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FINAL REPORT

A Low-Cost Flexible Mirror

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Small Business Innovative Research Phase I

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ABSTRACT

Adaptive optical systems are designed to detect and correct in real-time aberrations in optical systems. Included are those aberrations due to fabrication errors, those caused by mechanical or thermal sources, and those caused by changes in the atmospheric path. In analyzing these errors, it is realized that the amplitude of the error drops dramatically with Zernike mode, and that in some instances, a mirror with tip/tilt, focus and astigmatic correction would be entirely sufficient. In this program I seek to develop mirrors optimized for this function. They would be structured such that the actuators would generate modal as opposed to zonal corrections. Such a mirror could be used on conjunction with a zonal adaptive system to substantially reduce its cost as well.

I have also identified a unique and very high value application in the fabrication of eyeglasses. There has long been a desire to mold these lens, which have only focal and astigmatic correction, in the doctors office. A major impediment to this has been the requirement for over three-hundred separate molds to achieve the necessary range of prescriptions. These modal deformable mirrors could however be used as adjustable molds if their strokes could be extended to mm's and this would lead to a system with only a few molds. Using finite element modeling I have demonstrated that these high deformations can be achieved. This technology thus has the potential to play a critical role in extending the delivery of eyeglasses from the laboratory to the doctors office with a correspondent reduction in cost.

OUTLINE

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1. APPLICATIONS:

1.1. Imaging through turbulent media: Applications for military, commercial, and scientific users.

Scientific users: Adaptive optical systems are designed to detect and correct in real-time aberrations in optical systems. Included are those aberrations due to fabrication errors, those caused by mechanical or thermal sources, and those caused by changes in the atmospheric path. It is these atmospherically induced aberrations which have received the most attention due to being a key limitation in the performance of ground based telescopes, whether for imaging(space or ground based) or power projection systems.

In the ground-based imaging application, the distortions of the atmosphere causes stars to "twinkle" and the images are blurred in a random fashion. As a result, ground based telescopes imaging space objects have resolutions characteristic of telescopes of about 10 cm in diameter in spite of their increased light collection capability which may be as large as 10 meters. This severely limits the utility of ground based telescopes and drives observations to the very expensive space-based format. In the power projection application, the power would be spread into an area ten-thousand times larger than if the telescope and propagation path were perfect, a devastating limit to system performance.

Both imaging and power projection are important in multiple applications. NASA, all astronomers, and the USSPACECOM have a need to image space objects from the ground including science objects and artificial satellites. The observations of scientific objects supplement those of the Hubble Space Telescope(HST) and other space based telescopes. There is also a need to image artificial satellites to determine their health, especially when problems occur. For ground based strategic application, operators of military systems would benefit greatly if their visualization of enemy systems could be improved.

One of the technological impediments for the utility of this concept is the cost and feasibility of the adaptive optical system. I anticipate the requirement for four actuators for each ro diameter where ro is the atmospheric aberration coherence length. This leads to a conclusion that the adaptive optical system must provide over

100,000 actuators based on ro values of 8 cm at 0.8 microns and where the telescope diameter reaches 10 meters.

Conventional adaptive mirrors with drivers(the mirror and the drivers have approximately equal cost components) currently cost $2,500 per degree of freedom and this leads to an adaptive mirror costing $250M for a 10 m transmitter. Considering that at least one spare mirror will have to be provided, this cost is clearly unacceptable.

A low-cost modal mirror can reduce the cost of the adaptive optical system, and in some cases, replace it. The distortions induced on the wavefront propagating through the atmosphere follow the Kolmogorov spectrum. The accumulated strength of the distortions is characterized by the value of ro. This parameter is the transverse correlation length of the distortions and is formally defined as the diameter over which the variance in the aberrations is one radian. The Kolmogorov spectrum is characterized by its structure function **D** given by

$$\mathbf{D}(\mathbf{r}) = 6.88 \left(\frac{\mathbf{r}}{\mathbf{r_o}}\right)^{\frac{5}{3}} \tag{1}$$

where **r** is the separation between two points and **D** is the variance of the distortion in units of radians square.

According to Noll(see reference 1) the variance of the aberrations with various degrees of Zernike polynomials removed is given by

Piston	$1.03 \left(\frac{\mathbf{D}}{\mathbf{r_0}}\right)^{\frac{5}{3}}$
Tilt	$0.582 \left(\frac{\mathbf{D}}{\mathbf{r_0}}\right)^{\frac{5}{3}}$
Tip	$0.134 \left(\frac{\mathbf{D}}{\mathbf{r_0}}\right)^{\frac{5}{3}}$
Focus	$0.111 \left(\frac{\mathbf{D}}{\mathbf{r_0}}\right)^{\frac{5}{3}}$
Astigmatism 1	$0.088 \left(\frac{\mathbf{D}}{\mathbf{r_0}}\right)^{\frac{5}{3}}$

Astigmatism 2 $\quad 0.065\left(\frac{D}{r_0}\right)^{\frac{5}{3}}$ (2)

With the magnitude of the aberrations dropping dramatically with tip/tilt removed, virtually all systems are designed with separate tip/tilt removal mirrors. Keep in mind again that the cost of any correction task assigned to the individual actuators will be multiplied by 100,000. As a result, I ask the question as to what further cost savings would be achieved with yet further segmentation of the correction problem? In particular, if a proficient, low-cost, focus/astigmatism mirror were to be incorporated, then the stroke requirement on each of the 10,000 actuators would be further decreased and the net cost of the adaptive optical system reduced.

In Fig. 1 I plot the rms. stroke requirements for a ten meter telescope with an ro of 8 cm. Note that the total stroke requirement is selected to be as much as six times the rms. As can be seen, the stroke required drops dramatically with mode number at first, then, only slowly with mode number.

The result is that a system with an active focus/astigmatism corrector would have the stroke requirements on the individual 100,000 actuators reduced by an additional 30% over tip/tilt only. Thus, for example, a 300 volt driver could be reduced to 230 volts, or equivalently, a 100 layer PZT stack could be reduced to 76 layers. I estimate that the cost of the large deformable mirror could be reduced by 25%, a savings of many millions of dollars on large mirrors.

I now take this concept a step further and introduce the concept of adaptive optical systems with **ONLY** modal compensation. Consider then a system with only tip/tilt removal. A telescope with an aperture of ro and tip/tilt correction would be nearly diffraction limited. But, with tip/tilt removed, I again ask the question of what is the so-called tip/tilt removed ro, termed as ro*, of this wavefront, which is the diameter over which the wavefront variance is one radian with tip/tilt removed. This is easy to calculate from eq.(1) and the result is that ro* is 3.3 ro. Thus, a system with tip/tilt correction would have a near diffraction limited aperture of 3.3ro, or a light collection capability of nearly

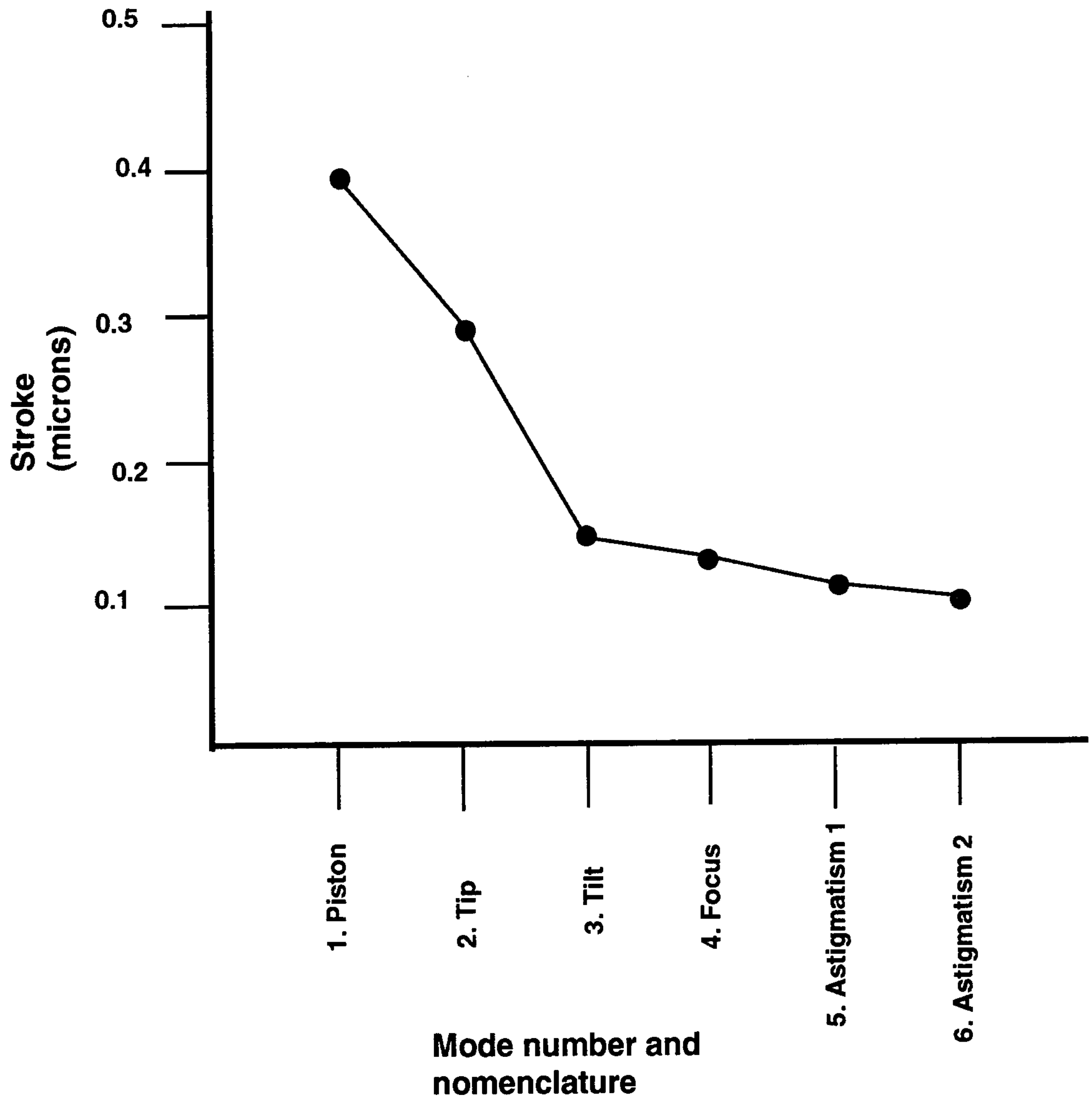

Fig. 1. Stroke requirement coefficients vs. mode removal for Zernike polynomials. Multiply these numbers times (D/ro)^5/6 to get actual stroke numbers in microns.

10 times that of one without tip/tilt removal. This is quite significant.

Now extend this concept to focus/astigmatism correction. I define the focus/astigmatism ro as ro# and, again, from eq.(1), I obtain that ro# is equal to 5.25ro. This aperture would collect 27.6 times more light than an aperture of diameter of ro, a profound improvement over no correction, but at the very modest cost of only using a modal adaptive optical system. Also, the resolution would be 5.25 times higher, a profound improvement as well.

As a result, many telescopes of modest aperture or used at longer wavelengths or at excellent sites can obtain substantial improvements with only using a modal adaptive optical system such as I would build with Phase II funding.

I will consider some specific examples. The value of ro scales as the wavelength to the 6/5 power. Consider then the interesting astronomical wavelength of 2.4 microns. A decent but not perfect site will have an ro at 0.5 microns of 15 cm and this grows to 99 cm at 2.4 microns. Thus, the value of ro# grows to 5.2 meters. There are only several telescopes world-wide with apertures greater than 5 m and 2.4 microns is a wavelength of great interest as are even longer wavelengths. Thus, a tip/tilt through astigmatism corrector would make a significant contribution to astronomy.

Not only will the images be sharper from these ground based sites, but fainter objects will be observable as well. A significant limit in observations is not just the light collecting area of the telescope which scales with area, which can be overcome with longer integration times, but sky brightness. In Fig. 2, I illustrate the benefits of sharper images in overcoming sky brightness limitations, and this problem is not overcome by using telescopes with larger apertures.

From the authoritative analysis by F. Roddier et all of ref. 8, I reproduce their Fig. 20 as our Fig. 3. Here, I note that the 5 Zernike correction gives an improvement in Strehl resolution(similar to Strehl ratio) over no correction of 10 times at a D/ro of 6(similar to the instance discussed above for the 5 m telescope.) The improvement in stellar magnitude is about 2.5, for an improvement in faintness of over 8 times.

The conclusion is simple: Modal adaptive optics have the potential to dramatically impact IR and near-IR ground based astronomy. Furthermore, it is unlikely that an artificial guide-star would be necessary. Consider that the isoplanatic angle for focal and astigmatic errors at these long wavelengths is very large and that even the laser guide-star systems must have a natural star for tip/tilt correction. Thus, the already necessary natural guide star should suffice in most instances. Consider also that most telescopes(even very professional ones) do not have accurate focus sensors or correction. From my own personal experiences, I can attest that working on a 1.5 m astronomical telescope is frustrating in terms of keeping it focused.

In space, optical systems must work while being subjected to extremes of cold/heat, launch forces, and residual fabrication errors. To deal with these, the primary approach is to field telescopes with very expensive and heavy primaries and with equally expensive high-quality figuring. It would be less expensive to instead reduce the mass and fabrication tolerance and allow a modal correction be made of the figure once in orbit.

A further step for IR telescopes would be to reduce the number of emitting surfaces by designing the secondary to be flexible.

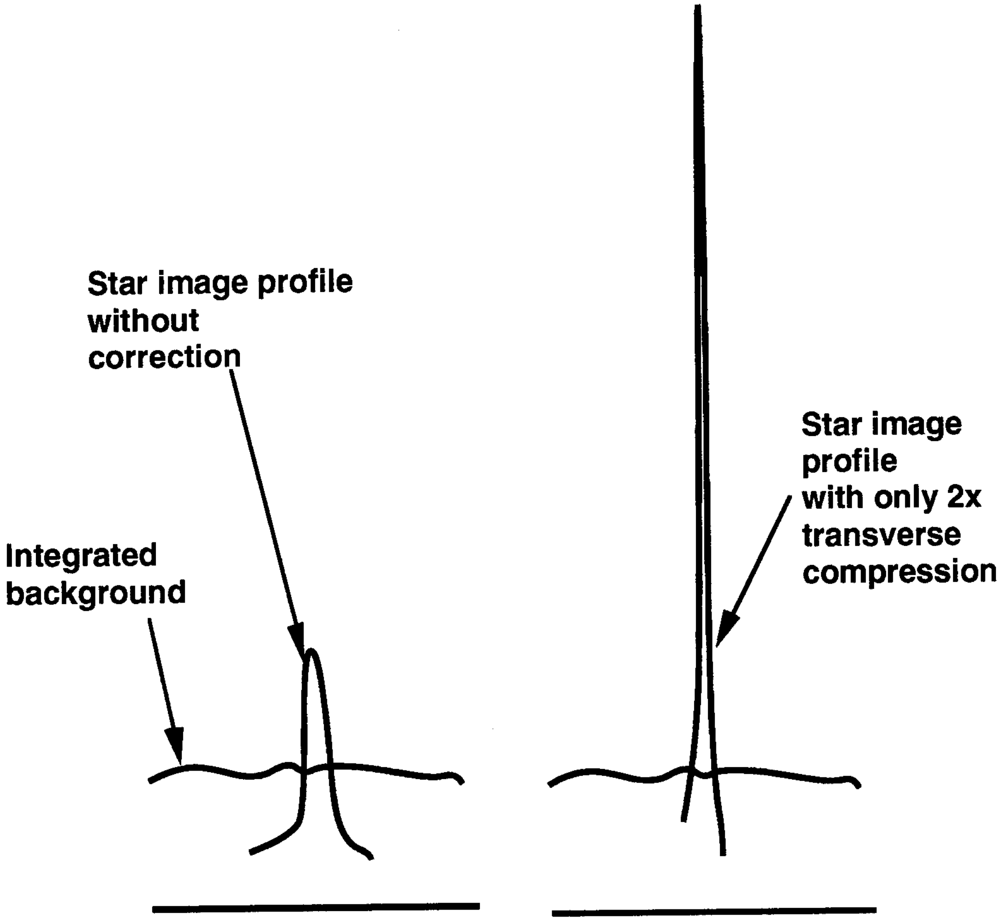

Fig. 2. Star image profiles with no and two-times transverse compression through adaptive optics.

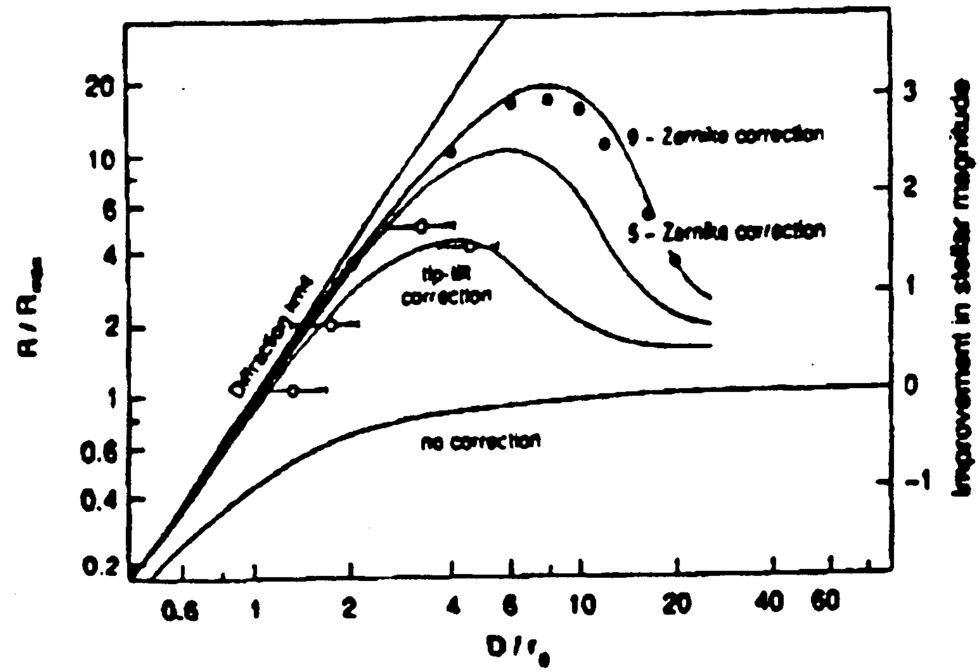

FIG. 20—A comparison between the performance of our simulated system (black dots) and that expected from theory (see Fig. 2). Open circles show the performance of the European AO system COME-ON which has a 19-actuator mirror (the horizontal bar is the uncertainty on the seeing estimate).

Fig. 3. This is Fig. 20 from the authoritative and detailed study by F. Roddier(ref. 8) showing the improvement in imaging resolution and faintness at near-IR wavelengths for large telescopes and low-order adaptive optics.

1.2. Ophthalmic applications: Retinal imaging and objective autorefractors.

This is an application with mirror requirements between the extremes of the scientific applications and the spectacle lens fabrication requirements. In the retinal imaging system, the clinician obtains images of the retina through the eye. There are many technical problems in obtaining high quality images. First and foremost however is the rudimentary focusing of the camera on the retina.

Even though the clinician may carefully focus the camera, the human may change his/her accommodation. That is, the human subject may defocus before the image is obtained. There is no way of preventing this from happening but a real-time focusing system would eliminate this as a problem.

Most manual focusing systems change the spacing between two lens are much to slow. Consider that the depth-of-focus of the typical eye at maturity is from 0.20 meter to infinity or a range of 5 diopters. Since the depth of dynamic accommodation should be much less than this, a dynamic range of 1 diopter should be more than sufficient.

I know of no camera which provides the ability to set astigmatism at all and for many eyes this is a further problem in obtaining high clarity images.

In a potential camera, there would be a control to set astigmatism and base focal errors. Then, there would be a real-time controller for dynamic shifts in the fine focus. In a more advanced system for very high resolution, a full-scale adaptive optic would be used to resolve the neural optical fiber layers.

While the dynamic mirror would have a one diopter range, it would have to have a dynamic bandwidth of at least 10 Hz and this implies a first resonance at 100 Hz. I would also want a figure quality intermediate between that of the astronomical mirror and the spectacle lens fabrication mirror.

Autorefractors are used to automatically measure the optical errors of the eye. Using an autorefractor, the doctor can in theory prescribe glasses from the output of a machine. There will always be the requirement for the doctor to refine the prescription as some patients cannot utilize a full correction due to muscle problems or other issues.

Autorefractors are classified as either subjective or objective. In the objective system, the machine completely determines the refraction. In the subjective system, the patient is asked as to whether one refraction or the other is better. However, in both systems there must be a system to null out the refraction error. In current systems, which are expensive, this is performed by a complex set of lenses and actuators. It is my objective to implement a single mirror to substantially reduce the parts count and cost.

There may continue to be a large resistance by the medical community in the U.S. to using autorefractors since this implies that some of the optometrist job can be performed by a machine. Cost containment may change that.

In third world countries, the opposite is true. The health officials in these countries welcome any cost-effective method to serve their populations and are much more receptive to mechanization.

1.3. Spectacle lens fabrication: Moldable eyeglass lens.

Spectacle lens or eyeglasses are worn by nearly 50% of the U.S. population. Thus, there are about 100M wearers in the U.S. alone. With replacement lens being obtained nearly once a year, this implies a yearly manufacturing rate in the U.S. of approximately 100M pairs. Obviously, a lower cost or more proficient method of manufacture would have great economic value.

The lens are prescribed in terms of dioptric power. The dioptric power is the inverse of the lens focal length in meters. Thus a 1 D lens has a focal length of 1 meter. The reason for using this unit of measure is that when the refractive power of a lens is described in diopters and when it is close to another lens, then to first order, the total dioptric power is the sum of the dioptric powers of both lens. For example, if the front and rear of an ophthalmic lens had dioptric powers of +6 D and -5 D(the inside curve is minus), the net power of the lens would be 1 D.

Lenses are prescribed with dioptric power of sphere and astigmatism The astigmatic correction compensates for eyelens and corneas which have a different radius of curvature in one axis than another. Most sphere corrections are +/- 2 to 4 D with the astigmatic correction being below 2 D.

Taking advantage of this, most laboratories stock lens with the most common dioptric powers. When the prescription is ordered, they take the blank, usually 70 mm in diameter, and "edge" it to fit in the patients eye-glass frames. Care must be taken to center the optical axis in the frame so that it will lie on the center of the patients pupils(to fit the pupillary distance or PD, also given with the prescription.) Also, the axis of the astigmatism is rotated to properly correct the patients astigmatism, an angle given with the prescription.

The time delay for obtaining glasses can be from one hour to two weeks and may involve various delays such as transportation of the frames to the shop and the necessary backlog in the shop to keep the operating efficiency at 100%. Many vision plans, such as VSP in California, only pay for the very lowest cost laboratories to fill the prescriptions and these are always the slowest.

The current practice for fabrication involves either traditional grind and polish operations such as used for precision optics and which have been in use since the 1700's or casting of the plastic to the prescription. With the later approach, obtaining good and long-lasting molds has been a major problem.

Many market watchers believe that an "in-office" lens casting system would appeal to many prescribers, providing the consumer with "one-hour" lens but without the high-cost of the stores based in expensive mall outlets(i.e., Lens Crafters.) Another market would be regional fabrication laboratories. Yet another very large market would be third-world countries.

In this approach, the doctor is supplied with a quick-setting polymer and a large number of molds. He selects an appropriate set of front and rear molds, sets the astigmatism angle, pours the resin in the mold, and waits for it to cure. Many, many, unsolved problems have prevented the successful application of this approach.

Consider in particular the economic problem of the molds. A great problem lies in the large number of molds required. The practitioner is supplied with a set of rear and front molds so that a reasonable percentage of the prescriptions can be fabricated. Complicating this considerably is the requirement for bifocals. In Fig. 4 I show the distribution of prescriptions and those familiar with the issues here recommend providing focal power between +/- 4 D and astigmatism to 2 D . I estimate the number of molds required thusly:

1) A minimum of three front molds are needed for the different required "base curves." The bifocal is placed on the front lens, and dioptric powers of from 0 to 3 diopters are provided in 1/4 diopter steps.

There are 36 front molds required.

2) The rear mold must select focal powers from +/- 4 diopter in quarter power steps, for 33 molds. However, one must also have astigmatism from 0 to 2 diopters in quarter diopter steps.

There must be 324 rear molds.

With these molds, the doctor can provide prescriptions for approximately 90% of the population.

The total number of molds would be the order of 360.

The molds cost about $35 each so that the total cost of the molds can be as much as $10K. This is a significant cost item on a unit which should reach the doctors office for $30K and the professional lab for $60K.

Economic analysis:
Eyeglasses are sold through ophthalmologists(medical doctors who specialize in the treatment of eye disorders,) optometrists (specialists trained in prescribing eye glasses and in screening for eye disorders, and of recent, treatment of simple eye disorders but no surgeries), and opticians, persons trained to dispense glasses but not to prescribe.

The market is in a state of turmoil with many competitive forces at play. I list for example national "SuperStores" and Chains in Fig. 5. Some important retail forces include:

SPHERE \ CYLINDER	0.0 TO -1.0 D	-1.0 TO -1.5 D	-1.5 TO -2.0 D
2.0 TO 3.0 D	+12.9%	+1.5%	+0.8%
2.0 TO -2.0 D	65.3%	+4.75%	+2.7%
-2.0 TO - 3.0 D	+1.2%	+0.4%	+0.4%

Fig. 4. Distribution of ophthalmic prescriptions.

The Superstore
(As part of Chain or Superstore Chain)

Chain or Superstore	Sites	Site Range (Sq. Ft.)	Main Markets
1. Pearle Health Services, Inc. (Grand Met)	1300	800-6,000	43 States
The Visionary	3	6,000	Dallas
2. Cole National (Private)	560	400-10,000	38 States
The Eyeworks			
3. Precision Lens Crafters(U.S. Shoe)	160	6,500-10,000	12 States
4. Eckerd Optical (Eckerd Drug)	154	300-10,000	Southeast
Vision Works	3	10,000	F.L & N.C.
5. NuVision (Public)	104	800-7,500	M.I., IND. N.J., CA
NuVision	3	7,000	?
6. D.O.C. (Public)	100	900-22,000	MI, OH, WI IND, MO
D.O.C. EyeWorld	5	15,000-22,000	MI, OH
7. EyeLabs (Cole Int.)	23	7,000-15,000	NY, NJ, PA FL, VA, IL, MD, GA
8. Eye+Tech and EyeWorld (Gillette)	19	4,200-8,000	MA, TX, CA, NY
9. EyePro Express (Public)	10	6,000	TX
10. Eye Masters (Private, merged with EyePro)	8	6,000-10,200	LA, TX
11. Optometric Express	2	7,000	CA

Fig. 5 A list of SuperStores circa 1980.

•Lens-Crafters("In about one hour"): Specialists in providing eye glasses in about one hour, generally located in high traffic centers such as shopping malls. These operations maintain expensive laboratories, have high-overhead, and charge a premium to the customer.

•Super-Stores: Very large free-standing retail outlets. Specialists in providing fashion as much as vision aids.

•Chains: Such as Site-for-Sore-Eyes, etc., and recently WalMart and Sears.

•Optometrists/Ophthalmologists: The O.D.'s are competing against the retail outlets by offering complete eye care, more personal attention, etc. They may feel a need to fill prescriptions quicker and cheaper to attract the final purchase to their outlet as opposed to just providing the lower margin professional services. Even the M.D.'s are wanting to get into dispensing as their reimbursements are being cut and they are looking hard at revenue enhancement opportunities.

•HMO's and PPO's and Vision Plans: Kaiser Permanante(a very large HMO in California and some other locations) is a prime example of a large HMO which provides optometric care and dispensaries as well. Vision plans such as VSP in California cover many people and contract for glasses to come from certain discount laboratories.

Let us imagine a future with one-hour dispensing available at low-cost virtually everywhere. This vision portrays a small table-top machine capable of casting 90% of the prescriptions within one hour. Its cost would vary, but I imagine a machine selling at $30K for smaller sites and $60K for larger sites. This is a considerably smaller capital equipment investment than for example is involved with a LensCrafters site. The doctor would also have a lens edger(inexpensive). The floor-space cost would be small so that the amortization of the machine, the cost of labor, and the cost of materials would dominate the economics.

Such capital equipment prices could not be meet with existing technology for the molds. It is not likely that these small retail outlets could support a higher purchase price and the $10K and up cost for the molds is too expensive for the system to be sold at these prices.

To complete our economic analysis, I estimate the U.S. market size for the capital equipment thusly:

Small Laboratories	5,000	$300M
O.D./M.D. (out of 45,000 practitioners in the U.S.)	10,000	$300M
Super-Stores and Chains	3,000	$1,800M
TOTAL MARKET U.S.		$2,400M

Thus, the economic feasibility of the concept of one-hour low-cost eyeglass dispensing rests on lowering the costs of the molds. It is the objective of this program to show how the cost can be lowered using an extension of technologies developed for DOD, that is, the extension of modal adaptive optics to adjustable molds for casting eyeglasses.

2. TECHNOLOGY:

Low-stroke modal mirrors have been built in government laboratory settings but have not been made available commercially at low-cost. High-stroke modal mirrors have not been fabricated and have not benefited from a through analysis or demonstration. As a result, the greatest uncertainly and developmental effort would center on extending the stroke of the mirror and utilizing it in the novel application of adaptive molds.

I will discuss the existing results for the low-stroke mirrors and then the extensions to commercialization of these mirrors and follow this with the basis for extension to the high-stroke mirrors and molds.

Review of Current Technology:

To provide for a spherical deformation I attempt to tailor the thickness of the disk as shown in Fig. 6. That is, if the mirror were to be made from a thin sheet of metal then a central force may cause the front surface to make a "tent" shape. If the mirror were too thick, then the deformation shape may be a broad Gaussian. Thus, at issue is the existence of a thickness profile and actuation location/set so that when a single actuator is activated, the mirror distorts spherically or astigmatically as desired. In fact, such tailoring has been shown to be feasible and has been demonstrated on mirrors suitable for defense and science applications. In these applications, the deformations are only a few microns, but the quality of the fit to a spherical or azimuthal deformation must be very high. I will review these results and then their extensions to the high stroke mirror.

In refs. 5 and 9 for example, something called "stressed polishing" was used. This was a technique used to fabricate the off-axis paraboloid segments for the Keck telescope. The Keck telescope is a 10 meter astronomical telescope being installed on Mona Kea in Hawaii. The primary is comprised of a set of 19 each 1.8 meter diameter segments. The segments much conform to an off-axis section of a paraboloid. Polishing and testing such a surface is very difficult. To circumvent this, the segments were placed in a warping harness and pre-stressed in a pre-determined way. Then, they were polished to a sphere, something which is relatively straightforward. When the stress is released, the segments will in theory release into the desired shape. Results have been mixed to date but keep in mind that the segments were 1.8 meters in diameter and tolerances were to a fraction of a micron.

In ref. 7 the author attempts to construct a spherically controlled mirror using a special construction of piezoelectrics. While this approach may be suitable for the scientific application, it is highly unlikely that it would be suitable for the lens casting application.

In ref. 11 M. Massie(no relation to the author of this report) describes a thickness profile for which a spherical deformation would be the result when the mirror is subject to a uniform hydraulic load. The results are encouraging and the calculation shows excellent spherical shape for a 75 micron deformation on a 5 cm diameter mirror with only 21 psi. This readily scales to our zero-order

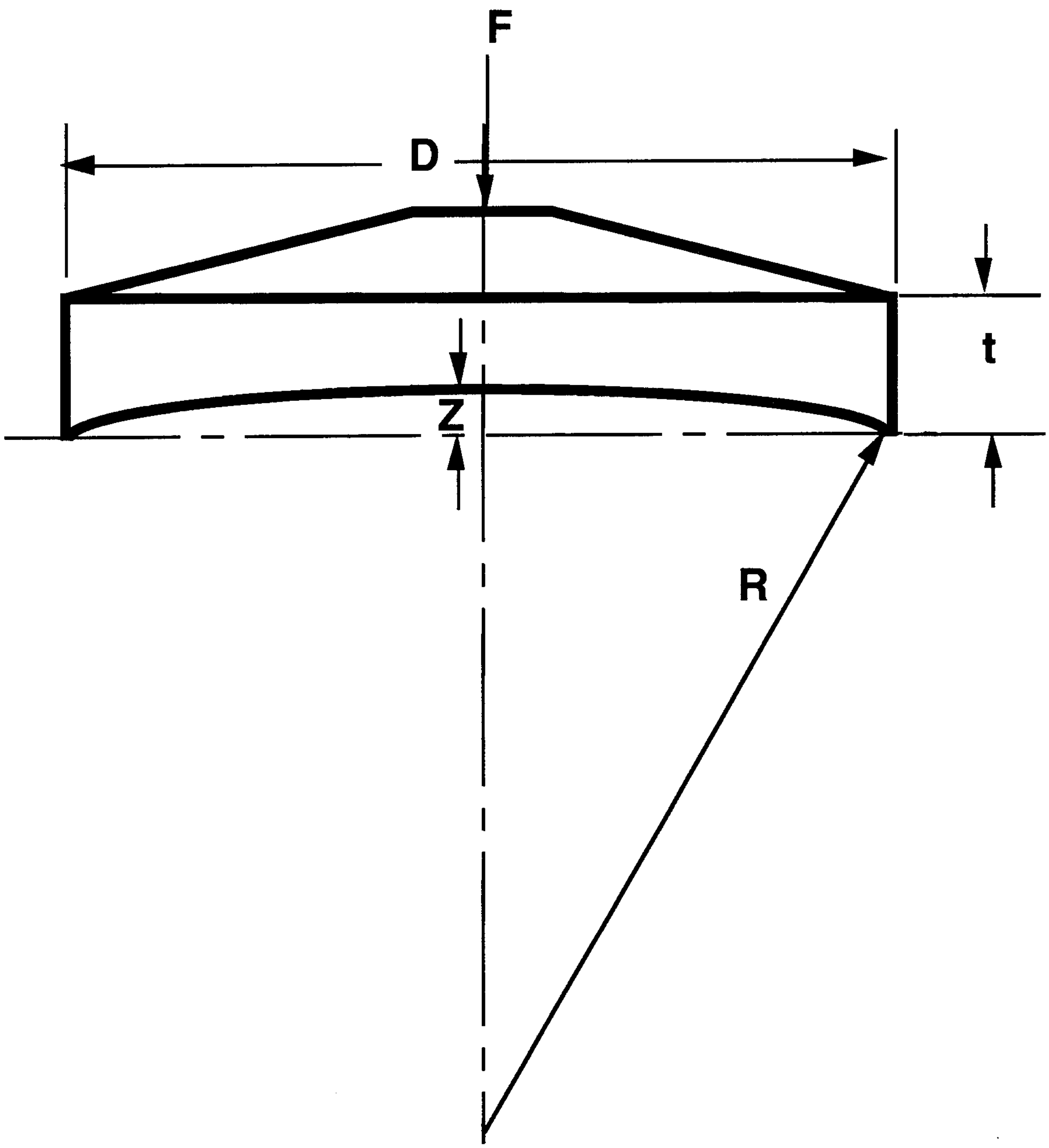

Fig. 6. One seeks to discover the shape which will provide a spherical deformation in response to a single force.

application of a 1 mm deformation on a 70 cm mirror. The author is personally aware of the work of M. Massie et al and is aware that the mirror performed well in an actuator system(a Link flight simulator.) This result is the order of what is required for the lens casting application.

R. Scott in ref. 10 describes a detailed analysis using reactionless sets of actuators on the rear of the mirror. His system is designed to be used for achieving even higher order Zernike modes and I believe it was an early study for the Hubble Space Telescope. The adaptive mirror approach was eventually discarded as it was determined that the mirror could be delivered to space with a stable figure. Even though the deformations were designed to fit the scientific application, I believe he points the way to reactionless actuation, perhaps a key feature.

J. Nichols et al of the Air Force Weapons Laboratory in ref. 14 describe test results of an edge-actuated, modal mirror. This was for directed energy weapons and had only small deformations.

In ref. 13 A. Fushetto presents results of an FEM analysis of a three actuator, reactionless system for modal deformations. Again, the idea of reactionless modal deformation is studied and found to be of merit, but not considered beyond the level of small deformations.

Perhaps the most recent work and the most complete is that of R. Sawicke et al of the Lawrence Livermore National Laboratory. They analyzed, constructed, and tested modal mirrors. They demonstrated accurate focal and astigmatic correction and even built mirrors with Gaussian corrections to compensate for the thermal distortions of Gaussian laser beams.

2.1. High precision, low-stroke, active mirrors.

Adaptive mirrors have usually been built around the concept of using a lot of piezoelectric actuators acting on a thin mirror facesheet. This has been appropriate since the wavefront distortion contained very high order distortions and many degrees-of-freedom were required for achieving a high Strehl.

However, in this instance, I desire to only modify focus and astigmatism. This first issue becomes this:

> Can a mirror/mold be fabricated so that when a single actuator is activated that the surface will deform purely in focus or astigmatism.

From the above technology review we know that these mirrors can be fabricated. However, there remain substantial issues yet for commercialization and these will be discussed below.

2.2. Low-precision, high-stroke quasi-static mirrors.

Technical Analysis of Adjustable Molds Requirements for spectacle lens fabrication.

Consider the design of spectacle lens and the potential for low-cost modal mirrors to solve the mold cost problem. The total dioptric power is given by the sum of the dioptric power of the front and rear surfaces. Thus, the typical 1.5 diopter lens may have a front of 6 D and a rear of -4.5 D for a total prescription of 1.5 D. A simplified drawing is shown as Fig. 7 and note that the central thickness **t** must be so as to meet certain minimum safety standards.

As a beginning and as an input to our finite-element modeling(FEM), I calculate a simple case for the performance properties of an ophthalmic mold. This mold will accommodate a spherical correction change of one diopter and will mold a lens at the standard diameter of 70 mm. It will have an objective of maintaining the ANSI standard for ophthalmic lens quality of no more than 1/8 diopter variation over the entire lens.

Consider a lens then with a front dioptric power of $\mathbf{D_f}$ and a rear dioptric power of $\mathbf{D_r}$ and a total dioptric power $\mathbf{D_t}$ of

$$\mathbf{D_t} = \mathbf{D_f} + \mathbf{D_r}. \qquad (3)$$

The front is assumed to be positive and for example may have a power of 6 diopters. I wish to design a mold that will change the power of the entire lens from 2 to 1 diopter. Thus, the rear power will be varied between

$$-5 < \mathbf{D_r} < -4. \qquad (4)$$

in 0.25 D steps with 1/8 D precision. This will be accomplished by deforming the mold for the rear surface of the lens. Keep in mind however that the front mold can be deformed as well for an even greater range of total dioptric powers.

Consider some basic optical refraction concepts first. The focal length of the resultant lens would be given by

$$\mathbf{f} = \left(\frac{\mathbf{n_1}}{\mathbf{n_1} - \mathbf{n_2}}\right)\mathbf{R} \qquad (5)$$

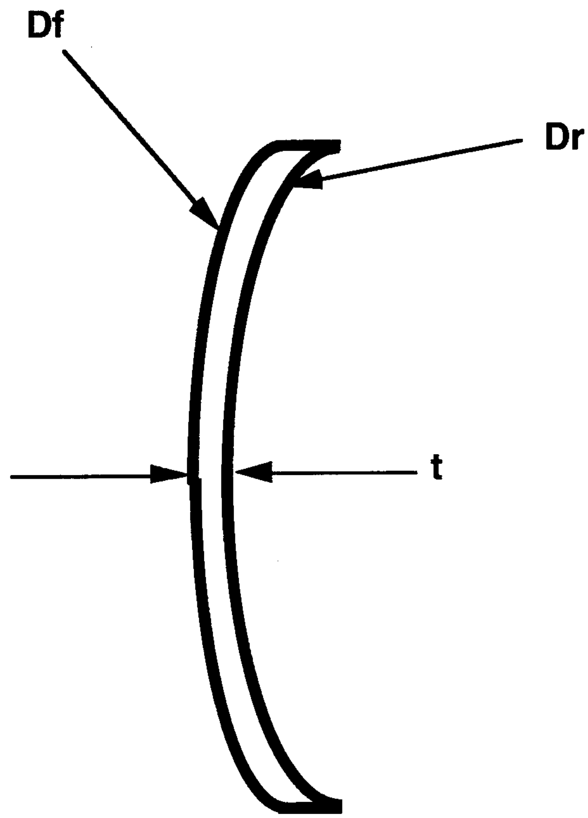

Fig. 7. Construction of a basic ophthalmic spectacle lens.

I use for simplicity that most indices of refraction for common materials are about 1.5 and that the index of refraction for air is about 1.0. Thus, approximately,

$$\mathbf{f} = 2\ \mathbf{R}. \tag{6}$$

Or, in terms of diopters,

$$\mathbf{D} = \frac{1}{2\ \mathbf{R}}. \tag{7}$$

The depth or sag Z at the apex of the spherical lens is approximately given by

$$\mathbf{z} = \frac{\mathbf{r}^2}{2\ \mathbf{R}} \tag{8}$$

or that

$$z = r^2 \, D. \qquad (9)$$

Consider that r is approximately 0.035 m so that r^2 is 1.2x10^-3, I have that

$$z = 1.2\times10^{-3}\ D \quad \text{meters.} \qquad (10)$$

As a conclusion, the sag is about equal to the diopters in units of mm. A typical front lens may be 6 diopter and thus your eyeglasses may have a bulge in the middle of about 1/2 centimeter.

The first objective is to change the rear mold by one diopter and our answer is immediate that this represents a 1 mm change in sag. Thus, the center of the mold must move 1 mm and the mold must maintain a spherical shape to the ANSI tolerance of better than 1/8 diopter.

Now, by using the adjustable mold, in contrast to the fixed molds, I could potentially use:

> **Front molds with bifocal adds to 3 D and adjustment in focus:**
>
> **12 molds.**
>
> **Rear molds with +/- 2D adjustment range in focus and 2 diopter in astigmatism:**
>
> **1 mold.**
>
> **Net total would be 13 molds front and rear.**

These molds would be a little more costly, perhaps $60 each, so that the total cost might be $1K as opposed to $10K.

Analysis of tolerances for lens casting:
The industry accepted tolerance and that specified in the ANSI specification is that the central portion of the lens be within 0.125

diopter of the prescription. I wish to recast this in terms of control of the radius of curvature of the mold. From eq.(1) above I have that

$$\mathbf{D_t} = \mathbf{D_f} + \mathbf{D_r}. \qquad (11)$$

and that the error $\delta \mathbf{D_t}$ must be below 0.125 diopters. From the definition of dioptric power I have that

$$\mathbf{D_t} = \frac{1}{\mathbf{R_f}} + \frac{1}{\mathbf{R_r}} \qquad (12)$$

and that the error $\delta \mathbf{D_t}$ is given by

$$\delta \mathbf{D_t} = \frac{\delta \mathbf{R}}{\mathbf{R_f^2}} + \frac{\delta \mathbf{R}}{\mathbf{R_r^2}} \qquad (13).$$

We approximate that the front and rear radii are nearly equal as far as weighting the error and I assume the worst case where the errors from both surfaces add to get the total allowed error in radius as

$$\delta \mathbf{R} = \frac{\delta \mathbf{D_t}}{2\mathbf{D}^2} \qquad (14).$$

For a numerical example, consider a dioptric power of 2 and the tolerance in dioptric power of 0.125 for a surface radius tolerance of 0.015 m.

To translate this into a tolerance in sag, from eq.(6) I derive that the sag tolerance for each surface is

$$\delta \mathbf{z} = 0.063\ \mathbf{mm} \qquad (15).$$

Now, I wish to calculate this tolerance in terms of rms surface error. This is a little bit misleading in the since that local errors of greater than 0.125 Diopter are not allowed, but for estimates of general requirements, can be used as a guideline.

Consider then two molds of 0.125 Diopter difference in power and now I calculate the rms. difference between them. This difference between them is given by

$$\phi = \frac{\mathbf{D}\ \mathbf{r}^2}{2} \tag{16}$$

and the area weighted error is given by

$$\sigma = \left[\left(\frac{4}{\pi\ \mathbf{r}_0^2}\right)\int_0^{r_o} 2\pi\mathbf{rdr}\left(\frac{\mathbf{r}^2}{16}\right)^2\right]^{\frac{1}{2}} \tag{17}$$

For 0.125 Diopter maximum error and a lens cast at a radius of 3.5 cm the maximum area weighted rms. error would be 44 microns.

Results of the feasibility study:
Now that we understand what is required in terms of a deformable mold I have to address the issue of the feasibility of the mold. The objective is to determine that there exists a thickness profile for which a single force can generate focal changes and that another single force can generate astigmatic changes. In addition to the thickness profiles, there are issues as to the linearity of the deformations at high deformation levels.

In Fig. 6 I depict the mold in cross section. and ask again as to the feasibility of deforming a mold at the 1 mm range with sufficient tolerance. A firm specializing in finite element modeling(FEM) was retained for this portion of the study. FEM has proven very accurate in forecasting the performance of mechanical designs and is widely respected and used in the design of complex mechanical systems. This system with its extreme simplicity should be accurately modeled by this approach, especially since nonlinear properties of metals are included in the model.

A finite element model of a mold was created using the leading FEM code NASTRAN. A nonlinear solution formulation was used which means that higher-order terms in the underlying elasticity theory were retained. This makes it possible to track any nonlinearity in the deformations as a function of load level that may arise due to finite displacement levels.

In this feasibility study we define the following objective:

> **Does there exist a thickness profile and a single force that can make a large spherical deformation to ophthalmic tolerances on a mirror whose initial shape is spherical. This differs from previous results in that the deformations are 1000 times larger, the tolerances are considerable relaxed, and the initial state of the mirror is curved and not flat. We will use a Ni mold of similar shape and thickness to what is used for lens casting at this time.**

Note that larger forces are necessary to deform a mirror which begins as a sphere. We asked that in this first effort with its very limited funding that only 1 diopter of sphere be provided.

In Fig. 8 the mesh that was used is shown and just setting the problem up in the computer required most of the resources which were available. A number of configurations were tried until one was obtained which retrains its spherical shape rather well when loaded.

For example, using a quadratic thickness profile the rather unacceptable deformations as shown in Fig. 9 were obtained. Finally, using the simple profile as shown in Fig. 10, the very encouraging profile of Fig. 11 was obtained.

The deformation moves from 2.5 mm to 1.25 mm and the final (not area weighted) error was 73.6 microns, only slightly greater than the allowed error of 44 microns. This is quite good and is only slightly greater than the tolerance of 44 microns. Especially considering that the entire task funding was for less than 40 hours and considering the extremely simple thickness profile, this is a very encouraging result.

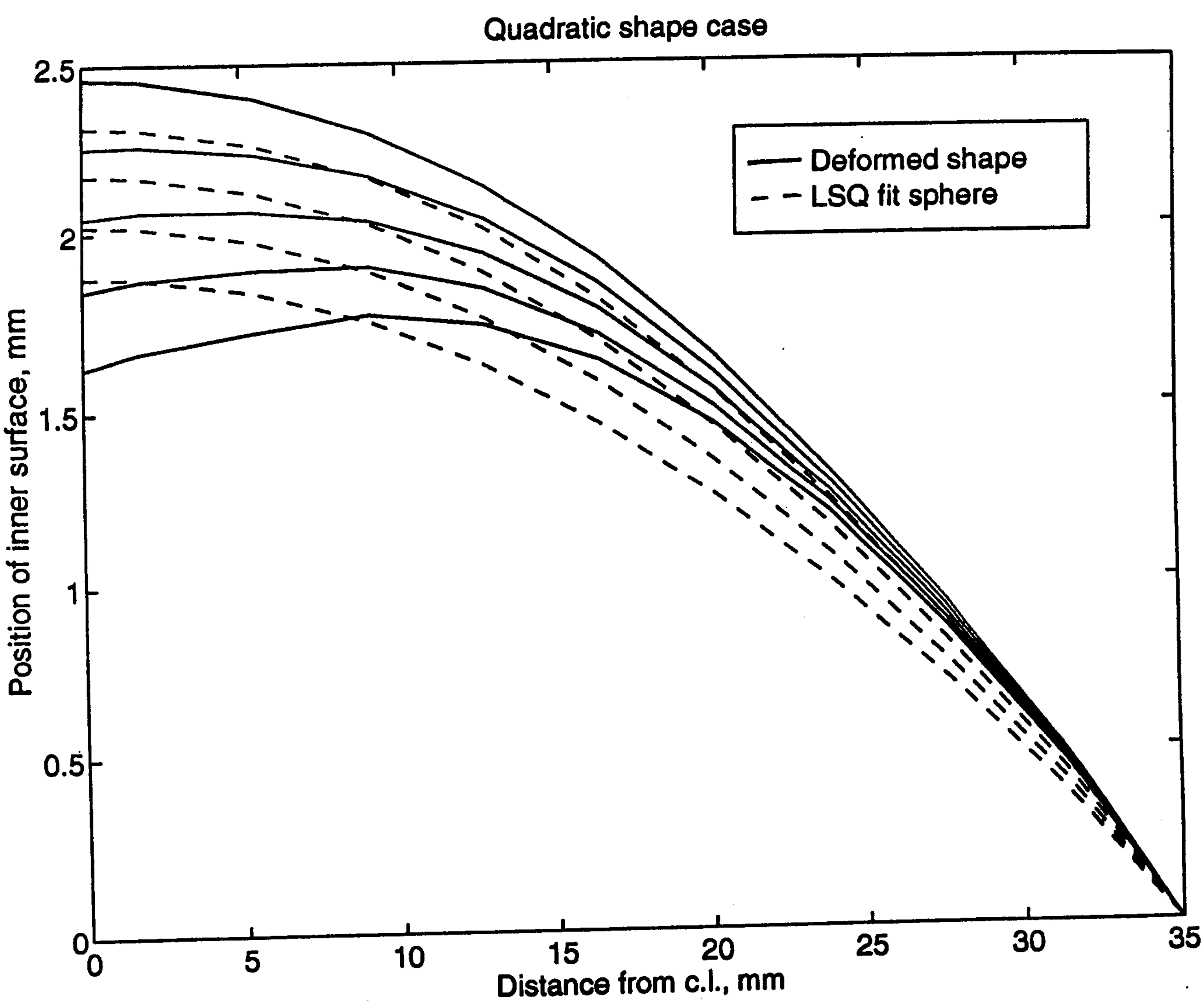

Fig. 8. A deformation result using a Gaussian thickness profile.

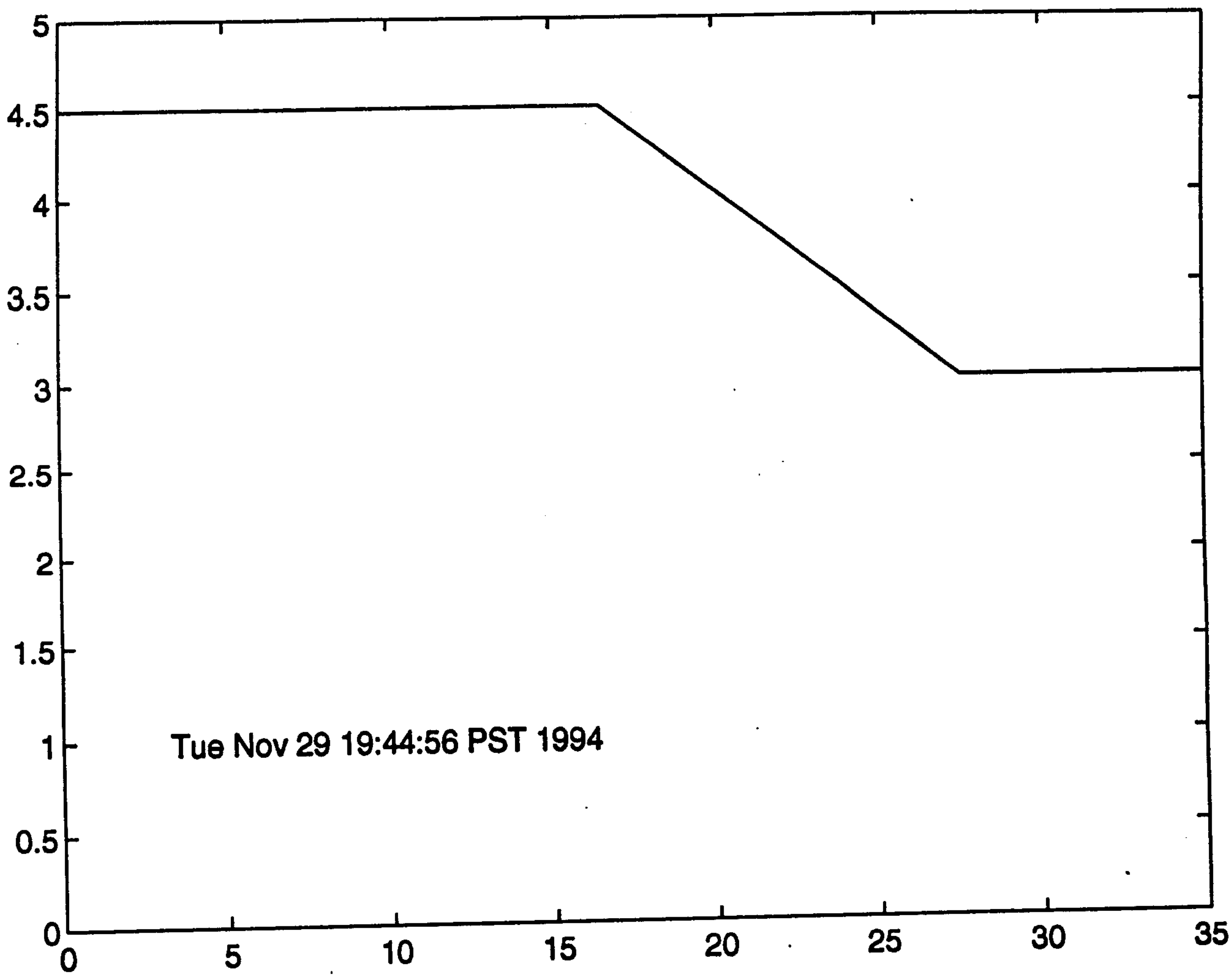

Fig. 9. Final thickness profile developed under Phase I.

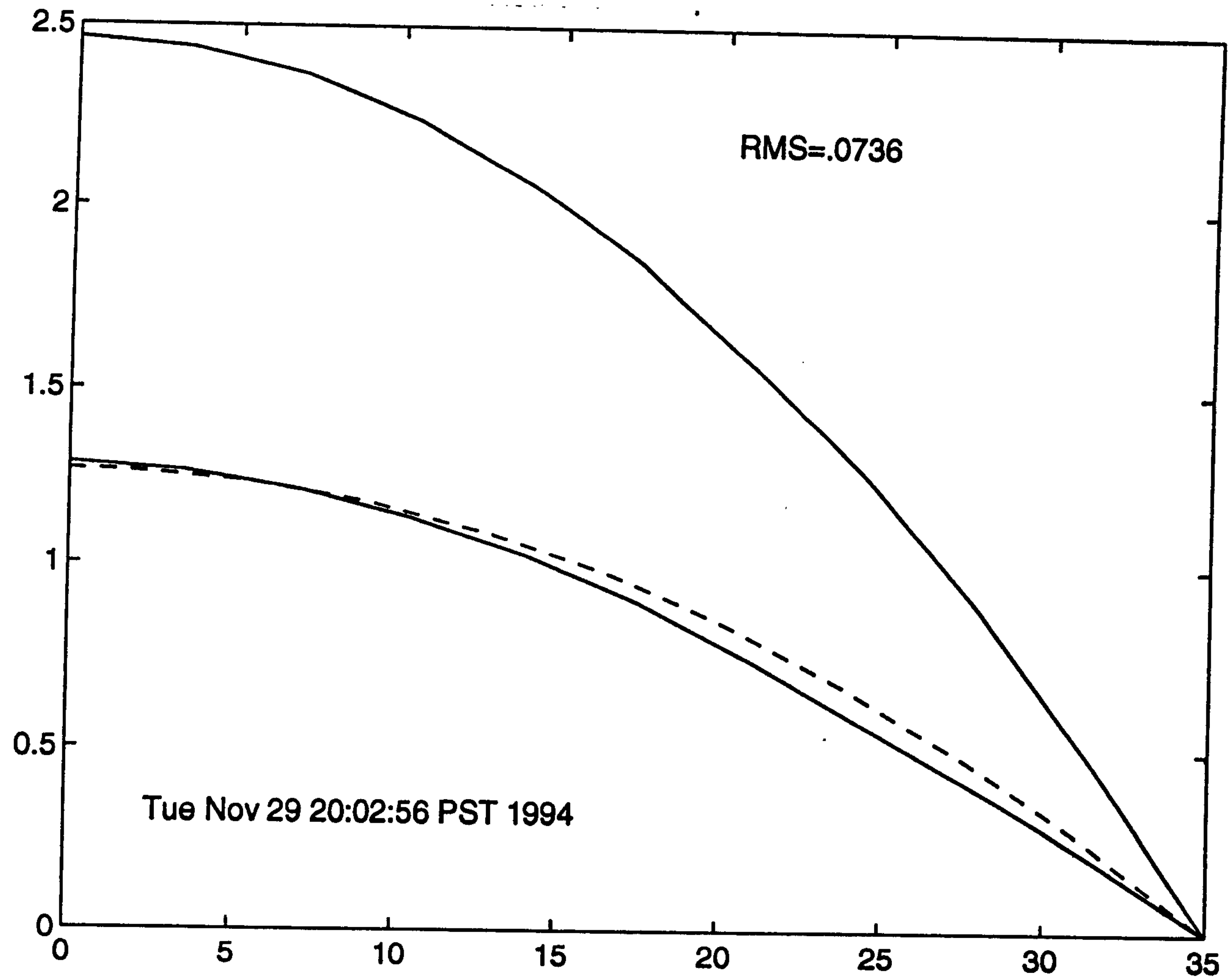

Fig. 10. Deformation profile for the thickness profile of Fig. 9.

BASIC SYSTEM DESIGN CONCEPTS:

System definition:
In a commercial system, key issues include cost, reliability, serviceability, and dynamic range of corrections.

I propose then an initial objective system definition for the R&D effort. It would provide a total range of focus of +/- 2 diopter in focus and 1 diopter in astigmatism. There will be a 2 diopter range of front curves and the front/rear diopter powers could be perhaps scheduled as Table 1 shows:

DIOPTERS SPHERICAL POWER
REAR MOLD

DIOPTERS SPHERICAL POWER FRONT MOLD	8	7	6	5
6	-2	-1	0	1
7	-1	0	1	2

NET SPHERICAL DIOPTRIC POWER

Table 1. Potential front/back dioptric powers for an adjustable mold.

Actively controlled molds:
A concept which will receive close attention in the Phase II program, is that of actively controlled molds. By this I mean that a mensuration system(discussed below) will be installed which measures the mold shape in real time. The measurements from this

system would be used in a closed loop to control the actuators so that the optimum deformation can be obtained.

In such a system, the mirror might be controlled by a number of actuators of the "set and forget" variety. By this we mean actuators such as differential ball screws which remain at the actuated position after the drive voltage is turned off. Such a system could operate with very thin facesheets and the mold could derive a great deal of its stiffness from the actuators. A further advantage is that aspheric shapes could be molded, opening up the use of advanced designs.

Mold inserts:
In some existing molding operations the surfaces become damaged after a number of pulls. In our system, we would seek a tougher surface preparation than is currently used.

However, if such a surface cannot be obtained or utilized, then the mold holders(containing the actuators) will be built such that inserts can be used which contain the polished surface. These inserts could be potentially inexpensive.

2.3 A system for mensuration of mold/lens quality.

A problem with existing molding systems is the failure to incorporate a quick and accurate lens mensuration system. In our molder, a full aperture lens quality measuring system would be incorporated. It is thus an important task of the Phase II effort to develop this system and this would be key to the concept of actively controlled molds discussed below.

This testing equipment should have an economic benefit of its own as a lens quality tester. I note that currently lens are only tested in the center to verify that the prescription is correct and the practitioner does not have the capability to check the quality of the lens dispensed.

Beam splitting interferometry is generally not useful for testing ophthalmic lens since it is too sensitive and does not have the dynamic range desired. As a result, we would focus on developing shearing interferometry or Moiré deflectometry(ref. 16-20.)

In shearing interferometry, an optical beam is collimated and passed through the optic to be tested. Then, the beam is split and recombined with itself but with a slight shear. Thus, the interference pattern is given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\phi(x) - \phi(x-\delta)\right) \tag{18}$$

Since we can vary to amount of shear, we can vary the sensitivity of this approach. However, for a complete reconstruction of the wavefront I would need shears in both the x and y directions.

A simple shearing interferometer is shown in Fig. 11. Here, a glass plate is made with a small wedge between the front and rear surfaces and the reflected beams are recombined with both a lateral shear and a small wedge. If the incident beam is collimated, the fringe pattern is straight and normal to the gradient of the wedge.

Now, I inject a beam with curvature. The fringes rotate and the angle of rotation is proportional to the curvature(and therefore the power of the lens). If the fringes are straight then the wavefront(lens) has only power.

The path difference function which gives rise to the fringe pattern is given by

$$\delta Z = \frac{x^2 + y^2}{2R} - \frac{(x - \Delta)^2 + y^2}{2R} - \beta x \tag{19}$$

where Δ is the shear, R is the radius of curvature(or 1/D), $\beta$is the tilt bias, and x and y lie the plane of the interferogram. Equation (19) reduces to

$$\delta Z = \frac{2\Delta x + \Delta^2}{2R} - \beta x \tag{20}$$

which clearly tilts the wavefront.

Actually, I would need to use two shear plates to get all of the information on the lens and then a simple least squares reconstruction code would reconstruct the actual wavefront.

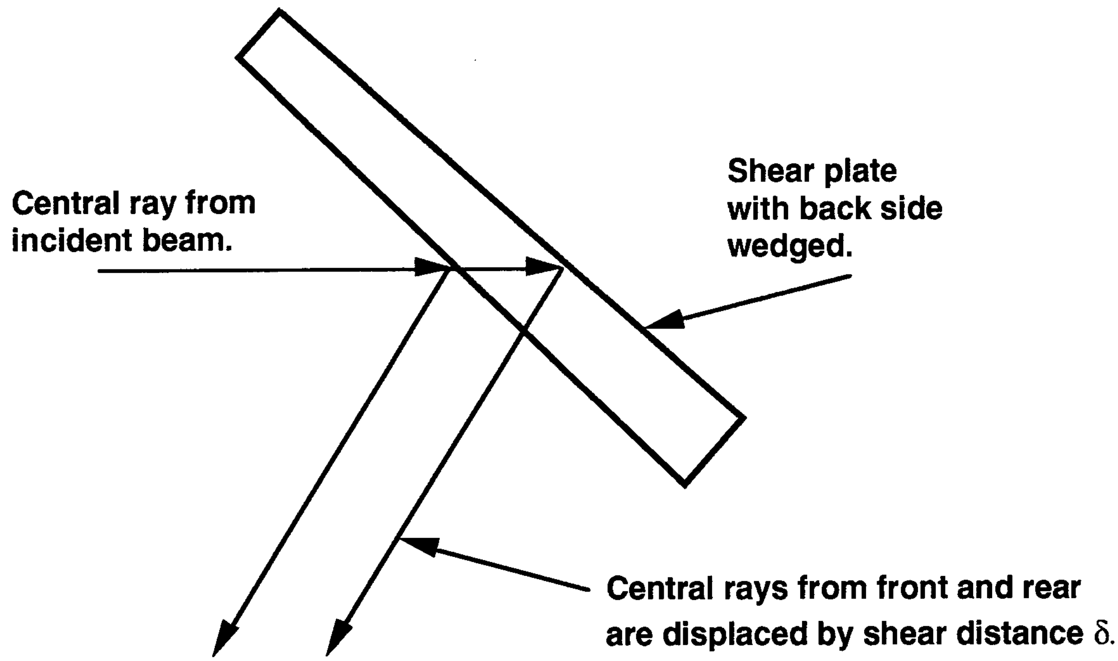

Fig. 11. Operation of shear plate for measuring lens power and quality.

In Moiré defectometry, the deflection of the rays by the lens is measured. A typical set-up is depicted in Fig. 12. Two gratings are used in general and the lens is placed in front of the gratings and the power of the lens is given by the rotation of the lines in the Moiré pattern.

The ray deflection angle of a perfect lens in the paraxial approximation is given by

$$\phi\,(y) = \tan^{-1}\left(\frac{y}{f}\right) \cong \frac{y}{f} \qquad (21)$$

where r is the radial distance from the lens' center and f is the focal length. The fringe shift is given by

$$z'(y) = \frac{d\,\tan^{-1}\left(\frac{y}{f}\right)}{\theta} \qquad (22)$$

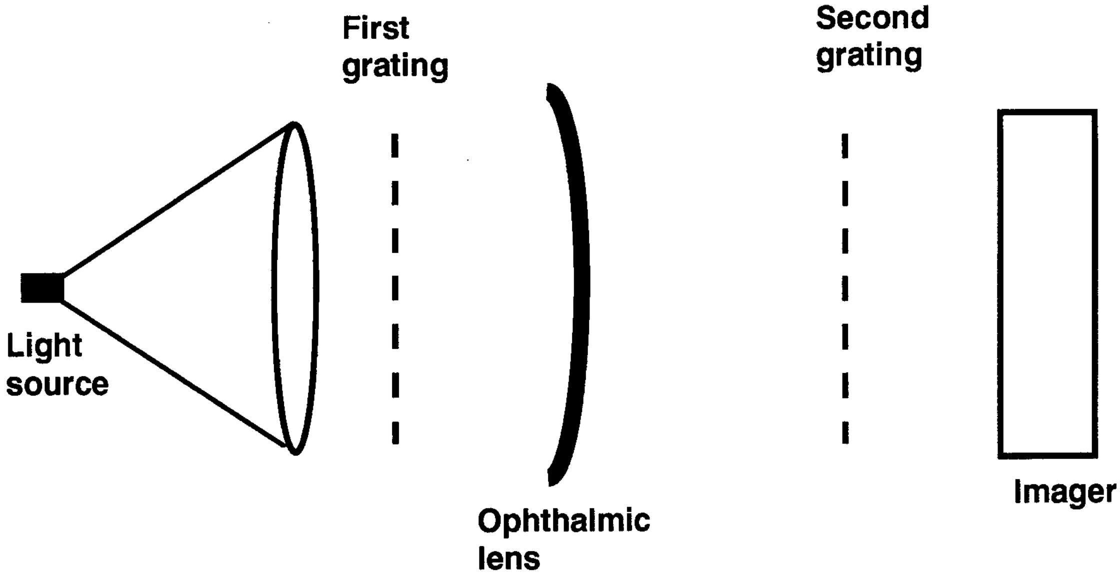

FIG. 12. Typical set-up for Moiré deflectometry.

where θ is the angle between the two Moiré gratings. Note that x is linearly proportional to r, and the effect of the lens on the Moiré deflectogram is rotation of the fringes about the lens' center. The rotation angle is given by

$$\alpha = \tan^{-1}\left(\frac{y}{f}\right) \qquad (23)$$

Thus, the focal length is

$$f = \frac{d}{\theta \tan(\alpha)} \qquad (24).$$

Deviations from straight lines indicate a lens which is not spherical. Thus, an astigmatic lens would have lines of varying curvature.

The nice feature of this approach is that coherent light would not be required, that is, a long coherence length laser is not required. Also, the second grating can be virtual, i.e., can be generated in the computer. Thus, it can be of varying pitch, angle, etc., and can be set to make the analysis easy. This is our preferred approach and would be a simple and low-cost device.

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