An alignment procedure for multi-element precision cylinder lenses and modular enclosure to house them

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ABSTRACT

We present a method for the precision alignment of cylinder lenses which has been employed for the null lenses used to test the segmented mirrors for the IXO x-ray telescope. We also present a design for a housing for such a lens.

Keywords: Optical metrology, optical alignment, cylindrical optics

1. INTRODUCTION

The use of cylinders and toroids is commonplace in optical system design, however, it is normally restricted to a few elements to correct or introduce an anamorphic magnification. Here we use multiple elements to produce a very precise cylindrical wavefront for optical testing. Such a wavefront is most commonly produced for optical testing by a computer-generated hologram. Instead, we have opted for the refractive solution because the refractive solution can test both cylinders and cones with the same optic. The diffractive solution, by contrast, has a very limited range of cone angles accessible since the diffraction condition needs to be maintained. The highly off-axis aspheres employed in x-ray telescopes are approximated by cones to a few waves or less and so we are able to test all 772 aspheric prescriptions in our telescope (the International X-ray Observatory[1]) with a single test optic under near-null conditions. This has an additional advantage over diffractive testing for this purpose. The very thin (0.4 mm) mirrors distort during ground testing and this can alter the cone angle and yet we are still able to measure the part.

2. ALIGNMENT METHODOLOGY

The design process of a precision cylinder lens for optical testing is analogous to that of a fast transmission sphere for a Fizeau interferometer. This is where the similarity ends, however, since the tolerancing, specification, mounting, and alignment are very different than for spheres or axially-symmetric aspheres. Here we will talk about the alignment process and one of mountings we have developed that ease the alignment process.

In a previous publication[2] we outlined a method for performing alignment of cylinders. We found, however, that for the lens system pictured in Fig. 1, our previous method proved too inaccurate with regard to determining the inter-lens spacing. A modification to the method was desirable; hence, the method that follows was developed. We will outline the current method and refer to the aspects that were retained from the original method. This method assumes that the lenses have been precharacterized as outlined in our previous publication.[2]

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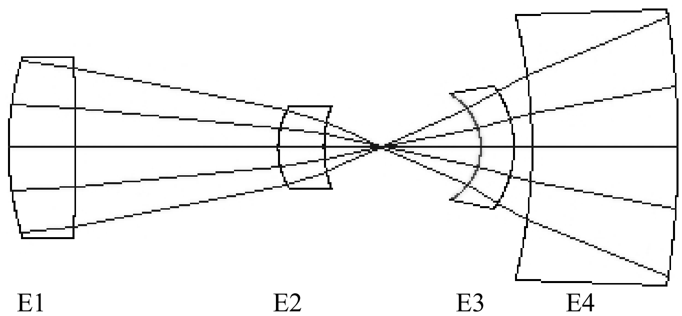


Figure 1: Four-element transmission cylinder lens designed for testing x-ray mirrors with a Fizeau interferometer. The design residual wavefront error is less than 1/20 wave P-V and it operates at faster than F/1.

Table 1 lists the equipment needed for the alignment procedure. As with the previous method it is centered on the use of a Fizeau interferometer. We align the radius bench to the interferometer in the usual way. Then at the end of the radius bench (or straddling it) we mount our first lens element in its housing. As in the original method it is advantageous to work toward the interferometer. Thus, for the lens in Fig. 1, we start at element 4 (E4). The lens is situated with its center roughly aligned with the center of the interferometer's flat. In our case the lens was 217 mm tall but the clear aperture of the interferometer was only 150 mm which limits the precision that can be achieved. The lens is rotated about its centerline (parallel to its long axis) until the line returns overlap (see Fig. 2). . This was done by a rigid body rotation of the housing. The lens is tipped to minimize the fringes from top to bottom of the lens. This constitutes the rough alignment of the first lens to the interferometer.

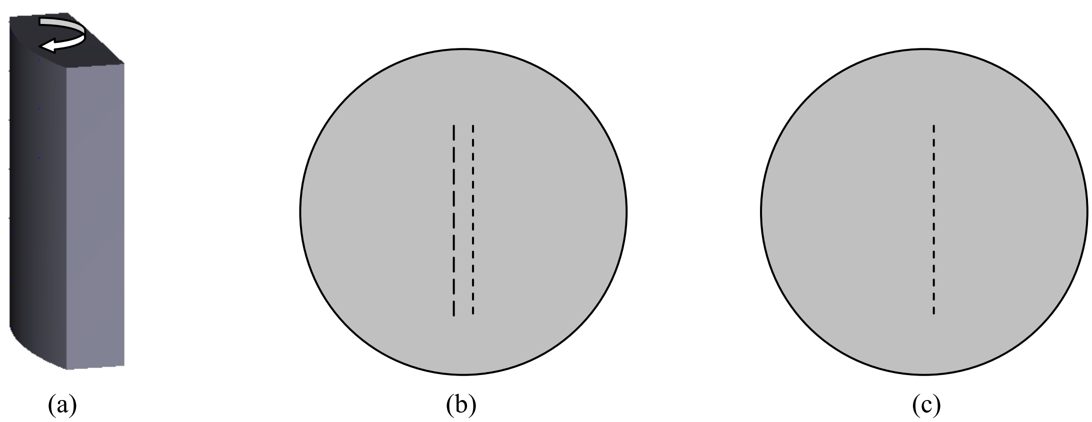


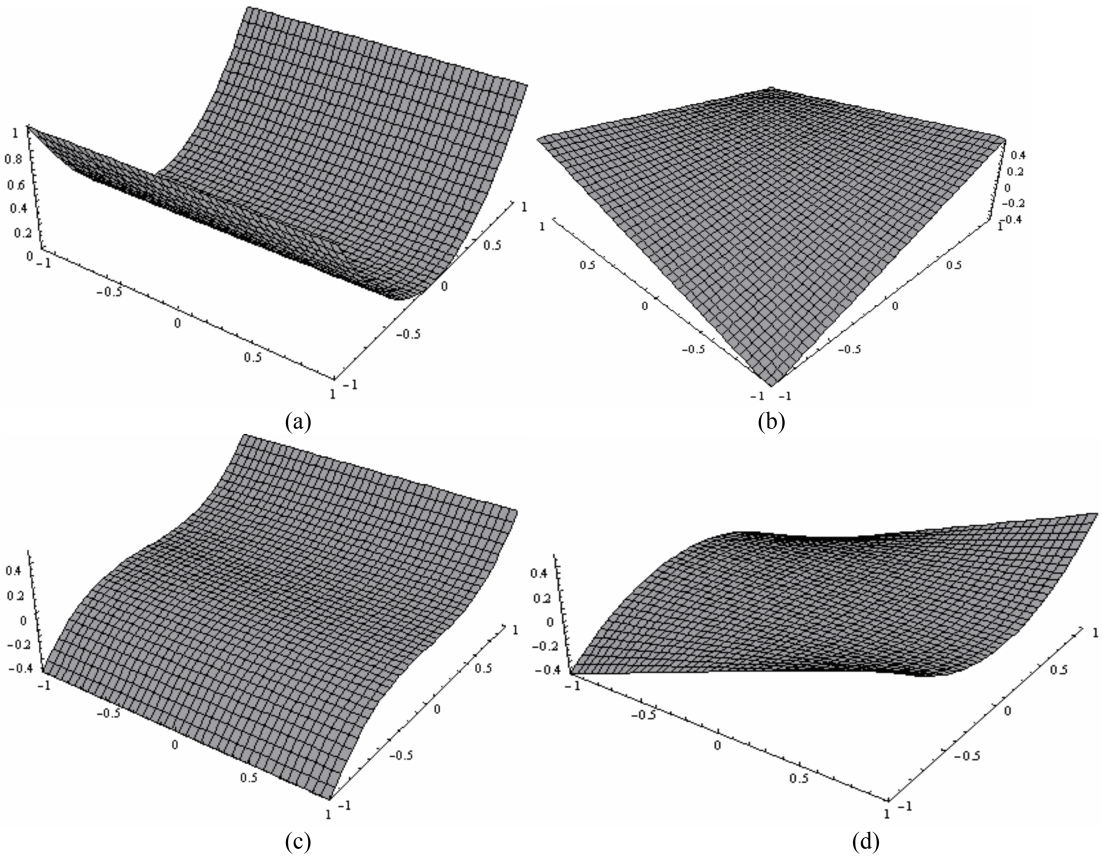
Figure 2: (a) Rotation of lens element about its axis to align to interferometer. (b) Interferogram before alignment. (c) Interferogram after alignment.

Table 1: Equipment needed for cylinder alignment method outlined here.

Equipment
Fizeau interferometer
Radius slide
Cylinder CGH or precision (slow) cylinder lens
Mounts

For the fine alignment of the first lens, we insert the cylinder CGH between the lens and interferometer. The use of a CGH for the alignment is particularly convenient in that the fiducial ring makes re-establishing normality to the interferometer beam trivial and reduces the mechanical accuracy required for the tooling attached to the radius slide. The CGH is moved on the radius slide until a null interferogram for the nearest surface is established. This aligns the

CGH axis to the axis of one surface of the elements (E4S1 in Fig. 1). The rotation of the CGH is then locked (or its' position recorded). The CGH can then be moved to examine the rear surface of the lens by looking through the first surface. In general a good null cannot be established and will be a combination of the aberrations shown in Fig. 3. The lens will need to be tipped and rotated about its centerline (Fig. 4) until the interferogram is bilaterally-symmetric and of the same magnitude top-to bottom. If these movements are more than a degree, you should remove the CGH and repeat the rough alignment procedure above.



(a) (b) (c) (d)

Figure 3: Misalignment aberrations for a cylindrical system [normalized]. (a) defocus, (b) twist (clocking of one element axis to the next element's axis) (c) coma (1D coma from displacement of element axes perpendicular to the axes) (d) conical (tip of element axes so the are no longer parallel but would eventually intersect; this yields defocus varying as a function of axial position) [after Ref. 3].

The next step is to roughly place the second lens. This is done just as with a lens bench. The CGH is moved to the mechanical position of the next lens to be placed, for example, E3S1 in Fig. 1. It is important to not rotate the CGH during the movement to the new position (or use the CGH fiducials to re-establish the rotation) . The lens is rotated and translated until a good interferogram is obtained. This is exactly in analogy with the use of a lens bench in traditional lens assembly. This step will typically place the lens to less than 0.5 mm in three-space. Then the lens needs to be rotated about its center as in Fig. 2. This is most easily done without the CGH by merely blocking the light from E4 and rotating the lens as in Fig. 2. If the CGH holder is very repeatable, one can replace the CGH and reposition the lens again to get a good interferogram. We have found that this replacement is not typically adequate for our purposes.

We have to now align the second lens to the first. For example, in Fig. 1, this would be E3 to E4. We remove the CGH and unblock the return from E4 and align the line returns by translating or rotating as needed. This eliminates twist and coma from the set-up.

The CGH is re-inserted to determine the inter-lens spacing and conical aberration. The test conditions are determined via modeling using a lens design program. Two CGH positions are chosen that will yield good null interferograms (see

Fig. 4). Typically the front surface (the surface closest to the CGH) is one and either L4S1 or L4S2 as the other, the one with the minimum wavefront error being the best choice. It is important not to use a cat-eye position because they do not have to be on the centerline and do not yield relative tilt information. The interferograms themselves may yield all the pertinent alignment information (inter-lens distance and conical). The interferogram for a properly aligned lens pair will have two symmetry axes: left-to-right, and top-to-bottom (assuming the lens axes are vertical or horizontal.) The difference between the CGH locations for the two test positions (Fig. 4) is accurately measured with the radius bench and should be the same as that modeled. Thus, the inter-lens spacing can be determined very accurately.

The use of a cylinder lens or CGH is mandatory because the axial extent ensures the wavefront axes are aligned. This, in turn, assures that the distances measured by the radius bench are the orthogonal distances as modeled. Thus the longer the CGH is axially, the better one is able to determine the extent of the twist and conical aberrations (see Fig. 3). Unfortunately, many of the cylinder CGH's available commercially have a circular aperture. This lamentable practice makes identifying twist and conical very difficult. Fortunately, the line interferograms yield good information about twist and conical so can be employed to check these misalignments by the method outlined in Ref. 2. The proper choice of CGH also must include the back focal distance needed for this step which will depend on the length of the bench and the lens you are aligning.

For large cylinders discussed here, the conical aberration cannot typically be driven to zero with a single inter-lens spacing measurement. This is because the aberration varies slowly with lens height so that a sub-aperture measurement is not very sensitive. Thus, either two inter-lens measurements should be performed (near the top of the lens assembly and near the bottom) or the "cat-eye" measurement of Ref. 2. As a rule of thumb, if the cat-eye interferogram is wider than ~ 10 mm, it will be adequate to determine conical aberration to the needed precision. If not, you need to use the repeated inter-lens spacing measurement method which takes more time.

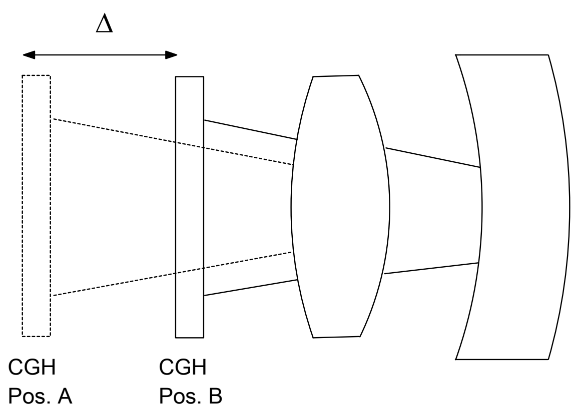


Figure 4: Schematic view of CGH measurement to determine the inter-lens spacing. The difference in the CGH positions for the two null interferograms Δ is measured via the radius bench.

This process can be repeated until all the lenses have been placed. The procedure is aided by a properly-designed lens housing. We report below on one such housing concept we have now employed for a couple of the lens assemblies and which has become our standard housing. The advantages of this housing are its modularity, reduced weight and ease of lens alignment. It is most appropriate for laboratory usage.

3. CYLINDRICAL LENS HOUSING

The housing must allow all the degrees of freedom needed to align one lens element to another and maintain the alignment when the alignment procedure is finished. Fig. 5(b) shows an isometric view (with dust covering removed) of an air-spaced cylindrical doublet with a 550 mm back focal distance operating at F/3.2 that will be used for measuring the IXO mirror-forming mandrels up to 1 meter in diameter. The design is shown in cross section in Fig. 5(a). The housing here is intended for use in a laboratory setting with the lens either upright [as shown in Fig. 5(b)] or facing up or down relative to gravity. The concept is readily adaptable to other gravity orientations with the addition of other brace bars.

Since the operational temperature range is modest (18-28º C), the lenses of the null lens assembly are mounted in 6061 aluminum lens cells. Aluminum was chosen for its superior strength-to-weight ratio and machinability. Due to the large size (and subsequent weight) of the lenses, aluminum was a good, light weight choice for the cell material. The base plate is fabricated from 416 stainless steel and was chosen for its lower coefficient of thermal expansion yielding adequate isothermal optical performance over the temperature range of interest. (The focal length changes slightly but the wavefront quality is maintained.)

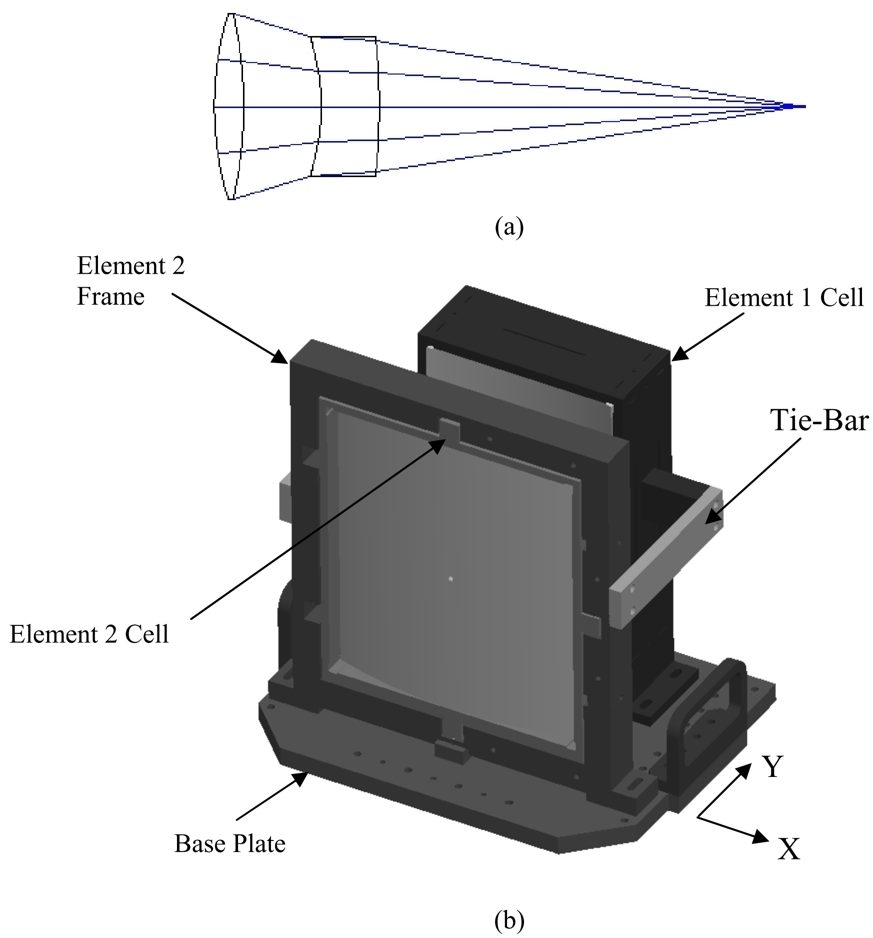


Figure 5: (a) Design for an F/3.2 air-spaced cylindrical doublet with more than a 500 mm back focal distance. (b) The lens in its housing. The axial height is more than 250 mm.

The cells are placed into frames that interface to the outer structure (a base plate and tie bars in this case). This accomplishes two things: 1) It further isolates the lenses from stresses induced by fasteners, etc.; and 2) allows the cells to be repositioned within the frame for fine alignment of the lenses to one another.

The assembly is constructed by first inserting the lenses into their respective cells. The lenses are then bonded into place with a slow curing (72 hour) aerospace-grade RTV adhesive to minimize birefringence due to shrinkage stress. The cells, as with traditional spherical lenses, create a metallic interface that can be manipulated without introducing unwanted stresses into the lenses themselves.

One cell is integral to the frame since one element is taken as the reference and other lens elements are aligned to it. The frames are mounted to the base plate and mechanically aligned. A precision machined squaring spacer is used to perform the rough alignment between the two frames. The spacer is inserted between the frames which are brought into contact with the spacer in both the X and Y directions. This fixes the location of the frames to within a fraction of a millimeter. The cell frames are then secured to the base plate and the squaring spacer is removed. Very stiff steel tie-bars are mounted between to each of the cells to add structural stability when the assembly is mounted with the gravity vector parallel or antiparallel to the light path.

The second element cell rests upon a steel gage ball and has five degrees of freedom: translation in the X and Y directions, pitch, yaw and equatorial rotation. The piezoelectric actuators (piezo-motors) are used to precisely align the lenses as outlined above and are set to establish the lens starting (nominal) position. Figure 6 shows the mounting of the piezoelectric actuators. A yoke is attached temporarily to facilitate the Y, pitch, and equatorial rotations needed for alignment. The lens frames accommodate the actuators that perform the X and yaw motions. Ball plungers are used in opposition to the actuators to provide resistance for smooth movement. The ball plungers are a good choice because they can be relocated as needed by screwing in or out if the lens or housing tolerance are such that the movement range needs to be adjusted.

The alignment is accomplished through the procedure outlined above. After the precision alignment step is complete, the lens is locked into place in the frame by carefully bonding glass shims made to size between the inner cell and outer frame. These are bonded in opposing pairs to eliminate all degrees of freedom and to assure that epoxy shrinkage results in *de minimis* misalignment.

After the epoxy has cured, the yoke and frame actuators are removed. This is done in the test configuration so any movement can be monitored. If more than one element needs to be aligned (as in the lens of Fig. 1) the process is repeated.

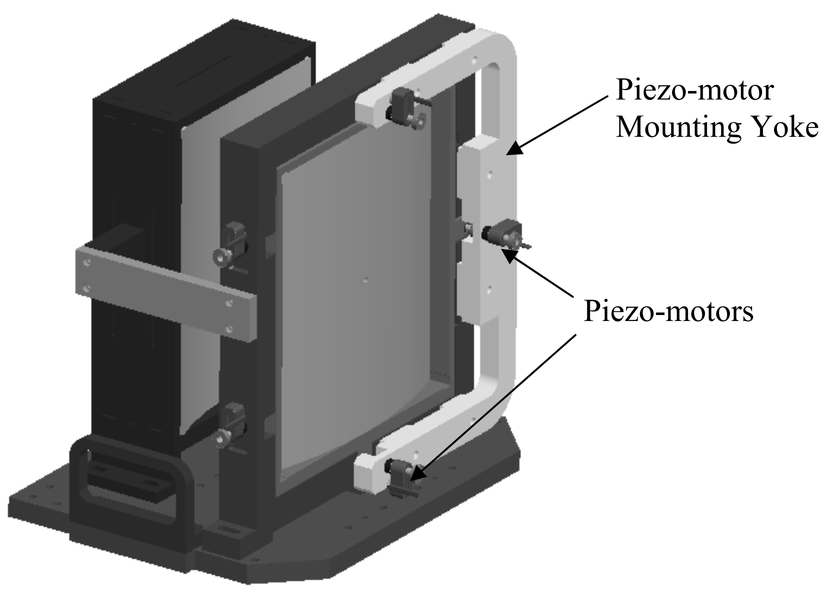


Figure 6: The housing of Fig. 5 shown during lens alignment. The piezo-motors and the yoke are removed after the shims are bonded in place.

Given the limited temperature range seen in laboratory use, the athermalization requirements for the mount in our case are not stringent. A degree of athermalization is accomplished by simply having the tie-bar fabricated from the same material as the base plate – 416 SS which is one of the more common low CTE stainless steels. The frame material has only a secondary effect on the lens positions so we can employ Al which reduces the overall weight of the structure. Going forward, the plan is to use a more sophisticated athermalization method more appropriate for maintaining wavefront over the wider temperature range expected on the optical shop floor seen with *in situ* metrology during mandrel fabrication. By using two different materials (such as aluminum and steel) and designing the tie bars to have lengths that are proportional to their CTEs, an athermalization method that encompasses a wider temperature range can be achieved. As the ambient temperature changes, the multi-material tie-bar will expand or contract in a way that will counteract the lens refractivity changes.

Operation of the null lens assembly calls for the optical axis to be approximately perpendicular to the mandrel under test. During polishing¸ the mandrel axis will be horizontal. So for *in situ* metrology, the null lens assembly will be mounted such that the optical axis is parallel to gravity. Finite element analysis was performed to optimize the location of the tie-bar to minimize distortion of the lens housings relative to one another. This assures that the wavefront is the same whether the lens optical axis is horizontal (for *ex situ* metrology) or vertical (for i*n situ* metrology). Finite element analysis was performed to optimize the location of the tie-bar while minimizing the weight of the structure as a whole. Figure 7 shows the deformed results for the *in situ* metrology orientation. The base plate would be fixed and the cell frames are cantilevered above the mandrel under test. The maximum change in the lens spacing is less than 1 micron which results in a imperceptible conical aberration (< 1/20 wave P-V) difference between configurations.

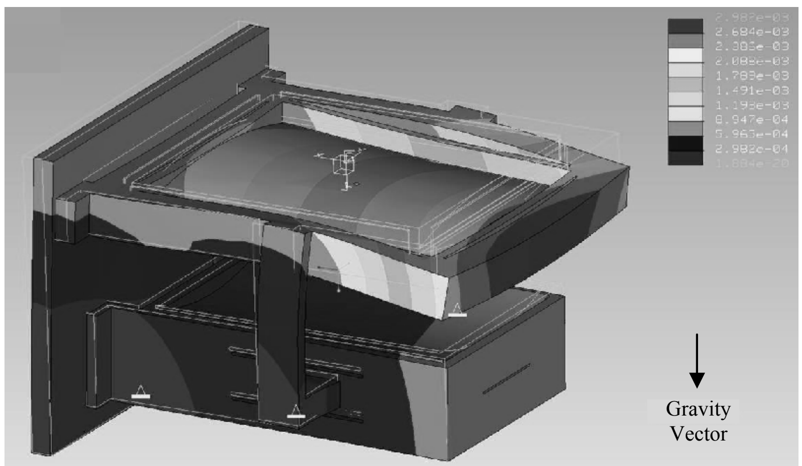


Figure 7. FEA Analysis of gravity sag effect on null lens assembly. (Displacements have been greatly exaggerated to emphasize the movements.)

4. SUMMARY

We presented a precision method of aligning multi-element cylinder lenses. The method employs materials common to most optical shops that manufacture cylindrical singlets. The method is relatively simple and adaptable to nearly any design form.

We also presented a cylinder lens housing concept that is modular and compatible with the alignment method. The housing is suitable for light duty or laboratory work although the concept could be extended to more rugged environments.

ACKNOWLEDGEMENTS

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