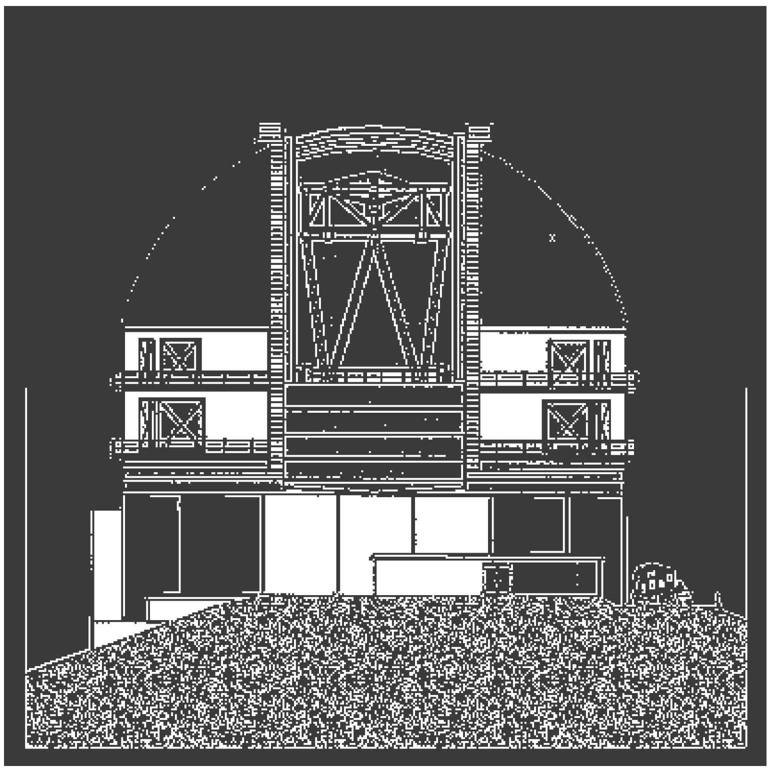
GEMINI
8-M Telescopes
Project

RPT-O-G0023

The Distributed Defining System for the Primary Mirrors



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THE DISTRIBUTED DEFINING SYSTEM FOR THE PRIMARY MIRRORS

1. Executive Summary

The Gemini Project has designed a distributed defining system for the primary mirrors. Distributed defining systems are better able to resist wind loading than other types of flotation systems that have three hard points (distributed defining systems have no hard points). Distributed defining systems can be mechanical, such as the defining system of each Keck Telescope mirror segment, or they can be hydraulic, as for example, the system designed by Zeiss for the 3.5-meter MPIA Telescope at Calar Alto.

The Gemini distributed defining system can operate in three different modes, including both kinematic and non-kinematic modes. They are, in order of increasing resistance to wind loading: 3-zone; damped 3-zone; and 6-zone. The characteristics, advantages and disadvantages of each of these modes are discussed in this report. Since the 3-zone system is a traditional kinematic design, the report concentrates on describing the other two operating modes, particularly the 6-zone mode.

The overconstraint introduced by the 6-zone mode significantly improves the resistance of the mirror to wind loading, but it also makes the mirror somewhat susceptible to bending of the mirror cell. This report demonstrates that only three modes of mirror aberrations can be introduced by flexure of the cell: two orientations of astigmatism, and one orientation of trefoil. These modes can be easily corrected by the active optics system.

The active optics system will operate slightly differently when the 6-zone defining system is in use. The average force required over each zone will be provided by adjusting the pressure in the six hydraulic systems, while the force differences from the average will still be provided by the individual active optics actuators.

The report also discusses the operational conditions that would favor use of each of the three operating modes.

2. Introduction

Modern large telescope designs have moved towards use of lightweight mirror substrates to reduce thermal inertia, total moving mass, gravity distortion of the telescope structure, and cost. As primary mirrors get larger and relatively lighter, they become more susceptible to wind buffeting.

Traditional mirror supports have used kinematic defining systems (a defining system is a system that defines the position and orientation of the mirror). Kinematic defining systems have effectively six constraints, preventing motion in three orthogonal directions and preventing rotation about three orthogonal axes. Because it is not overconstrained, a kinematic defining system cannot, by itself, bend the mirror.

However, any external loads, for example wind loading, must be reacted by the defining system. The external load plus the reaction forces it produces at the defining points can bend the mirror. The response of a mirror to external loading depends on the configuration of the defining system.

Traditional defining systems often use three hard points behind the mirror; when the wind exerts a uniform pressure on the surface of the mirror it will deform into a three-lobed pattern, sometimes called trefoil. When the wind exerts a spatially uneven pressure on the mirror surface it will normally deform into its lowest energy bending mode, which produces astigmatism.

In recent years, some large telescopes have used distributed defining systems. These systems are still kinematic and statically determinant--they constrain only six degrees of freedom. However, when wind pressure is exerted on the mirror surface, all the mirror support points produce reactions rather than just three. Two types of distributed defining systems have been used. The first is a mechanical whiffle-tree, consisting of levers and pivots that divide the weight of the mirror onto a number of points. The back support of each Keck Telescope segment is a mechanical whiffle-tree. The second type is a hydraulic system that has some similarities to the mechanical whiffle-tree; therefore, it is sometimes called a hydraulic whiffle-tree. In this type of system, friction-free hydraulic cylinders are combined together into three 120° zones of supports. The fluid volume in each zone is held constant, therefore the summation of piston displacements in the zone equals zero. Several telescopes have been built with this type of distributed defining system, including the 3.5-meter MPIA Telescope at Calar Alto[2], the 2.1-meter telescope on Kitt Peak (retrofitted with this type of system), and the 3.5-meter WIYN Telescope, soon to be commissioned on Kitt Peak. Hydraulic distributed defining systems are discussed in greater detail in the Gemini Technical Report, *Primary Mirror Forces from a Distributed Hydraulic "Axial" Support System.*

When a uniform wind pressure is exerted on a mirror having a distributed defining system, reaction forces are developed at all defining points, with their force magnitudes in the same relative proportions as the forces they exert supporting the mirror against gravity. Because the wind loads are two to three orders of magnitude smaller than gravity loads, the deformation of the mirror from a uniform wind pressure is negligible. However, when an uneven wind pressure is exerted the mirror can still bend into an astigmatic shape. The defining system, being kinematic, cannot prevent the mirror from bending.

To improve resistance to uneven wind loading, Gemini has designed a distributed defining system that can be divided into six zones instead of three. This can produce an overconstraint between the mirror and its mirror cell. Bending of the cell can affect the mirror; conversely, bending of the mirror from uneven wind loading can be prevented by the cell. The conceptual design of this system is described in the Gemini Technical Report, *Conceptual Design of the Primary Mirror Cell Assembly*. A brief system description is included below in Section 3.

There are several possible modes of operation of the Gemini defining system, ranging from a completely kinematic 3-zone system to an overconstrained 6-zone system. These are described in Sections 4-6. The operational implications of the different modes are explored, including the procedure for adjusting mirror position and orientation, the operation of the active optics system, and the reaction of the mirror to bending of the mirror cell. Section 7 discusses the conditions that would favor each mode of operation.

3. System Description

Figure 1 shows a schematic of the six-zone system. There are 120 units in the defining system, arranged in five rings. The locations and sizes of the 120 hydraulic cylinders are discussed in the Gemini technical report, *Optimization of Support Point Locations and Force Levels of the Primary Mirror Support System.* The piping connections that are shown in Figure 1 are schematic; they are logically correct but the layout has been simplified for clarity.

Each defining unit is a dual Bellofram cylinder. One chamber of each unit is used in the defining system, the other is a hydrostatic head pressure compensator.

The system is divided into six 60° sectors. Between each pair of sectors is a connection with a computer-controlled constant-fluid-displacement valve that can be used either to shut off all flow, or as a throttling valve to limit fluid flow. Each sector has an associated master cylinder (MC) to control fluid volume in the sector.

The defining system can be operated in three different modes:

- 3-zone kinematic system
- Damped 3-zone system having time-dependent overconstraint
- 6-zone system

Each of these operating modes is described below.

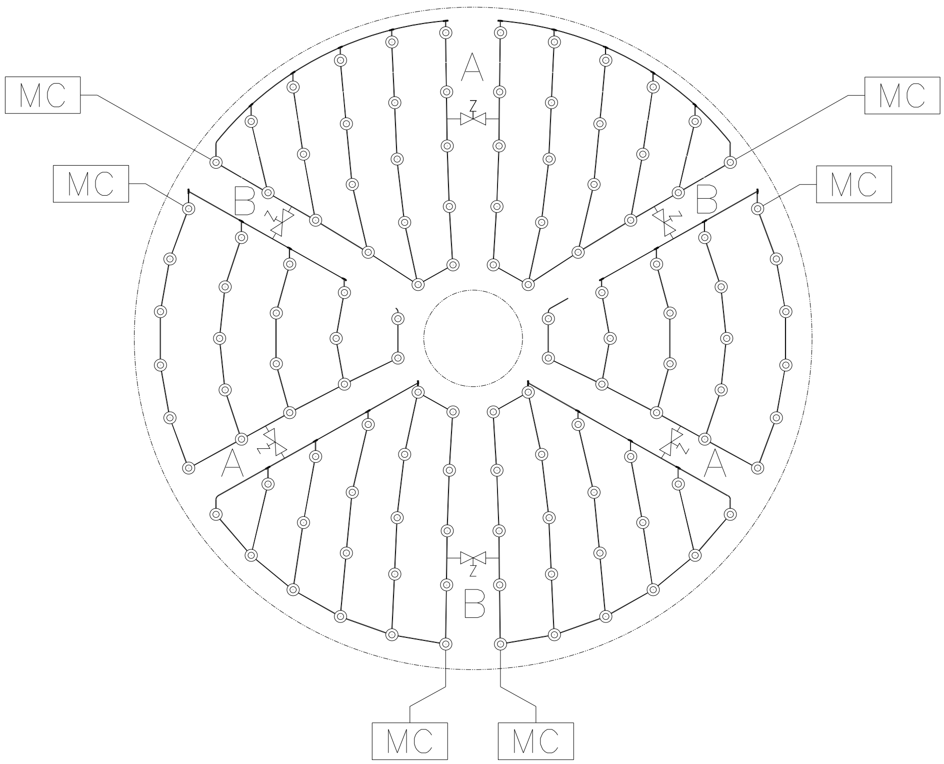


Figure 1. A schematic of the 3-zone / 6-zone defining system.

4. Kinematic Operation

If the three valves marked "A" are closed and the valves marked "B" are left open, the system will perform as a 3-zone hydraulic whiffle-tree. Because the system is kinematic, no special operational procedures will be required.

The position and alignment of the mirror can be changed in a straightforward manner. Each of the support zones will have a master cylinder that controls the fluid volume in that zone. Master cylinders of this type are currently used on the WIYN Telescope primary mirror support. To tilt the mirror the master cylinders can be compressed slightly by an electro-mechanical positioner, pushing more fluid into the zones, or extended slightly, pulling fluid out of the zones. By raising or lowering all three zones simultaneously the mirror can be moved up or down along the optical axis. The resolution of the WIYN master cylinder mechanisms is less than one micron, and the area ratio between the master cylinder and the zone of supports for the Gemini design will be approximately 1 to 100, yielding a mirror positioning resolution of about 10 nm.

The active optics system will operate just as on many other telescopes. Controlled forces, either push or pull, will be exerted on the mirror at the support points. To prevent rigid body motion of the mirror, the forces will be applied so as not to exert any total net force or moment on the mirror. This is equivalent to saying that the summation of active forces in each of the three 120° zones must be zero. Because of this condition placed on the active optics solution, the active optics system will not change the pressures in the hydraulic defining system.

Bending of the mirror cell will not change the forces exerted on the mirror by the defining system, and therefore will not bend the mirror.

If the three valves marked B are left open, but the valves marked A are closed, the system will have the same 3-zone, kinematic properties but with a different orientation of the zones. Having the ability to select the orientation of the 3 zones may be very useful. This type of system is most susceptible to external load variations that are aligned with the dividing lines between zones; for example, if the highest wind pressure is aligned with a zonal dividing line it can cause more than a factor of four larger deformation than if it is aligned with the center of one of the zones. Therefore, if a standing pattern of wind pressure is produced by the interaction of the wind with the enclosure or the telescope structure, it is likely that one of the two available orientations will resist the pattern more successfully. This effect is discussed in detail in the Gemini technical report *Wind Buffeting Response of the Primary Mirror*.

5. Damped Three-zone Operation

If the three valves marked A are closed and the valves marked B are throttled down to limit fluid flow, the system will operate as a damped 3-zone system. The flow restrictions will serve as a bandwidth filter, allowing the system to accommodate changes that are slow but resisting rapid effects that would transfer fluid between zones. This type of effect is sometimes referred to as high frequency overconstraint (HFOC). By properly setting the flow restrictors it should be possible to create a system that is more resistant to uneven wind loading than a kinematic design, but much less susceptible to mirror deformation caused by bending of the mirror cell, because cell bending will occur much more slowly than wind variations.

The operation in this mode would be very much like operating the kinematic system. The only difference would be that any adjustments of the fluid volume by the master cylinders should be done slowly; this is a good idea for the kinematic system as well.

X. Cui and L. Noethe of the ESO VLT Project have studied this type of damped system[1]. They predict that in the ESO VLT it would reduce wind deformation by about a factor of 2 compared to a kinematic system. In the Gemini system somewhat larger improvements may be possible owing to the larger stiffness of the Gemini mirror cell structure.

As in the kinematic mode, the orientation of the damped 3-zone system can be changed by switching the valves, closing the valves marked B and throttling the valves marked A.

6. Six-zone Operation

If all valves marked A and B are closed the system will be divided into six independent zones. Each zone will have a master cylinder to control the fluid volume in the zone.

6.1. Alignment Procedures

To change the alignment of the mirror the fluid volumes in all six zones must be controlled. The pressure in each zone will be monitored to ensure that the realignment does not deform the mirror. The effects of zonal pressure changes are discussed in the next section.

6.2. Susceptibility to mirror cell bending

The force exerted on the mirror by each defining mechanism is simply the product of the hydraulic fluid pressure times the piston area. If the mirror cell bends, the pressures in the six hydraulic zones will change, producing proportional changes of the forces at the defining mechanisms. Since the mirror weight and weight distribution will not have changed, static equilibrium requires that the summation of these force changes must be zero, and the summation of changes in applied moments about the center of the mirror must be zero. The total area of pistons in each sector is the same; therefore any fluid pressure changes must follow the same rules of static equilibrium.

To evaluate the possible effects of these pressure changes it is important to know whether any arbitrary pattern of such changes can be expressed as the summation of a finite number of characteristic modes, combined in different proportions. As demonstrated below, there are three such characteristic modes for this six-zone design.

To demonstrate this, first define a coordinate system in which the Z-axis is the optical axis of the telescope, and the X and Y axes are oriented relative to the six zones as shown in Figure 2. Any arbitrary pattern of fluid pressure changes in the six zones can be described as the summation of four separate cases having the following conditions of symmetry:

- Symmetry about the X-axis, Symmetry about the Y-axis: (SS)
- Symmetry about the X-axis, Anti-symmetry about the Y-axis: (SA)
- Anti-symmetry about the X-axis, Symmetry about the Y-axis: (AS)
- Anti-symmetry about the X-axis, Anti-symmetry about the Y-axis: (AA)

Let the sectors be designated by the letters A through F as shown in **Figure 2.** Then the possibilities of each of the four symmetry conditions can be explored.

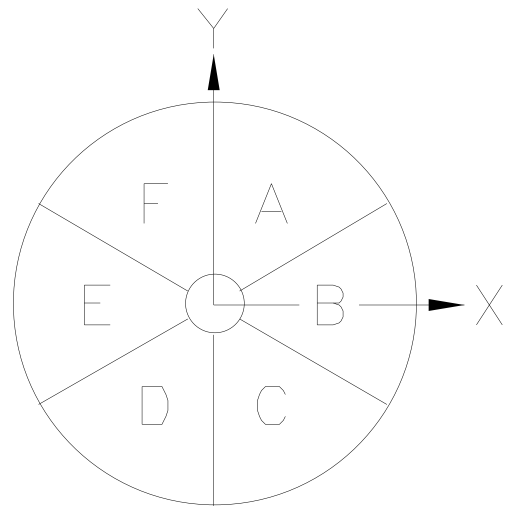


Figure 2. Coordinate axes defined relative to the six zones.

For the SS case, assume sector A has a fluid pressure change of +1. It follows that sectors C, D and F must also have a change of +1. The only possible way to achieve summation of forces and moments equal zero is for sectors B and E to have a change of -2.

For the SA case, again assume sector A has a fluid pressure change of +1. Sector C must be +1, while D and F must be -1. To achieve static equilibrium B must be -1 and E +1.

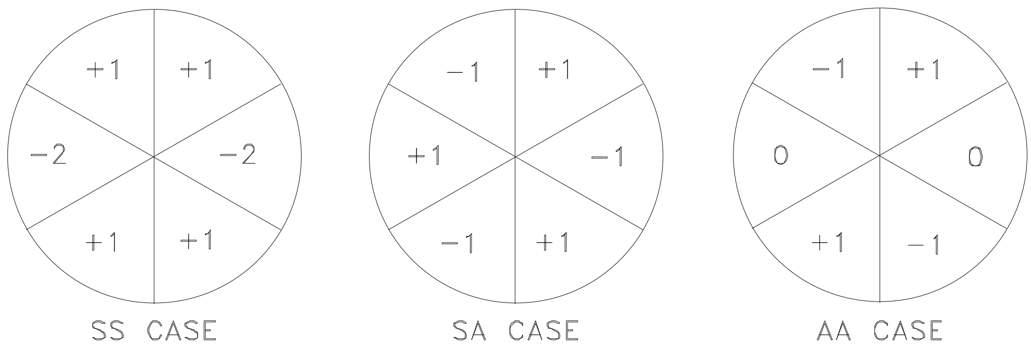
The AS case has no solution. If we assume sector A has a pressure change of +1, then C and D must be -1 and F must be +1. This produces a net moment about the X-axis which cannot be corrected by any values for B and E, since they are on the X-axis. This case is not possible because it violates the assumption of static equilibrium.

For the AA case, if we assume sector A has a change of +1 then sector C must be -1, sector D must be +1 and sector F must be -1. This pattern satisfies static equilibrium. B and E must be zero, because any non-zero pressure change in these sectors will result in a net moment about the Y-axis, because of the anti-symmetry about the Y-axis.

The three possible characteristic modes of zonal pressure variation are illustrated in **Figure 3**. Any arbitrary pattern of pressure changes can be described by the following expression:

$$P = c_1(\text{SS case}) + c_2(\text{SA case}) + c_3(\text{AA case})$$

What are the possible mirror aberrations that can be produced by the three characteristic modes? Mechanical intuition suggests that the SS and AA cases should produce astigmatism, while the SA case should produce trefoil. Finite-element analysis bears this out.



The three different symmetry cases were modeled using finite-element analysis. For each case the loading input was based on unit pressure differences arranged in the prescribed pattern.

Figure 3. The three characteristic modes of zonal pressure variation.

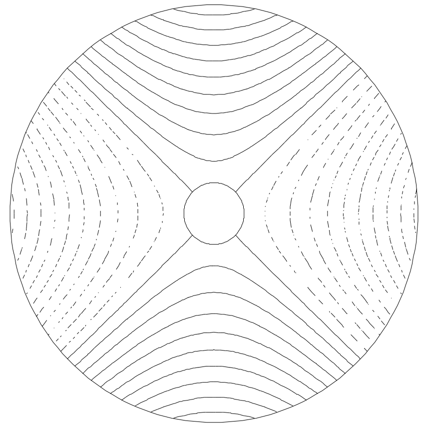
The forces at the 120 defining points were calculated by multiplying the piston areas by the zonal pressures. **Figure 4** shows surface contour plots for each of the three cases.

It can be seen that in the SS and AA cases astigmatism dominates, while the SA case is almost pure trefoil. Fitting Zernike polynomials to the surface deformations confirms the visual impression. **Table 1** contains the Zernike coefficients for each case, numbered in the same order as in the Fringe program. For the SS and AA cases astigmatism is an order of magnitude larger than the other terms; in the SA case trefoil is an order of magnitude larger than the other terms.

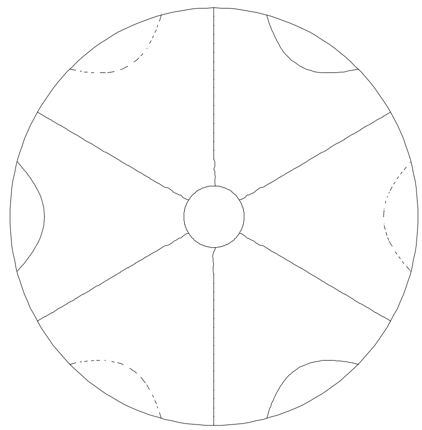
Zonal fluid pressure changes caused by mirror cell bending can produce only three Zernike terms in significant amplitudes: two orientations of astigmatism and one orientation of trefoil. This effect is of concern only over the time interval between successive active optics updates. The susceptibility of the mirror to bending of the mirror cell from gravity and thermal effects is discussed in the Gemini technical report, *Primary Mirror Cell Deformation and its Effect on Mirror Figure Assuming a Six-zone Axial Defining System.*

Since the six-zone defining system only couples the mirror to the cell for three bending modes, the only modes of wind-induced mirror bending that can be prevented by the six-zone defining system are astigmatism and trefoil. However, these are precisely the modes of mirror bending most likely to be produced by the wind (along with defocus, which is controlled by the fast focus system). The beneficial effect of reducing the amplitude of these modes by use of the six-zone defining system is described in the Gemini technical report, *Response of the Primary Mirror to Wind Loads*.

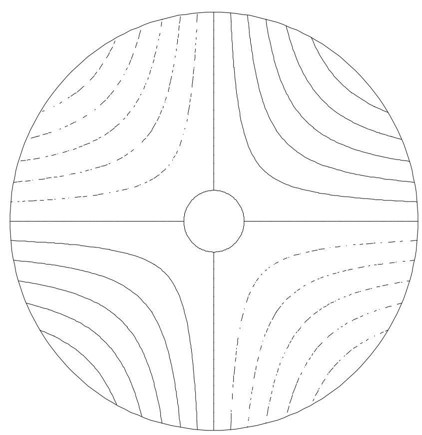
SS CASE
P–V: 2004 nm
RMS: 432 nm



SA CASE
P–V: 283 nm
RMS: 57 nm



AA CASE
P–V: 1159 nm
RMS: 250 nm



6.3. Active Optics Operation

The active optics system for the kinematic mode was described in Section 4. It was explained that the system will be controlled so that the summation of active forces on each of the three 120° zones will be zero. This prevents rigid body motion of the mirror and insures the

Figure 4. Optical surface deformations resulting from unit amplitudes of the three possible zonal fluid pressure symmetry conditions. The same contour interval is used on all three plots. Positive displacements are indicated by solid lines, and negative displacements by dashed lines. Actual mirror deformations are predicted to be approximately two orders of magnitude smaller (see Gemini technical report *Primary Mirror Cell Deformation and its Effect on Mirror Figure Assuming a Six-zone Axial Defining System*).

Table 1. Zernike coefficients for the three possible symmetry cases of mirror deformation from zonal pressure changes.

ZERNIKE TERM	ZERNIKE COEFFICIENT (Nanometers)			ASSOCIATED ABERRATION
	SS CASE	SA CASE	AA CASE	
3	-0.	0.	0.	Defocus
4	-1055.	-0.	-0.	Astigmatism
5	0.	0.	-609.	Astigmatism
6	-0.	-0.	0.	Coma
7	0.	0.	0.	Coma
8	0.	-0.	-0.	Spherical Aberration
9	0.	-158.	-0.	Trefoil
10	0.	0.	0.	Trefoil
11	92.	0.	0.	
12	0.	0.	53.	
13	0.	-0.	-0.	
14	-0.	0.	0.	
15	0.	-0.	-0.	
16	-36.	0.	0.	Quatrefoil
17	0.	0.	21.	Quatrefoil
18	0.	26.	0.	
19	-0.	-0.	-0.	
20	-20.	0.	-0.	
21	-0.	0.	-12.	
22	-0.	-0.	0.	
23	0.	0.	-0.	
24	0.	-0.	0.	
25	0.	-0.	-0.	
26	0.	-0.	0.	
27	9.	-0.	0.	
28	0.	0.	-5.	
29	-0.	-6.	-0.	
30	-0.	0.	0.	

31	8.	-0.	-0.	
32	0.	0.	5.	
33	-0.	-0.	-0.	
34	-0.	-0.	-0.	
35	-0.	-0.	0.	
36	0.	-0.	0.	

active and passive systems do not oppose each other. It would be pointless to have the active optics system change the pressure in the hydraulic system by having all the actuators in one zone pulling down on the pistons, or by having all of them pushing up thereby taking the load off the pistons. An analogous situation holds for the six-zone system.

The six-zone system will be controlled so that the summation of active forces over any one zone will be zero. This also means that the summation of active forces and moments on the entire mirror will be zero, thereby avoiding rigid body motion of the mirror.

When the active optics system calculates a new force correction, the system will determine the required force at each actuator as well as the average force per actuator in each of the six zones. This average force will be applied by changing the zonal fluid pressure, which is done by adjusting the volume of hydraulic fluid. The force variations relative to the average value will be applied by the active optics actuators. The active optics system will have two control loops, one to control zonal pressures and one to control individual forces. However, the net forces exerted on the mirror at the 120 support points will be the same as if the defining system were kinematic. This means that no active optics performance will be lost when switching from 3-zone to 6-zone operation.

The active optics system is described in greater detail in the Gemini technical report, *Active Optics Capability of the Primary Mirror System.*

7. Operational modes

Each of the three operational modes, 3-zone, damped 3-zone and 6-zone has advantages and disadvantages. The following section discusses when each would be expected to be used.

The 3-zone system is the simplest of the three. It has no overconstraint and little damping in the hydraulics, so its settling time will be short. Bending of the mirror cell will not affect the mirror when operating in the 3-zone mode. However, the damped 3-zone system has most of the same advantages and it will resist uneven wind significantly better. Therefore, most of the time the system will either be used as a six-zone, or a damped 3-zone.

The 3-zone system may be used when slewing large distances across the sky, to minimize the effects of the relatively rapid cell flexure. It will also be used at times when the mirror support control system is not operating, for example, during the daytime.

The damped 3-zone system has very promising properties. It resists uneven wind loading better than the 3-zone, and is not subject to slow cell flexure as is the 6-zone system. This may be the preferred mode of operation when the wind speed is low to moderate. It is our understanding that ESO currently plans to operate the VLT primary mirror cells in this mode.

If the wind produces a steady pattern of average pressures, perhaps because of the effects of partial shielding by the enclosure or telescope structure, then one of the two orientations for the damped 3-zone system may perform better than the other. This will be determined empirically during commissioning; both orientations will be available.

At high wind speeds, the 6-zone system will provide even greater resistance to wind buffeting than the damped 3-zone. Another advantage of this operational mode is the increased resistance to force errors, which is discussed in the Gemini technical report, *Response of the Primary Mirror to Support System Errors*. Because of this property, the 6-zone mode may be the preferred mode of operation at all wind speeds, provided the active optics system corrects the long term effects of mirror cell flexure.

Mirror cell flexure in the Gemini system will occur very slowly. As is shown in the Gemini technical report *Primary Mirror Cell Deformation and its Effect on Mirror Figure Assuming a Six-zone Axial Defining System*, with the use of look-up tables cell flexure would stay within acceptable limits for periods of tens of minutes without active optics correction, while active optics updates are actually planned to occur about once a minute. This means the cell flexure effects will remain within the error budget limits indefinitely.

8. Summary

This report has described the properties of distributed defining systems, and in particular, distributed defining systems using overconstraint. The Gemini primary mirror assembly will use a distributed defining system having three different operational modes; all three of them have been described in this report.

The damped 3-zone and 6-zone modes are new designs. The 6-zone defining system in particular has certain operational differences compared to a kinematic system. These operational factors have been described in this report.

The mirror surface figure influence modes that could be produced by the overconstraint have been derived. There are three possible symmetry conditions, which result in three characteristic modes of mirror influence. All possible effects of the overconstraint on the mirror can be expressed as the superposition of these three characteristic modes.

9. Acknowledgements

The authors would like to thank Earl Pearson and Eugene Huang for numerous discussions that have been helpful in working out the properties of overconstrained defining systems. We would also like to thank Joe DeVries and John Roberts for preparing the figures used in this report.

10. References

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