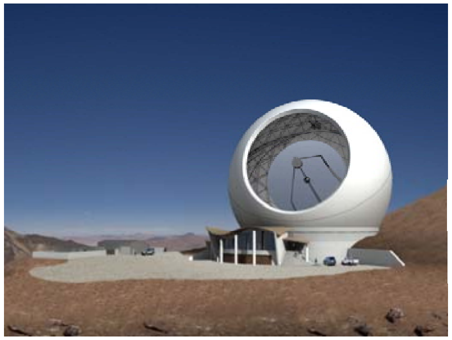


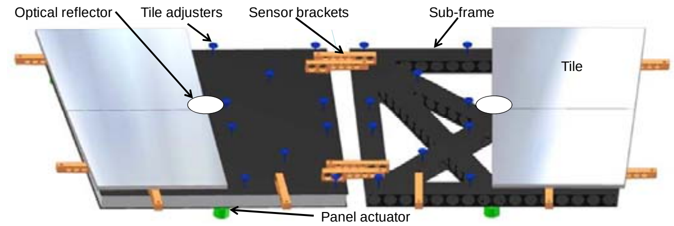
Drawing of CCAT in a Colotte dome at the 5612 m level on Cerro Chajnantor.

A Design for the CCAT Active Surface

David Woody[1] and Dan MacDonald[2]

[1]Caltech, Owens Valley Radio Observatory, PO Box 968, Big Pine, CA 93513 USA, dwoody@caltech.edu
[2]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109-8099 USA, danmac@s383.jpl.nasa.gov

The Cornell Caltech Atacama Telescope (CCAT) is a 25m telescope that will operate at wavelengths as short as 200micron . Meeting the surface accuracy specifications requires an active surface to correct for gravitational and thermal distortions of the reflector support structure. This paper describes a design for the reflector that uses panels consisting of four reflector tiles mounted on a ~2 m x 2 m CFRP sub-frame supported on three linear actuators. Edge sensors and a Shack-Hartmann camera used for measuring the absolute tip-tilt of the compound panels are used by the control system to maintain the surface figure with a net accuracy of <7microns.

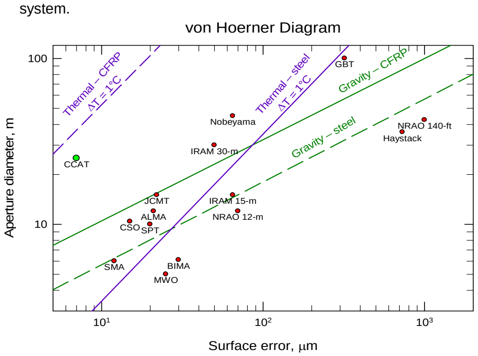


Compound panels consisting of 2 m x 2 m CFRP sub-frames and 1 m x 1 m reflector tiles. This compound panel concept separates the stiff and stable sub-frame structure from the precision reflecting tile surface.

Table of key CCAT parameters

	Requirement	Goal	remark
Wavelength	350 – 1400	200 – 2500	μm
Aperture	25 m		
Field of view	10'	20'	
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

The plot below shows the natural limits for passive telescopes. It is clear that CCAT will require an active surface to meet the demanding wave front error (WFE), especially considering that only ~**7 microns** of the error budget is allotted to the primary surface and control system.



The plan for CCAT is to use edge sensors mounted on the panels to measure the surface and slope continuity between neighboring panels, similar to what is done on the Keck optical telescope.s The sensors are used by the control system to measure the distortions in the reflecting surface and the control system uses feedback to adjust the three actuators supporting each panel to restore the reflector to the desired shape. This is essentially a nulling system and the sensors need ~0.1 micron resolution over the central 1 mm of their range, although the actual actuator range required is ~1 cm.

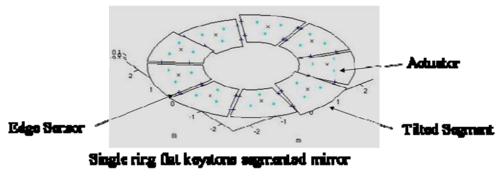
The control matrix is based on the response matrix, A_{ij}

$$s_i = \sum A_{ij} a_j$$

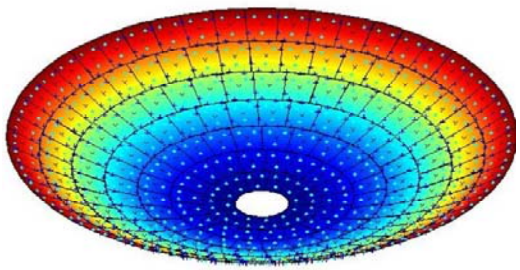
where a_j is the actuator motion and s_i is the sensor response. The control matrix, B_{ji}

$$a_j = \sum B_{ji} s_i$$

is the pseudo-inverse of A_{ij}. Singular Value Decomposition (SVD) is used to find the pseudo-inverse since there are many more sensors than there are actuators.

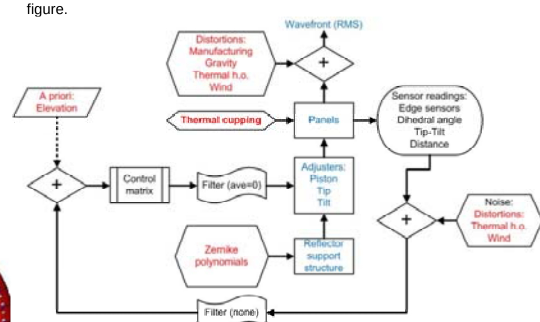


The above figure shows a simple ring of 9 keystone panels with edge sensor and actuators. A configuration for a 210 panel CCAT primary is shown below.



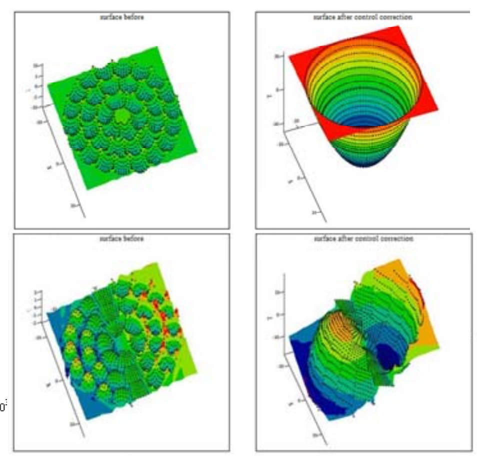
The SVD produces the set of orthogonal Eigen modes and Eigen values that uniquely relates the distortion modes at the actuators to the sensor readings. The modes look very much like Zernike modes, especially the low order modes with small Eigen values. The graph below shows the inverse of the Eigen values. This is known as the Error Multiplier Factor (EMF) and modes with higher values are harder to control. A mode with an EMF of 1 means that an RMS noise of 1 micron at the sensors will introduce a 1 micron RMS error into the surface. Note that the first three modes (piston, tip and tilt) are not sensed or controlled at all.

The basic control flow diagram is shown below. The dominate perturbations that the control system needs to control or correct are the gravity and thermal distortions of the reflector support structure. These distortions are transferred to the surface via the actuators and if the sensors correctly sensed the distortions then the control system will accurately restore the surface to the "ideal" figure.



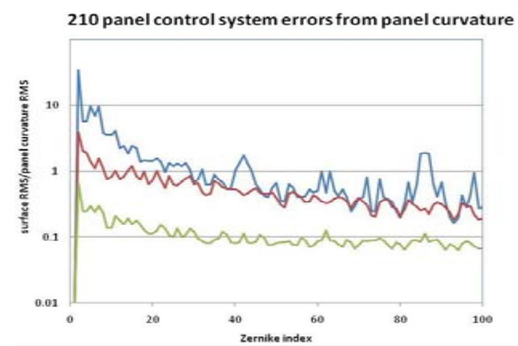
This system works very well if, as with the Keck telescopes, the panels are very stable and do not distort. The panels are the reference system for the control system, so distortions in the panels are hard to distinguish from distortions in the reflector support structure. In the best case the panel distortions effectively add random noise to the sensor readings. In a worst case the distortions are uniform across the aperture and introduce large scales distortions to the surface.

The distortions produced by thermal gradients through the panels are particularly difficult to deal with. The control system tries to match the surface and slope continuity between neighboring panels. In the first example shown below the control system takes panels with uniform cupping and turns the surface into a bowl. The plot on the left is the surface before turning the control on and right plot is after turning the control on. The second set of plots show a similar set of plots for a gradient of cupping across the aperture. This results in a strong astigmatism.



One method for controlling the annoying large scale distortion modes is to add another type of sensor. CCAT will be at a good optical site and so it is natural to barrow the optical technique of using a Shack-Hartmann wave front sensor operating at infrared or optical wavelengths. A small optical quality reflector is added to the center of each panel. It will be used to reflect star light to the secondary and on to the Shack-Hartmann camera. This camera detects the absolute tip-tilt error of each panel relative to the ideal telescope surface. This tip-tilt information is then added to the sensor data and the SVD of the response matrix gives good control of all modes.

The plot below shows ratio of the RMS surface error to the RMS panel cupping error for different distributions (given as Zernike modes) of cupping across the aperture. The blue line shows the EMF for the cupping modes without any tip-tilt sensing, The red line shows the improvement when 25 absolute distance measuring devices are added. The green curve shows the EMF when just edge sensors and a Shack-Hartmann camera are used.



The Shack-Hartmann camera will be used on optical stars once every 10-20 minutes when the telescopes slews off to look at an appropriate bright star. The thermal cupping of the panels is a result of the changing thermal environment and should be slowly varying and continuous measurement and correction should not be required.

Compound Panel 25m Diameter Telescope

environment parameters	
wind [m/s]	5.0
wind pressure [kgf/m^2]	1.6
Temp. change [K]	1.0
lateral Temp RMS for 1m [K]	1.0
tile parameters	
manufacturing RMS for 1m [micron]	**5.0**
aging RMS for 1m [micron]	**1.0**
adjuster design	
material	invar
sub-frame design	
core filling factor	0.0100
plate normalized thickness t/length	0.0015
core normalized thickness h/length	0.0500
Temp. change [K]	20.0
segment setting RMS for 1m [micron]	1.0
aging RMS for 1m [micron]	0.1

error budget						
design case	1	2	3	4	5	6
sub-frame size, diagonal [m]	2.83	2.83	2.83	2.83	4.24	2.83
number of compound panels	123	123	123	123	55	123
number of tiles per raft	4	4	4	4	9	4
tile design						
face sheet material	CFRPH	CFRPH	CFRPH	CFRPH	CFRPH	Ni
core material	Al	Al	Al	Al	Al	Al
net tile error, 5 point support	2.77	2.77	2.77	2.77	2.77	2.79
net tile adjuster error	2.11	2.11	2.11	2.11	2.42	2.11
sub-frame design						
face sheet material	CFRPH	CFRPH	CFRPL	CFRPL	CFRPL	CFRPH
core material	Al	CFRPH	Al	CFRPL	CFRPL	Al
sub-frame errors						
total panel areal density [kg/m^2]	25.7	24.4	25.7	24.4	33.8	36.4
dT back-front	0.06	0.19	0.06	0.19	0.19	0.06
gravity, including tile and adj. wt.	0.36	0.34	0.90	0.85	1.76	0.51
wind	0.02	0.02	0.05	0.05	0.08	0.02
temperature change	0.51	0.51	0.05	0.05	0.12	0.51
thermal cupping	0.13	0.38	0.01	0.04	0.06	0.13
lateral Trms	2.70	0.12	2.70	0.01	0.02	2.70
aging	0.80	0.80	0.80	0.80	1.80	0.80
net sub-frame error	2.89	1.09	2.95	1.17	2.52	2.91
net compound panel error	4.5	3.6	4.6	3.7	4.5	4.6
primary figure maintence						
edge deflection error	2.75	0.53	2.70	0.11	0.23	2.75
therm. cup. extrap. to half dia.	2.45	7.45	0.24	0.75	0.51	2.45
total surface error [microns]	5.8	8.3	5.3	3.8	4.5	5.9

The above table give a sample set of surface error budgets for several compound panel configurations, including the sensor and control system errors. It is seen that there are many configurations that meet the demanding CCAT requirements.