CELT Optics Alignment Procedure

Terry Mast*[a], Jerry Nelson[a], Gary Chanan[b], and Lothar Noethe[b]
[a] University of California, Santa Cruz, [b]University of California, Irvine

ABSTRACT

The California Extremely Large Telescope (CELT) is a project to build a 30-meter diameter telescope for research in astronomy at visible and infrared wavelengths. The current optical design calls for a primary, secondary, and tertiary mirror with Ritchey-Chretién foci at two Nasmyth platforms. The primary mirror is a mosaic of 1080 actively-stabilized hexagonal segments. This paper summarizes a CELT report that describes a step-by-step procedure for aligning the many degrees of freedom of the CELT optics.
Keywords: CELT, optics, alignment, telescope

1. INTRODUCTION

The California Extremely Large Telescope (CELT) is a project to build a 30-meter diameter telescope for research in astronomy at visible and infrared wavelengths. The current optical design calls for a primary, secondary, and tertiary mirror with Ritchey-Chretién foci at two Nasmyth platforms. The f/1.5 primary mirror is a mosaic of 1080 actively-stabilized hexagonal segments. Many aspects of CELT are described in CELT Report No. 34. This paper summarizes a detailed CELT report that describes a step-by-step procedure for aligning the many degrees of freedom (~6600) of the CELT optics. That report describes both analytical and numerical calculations that can be readily modified as the optical design changes. The report will be posted at the CELT website: celt.ucolick.org.

1.1 CELT reference optical design

We are currently using a reference optical design for CELT. In the next design phase we will make a quantitative trade among costs to define the final optical design. The reference design calls for a Ritchey-Chretién system with a tertiary flat mirror to position a focus at either of two Nasmyth platforms. There will be no prime or Cassegrain foci. The primary mirror is a mosaic of 1080 hexagonal, actively stabilized, segments each with a circumscribed radius of 0.5 meters. The design calls for sets of 19 segments to be mounted on a cluster frame, and the frames to be mounted on the mirror cell. The following parameters define the optics.

Primary radius of curvature	$k1 = 90$ meters
Primary conic constant	$K1 = -1.002837$
Secondary radius of curvature	$k2 = -12.4242$ meters
Secondary conic constant	$K2 = -1.524$
Back focal distance	$e = 16.5$ meters
Primary Diameter	$D1 = 30$ meters
Number of Hexagonal Segments	Nseg = 1080
Segment Circumscribing Radius	$a = 0.5$ meters
Field of View Radius	$\theta = 600$ arc seconds

Parameters derived from these include

Primary focal length	$f1 = 45$ meters
Secondary focal length	$f2 = -6.2121$ meters

---

* contact: mast@ucolick.org, 1-831-459-3807

Final focal length	f = 450.0 meters
Primary F-ratio	F1 = 1.5
Final F-ratio	F = 15.000
Magnification = f/f1	m = 10.00
Primary-secondary distance	d = 39.41 meters
Δ = e / f1	Δ = 0.367
plate scale	p = 2182 microns/arc second

1.2 Degrees of freedom

We will actively control the figures of the secondary and tertiary mirrors and assume here 61 figure control actuators for each. These degrees of freedom and those for the alignment of the 1080-segment primary, secondary and tertiary mirrors are listed below.

position of primary array in the telescope structure	= 6
in-plane segment motions Nseg x 3 - 3	= 3237
out-of-plane relative segment positions Nseg x 3 - 3	= 3237
secondary rigid-body motions	6
tertiary rigid-body motions	= 6
secondary figure actuators (assumed)	= 61
tertiary figure actuators (assumed)	= 61

Thus, there are about 6600 degrees of freedom to be measured and set.

1.3 Major issues of alignment

The alignment procedure addresses the following major issues.

- The very large number of degrees of freedom to be defined.
- The ambiguity between secondary tilt and secondary decenter.
- The ambiguity between global aberrations induced by secondary rigid-body motions and a primary-segment-faceted approximation of those aberrations.
- The multiple sources of a final wavefront error: primary, secondary, and tertiary figures.
- The zenith angle and temperature variation.

1.4 Constraints

The alignment procedure has been developed to be consistent with the following constraints.

- As the elevation angle changes, the primary mirror support (the mirror cell) deforms, and the segment-control actuators move the segments in tip, tilt, and piston to maintain their relative positions. However, the segment-control actuator range is limited. We select a coordinate system to minimize the required actuator range, and shim the cluster frame positions to minimize the required range.

- As the elevation angle changes, we align the secondary to maintain the Ritchey-Chretién configuration.

- Each instrument is fixed at a focus. As the elevation angle changes, we align the tertiary to move the telescope focal surface to coincide with the fixed instrument focal surface.

2. SENSITIVITIES

To indicate the magnitude of the alignment issues we list below the expected motions of the optics under the varying gravity load and temperature. The expected gravity-induced motions are from a structural analysis of the current structure design. The image sizes (100% enclosed-energy diameters) resulting from these motions are indicated.

Gravity (z = 0 to 65°)	**Motion**	**Image Size [θ(100)]**
primary as a whole	15.2 mm (in-plane) 10.7 mm (along optical axis)	
segments in-plane	1 mm radial	0.0027 arc sec
	0.01 mm edge rotation	0.0003 arc sec
secondary - primary	25 mm decenter	9.6 arc sec
	99 arc sec tilt	1.0 arc sec
	4.4 mm piston	13.6 arc sec
Temperature (ΔT = 1°C)		
segment radial	0.18 mm	0.0005 arc sec
secondary piston	0.47 mm	1.5 arc sec
Temperature Gradient (∇T = 0.1°C/m in X-Y plane)		
Secondary decenter	0.96 mm	0.37 arc sec
Secondary tilt	9.9 arc sec	0.10 arc sec

3. ERROR BUDGETS

The initial error budgets for CELT are described in Chapter 11 of CELT Report No. 34 and in CELT Report 10 (in progress). The error budgets for the AO-off mode are written in terms of the 80% enclosed-energy diameter, and those for the AO-on mode are written in terms of the rms wavefront. The table below gives a feeling for the tolerances, the fraction of the expected motion, and the budgeted 80% enclosed-energy diameter.

	80% diameter
Primary-secondary despace	
0.15 mm (0.035 of gravity motion)	0.059 arc sec
Primary-secondary decenter	
1.0 mm (0.04 of gravity motion)	
Primary-secondary tilt	
5.9 arc sec (0.06 of gravity motion)	0.059 arc sec
Segment in-plane motions	
4.5 mm radial motion	0.010 arcsec
2.5 segment rotation (mm at edge)	0.048 arcsec

4. AMBIGUITY BETWEEN ERROR SOURCES

The alignment procedure addresses three critical ambiguities in the system.

- **Primary-secondary relative rigid-body motions.**

Secondary tilt and secondary decenter both result in a global coma aberration. In practice these cannot be distinguished. We will use surveying to define the secondary decenter with respect to the primary to within about 1 mm, and then correct the residual coma using secondary tilt.

- **Secondary and tertiary figure errors**

On-axis aberrations can result from either the secondary figure errors or tertiary figure errors or both. We will measure the wavefront errors for different off-axis source positions to sweep the beam over different regions of the secondary and tertiary (See Figure 1). This will allow separation of the figure errors.

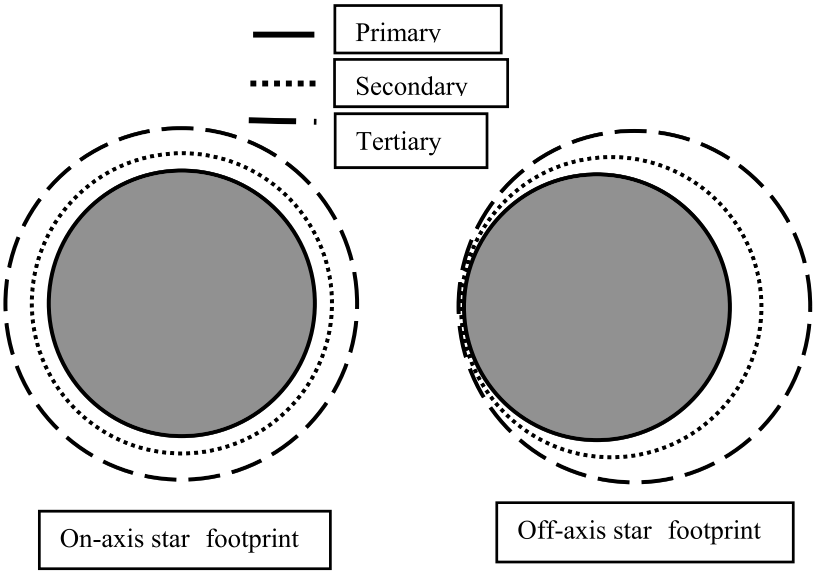

Figure 1. Footprints of the beam on the primary, secondary, and tertiary mirror for an on-axis and an off-axis star.

- **Primary mirror segment pistons/tips/tilts faceted-approximation to the above aberrations**

Secondary and tertiary figure errors and alignment errors can ambiguously be approximately corrected by a set of primary segment tips, tilts, and pistons. This is a faceted approximation (Figure 2 illustrates the concept) with a scalloped residual wavefront error. For secondary despace this ambiguity results in a significant residual scalloped residual. The alignment procedure removes this ambiguity.

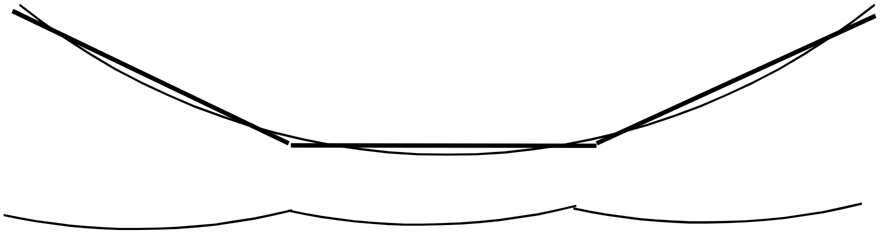

Figure 2. Illustrating the scalloped residual resulting from a faceted-approximation to a smooth aberration. The upper curve shows the uncorrected smooth aberration and the segment approximation. The lower curve shows the difference between the two.

5. PROCEDURE OVERVIEW

As explained above, the detailed alignment procedure with supporting analytical and numerical calculations is described in a CELT Report. We list here the major categories of the steps in the procedure.

5.1. With the secondary, tertiary, dummy loads for the primary mirror and instruments; and with surveying targets installed.

• Use theodolites on the Nasmyth platforms to measure the segment cluster attachment points at the zenith and at other zenith angles Zj (for example, every 10 degrees). For each zenith angle find the best-fit plane through the cluster attachment points. At the zenith use the best-fit plane and the design geometry to define the Telescope Coordinate System.

X axis	coincident with design elevation axis, positive toward the right Nasmyth platform
origin =	the point on the X axis and midway between the two Nasmyth vertex points.
Z axis	a line passing through the origin and the mean of the zenith cluster attachment points, positive toward the stars
Yaxis	perpendicular to X and Z in a right-handed system

Rotate the best-fit plane for each Zj back to the zenith. If there were no deformations of the structure as the zenith angle changed, then the planes for all Zj would coincide. Deformations cause these planes to differ in general by six degrees of freedom (3 translations and three tilts).

We consider one degree of freedom at a time. First note:

There are 5 degrees of freedom of the secondary with optical consequences.
There are 3 degrees of freedom of the tertiary with optical consequences.
There is a point in space at the center of curvature of the telescope focal surface (CCTFS). For the CELT reference optical design it is the center of a sphere with radius equal to 5.76 meters.
There is a point in space at the center of curvature of the instrument focal surface (CCIFS). This point in fixed relative to the Nasmyth platform, since the instrument is fixed on the Nasmyth platform.

One of the six degrees of freedom is special: Rotation of the plane about the Z axis.
This has no imaging effect, rotates the pupil, is expected to be very small since the structure is symmetric ±X, is expected to have a negligible effect on instrument performance, and cannot be corrected by moving the secondary and/or tertiary. Thus we must live with this small pupil rotation.

For each of the other 5 degrees of freedom there are two consequences: 1) image degradation and 2) motion of the pupil. We conceptually envision a two step alignment process (A and then B1 or B2).

A) As the zenith angle changes, move the secondary to re-establish the Ritchey-Chretién primary-secondary configuration.

With the primary and secondary locked together in the Ritchey-Chretién configuration, a second degree of freedom is also special: Tilt of the plane about the X axis. This does not degrade the image, does not move the pupil, and corresponds to a zenith-angle change. It will be corrected by the pointing algorithm.

This leaves 4 degrees of freedom, and in principle we have two options.

B1) For 3 of the 4 degrees of freedom move the tertiary to make the CCTFS and CCIFS coincide. This completely removes the image degradation, leaving only residual pupil motion (See Figure 3.).

B2) For the remaining 1 degree of freedom, move the secondary again to minimize the image degradation. This will move the configuration slightly away from the Ritchey-Chretién configuration. The residual effects will include some image degradation and some pupil motion.

For which three degrees of freedom we use B1, and for which one degree of freedom we use B2, depends on the magnitude of the deformations and the residual image degradations and pupil motions. In principle, this selection can be made after we know the magnitude of the deformations and have calculated the consequences of the selection.

In principle, this choice can be made independently for each elevation angle. In practice, we want to have alignment motions continuous with zenith angle, and thus we must make a single selection of degrees of freedom that applies to all zenith angles. The selection can be based on the zenith-averaged consequences of image degradation and pupil motion.

In practice, however, we expect the effects of pupil motion to be small. If they are negligible, then there is no need to select B1 versus B2, and we will simply use B1. Moving the tertiary (3 degrees of freedom) to superimpose CCTFS and CCIFS (3 required translations) will correct image degradation caused by all four sources. In addition, we expect these motions to be continuous with zenith angle.

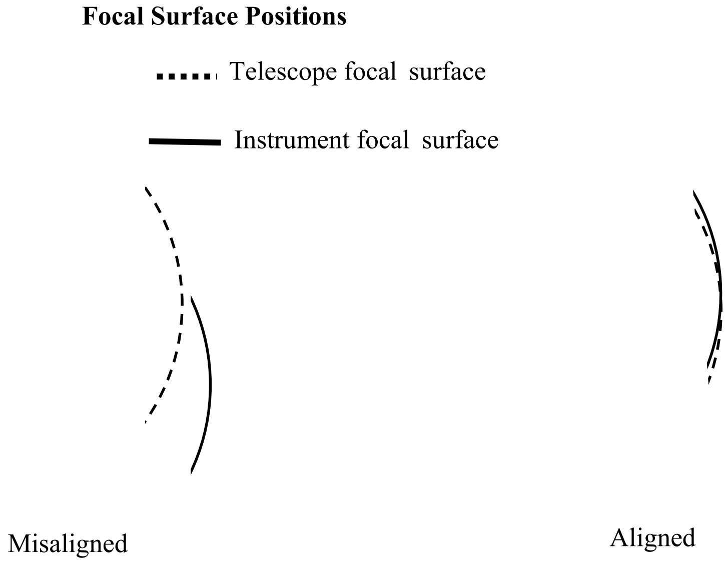

Figure 3. Telescope and instrument focal surfaces when the centers of curvatures don't concide (Misaligned) and do coincide (Aligned).

Primary Mirror Segments

- Add shims to position each cluster at the correct Z position and move the cluster attachment points in-plane (X-Y) to the design positions. Install the segment clusters with their segments.

Secondary

- Translate and tilt the secondary to the design position (Ritchey-Chretién configuration) with respect to the primary.

Tertiary

- Position the tertiary until a target at the center of the tertiary is at the design position in the Telescope Coordinate System. Tip/tilt the tertiary until a target at the center of the tertiary is seen (with a telescope or theodolite at the design instrument focus) to coincide with the target (reflected in the tertiary) at the center of the secondary. This defines the zenith position tilts of the tertiary.

5.2. With the telescope near the zenith using starlight

- Activate the segment active control to stabilize the primary array.

- Install a Star Stacking camera (See Section 6) at the Nasmyth, centered on the telescope-focal-surface vertex and use it to determine the initial segment tip and tilt (2 x 1080 – 2) degrees of freedom.

- Install a Shack-Hartmann/Phasing camera (See Section 6) at the Nasmyth, centered on the telescope-focal-surface vertex.

- Activate the Shack-Hartmann mode, and use it to measure x- and y-centroids for 7 (See Figure 4) sub-apertures per segment and at 5 field positions in order to
    - refine the X,Y tilts of the secondary
    - distinguish secondary piston from primary-array focus mode, and refine the secondary piston
    - define the figures of the primary, secondary, and tertiary
      i.e. refine all desired sensor readings, and figure control actuator values.

- Activate the Phasing mode and use it to align the segment pistons (1080 − 1) degrees of freedom using a Keck PCS-type broadband phasing algorithm.

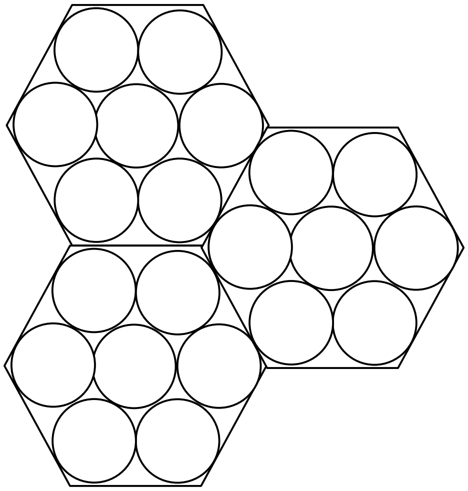

Figure 4. Illustrating the Shack-Hartmann geometry of seven sub-apertures per segment.

5.3. With the telescope at different elevation angles (different gravity loads)

- Use the measurements of the structure in Section 5.1 to open-loop correct the secondary piston, tip, and tilt so it is locked with respect to the primary (motion required ~ 20 mm) in the Ritchey-Chretién configuration.
- As the structure deforms the (now locked) secondary-primary combination will move in Z with respect to the elevation axis (~ 10 mm). Tip, tilt, and piston the tertiary to match the telescope focal surface with the instrument focal surface.

- Use the Shack-Hartmann Camera and the Phasing Camera to measure the parameters measured in Section 5.2 above at different zenith angles (for example, every 10 degrees).
  For example: 7 apertures/segment * 1080 segments * 2 centroids/aperture
  * 5 field positions * 6 zenith angles = ~ 450,000 measurements
- Fit all degrees of freedom to a smooth function of z
  For example: ~ 6,600 degrees of freedom * 3 zenith-function parameters = ~ 20,000 parameters
- During observations
  - Use the fitted functions to control all degrees of freedom.
  - Make small real-time corrections of the secondary tilts and piston based on the continuous monitoring of the Telescope Wavefront Sensor.

5.4. With the telescope at different temperatures

[Temperature variation effects will be smaller than those of gravity load variations.]

- Install temperature sensors on the structure.
- During observations make open-loop corrections based on the sensor measurements and temperature modeling of structure.

6. ALIGNMENT TOOLS

The following tools will be used in the alignment procedure. Their detailed design is a critical part of the next phase of the CELT design.

- Theodolites
  We currently envision using four commercial theodolites with automatic target acquisition and 0.5 arc-second accuracy.

- Star-Stacking Camera
  This will be an imaging camera used to coalesce images from all segments ("star stacking"). With a 1024 x 1024 pixel CCD, we will have about 40 x 40 pixels per segment image. The plate scale may need to be varied to cover the full range from initial acquisition of all segment images t final required centroid precision.

- Shack-Hartmann mode of the Shack-Hartmann / Phasing Camera
  This camera will follow the design of the Shack-Hartmann camera currently used to align the Keck Telescope optics. For CELT we will use seven spots/segment to separate primary array "focus mode" from secondary despace.

- Phasing mode of the Shack-Hartmann / Phasing Camera
  This camera will follow the design of the Phasing Camera used to measure the relative pistons of the Keck Telescope segments. The diffraction-dominated image, from each sub-aperture bridging the gap between adjacent segments, will be used to measure the local relative height across each inter-segment gap. The set of all local relative heights will be fit to determine the $1080 - 1$ relative pistons. We expect the initial segment piston acquisition range will be ± 30 μm.

- Telescope Wavefront Sensor
  We currently plan to have a wavefront sensor associated with each instrument in order to continuously monitor low spatial frequency wavefront aberrations. This will probably be operated at a bandwidth lower than the edge sensors and the active control.

7. SUMMARY

We have defined the procedure for aligning the CELT optics, including quantitative sensitivities and error budgets. In the next design phase we will

- Design in detail the required cameras and sensors.
- Build a computer model of the optics and alignment procedure.
- Simulate data sets and reduce the data.
- Confirm that the procedure meets both the telescope image size and wavefront error budgets.
- Confirm that errors do not cause adjustment mechanisms to exceed their range.

REFERENCES

Conceptual Design for a 30-Meter Telescope. CELT Steering Committee, editors, (contact: Jerry Nelson). CELT Report No. 34. (2002)

Phasing the Mirror Segments of the Keck Telescopes: the Broadband Phasing Algorithm, Gary Chanan , Mitchell Troy, Frank Dekens, Scott Michaels , Jerry Nelson, Terry Mast, David Kirkman, Applied Optics **101**, 140 (January 1998).

CELT Optics Alignment Procedure, Terry Mast, Jerry Nelson, Gary Chanan, Lothar Noethe, CELT Report (in progress)

CELT Error Budgets. Terry S. Mast and Jerry E. Nelson, CELT Report No. 10 (in progress).