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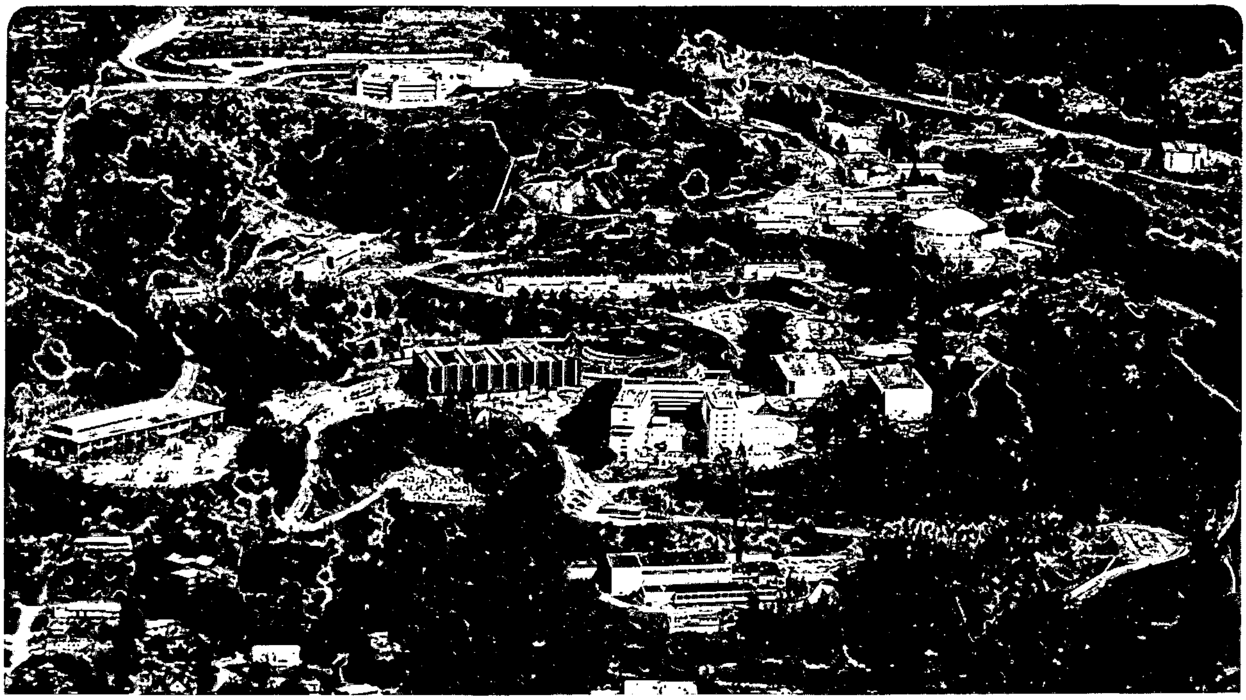

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ABSTRACT

The ten meter diameter primary mirror of the W. M. Keck Telescope is a mosaic of thirty-six hexagonal mirrors. An active control system stabilizes the primary mirror. The active control system uses 168 measurements of the relative positions of adjacent mirror segments and 3 measurements of the primary mirror position in the telescope structure to control the 108 degrees of freedom needed to stabilize the figure and position of the primary mirror. The components of the active control system are relative position sensors, electronics, computers, actuators that position the mirrors, and software. The software algorithms control the primary mirror, perform star image stacking, emulate the segments, store and fit calibration data, and locate hardware defects.

We give an overview of the active control system, its functional requirements and test measurements.

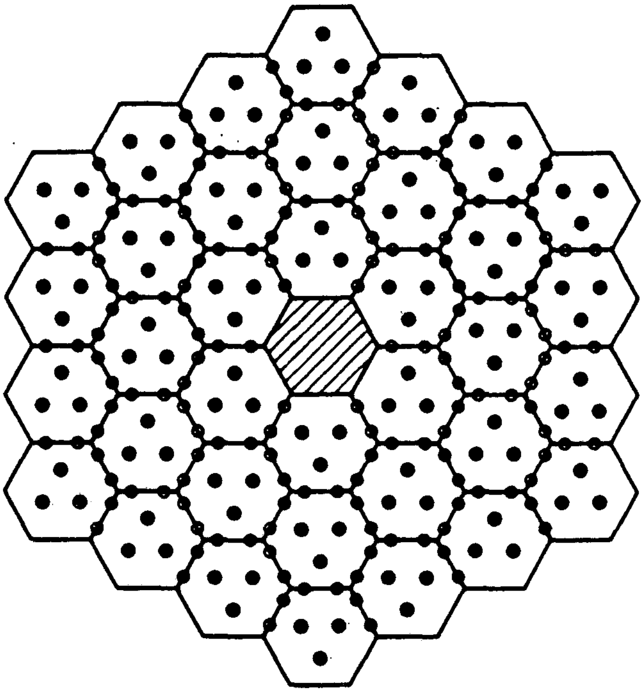

Fig. 1 The locations of the actuator and sensors from the concave side of the primary.

1. INTRODUCTION

The ten meter diameter primary mirror of the W. M. Keck Telescope is composed of a mosaic of thirty-six hexagonal segments. A great many aspects of the design and construction of the Keck Observatory are described by Nelson et al.[1-2]

The main function of the Active Control System (ACS) is to turn the thirty-six mirrors into a monolith by electronically gluing the mirror segments together. Three of the six segment degrees of freedom are controlled by the ACS. This is accomplished by measuring the relative position of each mirror, calculating the necessary movement to correct errors and then repositioning the mirrors two times a second. The position control system corrects the low frequency disturbances due to temperature, gravity and external perturbations. Secondary functions that support this effort include maintaining the attitude of the primary mirror in the telescope structure, superimposing the images of the segments (star stacking), generating control matrices, maintaining and fitting calibration data, emulating the mirror hardware, providing a user interface, and providing maintenance software. The mosaic of 36 mirrors is shown in Figure 1 with the locations of the 108 position actuators and 168 relative position sensors indicated. Actuator locations are indicated by filled circles. Sensor locations are indicated by open circles.

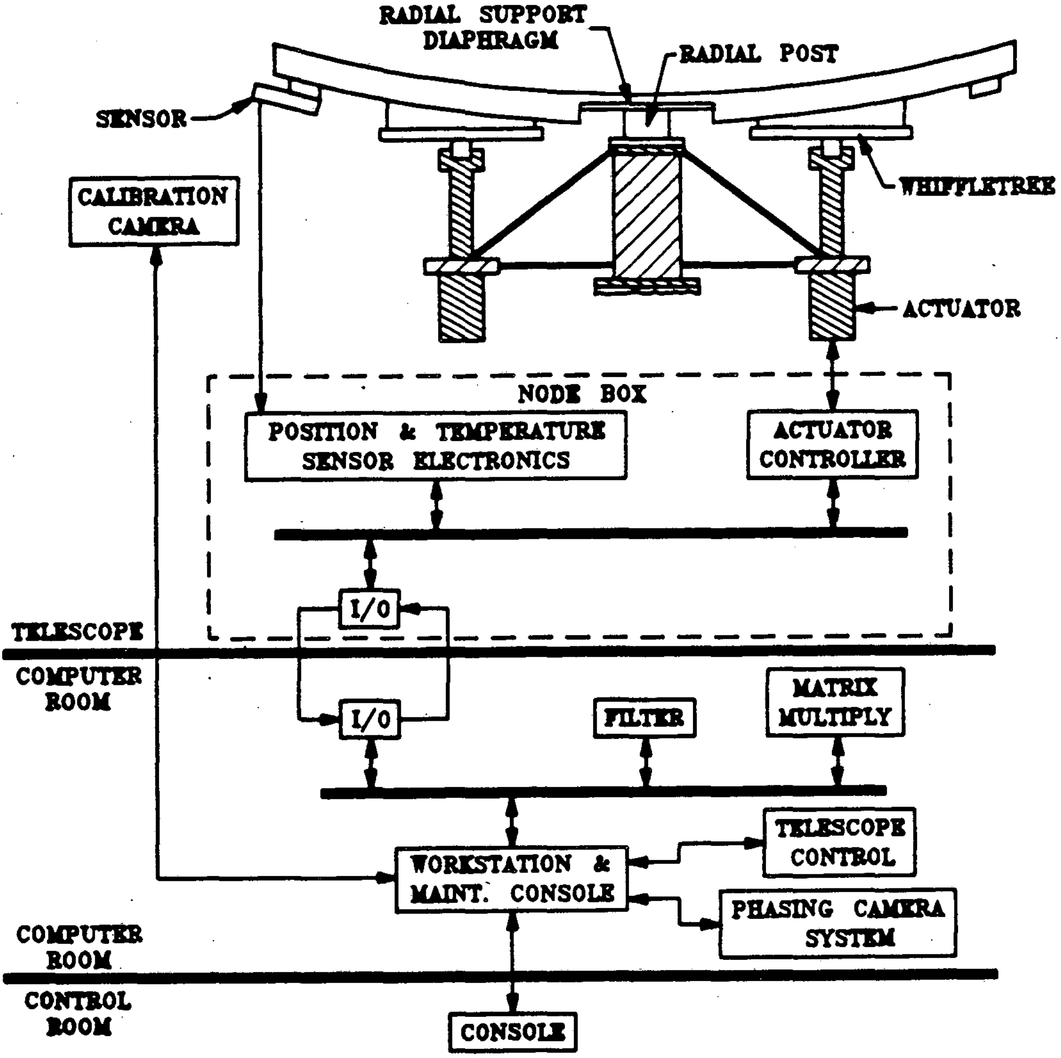

Fig. 2 The primary mirror support system.

A simplified electronic/mechanical view of the ACS is shown in Figure 2. A radial support post at the center of each mirror is coupled to the mirror by a flexible diaphragm that mechanically constrains the x,y position and rotation in the mirror segment plane. The three degrees of freedom controlled by the ACS are piston and x and y tilts. These three degrees of freedom are adjusted by the actuators connected to each mirror segment via whiffletrees. Actuator motion commands are calculated every half second from the filtered position sensor data. Position sensors measure the relative height of adjacent segment edges.

There are three external inputs to the ACS mirror control system. One is from a Drives and Control System (DCS) that controls the telescope slewing and tracking (Telescope Control in Figure 2). The DCS issues commands to initialize, start and stop the ACS. Error reports are sent to the DCS. The second input is from a Phasing Camera System (PCS). The PCS provides commands to piston and tilt the segments, and save the current configuration in the calibration data base. The PCS measures the relative piston and tilt of segments and the optimal figure of undivided segments and the primary mirror. The third input is from a star stacking camera system that measures the overlapping of the 36 images from the segments, actuator gains and sensor sensitivities.

2. GLOBAL SPECIFICATIONS OF THE ACS

A summary of the ACS requirements are shown below (Appendix A gives additional specifications):

Control loop bandwidth	> 0.2 Hz
Control loop period	< 500 ms
Step response settling time	10 seconds
Maximum correction for primary mirror cell distortions during tracking	27.5 nm/second

The control loop bandwidth is controlled by the dominant pole frequency of the ACS position control system and the gain. The control loop period is the period for updating the actuator lengths. The step response settling time is the time required to re-establish the segment positions after a command from the calibration cameras to change the actuator lengths. Primary mirror cell distortions correspond to the maximum rate of change in the actuator lengths to compensate for changes in the primary mirror support structure during normal tracking.

3. MIRROR POSITION CONTROL SYSTEM

A simplified representation of the position control system with one actuator and sensor is shown in Figure 3. The difference between the position sensor reading and a reference input is passed though a lowpass filter and amplifier. The resultant signal causes the actuator to move and correct the sensor reading. The reference input is a function, f(z,T), of zenith angle, z, and mirror temperature, T. It prescribes the Desired Sensor Readings (DSR) due to the effects of gravity and temperature. The DSR are derived from the calibration data. Lowpass filtering is used to limit the bandwidth of the system.

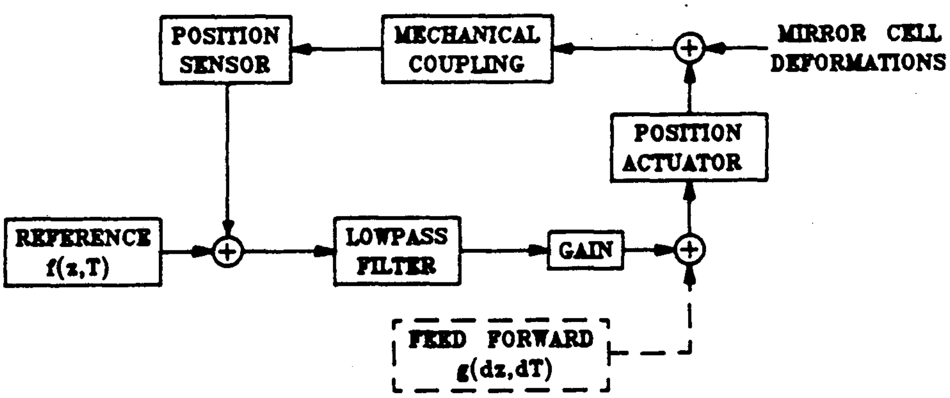

Fig. 3 Simplified position control system.

One of the problems with this position control loop is that the disturbance input from the primary mirror cell (thermal and gravitational distortions) of 0 to 27 nm per second depending on segment location and zenith angle rate of change is not properly corrected for in the dynamic situation. The phase delay of the 0.2 Hz lowpass filter will result in those parts of the primary mirror that should be moved at 27 nm per second being about 50 nm behind the correct mirror position. The resulting image width due to this effect is about 0.05 arc seconds, which is unacceptable.

A possible solution to this phase delay effect is to reduce the phase delay by increasing the lowpass filter cutoff frequency. However, the upper limit (imposed by resonances in the telescope structure[3]) for the system bandwidth is 0.5 Hz. One half Hertz is insufficient bandwidth to adequately compensate for the effect. Other solutions are possible, such as velocity correction, but would add complexity to the mirror position control system. The dotted area of Figure 3 shows a simple solution to correct the phase delay effect. Feed forward has been added to the position actuator input. The feed forward (g(z,T) for actuator lengths) is an open loop correction to the actuator lengths for changes in the mirror cell structure. If this correction system were error free there would be no need for the closed loop control system to correct for the effects of gravity and temperature. Simulations using feed forward have shown that mirror surface errors are predicted to be less than 5 nm, which is a negligible amount. Feed forward also maintains the mirror figure during slew. Feed forward g(z,T) is obtained from the actuator lengths recorded in the calibration camera data during star stacking and/or mirror phasing.

The calibration camera system requests the ACS to move actuators in steps as the mirrors are pistoned and tilted in the calibration process. The simple control system with the 0.2 Hz filter would take 10 to 20 seconds to settle after making a move of 10 micrometers, which is unacceptably long. A solution to this effect that uses a different form of feed forward is shown on Figure 4. Figure 4 shows the complete ACS position control system. DSR's are the values read from the position sensors when the mirrors are in the proper position. DSR increments are calculated (Compute Feed Forward on Figure 4) from the calibration camera actuator move request. Then the actuators are moved. Halfway though the actuator move the DSR reading increment is added to the reference input. This results in the lowpass filter storing less energy. Settling time of the ACS is reduced to about 5 seconds which is an acceptable value.

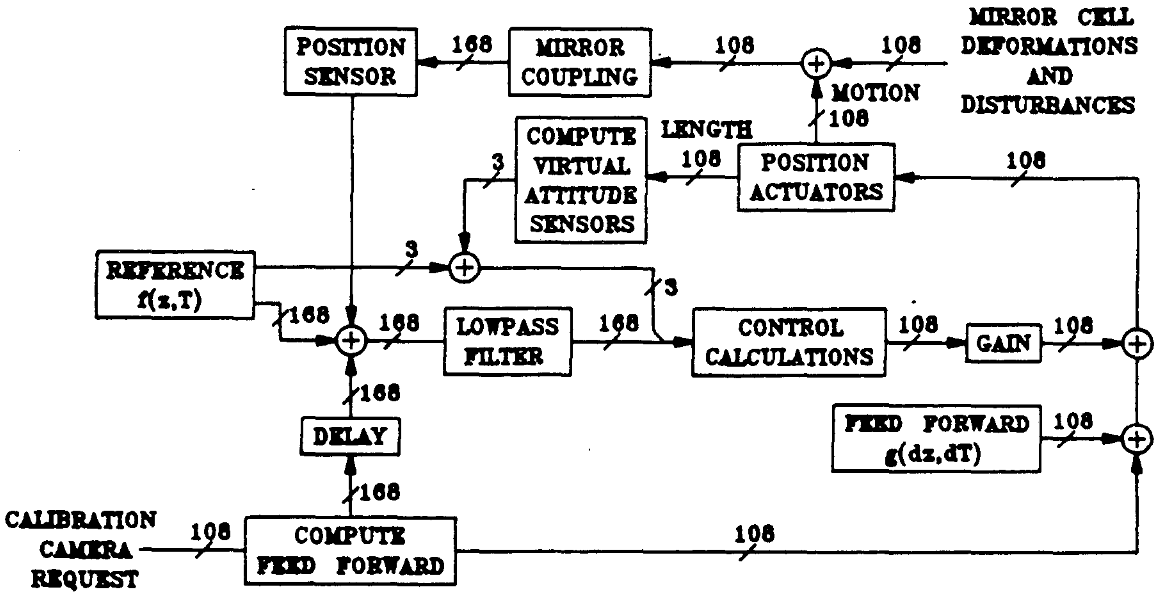

Fig. 4 Complete position control system of the ACS.

The overall piston and tilts of the primary mirror in the telescope are calculated from the lengths of the actuators. These three virtual ("attitude") sensors define the piston and two tilts of the primary mirror. The 171 (168 relative position error and the 3 virtual attitude sensors) sensor errors are used to calculate the 108 actuator moves needed to correct the mirror position. This is accomplished by a control matrix multiplication (Control Calculations in Figure 4). The control matrix is the result of pseudo-inversion of a matrix that incorporates the equations describing the mechanical coupling of the actuator movements to the sensor readings.

The digital control loop implementation of the above scheme uses 12 processors. The resultant control loop is quantized. Timing is shown on Figure 5. A state is defined as the time period between readings of the sensor values into the processors (nominally 10 ms). The number of states is defined by the period between actuator move request (nominally 500 ms [user defined]). Position sensors are read, the DSR values are subtracted and the digital lowpass filtering is performed on every state. Control calculations composed of control matrix multiplication, feed forward calculations, and DSR calculations are started on the last state. Actuator motion commands are issued on a state after the control calculations are performed. Actuator moves take about 200 ms. These moves are profiled to reduce excitation of resonances in the whiffletrees and telescope structure. Halfway through the move the DSR's are changed. The resultant input to the filter is a bipolar signal that will reduce the stored energy in the lowpass filter. The above sequence is repeated regularly during operation of the ACS control system.

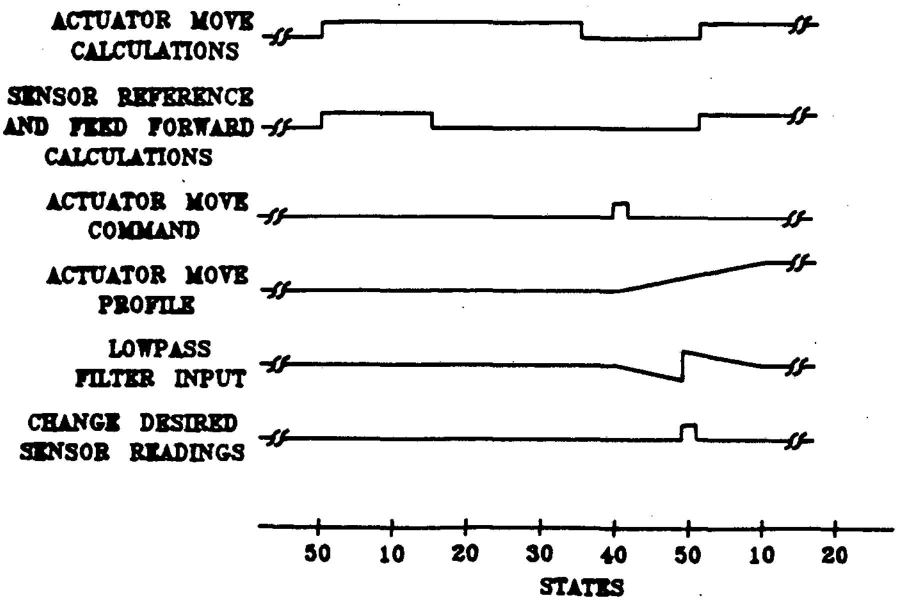

Fig. 5 ACS control loop timing.

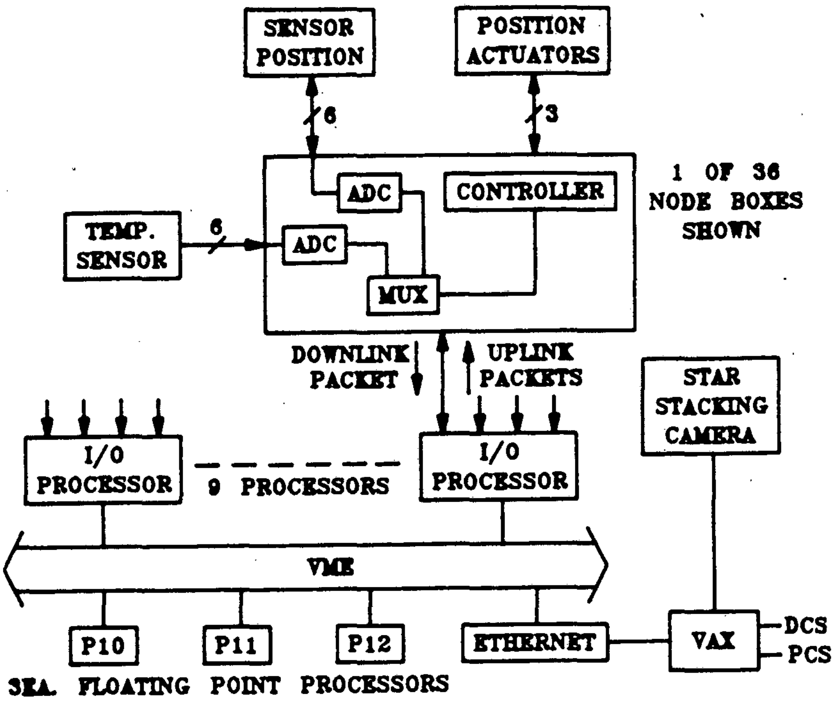

Fig. 6 ACS hardware architecture.

4. ARCHITECTURES OF THE ACS SYSTEM

The architecture of the ACS is shown in Figure 6. One node box containing electronics is located at each mirror segment. Each node box supports up to 6 position sensors, 6 temperature sensors and 3 actuators. The node boxes are connected to an input/output processor (I/O processor). There are nine I/O processors in a VME crate in the control room. Each I/O processor controls 4 node boxes. In addition, there are 3 floating point processors and a memory unit connected to the VME bus along with an ethernet interface to the VAX Workstation (VAX).

Node boxes contain the electronics located on the back side of the primary mirror. They contain the electronics needed to digitize the position and temperature sensor readings, control the position actuators and communicate with the I/O processor in the VME crate. Downlink packets are transmitted from the node boxes to the I/O processors for each control loop state. They include sensor readings and actuator lengths. Uplink packets are transmitted to the node boxes from the I/O processors. They contain actuator motion requests and position sensor range and gain. One of the I/O processors triggers the scheduler in processor 12 for each downlink packet received. The scheduler triggers the other processors to perform the control loop calculations at the times described above. In addition, a monitor task reports error data via ethernet and the VAX to DCS.

5. GENERATION OF THE CONTROL MATRIX

The equation that describes the relationship between desired sensor readings and actuator motion is:

$$s_n^{\text{measured}} - s_n^{\text{desired}} = \sum_k A_{nk} p_k$$

where s_n is the sensor readings, p_k is the actuator motions and A_{nk} is the geometric matrix (n=1,171, k=1,108). Rows of the A matrix contain the coefficients that define the geometric relationship between actuator displacements and sonar displacements. Virtual sensors are:

$$\text{Primary piston} = \sum_k z_k / k_{\max}$$

$$\text{primary x-tilt} = \sum_k y_k z_k / \sum_k y_k^2 \qquad \text{and}$$

$$\text{Primary y-tilt} = \sum_k x_k z_k / \sum_k x_k^2$$

where x and y are the coordinates of the actuator in the primary mirror cell and z is the actuator length. These equations represent the best fitting plane through a set of data points, assuming the actuators are symmetrically located about the origin. To find the optimum actuator motion given the sensor readings, one solves the 171 equations in 108 unknowns in a least squared sense by defining:

$$\chi^2 = \sum_n [\sum_k A_{nk} p_k - (s_n^{\text{measured}} - s_n^{\text{desired}})]^2$$

and setting:

$$\frac{\partial \chi^2}{\partial p_k} = 0$$

to obtain:

$$p_k = \sum_n B_{nk} (s_n^{\text{measured}} - s_n^{\text{desired}})$$

The pseudo-inverse B_{nk} is the matrix used in the control loop calculation of the actuator moves from sensor errors that will correct the mirror position. The redundancy in the measurement leads to better correction of sensor errors and the ability to operate the telescope with defective sensors/electronics eliminated from the A and B matrix. If all sensors had the same noise level the actuators would have 4.7 times the sensor noise. This noise magnification of the B matrix results from the coupling of the actuators to all sensor noise sources. The paper, "Analyses of the W. M. Keck Telescope Segmented Mirror Control Loop," in these proceedings provides more detail.[4]

5. POSITION SENSORS

Position sensors bridge the gap between adjacent mirrors on the back side of the mirror as shown on Figure 7. Sensors are composed of the drive and receive sides. The drive side has a paddle that crosses the segments and is fitted into the U-shaped receiver gap. The drive paddle rotates so that it is out of the way during mirror maintenance.

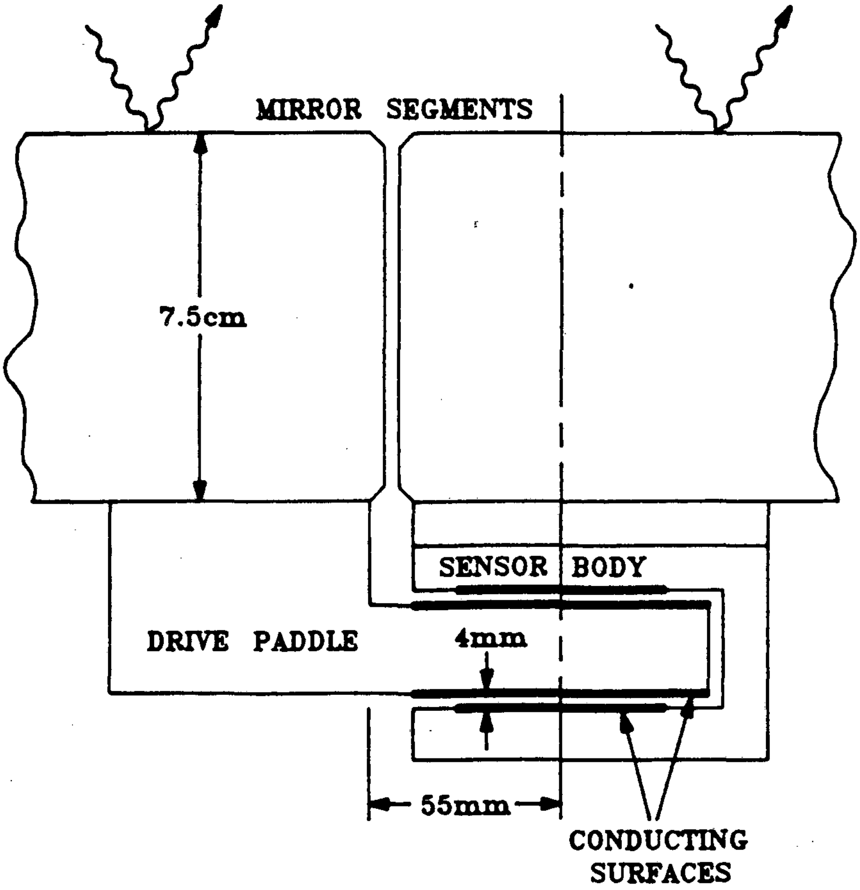

Fig. 7 Position sensors.

Capacitors are formed by a conductive coating on the sides of the receiver gap that face the drive paddle. The drive paddle is coated on both sides. These two capacitors (receiver to drive and driver to receiver paddle) are each about 3 pf when the drive paddle is centered in the gap. As the drive paddle moves, one capacitor increases and the other decreases. Capacitance values would have to be very stable (about 1:10**6) to meet (without corrections) the requirements. Sensors are constructed of the same material as the mirror (low thermal expansion coefficient 5*10**-8) and are designed to be mechanically rigid. Even with this care the total thermal effects can be ± 185 nm and gravity effects ± 200 nm. These effects are corrected by the reference input (f(z,T)) of the position control system.

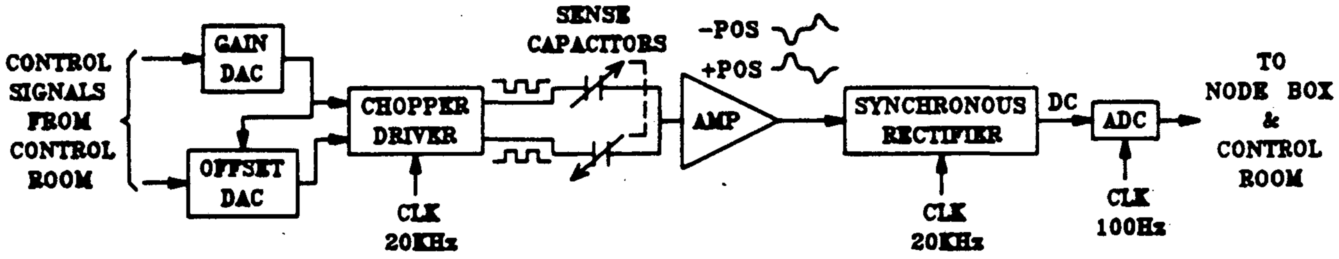

Fig. 8 Simplified sensor electronics.

A block diagram of the sensor electronics is shown on Figure 8. Position sensors are shown as two capacitors with the receiver side connected together. Two square waves 180 degrees out of phase drive the conductive areas on the drive paddle. The amplitude of the square waves is controlled by a Digital to Analog Converter (DAC). Sensor range is adjustable from 4 mm (the gap size) to 8 micrometers. Large range values are used to insure valid sensor readings during initialization of the position control system. The offset DAC makes fine amplitude adjustments to one of the drive signals to compensate for up to ± 180 micrometers of mechanical misalignment. When the sensor capacitors are equal in value the charge flowing from the two drive signal currents will be totally within the capacitors. The amplifier will not see a signal. When the drive paddle is not centered spikes of current are amplified and filtered by the amplifier as shown in Figure 8. The synchronous rectifier integrates for one half the clock period, then inverts the signal and integrates the remaining half to produce a voltage that is proportional to position. Analog to digital conversion is performed and transmitted to the I/O processors at a 100 Hz rate. The large bandwidth is for diagnostic purposes. Stability of the sensor and electronics is better than 3 nm per week. Noise at 30 Hz bandwidth is 1 nm rms. These values are well within the allocated error budget. For further information see the paper, "Displacement Sensors for the Primary Mirror of the W. M. Keck Telescope," in these proceedings.[5]

6. POSITION ACTUATORS

Position actuators adjust the 3 degrees of freedom controlled by the ACS (piston and the x and y tilts of the mirror segments). Each supports one third of the weight of the mirror along its axis. The load varies from about 300 lbs to minus 60 lbs depending on zenith angle. The actuator concept is shown in Figure 9. A preload spring to accommodate the minus 60 lbs of axial force is not shown. When an actuator move is desired, current is supplied to the motor to move the screw. An encoder on the end of the shaft produces a pulse for each 1:10000 of a rotation (about 4 nm of output shaft motion). When the required distance is attained, as indicated by the encoder pulses, the motor current is reduced to the holding level. The resultant rotation of the 1 mm pitch screw causes the screw nut to move the small bellows. The hydraulic section composed of the small and large bellows moves the output shaft by 1/24 of the screw nut motion. This hydraulic section is used to reduce the forces on the screw nut and thus minimize the effects of stiction. The range of the actuator is 1.1 mm. This is much larger that the ±0.3 mm sag of the primary mirror structure under the effects of gravity. The remaining range is used to accommodate the mechanical imperfection in the primary mirrors assembly process. Actuator length is recorded in the absolute position counter. This length is used to control the attitude of the primary mirror in the telescope structure.

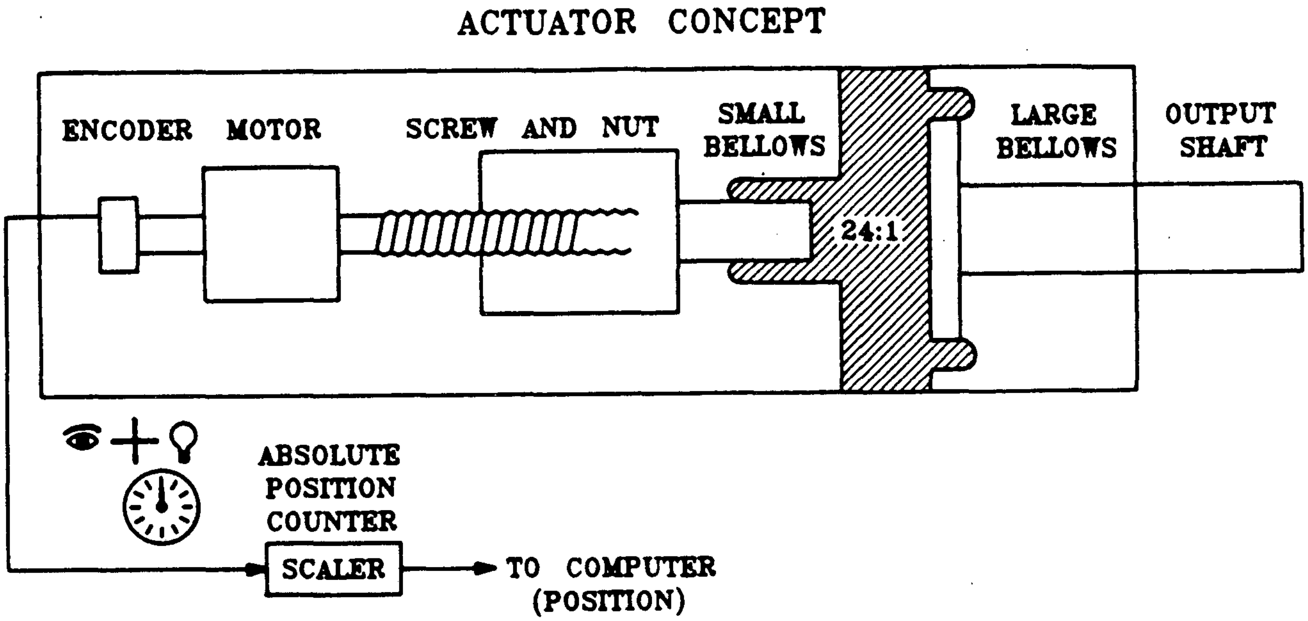

Fig. 9 Actuator concept.

The actuator control concept is shown in Figure 10. Move commands are loaded into the sequencer. A count train containing the number of encoder pulses and direction is loaded into a commercial motor controller chip from the sequencer. The count train frequency is used to profile the actuator motor current (indirectly the actuator move profile). As the motor turns the screw, the resultant encoder pulses are subtracted from the current sum of the count train pulses, thus reducing the motor current by that increment. If the gain of the motor control is high the result would be that the error (difference between the number of count train pulses and encoder pulses) would go to zero and then dither on one count. The result of dithering would be to excite the mechanical resonances in the structure and whiffletree. Dithering is unacceptable so the gain of the motor controls is low with a resulting error of a few encoder counts from the motor controller. The sequencer corrects this condition by enabling the error processing and turning on the slow clock after the count train is loaded. The error processing uses the motor controls error magnitude (8 bit significance) to determine the number and direction of the slow clock pulses to pass on to the the motor controller. This results in zero error for the original count train and a bias current that holds the actuator position. The controller and actuator combination results in a move profile that has a rise time of about 200 ms (10 to 90 percent). The rms position error for the moves expected in the telescope is about 5 nm. More information is contained in the paper, "Position Actuators for the Primary Mirror of the W. M. Keck Telescope," of these proceedings.[6]

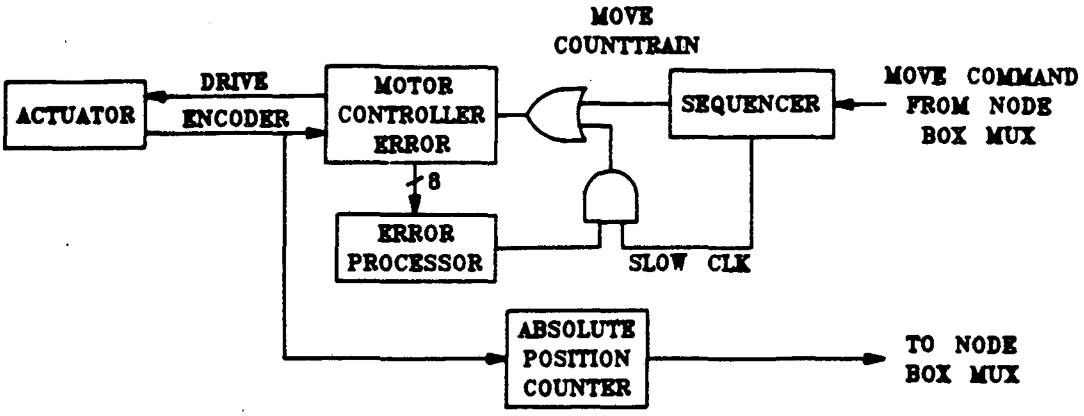

Fig. 10 Simplified actuator electronics.

7. SOFTWARE

Most of the algorithms that the ACS implements are contained in the software. These algorithms support the position control system, defect location (maintenance software), star stacking, calibration data fitting and storage, user interface and emulation of the mirror.

The position control system is shown in Figure 11. Tasks are shown in bubbles. Global data stores are between parallel lines. Dashed lines are triggers to start tasks or take actions. Solid lines show data flow. Double arrows on data flow indicate continuously available data. The nine I/O processors that communicate with the node boxes extract the raw sensor and actuator data from the downlink packets and store the data in a global data store. One of the nine processors interrupts the scheduler task that keeps track of the states detailed above. The IOP task then subtracts the desired sensor readings from the raw sensor data and performs a lowpass filtering of the differences. These filtered sensor readings, temperature data and actuator lengths are placed in global data storage for use by other tasks. The IOP task then sends the uplink data that was placed in data stores by other tasks to the node boxes. Normally 12 sensor DAC values are transmitted for each 100 Hz period. When a command to move the actuators is received from the scheduler task, the actuator motions are transmitted in the uplink packet. These processors use about 80 percent of the available processor time. On the last state the control function calculation task is triggered. It calculates the virtual attitude sensors from the actuator lengths. Then it triggers the parameter correction task, performs the B matrix multiplication to obtain the raw actuator motion commands and multiplies by the gain factor (about 0.2). Feed forward is then added. Results are placed in global data storage for use by the IOP task at the time specified by the scheduler task. The sensor control task is then triggered to calculate new sensor DAC values. Processor 10 uses about 60 percent of the available time.

The parameter corrections task calculates new desired sensor readings and actuator increments for feed forward. Feed forward has two components. The first is derived from differentials with respect to z and T of g(z,T) for the actuator. Actuator incremental lengths are obtained by evaluating the function at the present zenith angle and mirror temperature. The results are multiplied by the zenith angle and temperature rate of change. The second component of feed forward is from the calibration camera request (actuator motion) to tilt and piston the mirror segments. This actuator vector is also multiplied by the A matrix to obtain a component of the new DSR's. The other component of the DSR is obtained by evaluating f(z,T) for desired sensor readings at the current zenith angle and mirror temperature. New DSR's are transferred by the scheduler task to the data store for DSR's halfway through the actuator motion. More information is available in the paper, "The W. M. Keck Telescope Segmented Primary Mirror Active Control System Software," of these proceedings.[7]

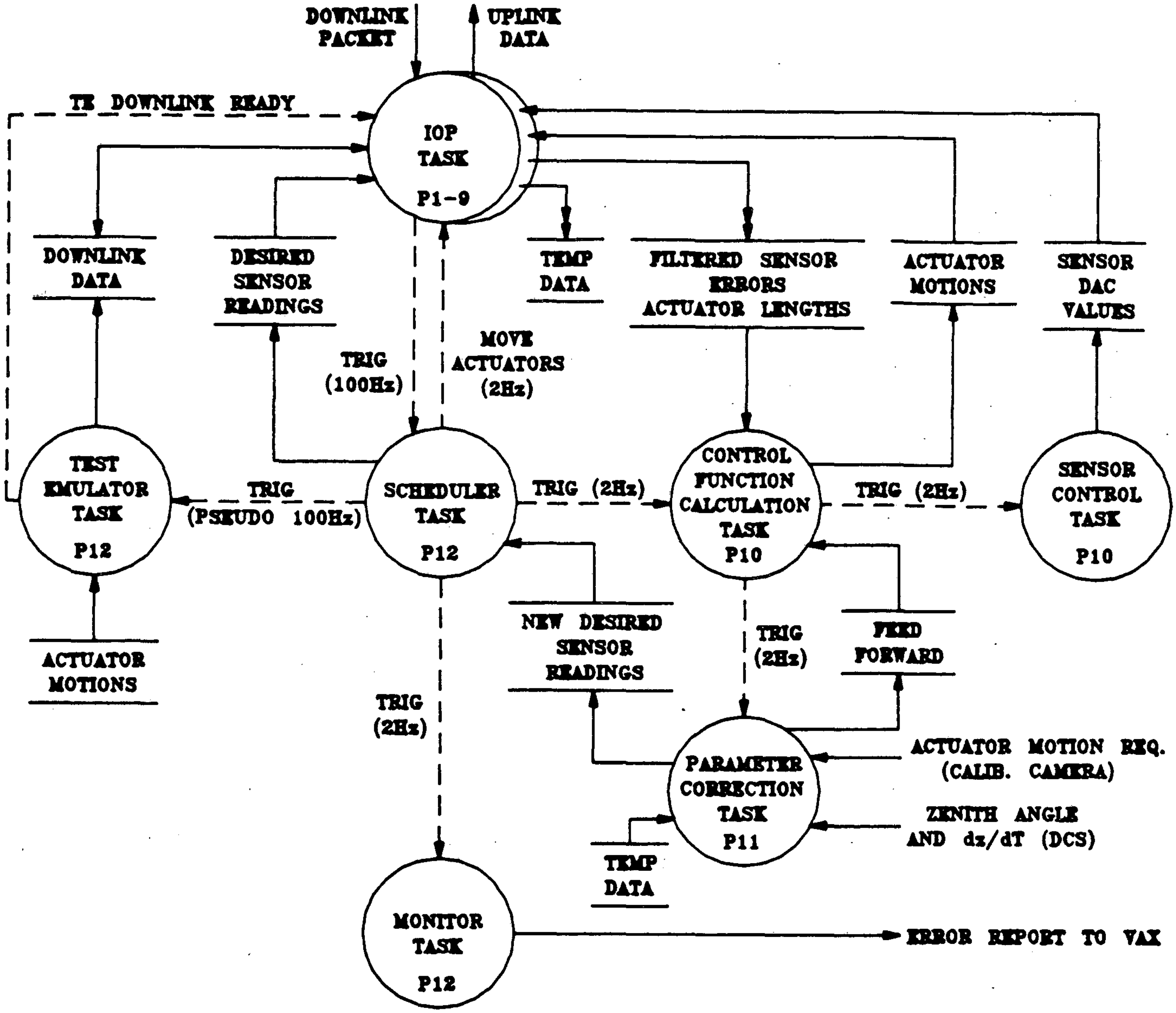

Fig. 11 Position control system tasks.

A test emulator task is also part of the position control system. Its function is to emulate most items that affect actuator lengths and sensor readings. When in operation it provides downlink data and triggers the IOP task. It is used to test software during the development phase and later to provide an off-line tool to find or understand problems in the ACS. Specifically, the task emulates gravitational/temperature changes in the mirror cell and sensors, actuator motion profile and whiffletree resonances. In addition, it has test pulsers and noise generators built in. More information is available in the paper, "An Emulator for the W. M. Keck 10 Meter Telescope," of these proceedings.[8]

The calibration and star stacking software allows the operator to measure the parameters of the sensors and actuators, to stack the images formed by mirror segments, to measure the effect of secondary-mirror tilt and piston on image quality and to store the results of these operations in a data base. The program measures the gain of a sensor (in nm/count) by changing the setting of its offset DAC and computing the gain from the resulting changes in the sensor readings. The resulting gain values are accurate to approximately 1%, limited by the DAC and the resistors used in the preamplifier summing circuit. The sensor's intrinsic offset (in analog to digital converter counts) is obtained from the sensor value when its gain DAC is set to zero. To measure actuator gains (nm/step), the program commands the actuators to move the mirror segments a specified distance (monitored by the sensors) and observes how many steps are needed to complete the move. The star stacking and secondary adjustment functions rely on a CCD camera mounted at the f/15 bent-Cassegrain focus. For star stacking (segment alignment), the segments are tilted by specified amounts to separate their images, and the image centroid positions are measured. The procedure is repeated with the segments tilted to a second set of angles, and the collected data are used to derive the sensor readings and actuator settings needed to coalign the segments. Despace (focus) is measured by moving the secondary to several different positions and measuring the image width. Resulting secondary position and image widths are stored in the data base. Tilt is measured by tilting the secondary mirror in x and y and measuring the resulting image widths. More information is available in the paper, "Alignment and Calibration of the W. M. Keck Telescope Segmented Primary Mirror," of these proceedings.[9]

Calibration data base and fitting software provides facilities to store data from the PCS and star stacking cameras and fit the results. The main fitting performed is to determine the coefficients of the function:

$$f(z,T)=k_1 + k_2 \sin(z) + k_3 \cos(z) + k_4 z + k_5 z^2 + k_6 T + k_7 T^2$$

for desired sensor readings and actuator lengths. The fitting can use up to 200 calibration data sets for evaluation of the coefficients.

Maintenance software is separated into two classes, on-line and off-line. Off-line software makes detailed measurements of the performance of sensors or actuators. On-line software tests for pass/fail conditions of the processors. When the position control system monitor task indicates a sensor or actuator problem, the off-line software is used to identify the details of the defect.

8. CONCLUSION/STATUS

All the hardware for the Keck Telescope ACS has been constructed and tested. Test results show that the ACS performance is within the requirements. Most software has been tested and integrated. Performance tests to date show that the system will perform as expected. The future looks good, but the performance must be proven as the ACS is tested with the telescope.

9. APPENDIX A

9.1 Specifications for the ACS

Early in the W. M. Keck Observatory project two studies related to the ACS specification were performed. One was a study by Lockheed[3] of the effects of resonances in the telescope structure and how they would effect control loop stability. Lockheed found resonances starting at 10 Hz with many at higher frequencies. A control loop simulation showed that the control loop would be stable for bandwidths below 0.5 Hz. The second study by T. Kiconiuk et al[10] used a wind tunnel to determine the effects of wind on the primary mirror. This study showed that the effects of wind were small and could be ignored. Based on these studies we set the ACS control loop bandwidth at 0.2 Hz and the update frequency for the control loop (actuators and desired sensor readings) at 2 Hz. In addition to the two studies above, a technical demonstration of the control of a mirror was performed at Lawrence Berkeley Laboratory. The technical demonstration provided proof of concept and information about the technical capabilities of sensors, actuators and the servomechanism. This information was used to set specifications for the ACS. Background information is contained in notes by Nelson and Mast.[11,12] The global specifications for the ACS that provide for correction of the effects of gravity, temperature and low frequency perturbations are shown below:

9.2 ACS Optical Requirements

	Requirement		Expected / Measured	
	Theta 80 arc seconds	rms nm	Theta 80 arc seconds	rms nm
Star stacking centroiding	0.05		0.05	
Sensor thermal effects	0.012	2.5	0.012	2.5
Sensor gravitational effects	0.054	9.0	0.043	< 9.0
Sensor intersegment motion	0.022	4.6	0.016	3.3
Sensor temporal drift	0.029	6.0 nm/week	0.018	< 3.0 nm/week
Sensor electronic noise	0.012	2.5	0.004	< 1.0
Actuator noise	0.031	12.0	0.013	5.0
High frequency residuals	0.050		0.050	
total optical	0.102		0.088	

Theta 80 is the image diameter that encloses 80 percent of the available energy from a point source. Star stacking centroiding is the image width that would be obtained if perfect images from the 36 mirrors were stacked to form one image. Sensor thermal effects are all residual errors in the sensor reading after table look ups that compensate for the thermal expansion/contraction of the 7.5 centimeters of mirror and the sensor proper. Sensor gravitation effects are the residual errors in the sensor readings after table look ups that compensate for the gravitation distortions of the sensors. Sensor intersegment motion is the residual errors in the sensor readings after table look ups that compensate for the 0.3 mm intersegment motion (mainly due to gravity) changing the sensor reading due to tilts of the sensor with respect to the plane of the mirror. Sensor temporal drift is changed in the sensor reading due to drifts in sensor mechanics and electronics. Sensor electronic noise is the noise of the sensor electronics at 0.2 Hz bandwidth. Actuator noise is the error in the actuator position after a typical move. High frequency residuals are undefined effects that the ACS does not compensate for.

9.3 ACS System Requirements

	Requirement	Expected
Control loop bandwidth	0.2 Hz	0.2 Hz
Mirror cell correction	27.5 up to nm/sec	>27.5 nm/sec
Step response settling time	10.0 sec	< 10.0 sec
Power dissipation near mirror	500 W	300 W
Sensor Operating range	± 12 micrometers	± 12 micrometers
Sensor offset adjustment	± 180 micrometers	± 180 micrometers
Actuator operation range	1.1 nanometers	1.1 nanometers
Actuator slew rate	10.0 micrometers/sec	16 micrometers/sec
Actuator absolute length error	6.9 micrometers rms	3.8 micrometers rms
Actuator update period	< 500 ms	500 ms
Temperature sensor accuracy	0.1 degrees C	0.1 degrees C
System operating temp. range	2 ± 8 degrees C	> 2 ± 8 degrees C

Control loop bandwidth is the closed loop bandwidth of the ACS (computer controllable). Mirror cell corrections are the effective change in actuator length due to changes in the cell that they are supported by during normal tracking. There are two components, temperature 7 nm/seconds and gravity 20.5 nm/seconds. Step response settling time is the time required to settle after a calibration camera mirror segment movement of about 10 micrometers. Power dissipation near mirror is the total power budget for all electronics in the vicinity of the back side of the primary mirror. Sensor operating range is the range require by the calibration cameras (12 micrometers is an image movement of 6.2 acs seconds). Sensor offset adjustment is the required adjustment range to compensate for sensor mounting and manufacturing tolerances. Actuator operating range is the movement needed to correct for cell deformation (± 0.3 mm) and mounting positions errors. Actuator slew rate is the change in length need to compensate for cell deformations in slew conditions. Actuator absolute length error is the accuracy needed per actuator to calculate the three virtual sensors that control the attitude of the primary mirror in the telescope structure. The length is the residual errors in the actuator length after table look ups that compensate for the temperature coefficient of the actuator. Actuator update rate is the period between actuator motion commands. Temperature sensor accuracy is the accuracy needed in the table look ups. System operating temp. range is the range of temperatures over which the ACS will meet all other specification.

10. REFERENCES

1. J.E. Nelson et al, "The Design of the Keck Observatory and Telescope," Keck Observatory Report No. 90 (1985).
2. J.E. Nelson et al, "Construction of the Keck Observatory," Proceedings of the EOS Conference on Very Large Telescopes and Their Instrumentation (Garching 21-24 March 1989).
3. J.N. Autrun et al, "An Analysis of the Segmented Alignment Control System for the W.M. Keck Observatory Ten Meter Telescope," Keck Observatory Report No. 143 (1985).
4. J. Llacer et al, "Analysis of the W. M. Keck Telescope Primary Mirror Control Loop," in this issue.
5. R.H. Minor et al, "Position Sensors for the Primary Mirror of the W. M. Keck Telescope," in this issue.
6. J.D. Meng et al, "Position Actuators for the Primary Mirror of the W. M. Keck Telescope," in this issue.
7. R.W. Cohen et al, "The W. M. Keck Telescope Segmented Primary Mirror Active Control System Software," in this issue.
8. J. Fuertes et al, "An Emulator for the W. M. Keck 10 Meter Telescope," in this issue.
9. C. Witebsky et al, "Alignment and Calibration of the W. M. Keck Telescope Segmented Primary Mirror," in this issue.
10. T. Kiconiuk, "Internal Air Flow Patterns for the Keck 10 Meter Telescope Observatory Dome," Keck Observatory Report No. 166 (1986).
11. J.E. Nelson, "Comments on the Attitude of the Primary Mirror," Keck Observatory Report No. 206 (1986).
12. T S. Mast, "Error Budget for the Keck Observatory Primary Mirror," Keck Observatory Report No. 144 (1986)

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