Apache Point Observatory 3.5-Meter Telescope
Primary Mirror Support System

Pneumatic Servo Upgrade Hardware Design Report

Prepared for

The University of Washington
Apache Point Observatory

by

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EXECUTIVE SUMMARY

The Primary Mirror Support System of the APO 3.5-meter telescope utilizes an array of small pneumatic pistons (often called "Belloframs") which are servoed to provide an appropriate distribution of force over the back of the mirror and on the upper inside surfaces of the honeycomb cells. The forces provided by the pistons is intended to maintain both the position and the figure of the mirror as the telescope changes elevation angle, and as it responds to transient loads caused by wind gusts or other disturbances. The Primary Mirror Support System has been upgraded by installing a new pneumatic servo system incorporating improved, high bandwidth servo valves, new pressure sensors for more precise pressure control, and more elaborate electronic servo controllers. The new system is supported by modifications to the air supply system incorporating a new recirculating pump system which simultaneously provides a pressurized air supply and a sub-atmospheric return circuit.

1.0 INTRODUCTION

The primary mirror of a large telescope is heavy enough that it cannot support its own weight without distortions that alter its figure significantly. Even if the mirror is uniformly supported across the mirror cell, the cell itself cannot be made sufficiently rigid to support the mirror without distortion throughout its entire range of motion. One solution to this problem is to provide a support system in the mirror cell which actively synthesizes a perfectly rigid mounting structure supporting the mirror uniformly over its entire back face. Such a system must respond to the changes in the alignment of the gravity vector due to telescope tracking motions. In addition to simply providing an even force distribution that exactly compensates each component of gravity, the system must also maintain the correct position and orientation of the mirror, responding to transient disturbances such as wind gusts and telescope tracking accelerations.

The Primary Mirror Support System (PMSS) of the 3.5 Meter Telescope at Apache Point Observatory (APO) uses an array of pneumatic pistons to provide active support of the telescope's primary mirror. Pistons distributed across the back of the mirror support it axially, while pistons placed on arms extending inside the honeycomb structure and bearing on the upper surfaces of the cells support the mirror transversely. Three axial position sensors and one transverse position sensor detect the position and orientation of the mirror relative to the cell. An electronic servo system controls the air pressure in the pistons so as to maintain the position and attitude correctly as the cell moves and as the mirror is subjected to wind loading.

2.0 SYSTEM DESCRIPTION

2.1 Support Actuator Arrangement

Since the 3.5 Meter telescope uses an altitude-azimuth mounting system, the primary mirror moves only in those two degrees of freedom. The mirror support system therefore needs only to support the mirror actively in two directions: axially (perpendicular to the face of the mirror), and transversely (parallel to the face of the mirror and in a vertical plane). The mirror is positively constrained against rotation in the cell and against horizontal transverse motion. Vertical transverse displacement is controlled by the transverse support system; axial translation, tip, and tilt are controlled by the axial support system. With the telescope pointed at the zenith, the axial support system bears the entire weight of the mirror while the transverse supports bear none; with the telescope pointed at the horizon, the axial supports bear nothing while the transverse supports bear the entire mirror.

The axial support system comprises an array of 78 air pistons distributed over the back face of the mirror and resting on the bottom of the mirror cell. In order to control tip and tilt as well as axial translation, the axial piston array is divided into three radial sectors, each with its own independent control system. Position feedback for each sector is provided by a strain-gage load cell captured between the mirror back plate and an adjustable post mounted to the mirror cell surface below the center of each sector. The control system adjusts the quantity of air in each cylinder array to keep the load cell compressed to a fixed setpoint.

The transverse support system employs 38 air cylinders mounted inside the honeycomb sections of the mirror. Each piston is mounted on a post anchored to the bottom of the mirror cell and extending through a hole in the mirror back plate into one of the honeycomb cells that make up the mirror body. The piston acts on the "top" flat surface of the honeycomb cell, thus providing a force transverse to the optical axis. The entire transverse support system includes a total of 38 pistons distributed over the entire mirror. The transverse position sensor is a load cell facing on the "top" of the inside of the Cassegrain hole in the center of the mirror. The load cell actually bears against the edge of the mirror backplate inside the Cassegrain hole.

The three axial sectors are referred to as sectors A, B, and C, starting at the back of the mirror and proceeding clockwise as viewed from above. The A sector is on the plane of symmetry as the telescope moves in elevation; the B sector is on the left, and the C sector is on the right. The transverse system is referred to as sector T. Figure 2-1 shows the arrangement of the axial sectors, the locations of the valves and manifolds, the locations of the hard points, and the layout of the major plumbing runs. The actuators for each axial sector are plumbed with 1/16 inch tubing from single manifolds denoted MA, MB, and MC. The valves for each axial sector are denoted VA, VB, and VC. The transverse valve is denoted VT. It feeds two manifolds, MT1 and MT2. MT1 (collocated with VT) serves the back half of the mirror; MT2 serves the front half of the mirror.

2.2 Hard Points

The three axial hard points are located in the triangular bays of the mirror cell, as shown in Figure 2-1. The transverse hard point is on the back of the Cassegrain hole. Each hard point assembly consists of a load cell and a Linear Variable Differential Transformer (LVDT) position sensor. The load cell is the actual position sensing device used to control the mirror; the LVDT is provided for diagnostic and monitoring purposes only. The load cells are designated XA, XB, XC, and XT; the LVDTs are designated LA, LB, LC, and LT.

The load cells are strain-gage tension devices (Sensotec Model 41/5741-04-04 equipped with Sensotec Model VPV amplifiers). The output span is 0-5 volts for a load span of 0-50 psi. The mounting of each load cells to its steel post includes a spring-loaded plunger with a breakaway force of 7 lb. The plunger is normally bottomed out, but in the event of a force exceeding 7 lb it begins to compress, thus protecting the load cells from overstress. The controller establishes the nominal setpoint of the load cell at 0.5 volt--corresponding to 5 pounds of force on the hard point.

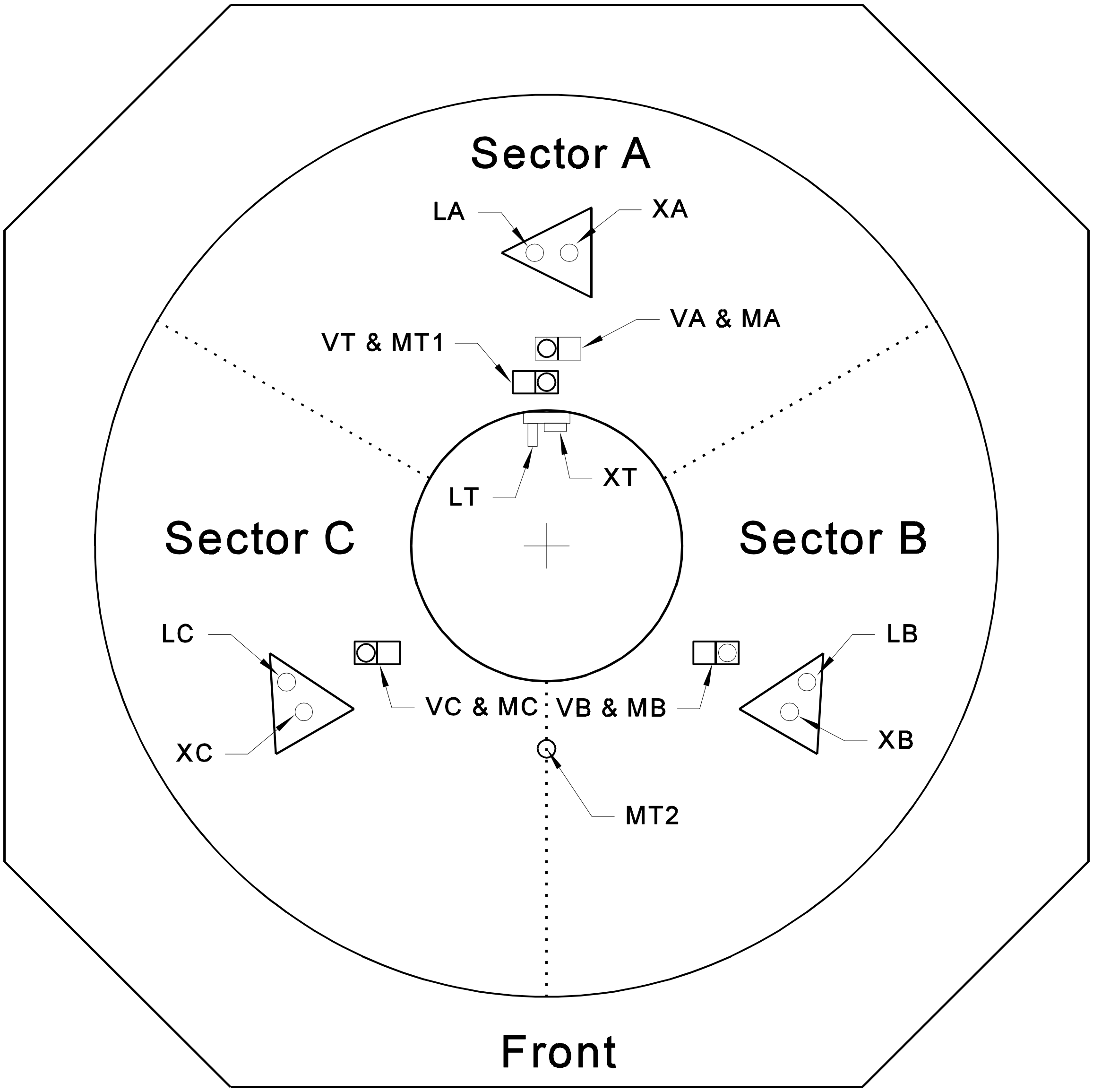


Figure 2-1. Layout of primary mirror cell, plan view, zenith position. Not to scale.

Next to each load cell, an LVDT position detector (Sensotec Model S2C) is also provided for diagnostic purposes. Each LVDT has a nominal sensitivity of 6.6 V/in using the 10 V excitation provided. It is essential to understand that although the load cells are made for the purpose of transducing force, they in fact transduce displacement over a span of 0.003 inch. The forces involved in deflecting the load cells are only a few pounds--negligible compared to the weight of the mirror. Although the load cell mounting posts are referred to as the mirror mount "hard points," they offer negligible stiffness to the mounting system. On a macroscopic scale, the "hard points" determine grossly where the mirror will rest; on the scale of interest, however, they are merely very sensitive position sensors. The stiffness of the mounting system is derived from the closed-loop control of the air pistons. Open-loop, the pneumatic system is quite soft, due to the compliance of the air; closed-loop, it is infinitely stiff except under transient loads--and even then, the stiffness is such as to permit only fractions of a micron of displacement before recovery. The stiffness of the load cells is essentially irrelevant to the dynamics of the system.

It may be tempting to think of the mounting system as a force control mechanism which uses the pressure in the air cylinders to relieve all but a constant small force on the load cells, which themselves provide hard position references for the mirror. This picture, however, neglects the very considerable inertia of the mirror. A disturbance will set the mirror in motion, and a compensating force must be generated to overcome that inertia. A constant force implies constant acceleration, not constant position.

2.3 Pneumatic Cylinders

The air cylinders are designed for a maximum piston area with minimum volume so as to minimize the effect of air compliance. The assemblies are made with rolling membrane seals: the piston is essentially a puck sitting on top of a bladder captured inside the cylinder. This design effectively eliminates the "stiction" effect common to conventional sliding seals. This type of air piston is manufactured by the Bellofram Corporation and is often called a "Bellofram."

There are three sizes of piston, each type being anodized a characteristic color. The piston dimensions and numbers used in each sector are shown in Table 2-1. All three types have approximately the same stroke (0.254 in).

As shown in Table 2-1, the pressure requirement to support the mirror on the transverse axis is nearly three times that required on the axial axes.

The cylinders are fed by 1/16 in Tygon tubing connecting to each cylinder by means of a 0.048-inch ID barbed fitting. Each group of axial support cylinders is fed from a single manifold close to its associated valve. The length of tubing from the manifold to each cylinder varies from a foot or so to more than 3 feet depending upon the distance of the actuator from the manifold. The T sector valve is mounted right next to the A sector valve and feeds two manifolds, one mounted on and serving the top half of the mirror (T1), and the other mounted on and serving the bottom half of the mirror (T2). The two transverse manifolds are connected by way of 1/8 inch tubing.

Table 2-1. Pneumatic Actuator characteristics and distribution.

Piston Type	Radius (in)	Area (in^2)	Axial per Sector Number	Axial per Sector Total Area (in^2)	Transverse Number	Transverse Total Area (in^2)
Large (Black)	1.39	6.07	4	24.28	0	0
Medium (Blue)	1.26	4.99	18	89.82	0	0
Small (Red)	1.07	3.60	4	14.40	38	136.8
Total Area (in^2)				128.5		136.8
Max Pressure Required (psig)				10.4		29.2

2.4 Control Valves

The air charge in the pneumatic cylinders of each sector is controlled by a high-bandwidth proportional valve (Dynamic Valves model PC-2). The PC-2 allows continuous air flow from its supply (pressure) port to its return (exhaust) port. A flapper between these ports controls the pressure in the valve chamber and thus the pressure to the control port. (See the spec sheet in the Appendix for a diagram.) Because the flapper has low inertia, there are no sliding surfaces, and there are no seals, the valve can achieve very high bandwidth with essentially no hysteresis or stiction. The disadvantage of the design is the requirement for a continuous flow of air through the valve--which amounts to something on the order of a half CFM for each sector. Each valve mounts to a manifold supplied by the manufacturer (Dynamic Valves P/N 55-0700-1; see the valve spec sheet in the appendix) which provides 1/8 inch NPT ports for the nylon tube fittings which connect to the supply, return, and pressure tubes. The valve and manifold assembly mounts directly to the manifold by way of a bracket which fits over the manifold mounting stud as shown in Figure 2-2. This arrangement minimizes the length of 1/8 inch

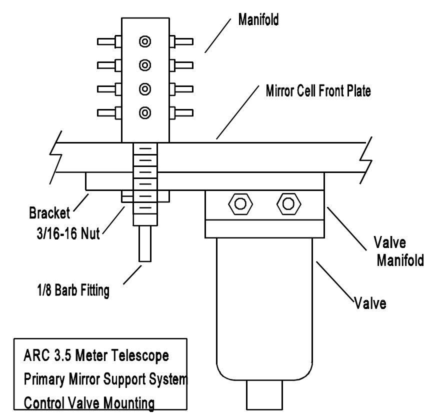


Figure 2-2. Mounting of control valves and manifolds on mirror cell face plate.

tubing required to connect the valve to the manifold.

2.5 Pneumatic Plumbing

Figure 2-3 shows a schematic of the in-cell plumbing. The supply and return tubes are carried to the mirror cell via the right candy-cane. The supply (pressure) tube is 3/8 braid-reinforced vinyl about 60 feet long. The return (vacuum) tube is 3/8 vinyl, also about 60 feet long. All fittings are nylon barbed fittings, except the connectors at the pistons and the manifolds.

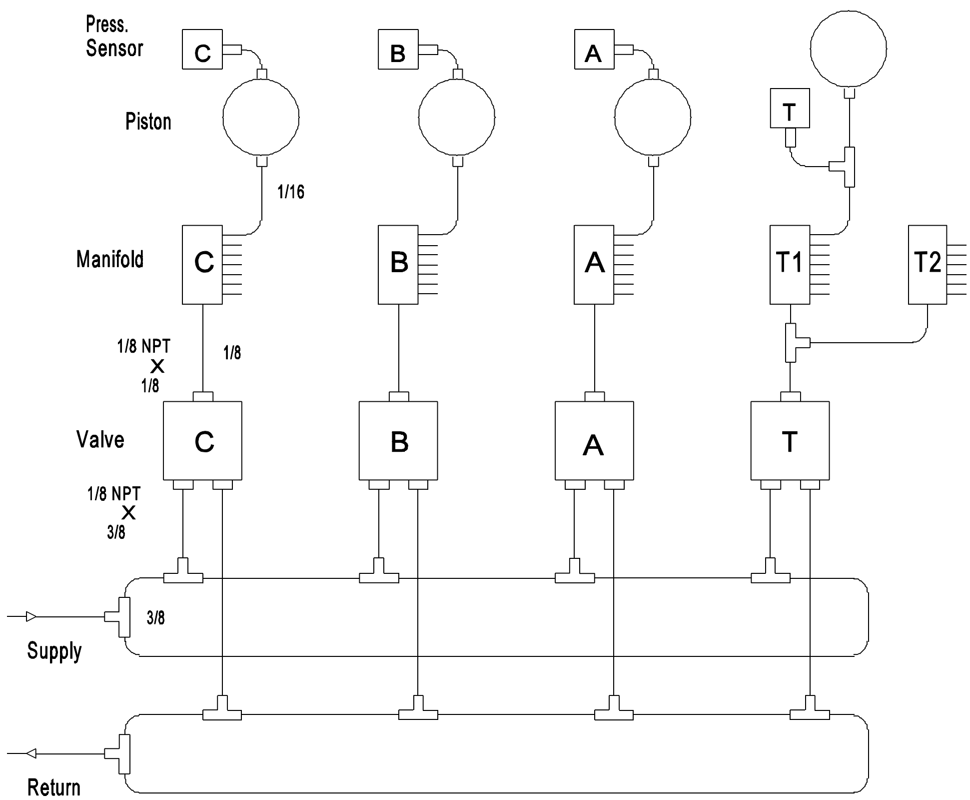


Figure 2-3. Schematic of in-cell plumbing.

2.6 Pumping Station

The Pumping Station provides pressurized air to feed the valves and vacuum to exhaust them. It is located on a balcony in the mid-level under the left candy-cane. This location minimizes the length of the tubing runs into the mirror cell. Figure 2-4 shows a schematic diagram of the pumping station plumbing. The pumps and solenoid valves in the pumping station are operated by a controller mounted in the relay rack below the balcony. The controller provides both manual and automatic control of the pumps and the valves by way of a bank of solid state relays housed in a cabinet above the pumps. A schematic diagram of the relay panel is shown in Figure 2-5.

Two electric rocking piston pumps (Gast model 71R647-P112-D500X) plumbed in parallel provide both pressure to the supply line and vacuum on the return line. Since the pumps are not capable of starting under load (i.e., with a differential pressure more than a few psi), a shunt valve (Parker Series 30) has been provided between the pumps to allow starting even when the system is pressurized. At the outlet of the pumps a three-way vent valve selects between exhausting to atmosphere for pumping water vapor out of the system, or discharging into the pressure receiver for normal operation. The pressure receiver smooths out pump pulsations and provides any surge air requirements (such as during response to a wind gust). The relief valve (Plasti-Valve model xxxxx) on the pressure receiver is set for 60 psig to allow exhaust of air buildup in case of a vacuum leak. The supply line is equipped with a desiccating filter and a pressure regulator. The pressure regulator sets the actual working pressure of 40 psig, a figure that provides about 10 psi of overhead above the maximum steady state pressure requirement of the transverse axis. Pressure hose from the pumps is 3/8 inch braided vinyl.

The vacuum side of the pumps is connected through a vacuum receiver to the return line. About 5 inches of vacuum is required for proper operation. More vacuum will enhance the dynamic performance of the system.

Air is supplied to the system from a facility air connection, regulated down to the minimum operating pressure of 45 psig (providing 5 psi of overhead for the supply line regulator). This connection provides makeup air for any leakage on the pressure side. It also charges the system correctly after initial startup.

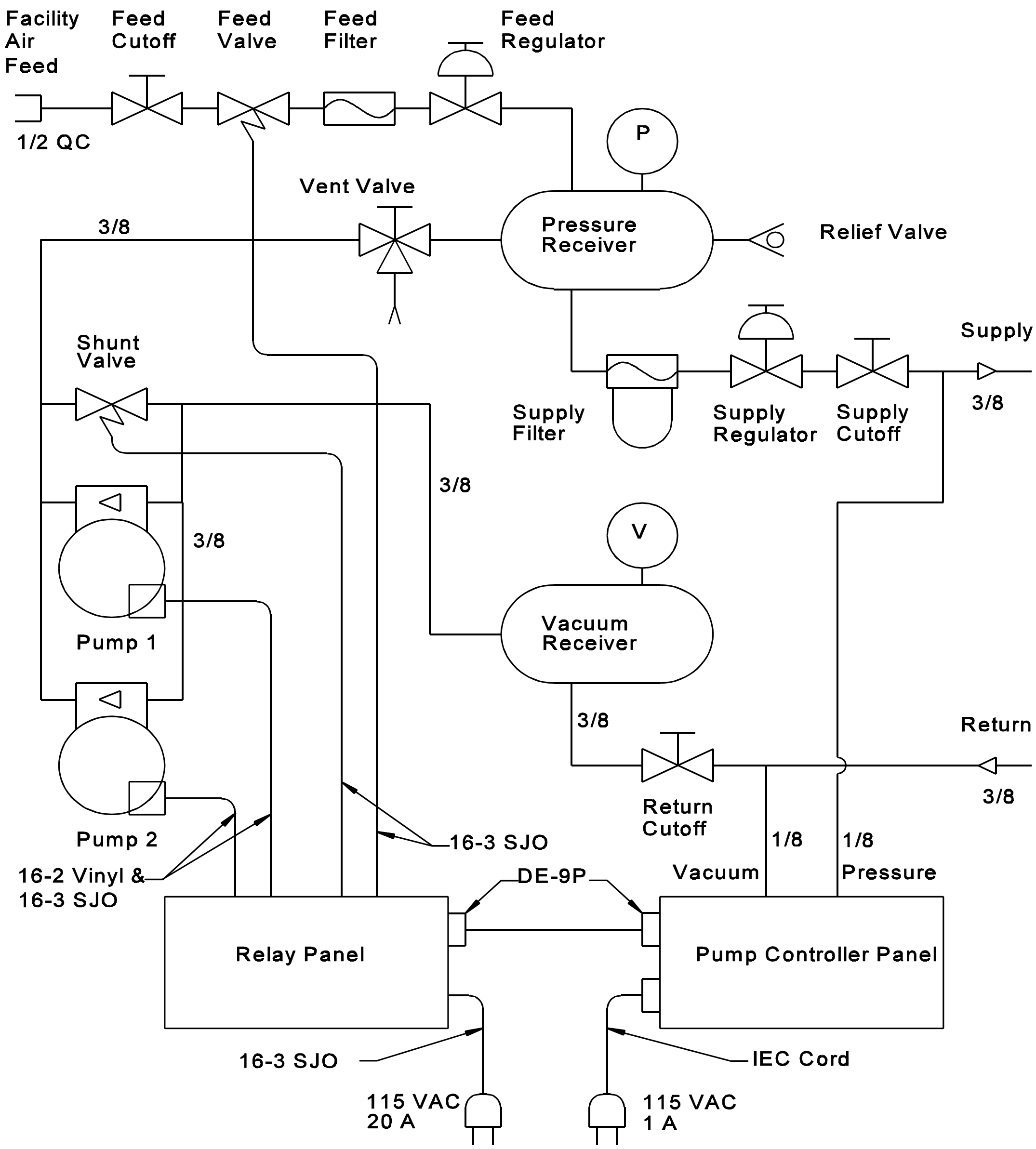
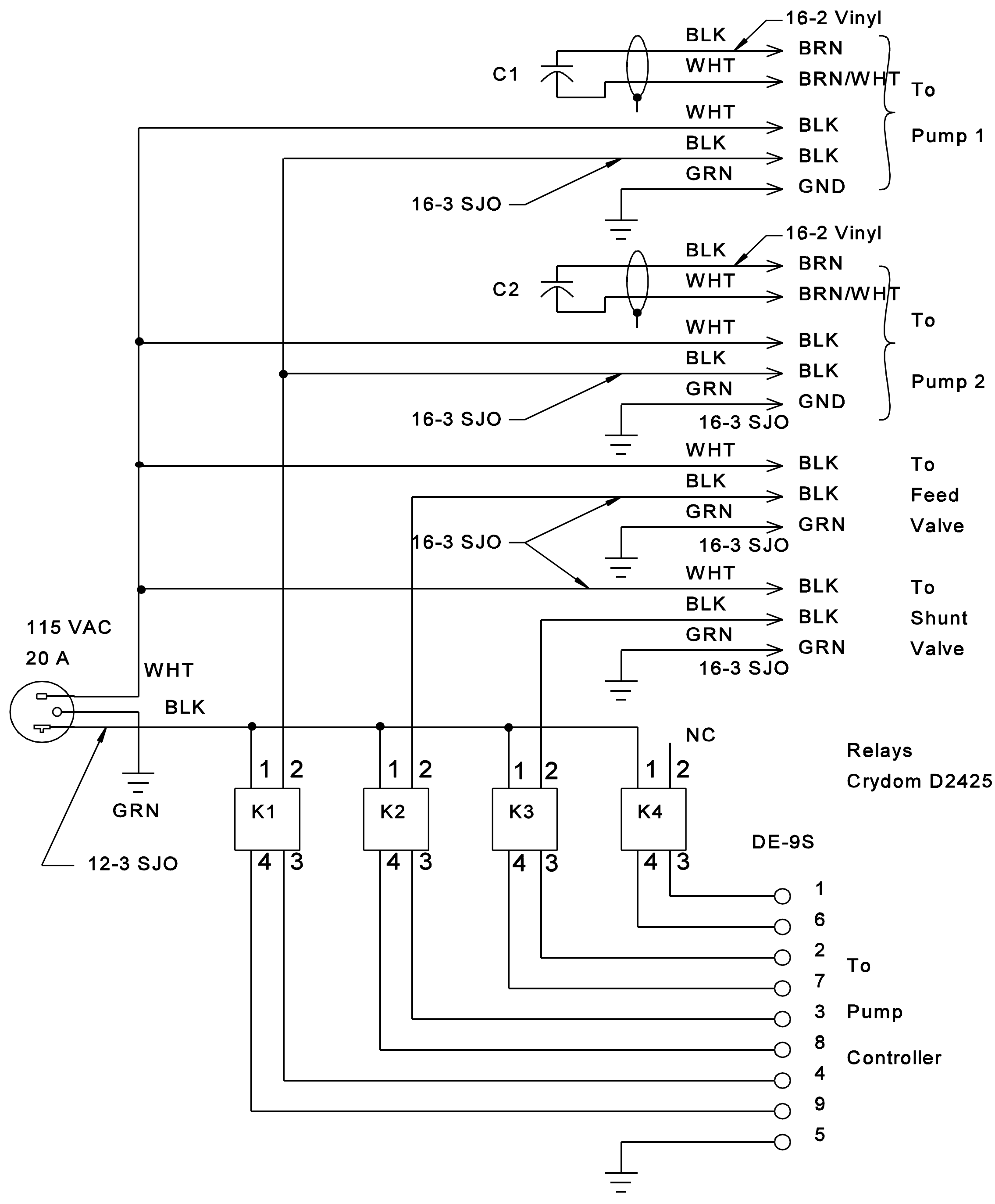


Figure 2-4. Pumping Station Schematic.



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2.7 Control Electronics

The Mirror Controller electronics resides in a cabinet on the front of the mirror cell. The cabinet contains four controller cards (one for each sector), a power supply, and the monitor patch panel. Circuits are given in the appendix. Each controller board implements the control elements described in section 4 (and shown in the block diagram in Figure 4-2), along with the signal processing and monitoring functions described in section 3.

The electronics cabinet is cooled by airflow through the cable access hole into the mirror cell. Although the power supply (Power One Model HBB-15-1.5-A) is rated for 40 W, actual total power dissipation is less than 10 W. An input fuse (3/8 AGC) is mounted next to the transformer on the power supply.

3.0 METROLOGY AND MONITORING

3.1 General Description

3.2 LVDTs

Each hardpoint includes an LVDT that senses displacements of the mirror at the position of the hard point, thus providing an indication of proper positioning and of dynamic response. The LVDTs are Sensotec Model S2C, DC-DC units with spring return plungers. The axial LVDTs bear directly on the back plate of the mirror by way of a plunger mounted in the front face of the mirror cell. The transverse LVDT bears on the edge of the Cassegrain hole in the mirror back plate. The LVDTs are aligned with the centers of the each sector (with the load cells slightly off center).

Excitation for the LVDTs is ±5 VDC for a total span of 10 VDC. With this excitation, the sensitivity of the LVDT is nominally 6.6 V/inch. [Accurate calibration data for the LVDTs is not available.]

The first stage of amplification has a fixed gain of ten, with an adjustable zero offset to allow for very sensitive displacement measurements. The second stage of LVDT amplification has a switch-settable gain of either unity or ten. Consequently the LVDT Gain Switch (S3, located near the center of the circuit board) sets the overall gain at either X10 (low gain) or X100 (high gain). In order to reduce noise and to eliminate residual chopping frequency feedthrough, the bandwidth of the LVDT amplifier is limited to 160 Hz with a single-pole filter. To reduce common-mode noise pickup, the LVDT is excited with a bipolar excitation supply, and the first amplifier couples differentially to the LVDT signal leads.

Normally the LVDT Gain should be set at X10 (low) and the LVDT Zero pot should be set for zero reference (as measured at U8-14). This setting can always be reproduced and allows monitoring of the nominal LVDT position. For sensitive dynamic measurements, the LVDT Gain can be set to X100 (high). In this condition, the nominal LVDT output may saturate the amplifier, so the LVDT Zero pot must be readjusted for zero output.

3.3 Proximity Sensors

Axial rotation of the mirror in the mirror cell is prevented by two struts that attach to the mirror near the front and rear edges of its back face. Adjustment of the struts is used to position the mirror laterally and rotationally. Lateral and transverse positioning can be measured conveniently using a micrometer depth gauge in the gauging ports provided in the Cassegrain hole for this purpose, but accurate measurement of rotational positioning is impossible by manual means. Consequently a pair of inductive proximity sensors has been provided sensing of the mirror axial rotation. The sensors are mounted inside diametrically opposite honeycomb cells on the lateral axis of the mirror. The difference between the left and right prox sensors is an indication of mirror rotational displacement.

[No technical information available on the sensors or their mounting.]

The controller cards do not include support circuitry for the proximity sensors.

3.4 Gauging Ports

The inside of the Cassegrain ring on the mirror cell is fitted with four ports that provide a firm gauging surface and an access hole to the inside edge of the mirror backplate. A micrometer depth gauge can be placed on each port to measure the position of the two transverse directions, thus indicating its centering relative to the mirror cell. The transverse hard point equipment is normally mounted in the top Gauging Port.

3.5 The Monitor Connectors

The main connector panel in the controller cabinet includes four DB-25S connectors that provide access to the eight monitor signals from each of the

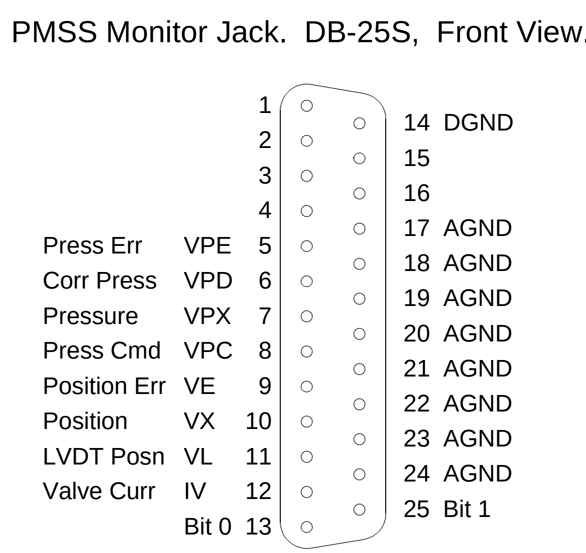

Figure 3-1. Monitor Jack Pinout. Monitor Jacks are located on the connector panel in the controller cabinet on the mirror cell front.

controller cards. Figure 3-1 shows the pinout for these connectors. Table 3-1 summarizes the characteristics of each monitor channel. The connector panel is electrically connected to the frame of the telescope, but signal ground is isolated from the frame. Therefore, do not use the shell of the DB-25 connector as a ground, and do not carry shield ground to the connector shell.

The signal outputs on the Monitor connector are all driven from low impedance op amp outputs. Although maximum output voltage is ±11 V, the signals are scaled for a ±5 V input data acquisition system.

Table 3-1. Monitor Channels.

Monitor Signal		Location (DB-25)	Scaling	Nominal Value
VPE	Pressure Error	5/17	+2.0 psi/V	0 V (0 psi)
VPD	Corrected Pressure	6/18	-2.0 psi/V	Approx 0 V at 45 deg
VPX	Absolute Pressure	7/19	(VPX-1)●10.0 psi/V	Axial: 3.04 - 2.15 V 20.4 - 11.5 psia Xvrse: 2.04 - 4.92 V 10.4 - 39.2 psia
VPC	Pressure Command	8/20	+2.0 psi/V	Approx 0 V at 45 deg
VE	Position Error	9/21	15.2 um/V	0 V (0 um)
VX	Load Cell Position	10/22	15.2 um/V	0.52 V (7.9 um)
VL	LVDT Position	11/23	370 um/V	A: B: C: T:
IV	Valve Current	12/24	19.6 mA/V	0 - 5 V (0 - 100 mA)

4.0 THEORY OF OPERATION

4.1 Plant Dynamics

4.1.1 Mirror Dynamics

Figure 4-1 shows schematically the arrangement of a single piston and the pneumatic system supplying air to it. Each piston supports a mass m corresponding to its share of the total mass of the mirror. For the axial pistons m is approximately 1/78th of 1800 kg, or 23 kg. Although the inertia of the mirror segment supported remains constant, the weight supported scales as the cosine of the telescope elevation angle θ. At any given moment, the cylinder contains n moles of air and develops a pressure P which, acting on the cylinder area $A = 32\ \text{cm}^2$, produces a force which counters the supported weight and provides any acceleration required. In addition, it must also counter the atmospheric pressure, P_A, operating on the opposite side of the piston. At the observatory's elevation of 9,200 feet, P_A = 71.86 kPa. Nominally, the cylinder contains n_0 moles of air and the piston floats a distance l_0 from the bottom of the cylinder. The position x of the mirror is thus measured relative to the nominal cylinder depth. The mirror position is transduced by a load cell with a position sensitivity k_x. When x is zero (actual cylinder depth is l_0), the load cell output V_x is a nominal voltage of 0.5 volts.

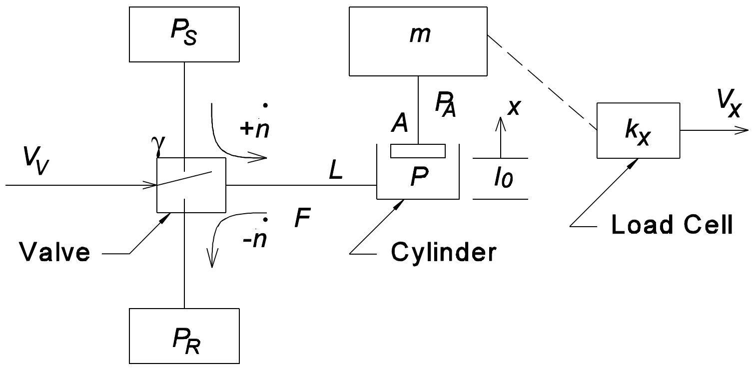

Figure 4-1. Mirror and Plant Dynamics.

Assuming isothermal conditions at temperature T, the pressure in the cylinder is

$$P = \frac{nRT}{A(l_0 + x)}$$

and the net force acting on its associated mirror segment is

$$m\ddot{x} = (P - P_A)A - mg\cos\theta$$

Consequently the entire mechanical equation of motion for the mirror segment is

$$m\ddot{x} = \frac{nRT}{l_0 + x} - P_A A - mg\cos\theta$$

With the mirror stationary at its nominal position, the nominal gas charge is

$$n_0 = \frac{l_0}{RT}(P_A A + mg\cos\theta)$$

producing a static pressure of

$$P_0 = P_A + \frac{mg\cos\theta}{A} = \frac{n_0 RT}{A l_0}$$

Note that for $x << l_0$, the pressure force is approximately linear in x, and the equation of motion reduces to the standard form of a simple harmonic oscillator:

$$\ddot{x} + \frac{k}{m}x = \frac{k}{m}l_0 - \frac{P_0 A}{m}$$

where

$$k \equiv \frac{n_0 RT}{l_0^2}$$

With a nominal air charge in the cylinders, the mirror will oscillate on the compliance of the air at a frequency

$$\omega_m = \sqrt{\frac{k}{m}} = \sqrt{\frac{n_0 RT}{m l_0^2}} = \sqrt{\frac{P_0 A}{m l_0}}$$

It is interesting to note here that the compliance of the air in the cylinder depends only on the equilibrium cylinder depth, so that (for a vertical orientation) the natural frequency is given by the familiar relation $\omega_m = (g / l_0)^{1/2}$.

The stiffness of the support system is governed by the value of l_0, with the smaller the better. For the values l_0 = 3.2 mm and $\theta = 45^o$,

n_0 = 5.5 x 10-4 moles,

P_0 = 120 kPa,

and

ω_m = 73 rad/sec = 12 Hz.

4.1.2 Gas Flow Dynamics

The air charge in the cylinders is controlled by a three-way pneumatic proportional valve which can admit air from a supply held at pressure P_S, or exhaust air to a return manifold held at a subatmospheric pressure P_R. The valve itself employs a flapper design, as suggested in Figure 4-1. Supply air at high pressure is admitted through an orifice, and returned by another orifice on the opposite side of the valve body. An electromagnetically controlled flapper modulates the relative flow of air through the two orifices, thereby controlling the air pressure in the valve body. The control port admits air from the valve body out to the pneumatic cylinders. This design offers two very distinct advantages over other designs: first, it primarily controls pressure rather than conductance; and second, it allows very rapid pressure control (specified bandwidth is 750 Hz). The disadvantage of the design is that the valve consumes air continuously, even under static conditions.

4.2 Control Strategy

The greatest challenge to supporting the primary mirror on pneumatic actuators is dealing with the compliance of the air in the system. Since air is compressible, the mirror mass will oscillate about the equilibrium position set by the quantity of air in the cylinders. For the axial supports with the telescope pointed to the zenith, the natural frequency of this oscillation is about 10 Hz; at the horizon it is zero. Ordinarily the designer may choose either to stabilize the system below the plant natural frequency and hope that the plant normal modes are never excited, or else to stabilize above the plant natural frequency and have the control system damp the normal modes. Since the plant natural frequency varies all the way to zero depending on elevation angle, the low-frequency approach is not an option. The high-frequency approach, however, demands the ability to move air rapidly and precisely

The basic control strategy adopted for the PMSS is to stabilize the natural oscillatory tendency of the mirror mass by implementing a pressure control loop, and then to close a position control loop around that. The inner loop (designed to be fast enough to damp any tendency of the mirror to oscillate on the compliance of the air) behaves as a free body with pressure corresponding to acceleration. A position control loop closed around the pressure control inner loop can then fix the mirror position with its own independent control parameters. Figure 4-2 gives a detailed block diagram of the complete control system for one sector.

The air charge in the pneumatic cylinders of each sector is controlled by a three-way pneumatic proportional valve. The valve admits air from a pressurized supply or exhausts it to a subatmospheric return as necessary to control the position of the mirror sector. The pressure in the cylinders is measured by an absolute pressure transducer mounted directly on one cylinder in each sector. Since the pressure in the cylinder is always at least atmospheric, and generally considerably more, it is convenient to subtract a constant value, V_{PO}, from the raw pressure signal V_{PX}. The resulting pressure signal is then bipolar, and small enough in magnitude that it may be conveniently amplified without exceeding the dynamic range of the amplifier. The pressure error signal, V_{PE}, is simply the difference between the actual pressure signal, V_{PD}, and a pressure command signal, V_{PC}. The pressure loop controller is a proportional-integral design, the proportional component providing immediate pressure error corrections, and the integral component offsetting steady-state errors that vary with telescope elevation and variations in atmospheric pressure.

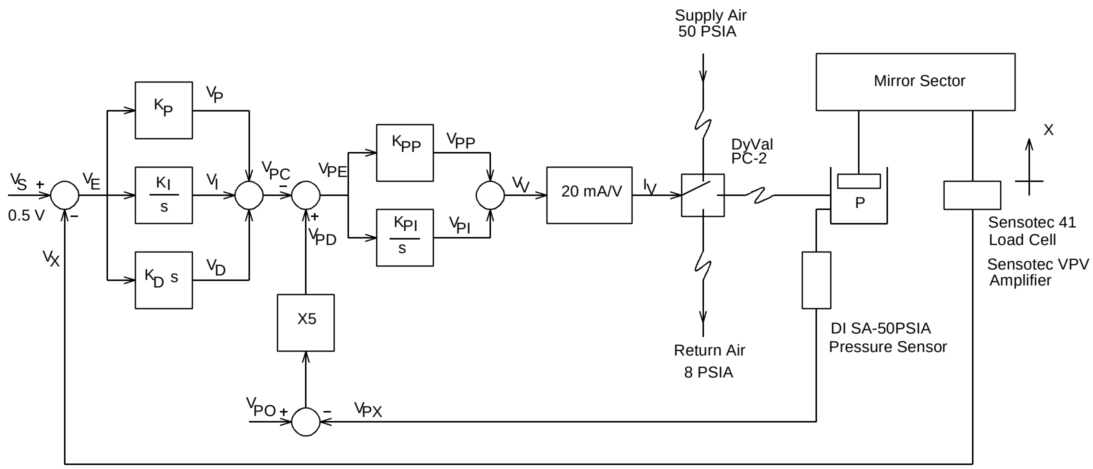

Figure 4-2. Block Diagram of the PMSS control system. For clarity, only one actuator is shown.

The outer loop derives its position signal from the load cell, and it derives a position error signal, V_E, as the difference between the position and a fixed position setpoint voltage, V_S. The position setpoint is 0.5 V, corresponding to a force on the load cell of 5 lb. The position controller is of the ubiquitous proportional-integral-derivative (PID) design, generating a pressure command to control the inner loop. (In practice, the control bandwidth of the outer loop has never been greater than about 1 Hz, and the derivative component has not been needed.)

The choice to stabilize the system above the maximum plant natural frequency of 10 Hz implies fairly demanding bandwidth requirements on individual components. Stability of the pressure control loop (if not the position loop as well) demands a control bandwidth of at least 10 times the plant natural frequency, or about 100 Hz. This requirement in turn implies that the individual components of the system have bandwidths another factor of ten or so greater still, or around 1 kHz. The three critical bandwidth-limiting components in the system are the position sensor (*i.e.*, the load cell), the pressure sensor used in the inner loop, and the pneumatic servovalve. Load cells are intrinsically high-bandwidth devices, and those used in the original system (Sensotec Model 41 with Model VPV amplifiers) were considered entirely adequate. For the pressure transducer, the Data Instruments Model SA-50PSIA was selected for its physical ruggedness, integral signal conditioning, and suitable bandwidth. The valves are DyVal Model PC-2 proportional valves, selected for their remarkably high bandwidth (about 750 Hz) and appropriate throughput capacity.

The DyVal PC-2 employs a flapper design as suggested by the schematic in Figure 4-2. The valve allows continuous air flow from its supply (pressure) port to its return (exhaust) port. An electromagnetically actuated flapper between nozzles mounted at these two ports differentially modulates their conductances, thereby controlling the pressure in the valve chamber, and thus the pressure supplied to the control port. Because the flapper has low inertia and uses no sliding seals, the valve can achieve very high bandwidth with essentially no hysteresis and no “stiction” effects. The disadvantage of this design is the need for a continuous flow of air through the valve despite the fact that the cylinders themselves consume essentially none.

A fourth bandwidth-limiting factor also required attention in designing the system. In order to minimize volume, the valves and the cylinders are interconnected by 1/16 inch flexible tubing. Friction in this tubing limits the flow speed of air, and thus the response speed of the overall system. Both a design simulation and experiments with a prototype indicated that tubing lengths greater than about 2 m introduced phase shifts that made stabilization of the pressure control loop difficult. Fortunately, the longest runs in the mirror cell are about this length, and the shortest runs are considerably less. The pressure transducers were placed on cylinders about 80 cm from the valve manifolds--a roughly average length of tubing.

5.0 OPERATING PROCEDURES

5.1 Initial Startup Procedure

Use this procedure when the system has been shut down for an extended period (more than a few days) or when the plumbing has been opened for any reason.

1. Verify that all switches on the Pump Controller panel except POWER are in the UP POSITION. In this configuration, the pumps are off, the shunt valve is open, and the feed valve is closed.

2. Verify that the Mirror Controller is OFF. (Unplug in the electronics cabinet on the front of the mirror cell.) The mirror will be settled even if there is some residual pressure in the system, because the valves will deliver zero pressure with no excitation.

3. Verify that the Feed Cutoff Valve is CLOSED.

4. Set the three-way Vent Valve to VENT. (The handle points up, toward the open vent port.)

5. Verify that the Supply Cutoff Valve is OPEN.

6. Verify that the Return Cutoff Valve is OPEN.

7. Allow any pressures in the system to relax to atmospheric. This operation may take some time since relaxation occurs by way of leakage through the control valves. If there is no vacuum, the process may be speeded up by reducing the Supply Regulator setting to zero. This operation will vent the supply side to atmosphere through the regulator.

8. Turn the Mirror Controller ON. (Plug in at the electronics cabinet.) This operation will equalize any remaining pressure in the system, since the axial control valves will go full open. Pressure in the return line and the Vacuum Receiver will vent through the Shunt Valve and Vent Valve to atmosphere. If the operating pressure is less than 10 psig when this operation begins, the mirror will not be moved off the stops.

9. Turn the Pump Controller ON (set the POWER switch to the UP position.) The following sequence will occur automatically:

   1. After a few seconds delay, the pumps will start. Verify proper pump operation by noting that both cooling fans are moving air.
   2. After a few seconds delay the shunt valve will close, so that the pumps will begin exhausting the system through the open Vent Valve. This operation will remove any water vapor from the system.
   3. After about 20 seconds, the Feed Valve will open. Since the Feed Cutoff Valve is closed, this operation is of no consequence.

10. The vacuum gauge on the vacuum receiver should begin indicating vacuum immediately. Continue pumping until the vacuum reading stabilizes (at 15-20 inHg). This operation evacuates the entire system, removing volatile contaminants such as water.

11. Set the three-way Vent Valve to NORMAL. (Turn the handle to point to the right, toward the pressure receiver.

12. Slowly OPEN the Feed Cutoff Valve, leaving it throttled so that the pressure in the Pressure Receiver rises slowly. Do not allow the pressure in the pressure receiver to exceed 45 psig. Adjust the Input Regulator if necessary.

13. SET the Input Regulator for 45 psig on the pressure receiver gauge.

14. SET the Supply Regulator to 40 psig on the Pump Controller panel pressure gauge. Some iteration between the Feed Regulator and the Supply Regulator may be necessary. The mirror will now be flying on the axial axis. If the telescope is at zenith, the mirror may not be engaged to the transverse hard point, but it will not have been pushed away by a pressure surge.

5.2 Shutdown Procedure

Use this procedure when the system is to be shut down for a long period, or when any maintenance or modification is performed on the system.

1. Turn the Pump Controller OFF (set the POWER switch in the DOWN position). This operation will cause the Pump Controller immediately to stop the pumps, open the Shunt Valve, and close the Feed Valve. The system pressures will slowly relax through the servo valves, gracefully settling the mirror.

2. CLOSE the Feed Cutoff Valve.

3. Turn the Mirror Controller OFF (unplug in the Mirror Controller Cabinet).

5.3 Brief Shutdown and Recovery

The system will shut down automatically during a power interruption, and will recover automatically when power is restored. This operation may be initiated manually using the POWER switch on the Pump Controller panel.

SHUTDOWN

1. Turn the Pump Controller OFF (set the POWER switch to the DOWN) position. The following events occur automatically:

1. The pumps stop.
2. The Shunt Valve opens.
3. The Feed Valve closes.
4. The system pressures relax through the servo valves. When the pressure drops below about 10

psig, the mirror will settle. (This condition may not occur spontaneously.)

RECOVERY

1. Turn the Pump Controller ON (set the POWER switch to the UP position.) The following sequence will occur automatically:

> 1. After a few seconds delay, the pumps will start. Verify proper pump operation by noting that both cooling fans are moving air.
> 2. After a few seconds delay the shunt valve will close, so that the pumps will begin charging the pressure receiver and exhausting the vacuum receiver.
> 3. After about 20 seconds, the Feed Valve will open. If any makeup air is required, it will flow into the system to bring the pressure up to its nominal value as set by the Feed Regulator.
> 4. If there is too much air in the system (an unlikely occurrence) the Feed Regulator will bleed the pressure side down to nominal.

5.3 Tuning Procedure

The tuning potentiometers are all 25 turn devices. Turning a pot past its endpoint will not damage it. The endpoint may be detected either by turning the pot more than 25 turns CCW, or by listening for the slight clicking sound it makes when passing through the endpoint. All pots turn CW to increase the gain of the associated stage. Increasing the gain of an integrator corresponds to decreasing its time constant: increasing gain increases "speed."

All turn counts are expressed as full 360-degree CW rotations from the full CCW (low gain) endpoint.

In tuning the system keep in mind that there are two control loops in operation: the "inner loop" which controls actuator pressure, and the "outer loop" which controls mirror sector position. Tuning therefore proceeds in three phases:

1. Tune the inner (pressure) loop for stability and response (with the outer loop open).

2. Tune the outer (position) loop for stability and response (with the outer loop closed).

3. Make fine adjustments as required to optimize performance.

The procedures below describe tuning at a single elevation angle. The nominal "mid-range" in elevation is 30 degrees elevation for the transverse system and 60 degrees elevation for the axial system. These are the elevations for which the force on the system is half the weight of the mirror. Tune the system at mid-elevation first, then check at its elevation extremes for anomalous behavior, and make further adjustments as necessary.

In principle, all three axial sectors should behave identically. It is therefore practical to tune one axial sector and then simply adjust the others to the same settings. Once the others have been set to match, however, go back and check the tuning since it may have been affected by readjustment of the other two sectors. The axial and transverse sectors are nearly decoupled, so there is not much interaction between their tuning settings.

Since all other axes must be working and stable to tune any one axis, it is important to start from an initial setting that is at least stable. If you are not already working from a stable setting, try the following: Press Int = 2, Press Prop = 5, Prop = 2, Int = 1, Deriv = 0.

Tuning will be facilitated by connecting a monitoring system that graphically displays position (VX), and at least numerically displays other parameters.

5.3.1 Inner Loop Tuning

Carry out initial pressure loop tuning with the sector fully loaded (zenith for axial sectors; horizon for transverse).

1. Move the shorting jumper on SELECT (J7) from VPC to VT. This operation breaks the position loop and enables the TEST VOLT pot. Adjusting TEST VOLT controls pressure in the actuators directly. CCW increases pressure. It is not possible to overpressurize the system using this adjustment.

2. Using appropriate instrumentation, monitor the LVDT output..

3. By adjusting the TEST VOLT pot, you should be able to drive the mirror either fully extended or fully retracted. Finding stable floating positions will be impossible without position feedback, but careful adjustment should allow you to find the pressure that just supports the mirror. You should be able to see the mirror move on and off the bumpers on the Belloframs, and watch its rate of motion on the LVDT signals.

4. With the Pressure Integrator capacitor shorted (S2 closed), adjust PRESS PROP for the desired response to a sudden change in TEST VOLT. The system should settle on a new pressure value in less than a half second.

5. With appropriate instrumentation, monitor the Pressure Error output (VPE).

6. Shorting and unshorting the Pressure Integrator capacitor (using S2) will allow you to see the integration time. You want the integrator output to drive the pressure error output (VPE) to near zero in about the same time constant as the total system response, but without any instability. A good starting point is 3 sec. With the integrator active, you can increase the proportional gain because the proportional amplifier will have more dynamic range available.

5.3.2 Outer Loop Tuning

Carry out initial position loop tuning with the sector half loaded (30 degrees elevation for axial sectors; 60 degrees for transverse).

1. Verify that the shorting jumper on SELECT (J7) is installed on VPC (not on VT). This operation insures that the position control loop is closed and that the pressure controller (inner loop) is receiving its command voltage (VPC) from the position controller.

2. Using appropriate instrumentation, monitor the Position Error output (VXE).

3. Observe the steady-state position error signal. It should be near zero mV and steady (the Position signal itself (VX) should be 500 mV and steady). If it is oscillating, adjust the Position Proportional Gain (PROP) for a natural frequency of about 1 Hz, and then increase the Position Integral Gain (INT) to increase damping. Keep the Position Derivative Gain (DERIV) at zero (full CCW). If these adjustments do not seem to affect the instability, or if there is some instability on top of the signal that the position parameters do affect, you may need to adjust the pressure loop tuning.

5. With a stable system, you can perform a rough step response test by momentarily shorting the Position Integrator capacitor using S1. After what may be a few seconds of wild gyration as the integrator catches up to the system, the Position output (VX) should settle cleanly to zero with a time constant on the order of 1 second.

6. A second method of inducing a disturbance is to perform a short slew excursion of the telescope. The position should recover smoothly within the desired time constant.

7. It should be possible to achieve control bandwidths on the order of 50 Hz by increasing the Pressure Proportional gain, the Position Proportional gain, and adding some Position Derivative (DERIV), but this regime has not currently been explored, and does not appear to be necessary for satisfactory telescope performance..

5.4 LVDT Zeroing Procedure

5.4.1 Normal Operation (Reference Zero)

1. Verify that Controller power is ON.

2. Clip the negative lead of a DVM (set to DC volts) to the Ground test pin on the card being adjusted.

3. Hold the positive probe of the DVM on pin U8-14, and ADJUST the LVDT Zero trimpot until the DVM reads zero. CW rotation increases voltage.

4. Set S3 (LVDT Gain Switch, near the center of the board) to LOW (X10) (handle towards the pots, away from the connectors).

5.4.2 Sensitive Operation (Output Zero)

1. Verify that Controller power is ON.

2. Clip the negative lead of a DVM (set to DC volts) to the Ground test pin on the card being adjusted.

3. Set S3 (LVDT Gain Switch, near the center of the board) to LOW (X10) (handle towards the pots, away from the connectors).

4. Hold the positive probe of the DVM on pin U8-1, and ADJUST the LVDT Zero trimpot until the DVM reads zero. CW rotation increases voltage. This operation roughly zeroes the LVDT output.

5. Set S3 (LVDT Gain Switch, near the center of the board) to HIGH (X100) (handle away from the pots, towards the connectors).

6. Hold the positive probe of the DVM on pin U8-7, and ADJUST the LVDT Zero trimpot until the DVM reads zero. CW rotation increases voltage. This operation precisely zeroes the LVDT output. (The output voltage may also be read on the monitor connector at pin 11 (ground at pin 23.)