function lengths that are important for setting the rms wavefront error.

The sky coverage requirement necessitates artificial beacons of some sort, probably Na beacons. Laser beacons require natural tip-tilt reference stars and their relative scarcity may prevent 100% sky coverage. Guide star densities are needed here.

Because cone effect is very large, multiple beacons and tomography is almost certainly needed to achieve the desired wavefront correction. Angular anisoplanatism will limit the reduction of wavefront errors on the beacons themselves, unless multi-conjugate adaptive optics is used.

Achieving the desired FOV may require multi-conjugate adaptive optics. Performance at edge of FOV may be slightly worse than at the center.

Note 12: The dome should limit the rise of the telescope temperature during the day to no more than 1° above the expected midnight temperature. This is a significant aid to preserving good seeing conditions for the telescope. Ventilation of the dome volume during the night should be adequate to maintain the telescope near ambient temperature (within 0.5°C) during the night. This can be carried out by any suitable combination of natural and artificial ventilation, radiation or other heat transfer techniques.

The exterior of the dome should limit the degradation of seeing due to heating or cooling of the external skin of the dome that might otherwise cause excess thermal turbulence in the light path.

The dome should attenuate the wind hitting the telescope to limit resulting wind shake. In high winds the velocity attenuation should be at least a factor of two at the top end of the telescope, and a factor of ten at the primary mirror.

The minimum dome opening should be checked for thermal IR adequacy.

Requirements Issues of special note

AO system requirements are now 133 nm over 2 arcmin FOV.

Should we include atmospheric dispersion compensation details

Should the telescope have baffles?

Should we define Nasmyth requirements more carefully?
    Multistory
    Vertical

Where should focus land on Nasmyth platform

We don't yet know the sky coverage of laser beacons

What are the requirements for the adaptive secondary?

How do we want to include environmental conditions for other sites?