

# More Cylinders in Vs

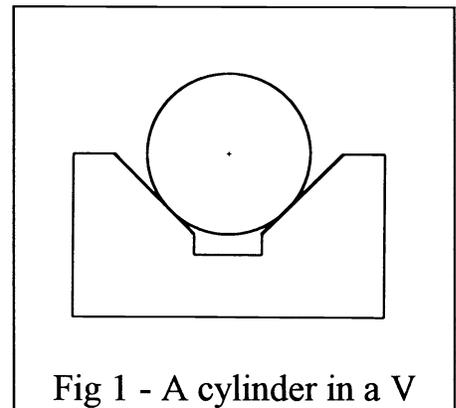
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## ABSTRACT

This paper considers a variety of techniques for an optomechanical system in which optical elements are mounted on cylinders that are located in Vs.

**Keywords:** optomechanics, lens mounting, cylinders, Vs, cylinders in Vs

This paper continues the development of an earlier one<sup>1</sup> of an optomechanical system in which optical elements are mounted in cylinders that are located in Vs, Fig. 1. The mechanical use of cylinders in Vs is ancient, and the optical use is old.<sup>2</sup> A number of particular embodiments have been discussed.<sup>3,4,5,6,7</sup> However, the author has found no literature in which the optomechanical use of cylinders in Vs has been systematized and fully exploited as a general method.



Aside from the cylinder-in-V methods per se, the approach taken here has several other aspects: (1) Components are simple and as few dimensions as possible are critical. (2) The method aims to use good machining practice and to use machine tools to their best advantage. For best accuracy, critical surfaces are, if possible, machined in the same setup. (3) It is assumed that the optical elements are within tolerance and the problem at hand is to put them in the right place. If the elements are sufficiently out of specification that tweaking is required, fine adjustment can be added.

## **Terminology**

As discussed in the earlier paper, the term “cylinder” is taken to have its most general definition, so cylinders are often, but not necessarily, round. Likewise, “V” has a general definition, although for the most part here a V is taken to be a simple trough with planar sides. There are several axes. For a V and a cylinder there is a nominal “system axis.” A rotationally symmetric optical element has an “element axis.” A round cylinder has a “cylinder axis.”

## **CENTERING ROTATIONALLY SYMMETRIC ELEMENTS**

The term “centering” is used here for the act of positioning optical elements that are figures of revolution so that their axes lie along the system axis. Centering involves four degrees of freedom, most easily thought of as two translations of the element in a plane perpendicular to the system axis and two tilts of the element axis relative to the system axis.

As discussed in the first paper, centering can be performed by rotating a sufficiently good cylinder of the correct diameter in a V and arranging an element in the cylinder to be free of runout. With this method centering accuracy is limited by the quality of the cylinder, and the procedure is limited to round cylinders.

### **Virtual centering**

Optical elements can be centered to the system axis with greater accuracy than that of the cylinders that hold them by a method we call “virtual centering,” Fig. 2. In this procedure the superior accuracies of fixtures are transferred to less perfect parts.

The method employs a precision spindle, preferably one with an axial through hole and a vertical rotation axis. A stage with two translations and two tilts is mounted on the spindle. A short master V is mounted on this stage so that the axis of a cylinder in this V is close to the spindle axis. There is a master cylinder is long enough to protrude sufficiently from the V.

The master cylinder is clamped in the V and the spindle is rotated. Using a precision indicator, the runout of the master cylinder is measured at the two most separate accessible positions along its length. The stage is adjusted to bring the cylinder axis into collinearity with that of the spindle. The master cylinder is now removed, leaving the V located relative to the spindle axis the same as it would be to the axis of the master cylinder.

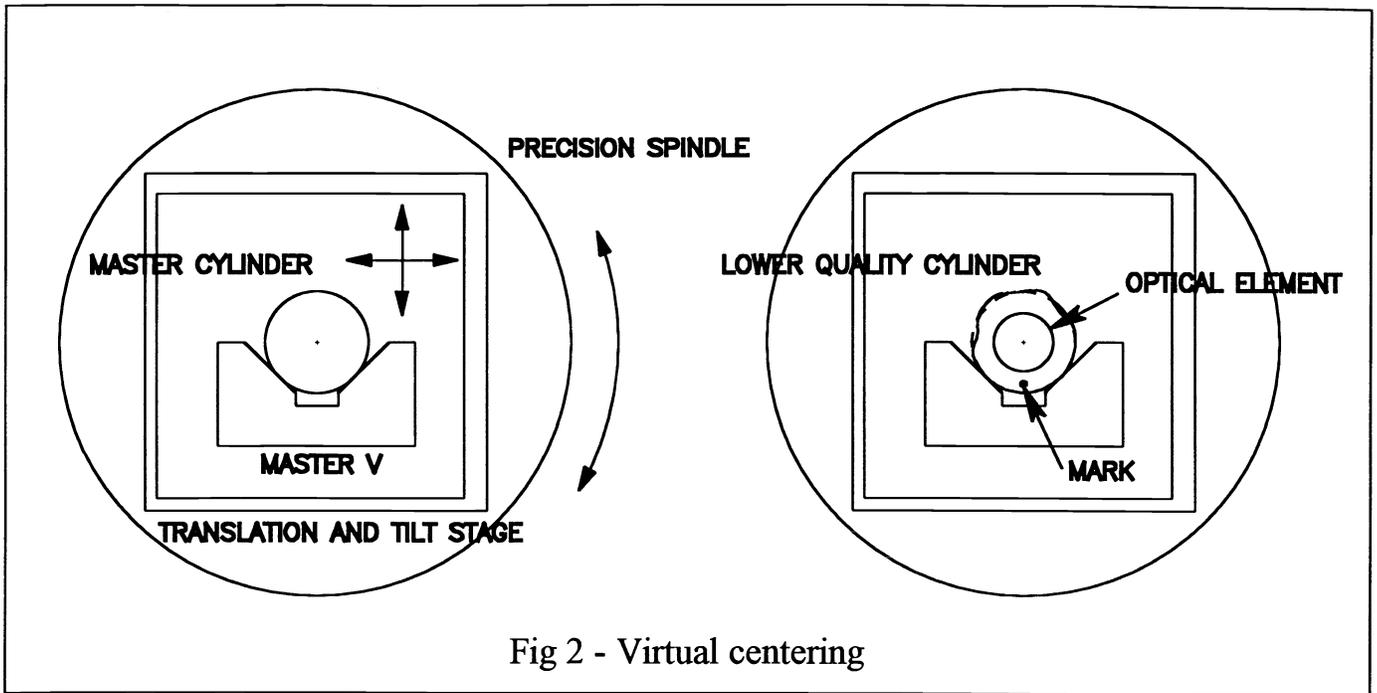


Fig 2 - Virtual centering

An ordinary cylinder is clamped in the V with a mark on its exposed end to indicate either the top or bottom position in the V. An optical element is placed in the cylinder and the spindle is rotated. The element is arranged in the cylinder to center it relative to the spindle axis. Runout can be sensed with any suitable indicator or optically, using transmitted light or reflected light and a video or visual system. The element axis is now collinear with the virtual axis of the master cylinder, and this geometry is maintained when the cylinder is transferred with the same azimuthal orientation to another V with the same angle, Fig. 3. The cylinder that holds the optical element need not rotate in a V, so it can have any shape, e.g., square, hexagonal, or octagonal.

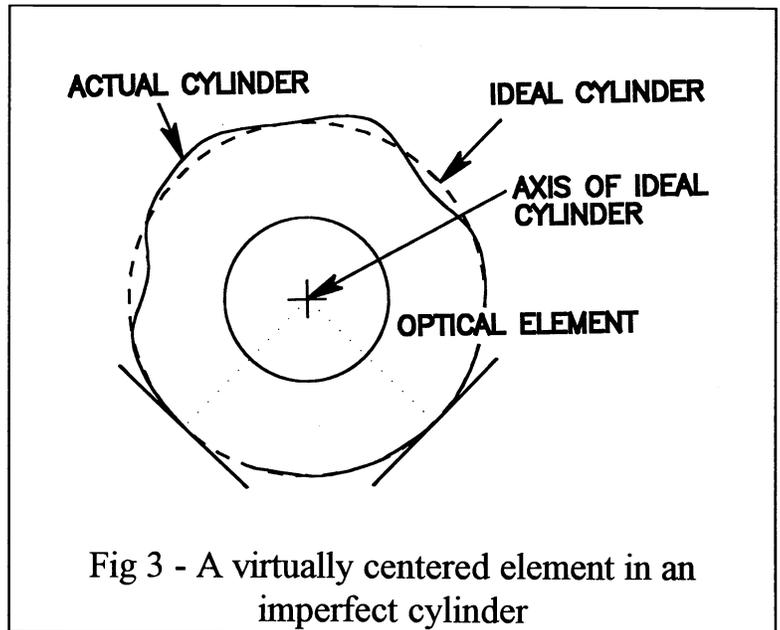


Fig 3 - A virtually centered element in an imperfect cylinder

(In our shop we use an air spindle with 2  $\mu$ inch runout. Tilt and centration are built in. The master cylinder, which was obtained from a gage house, is stainless steel 1" in diameter and 4" long, accurate to 1  $\mu$ m. The master V has glass contact surfaces, 2" long. So centering to about a micron is done with ordinarily machined cylinders.)

**Mechanically centering lens seats**

For purely mechanical lens centering, mounting surfaces can be machined on cylinders,<sup>8</sup> preferably in the same setup in which the outside of a cylinder is turned. The most general surface is a portion of a toroid,\* which works for convex, concave, and planar optical element surfaces, Fig. 4. A conical seat, a special case of the toroid, works for convex surfaces. The optical surfaces of the lens are used in this approach. Edge diameter and edge centration, which are in themselves optically irrelevant, do not come into play except for clearance. Centering is limited by friction.

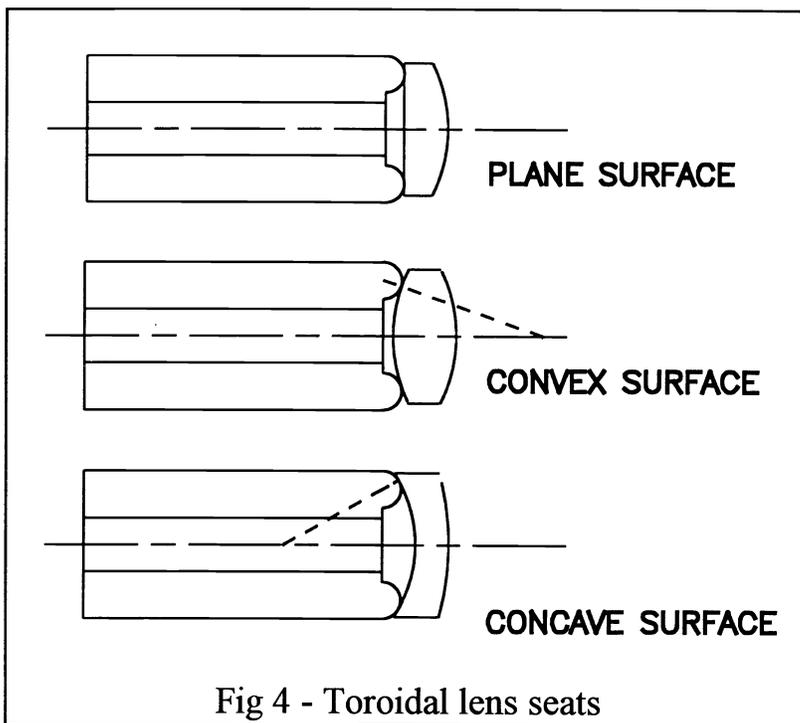


Fig 4 - Toroidal lens seats

A single toroidal seat puts the center of curvature of one surface on axis, and two toroids completely center a lens, Fig. 5.

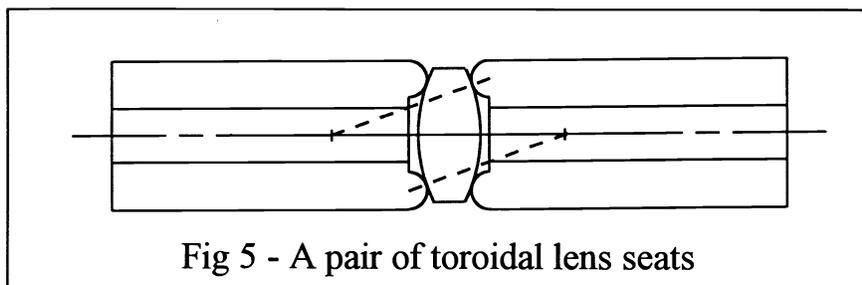


Fig 5 - A pair of toroidal lens seats

\* Toroid: "A surface generated by the rotation of a plane closed curve about an axis lying in its plane" Webster's New International Dictionary, 1936

Arrangements of this type can be used in a variety of ways. For temporary setups a lens can be held by pressure alone. A lens can be cemented to one cylinder while held in position by another. To verify centration before cementing, a beam of light passing through the cylinders can be observed. Since a lens surface and a toroid make good contact, vacuum can be applied to the tooling cylinder, with a window added if optical verification of centration is used. An application of vacuum is the placement of an optical element deep within a cylinder, Fig. 6. If the element is to be secured with UV curing cement, a light guide can be inserted in the fixture, with a diffuser added as necessary.

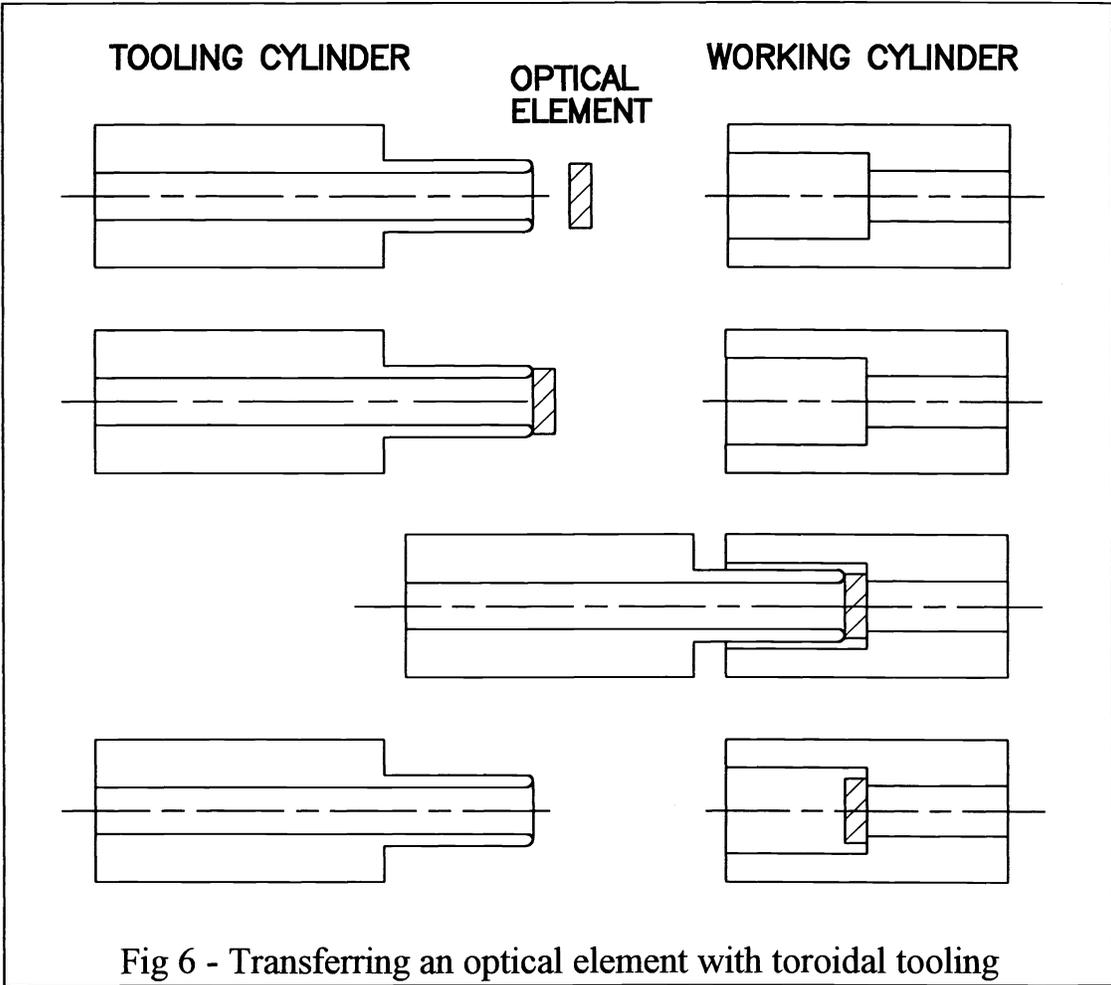


Fig 6 - Transferring an optical element with toroidal tooling

Only a small portion of a toroid is required for a given lens. Alternately, a toroidal surface can be devised to mount a family of lenses. To reduce contact stress, the profile of the toroid can be made close to that of the lens. Numerically controlled lathes can routinely produce such surfaces.

### Mounting seats on both ends

If lenses are mounted on both ends of a cylinder, centering accuracy is improved by turning both seats in the same lathe setup. This is often possible, since the central portion of the cylinder is usually a clearance space that does not require high accuracy and that can be machined last in a different setup. Thus the end of the cylinder closer to the lathe head can be supported by material that is later removed, Fig. 7.

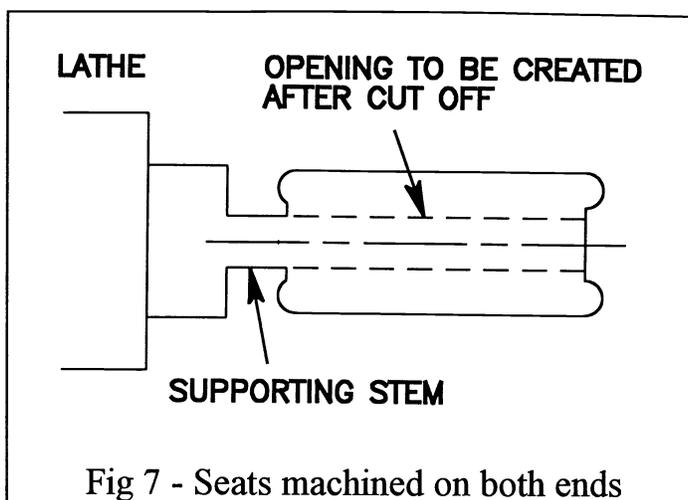


Fig 7 - Seats machined on both ends

### Stacked centering cones

The first paper described the centering of elements in truncated cones. For multiple elements, such cones can be stacked, possibly separated with shims or cylindrical spacers, Fig.8.

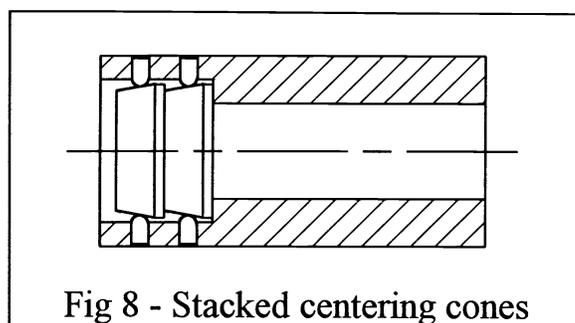


Fig 8 - Stacked centering cones

### AZIMUTHAL CONTROL

The azimuth of optical elements without rotational symmetry must be controlled. One way to do so is to rotate the cylinder holding the element, Fig. 9, and the following are some methods to do so. Some employ an arm referred to here as the "azimuth stop," Fig. 10. In some cases azimuth is controlled once for setup. In other cases the azimuth is varied in operation, e.g., with rotating polarization components. Sometimes absolute orientation is required, and sometimes known changes are needed. The previous paper discusses some aspects of this subject.

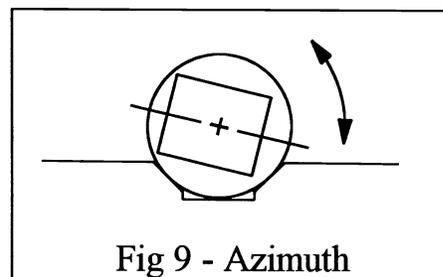


Fig 9 - Azimuth

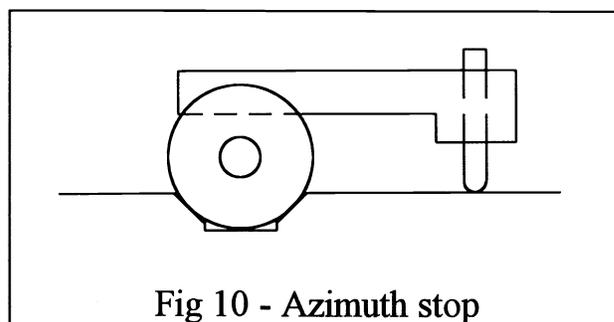


Fig 10 - Azimuth stop

The mathematical reference for azimuth is a plane containing the axis. The most convenient physical reference is a planar surface parallel to this plane, Fig. 11. It is assumed in this section and the next that the V is machined in a plate. The surface that the V penetrates is called the “V plate surface,” and is taken to be the physical reference surface for azimuth. This plane is said to be “horizontal,” and normals to it are “vertical.” The “axial horizontal plane” contains the axis and is parallel to the V plate plane. The “axial vertical plane” contains the axis and is perpendicular to the V plate plane.

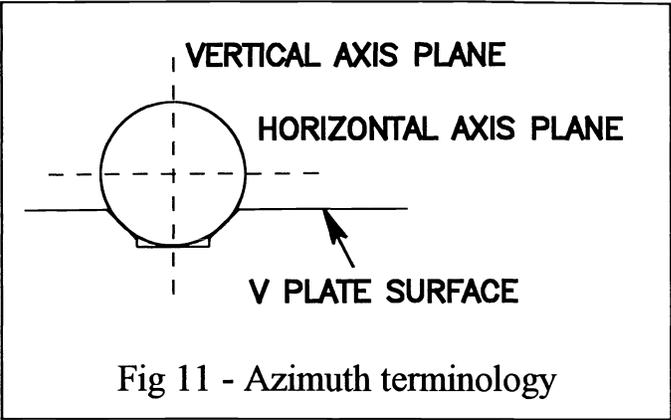


Fig 11 - Azimuth terminology

**180 degree rotation**

The 180 degree rotation is important because it is used to test for symmetry, as discussed below. This rotation can be accurately performed in a simple way, Fig. 12. A ball whose radius equals the distance from the V plate surface to the axis is attached to a cylinder by an arm. Swinging the cylinder between positions limited by the ball and the V plate plane gives a 180 degree rotation, regardless of the arm length. Such an arm can be temporarily attached for set up.

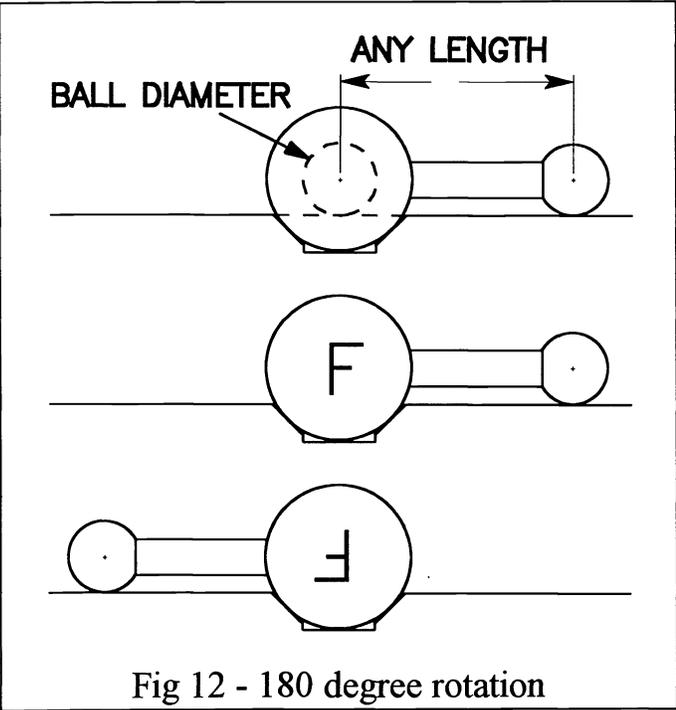


Fig 12 - 180 degree rotation

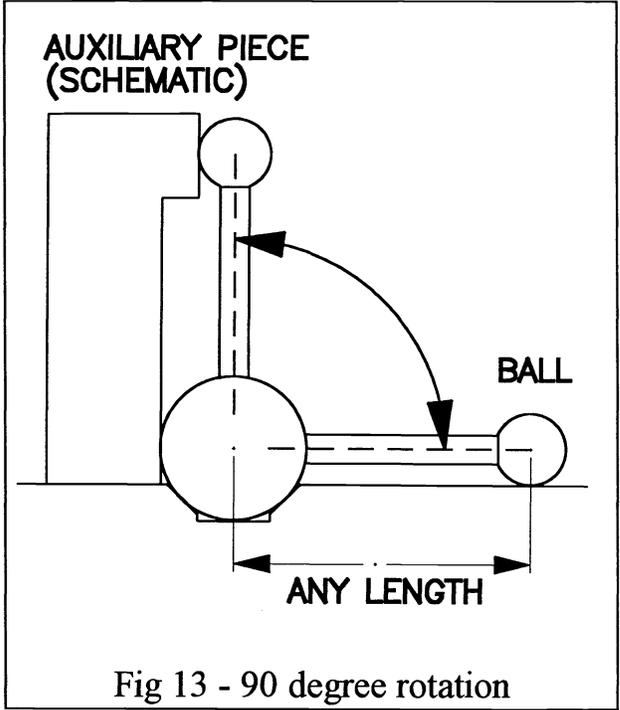


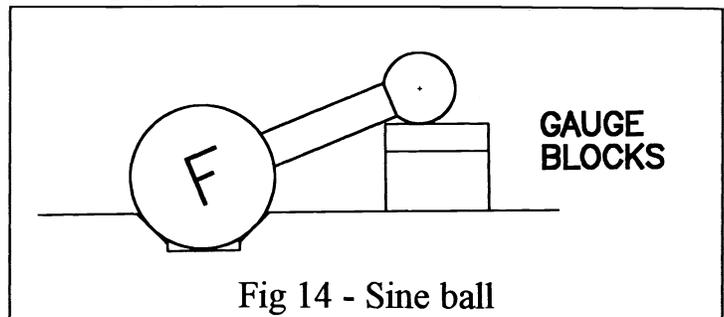
Fig 13 - 90 degree rotation

### 90 degree rotation

One way to rotate a cylinder 90 degrees uses the same arm and ball used for 180 degree rotation and an additional piece, shown schematically in Fig. 13. Again, the distance from the center of the ball to the axis of the cylinder need not be known. The stop has only one critical linear dimension, that of its step, which equals the difference between the cylinder and ball radii.

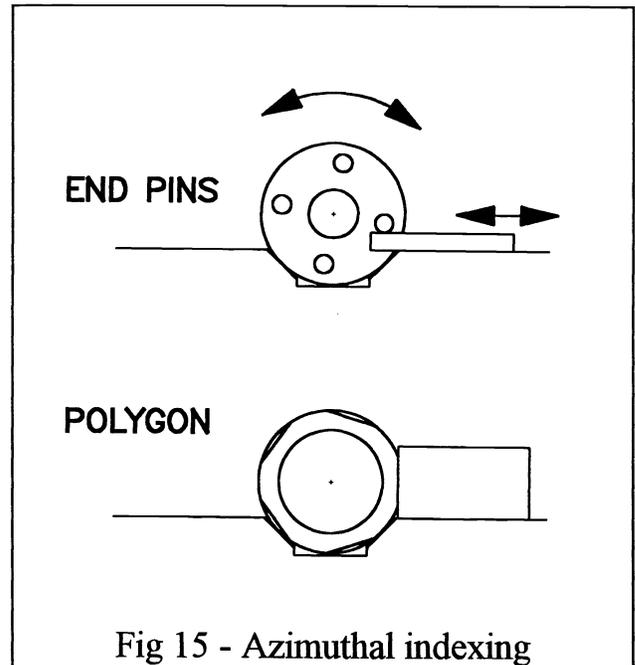
### Sine ball

Accurate azimuth changes can be effected using the principle of the sine bar, Fig. 14. The rotation of a cylinder in a V is controlled with gage blocks under a ball attached to the cylinder by an arm. The ball diameter and the distance between the center of the ball and the axis of the cylinder must be known. A cylinder could be used instead of a ball, but the machining is more difficult, and the additional contact area is not needed for instrumentation.



### Azimuthal indexing

Some ways to repeatably set a cylinder at a finite number of orientations are shown in Fig. 15. In one, a polygonal structure is machined on the cylinder and a rectangular piece or cylinder on end on the V plate contacts these surfaces. The accuracy derives from the relative angles of the polygonal surfaces, and their sizes are not critical. In another method, pins on the end of a cylinder are indexed with a rectangular piece on the V plate. A gear can be attached to the end of a cylinder and its teeth used.



## NON ROTATIONALLY-SYMMETRIC ELEMENTS

This section discusses the alignment on cylinders of some types of optical elements that are not rotationally symmetric, for instance, cylindrical lenses,\* polarizers, gratings, prisms, slits, cross hairs, rectangular openings. The elements treated here have symmetries that lend themselves to positioning with cylinder-in-V techniques.

Non-rotationally-symmetric elements fall into several categories. Some, e.g., cylindrical lenses and prisms, have shapes that make mechanical alignment possible. Planar elements can only be oriented optically. Some elements, e.g., slits, can be aligned by imaging, while others, e.g., retarders, cannot. Some elements, e.g., sheet polarizers, require only orientation control, and others, e.g., cylindrical lenses, require also the centration of a feature or a symmetry plane.

### Leveling

The term “leveling” is used here to mean orienting some direction associated with an element parallel or perpendicular to the V surface plane. Leveling can be done to put an element into its final position or to determine an initial orientation from which a controlled rotation gives the final orientation.

### Mechanical leveling

Some non planar optical elements can be leveled mechanically with a fixture like that shown in Fig. 16. An optical element is held on the end of a cylinder whose azimuth can be adjusted. The cylinder is in a V with a stop against the other end of the cylinder to prevent axial motion. There is a perpendicular slide on which an indicator is mounted. The indicator is moved across the element, and the cylinder’s azimuth is adjusted to eliminate runout. The leveled cylinder is transferred from the fixture to the instrument in which it is used, where the azimuthal stop replicates the orientation.

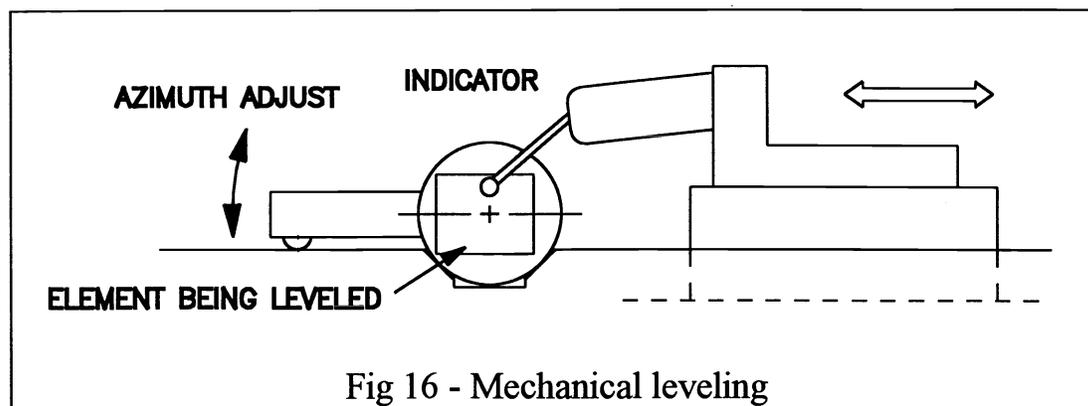


Fig 16 - Mechanical leveling

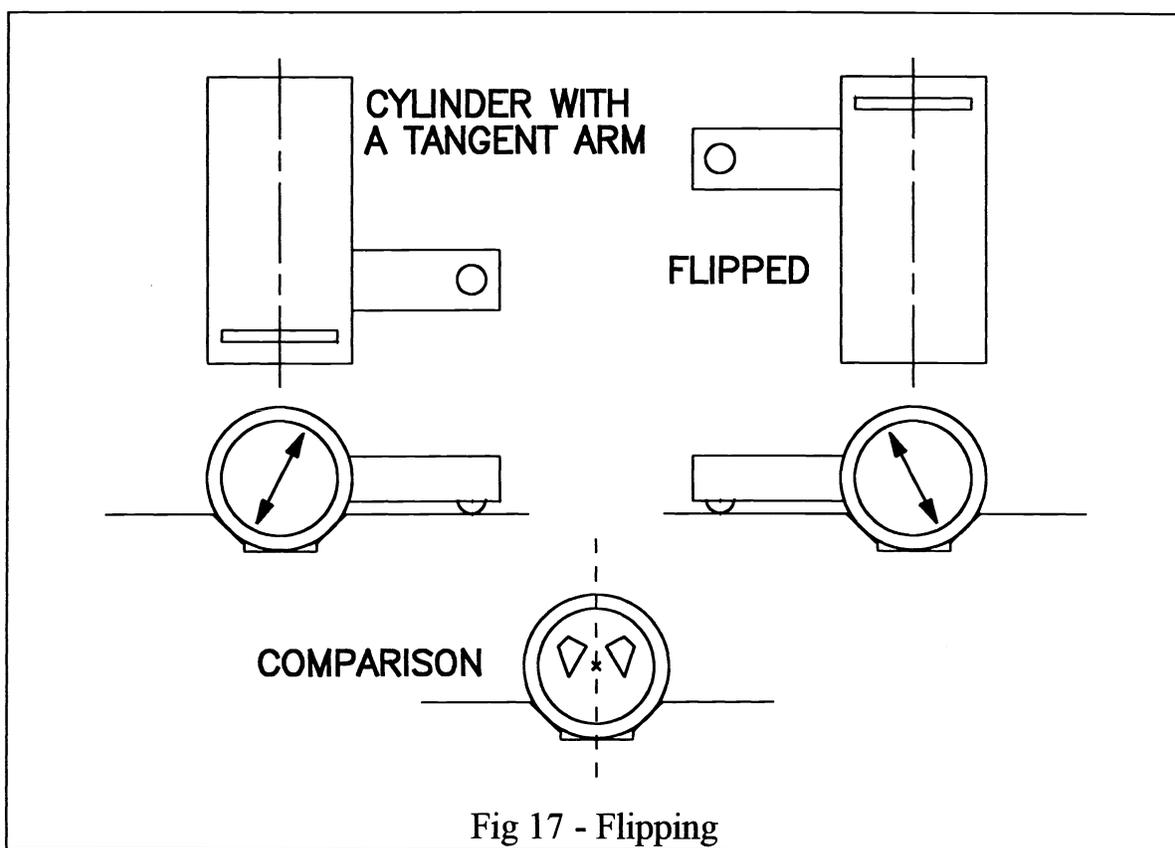
\* The term “cylindrical lens” has its common meaning.

### Optical leveling

Optical leveling, which is done with light, rather than touch, can be performed in several ways. An element can be compared with a previously leveled object. Some transmission elements can be leveled by flipping.

### Flipping

A cylinder with an azimuthal stop is flipped by lifting it from the V, rotating it 180 degrees about a normal to the V plate plane, and putting it back in the V with the azimuthal stop against the V plate plane, Fig. 17. If the cylinder holds a reticle, then flipping produces a mirror image of its pattern about the axial vertical plane. An element oriented vertically or horizontally remains so after flipping.



### Finding the vertical axial plane by flipping

A method of finding the vertical axial plane with a video system is shown in Fig. 18. A cylinder with an azimuthal stop holds a reticle with two lines. The reticle is illuminated and imaged to a video camera with a frame grabber that captures the image. The cylinder is flipped, the reticle refocused, and the image captured and compared with the first. The points at which the first and second reticle line images intersect lie in the axial vertical plane.

### Planar anisotropic elements

Plane gratings, sheet polarizer, and retarder plates have a directionality to be oriented. They can be leveled by flipping. Such elements are symmetric with 180 degree rotation, so this is not useful to orient them. They have no center or a symmetry plane that must be put on axis.

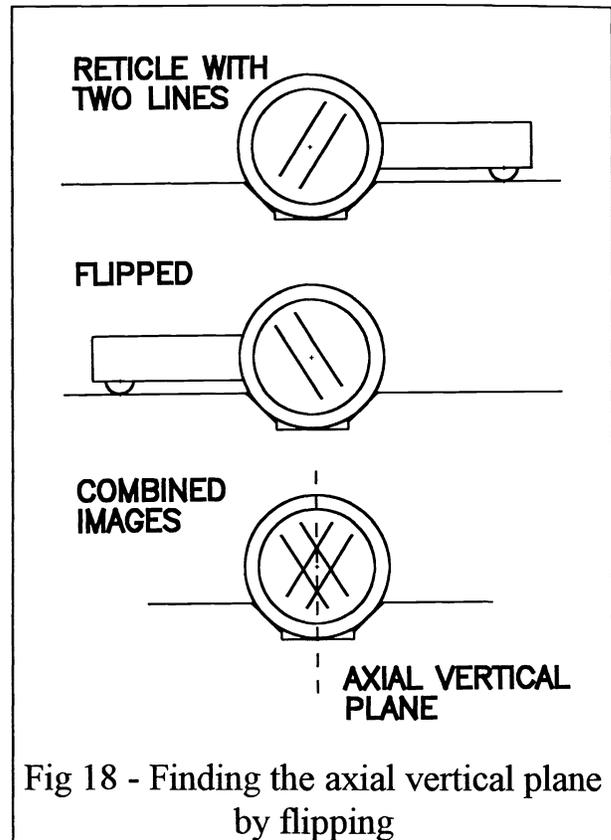


Fig 18 - Finding the axial vertical plane by flipping

### Gratings

If a grating is flipped and its diffraction orders remain in the same plane, then it is level. If the grating structure can be imaged, it can be leveled by reference to a level detector array.

### Polarization elements

Sheet polarizer can be leveled by the flipping method shown in Fig. 19. A polarizer to be leveled is mounted in a cylinder with an azimuth stop. Let  $\theta$  be the angle between the polarizer transmission axis and the axial vertical plane. A reference polarizer in the V that is not level is not moved. A beam of light passes through both polarizers and its final power is measured. The polarizer cylinder is flipped, so angle between the polarizer transmission axis and the vertical plane is now  $-\theta$ . The power transmitted by the polarizers in series differs for the flipped orientations unless the flipped polarizer is leveled. The flipping operation is not adversely affected by change in axial position so long as the beam is not obstructed for either polarizer position. This method is analogous to using a half shade plate. Wave plates can be similarly aligned between a pair of fixed polarizers.

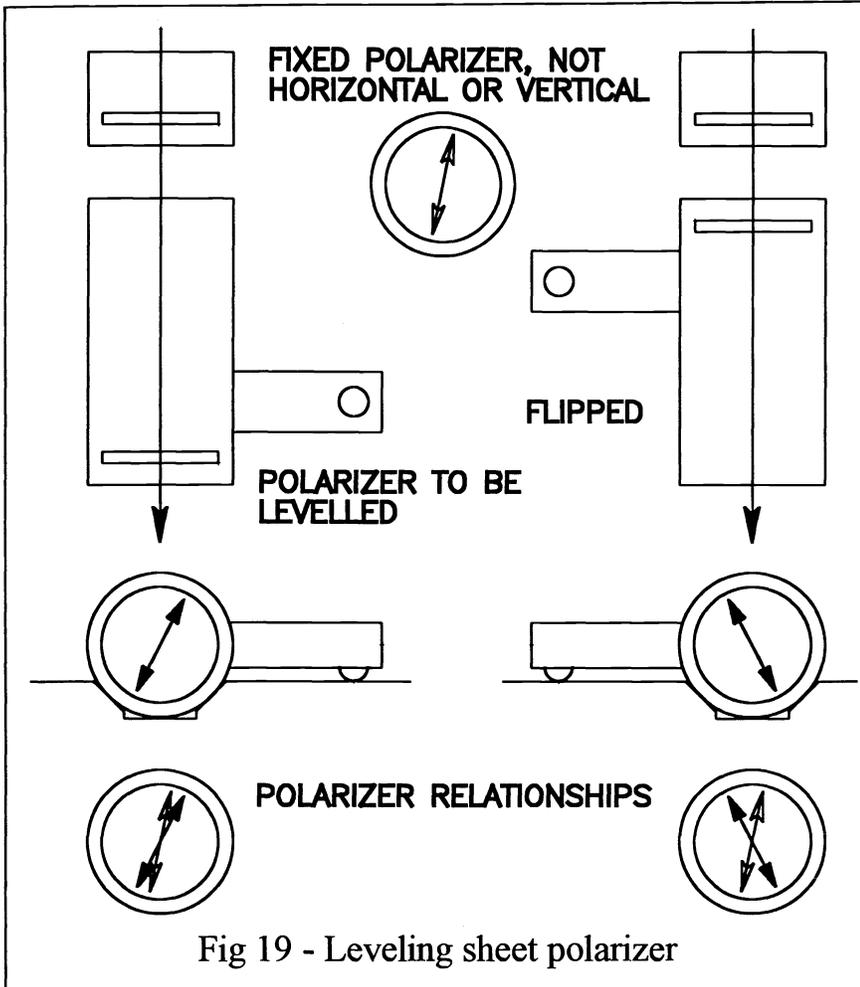


Fig 19 - Leveling sheet polarizer

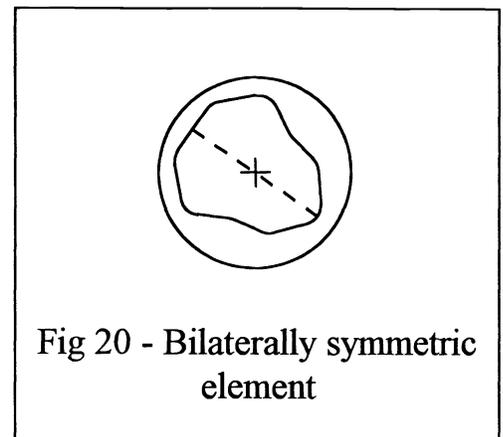


Fig 20 - Bilaterally symmetric element

### Bilaterally symmetric elements

An element with a plane of symmetry can be said to be centered when the axis passes through the plane of symmetry, Fig. 20. This constraint does not completely determine the element's position. There remains an in plane translation and a rotation about a normal to the plane. Optical elements with only bilateral symmetry are uncommon.

### Cylindrical lenses

In the common case each optical surface of a cylindrical lens is a figure of revolution about a line. The lines associated with the two surfaces are parallel and define a plane about which the optical surfaces are symmetric. The intersections with this plane and optical surfaces are two line segments. The central perpendicular to these two segments, which lies in the plane, can be taken as the axis of the cylindrical lens. Such a lens is said here to be centered when its axis is collinear to that of the system.

If a cylindrical lens is centered on a cylinder, then its position is reproduced by a 180 degree rotation of the cylinder, regardless of its initial orientation lens. Fig. 21 shows schematically a situation where this is not the case. There are several ways to test centration. With a small source of light near the system axis, a cylindrical lens produces a line of light that can be captured by a video camera. If the cylinder is rotated 180 degrees, the line is displaced unless the cylinder is centered. It is also possible to observe reflected light. The centering can be done in a V or on a precision spindle with a means of rotating 180 degrees. A cylindrical lens can be leveled mechanically.

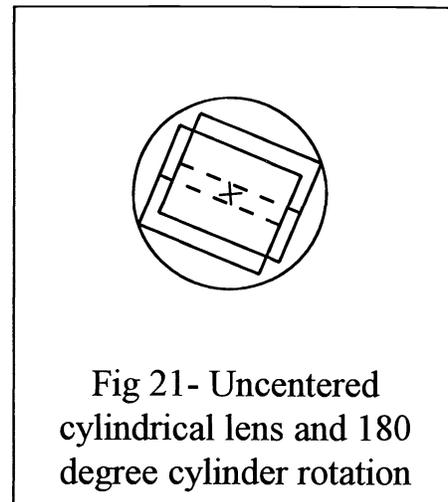


Fig 21- Uncentered cylindrical lens and 180 degree cylinder rotation

A plano-cylindrical lens can be mounted with its flat side against the end of a cylinder, in which case centering can be effected with a single motion, which can be a translation or a rotation, Fig. 22.

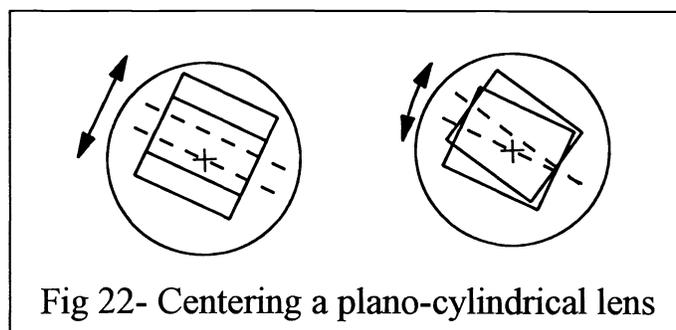


Fig 22- Centering a plano-cylindrical lens

**Slits, reticles, rectangular apertures**

Planar objects with patterns, e.g., slits, reticles, and rectangular openings, can be centered by imaging and leveled by imaging or flipping. Those objects with bilateral symmetry can be centered by 180 degree rotation.

**Prisms**

Prisms can be leveled mechanically or optically.

**Detector array centering and orientation**

A detector array can be centered on the system axis by translating the array so as to put the central pixel on a centered image. But it is easier and often acceptable, instead, to secure the array and then to determine which pixel is best centered. This can be done by imaging a centered object or by locating the axis by rotating a non-centered object, observing the locus of some point, and finding its center.

There are several ways to level a detector array. One described above is by flipping a two-line reticle. Another method is to image a straight edge parallel to the V surface plane. The straight edge need not be on axis. A good way to make a straight edge is by

cleaving a semiconductor wafer. Another method of leveling is by observing an object translating while mechanically referenced to the V plate plane, using an apparatus like that described above for mechanical leveling.

## TILT

In this paper “tilt” has to do with the direction of an element’s axis or normal. Uses of tilted elements include plane parallel plates to offset beams and mirrors to control beam directions. The optical effect in transmission of tilting a plane parallel plate does not depend on its rotation axes, so any number of mechanical arrangements can be used. It is often desirable that the reflecting surface of a mirror contain the center of rotation, and this is possible with the following devices.

### Ball in V

A ball to which a handle is attached has a through hole with a seat for a plate, Fig. 23. The ball can sit in the V with a third contact point at the end of a cylinder or attached to the plate. This unit can be locked or spring loaded from the other side.

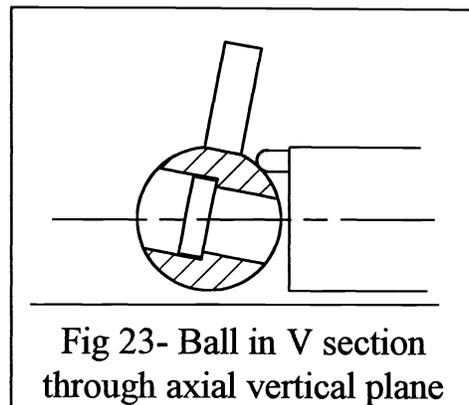


Fig 23- Ball in V section through axial vertical plane

### Ball in cone

In Fig. 25 a conical surface is machined in a cylinder. A mating piece has a spherical surface that contacts the cone and a stem against which screws bear to vary its angle. The contacting surfaces should be smoothed to reduce friction arising from their parallel machining marks. An axial through hole makes the device suitable for transmission.

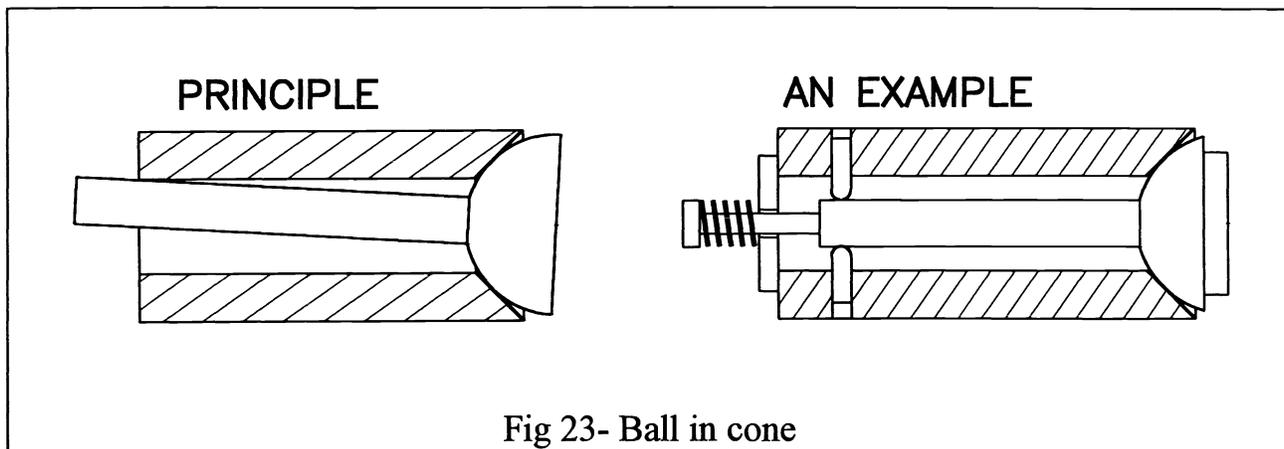


Fig 23- Ball in cone

**Sine bone**

A variant of the sine bar with two degrees of freedom or tilt might be called the “sine bone,” Fig. 25. Two spherical surfaces are connected by a bar. The diameter of one sphere equals that of the nominal cylinder, so its center is on axis. The other sphere is smaller. By shimming the two contact points of the smaller sphere, the direction of the line connecting the two centers is controlled. The center of the larger sphere can be fixed with an axial stop. This device can hold a mirror or a transmitting plate.

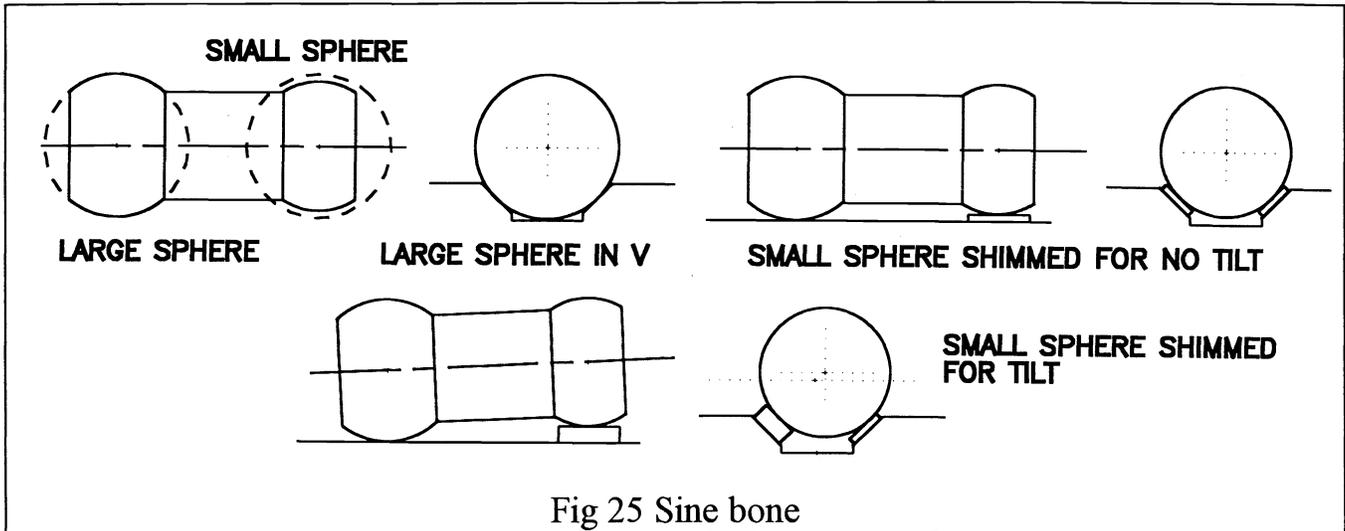


Fig 25 Sine bone

**Pair of plates**

A single tilted plate in a cylinder offsets an axial beam by a fixed amount in a radial direction that rotates with the cylinder, Fig. 26. The offsets of two such units in series add vectorially to produce a net offset whose magnitude and direction can be controlled. Two configurations are shown in Fig. 26. The sensitivity of control depends on the plate thickness and angle. This arrangement is analogous to Risley prisms, which control beam direction.

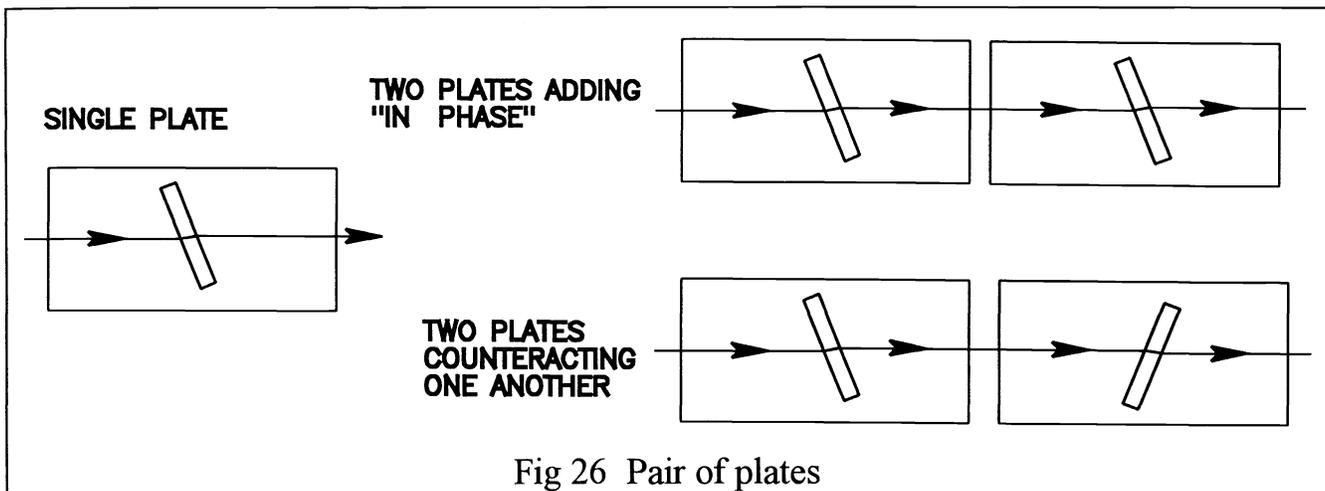


Fig 26 Pair of plates

## TWO-DIMENSIONSIONAL V ARRANGEMENTS

Cylinder-in-V methods can be extended to optical systems with multiple axes. If the axes are coplanar, the arrangement is said to be “two dimensional.” This section deals with such systems. The term “V plane” denotes the plane containing the axes. Within each V things are as before. What is added is means to redirect beams from the axis of one V to that of another. Producing a two-dimensional V structure in a plate is straightforward with numerically controlled milling machines.

### V depth

Shallow Vs are usually preferable to deep ones for two-dimensional systems. Fig. 27 shows orthogonal Vs of two depths. In one the cylinder axes lie in the V plate surface. In the other, the axes are a quarter of the cylinder diameter above the surface. The plate thickness in both equals the cylinder diameter. At the intersection of two Vs, the shallower the Vs are, the nearer to the intersection of the axes the Vs end and the less the possible overhang of cylinders. Shallower Vs leave more plate surface for apparatus such as clamps and for mechanical referencing. Shallower Vs also increase plate stiffness and thermal conduction.

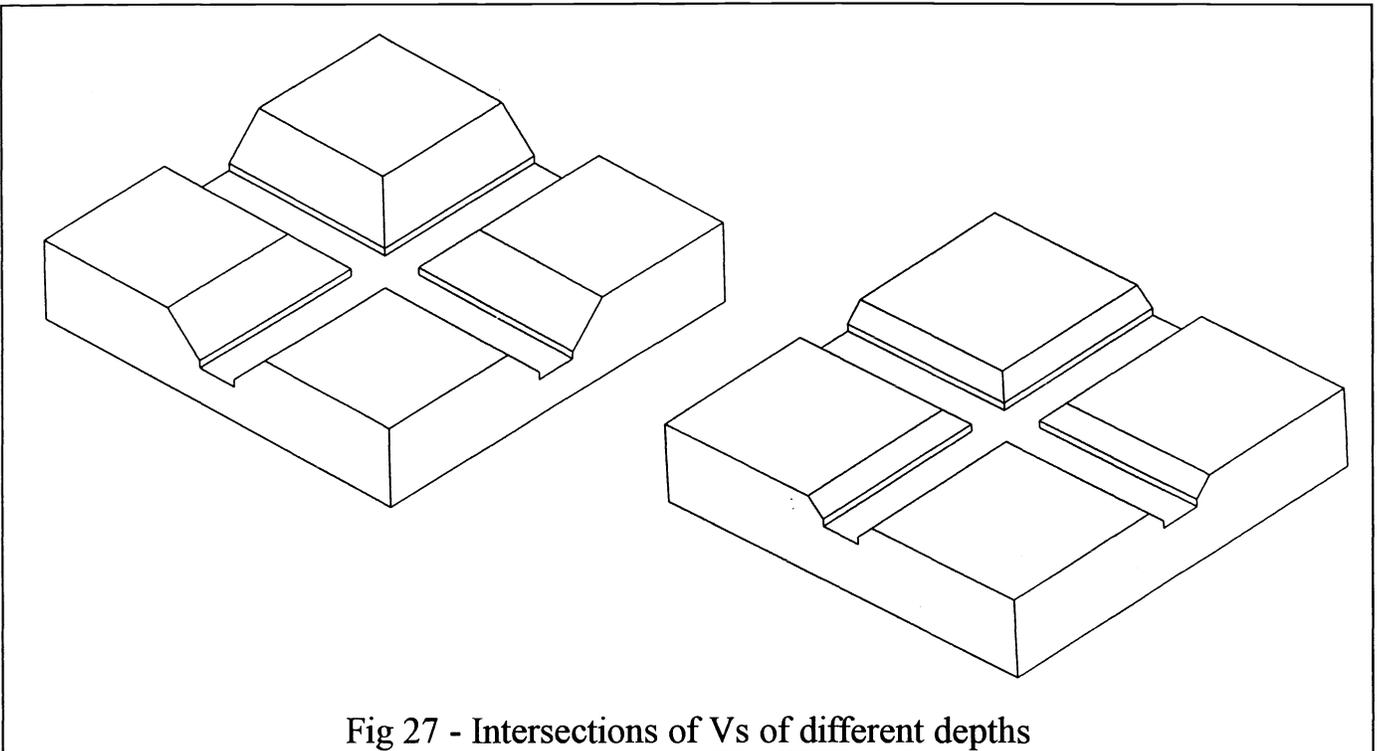
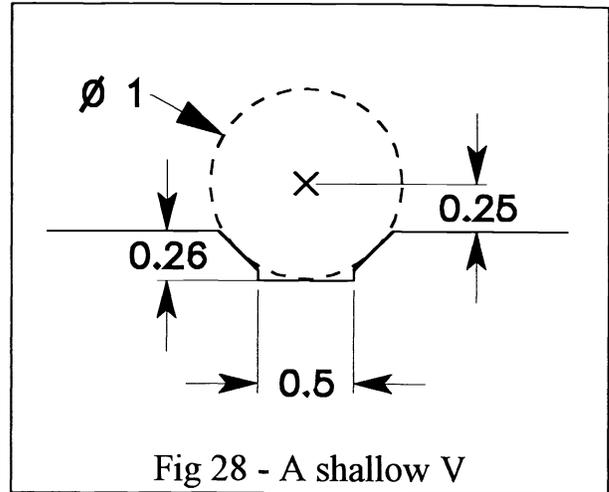


Fig 27 - Intersections of Vs of different depths

A generally useful geometry is a  $90^\circ$  V in which the axis is 0.25 of the cylinder diameter above the V plane. Fig. 28 shows such an arrangement with all dimensions normalized to a unit diameter cylinder. Most of the diagrams in this paper are shown with this configuration. At the bottom of the V is a trough with a width 0.5 of the cylinder diameter. There is a bottom clearance of 0.01 the cylinder diameter, but the trough can be deepened. (In the first paper, the common V depth was 0.5 the cylinder diameter and the trough depth was 0.75 the diameter.)

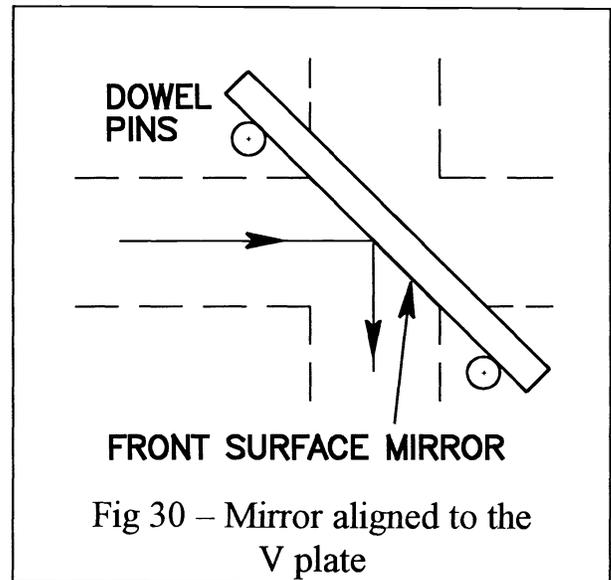


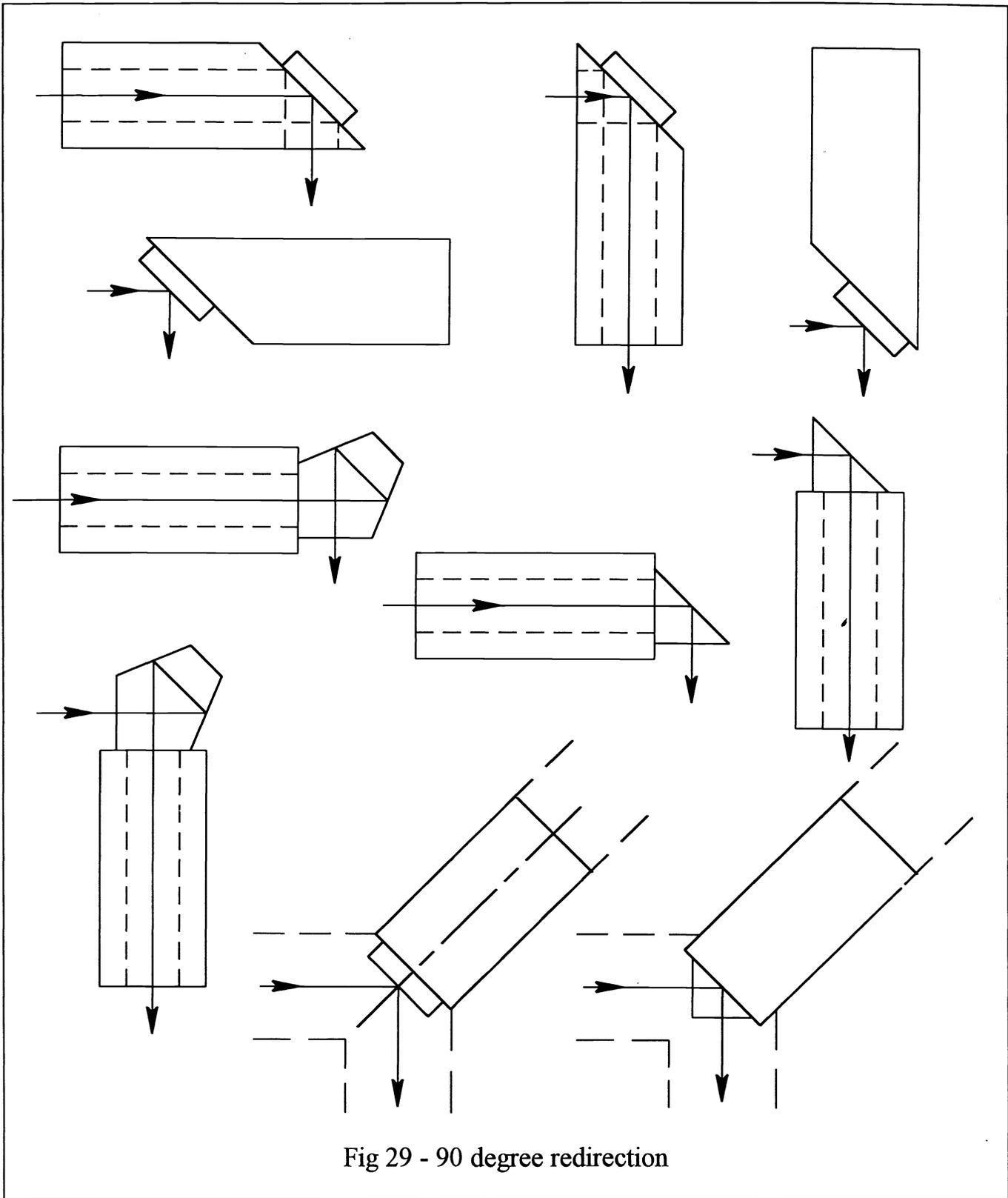
### Intersections

At V axes intersections, beams may be totally redirected by mirrors or partially redirected by beamsplitters. The redirection can be permanent or intermittent, in which case optics move into and out of the beam. The most common angle between Vs is  $90^\circ$ , and most of the drawings show such intersections, but most methods are general.

### 90 degree redirection

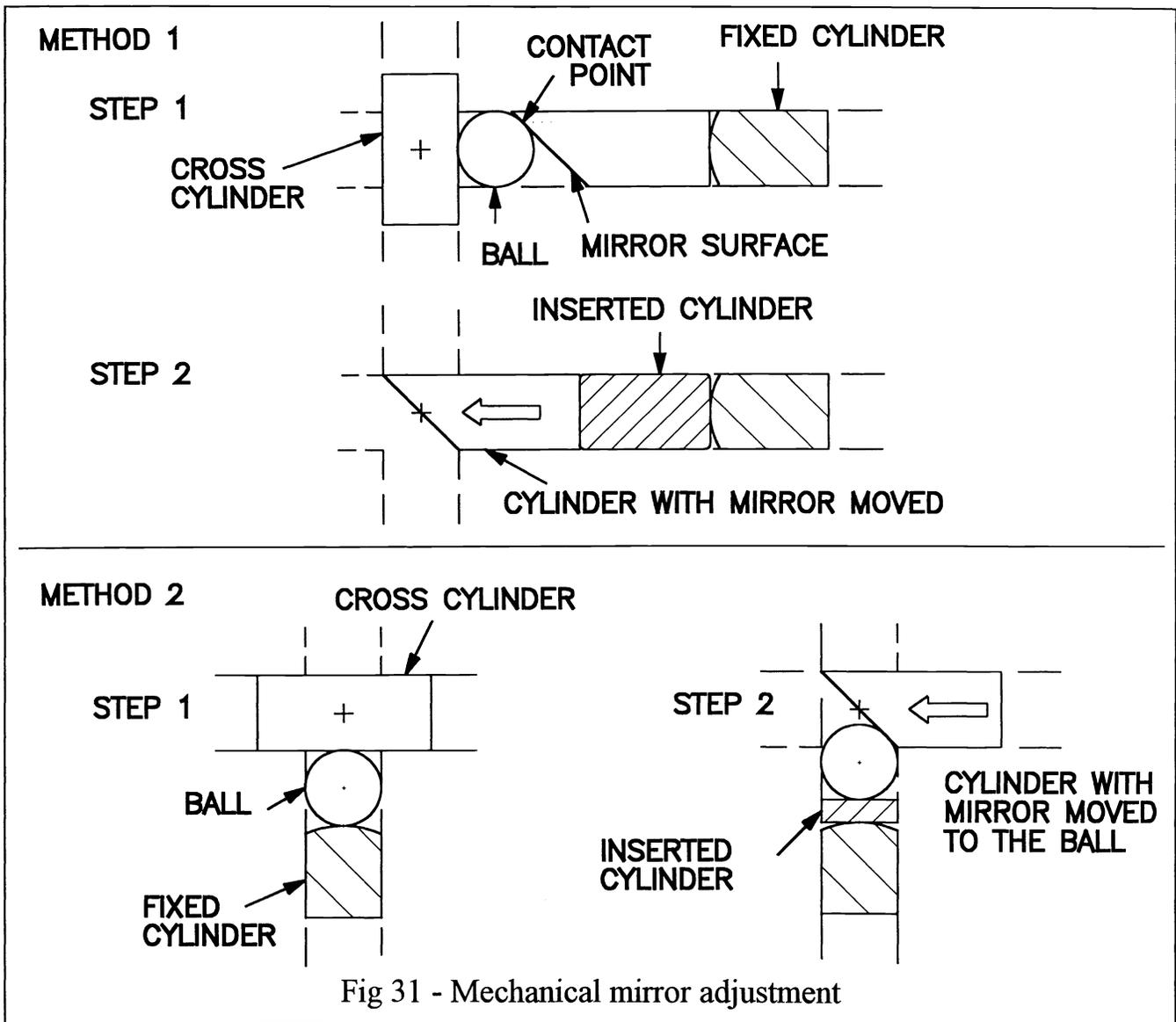
There many of ways to redirected along a beam 90 degrees. Fig. 29 shows a number of arrangements in which optical elements are held by cylinders in a V. The cylinders can lie in a V through which the beam travels, in an extension of such a V, in a perpendicular V, or in a V at another angle, e.g., one bisecting the corner. Factors in deciding which to use include space and adjustability. Some arrangements lend themselves better to mirrors that can be moved in and out of the beam. Mirrors can also be mounted to the V plate, referenced mechanically to features machined in the same setup as the Vs. An example is shown in Fig. 30.





### Mirror positioning

A cylinder with a mirror whose surface normal is not parallel to the cylinder axis has two degrees of freedom to be set so that light along one V axis is reflected along another. The azimuth of the cylinder can be set mechanically by letting the reflecting surface touch a bar or rod on the V plate surface. Alternately, mechanical alignment surfaces can be machined in the cylinder when the slanted end is produced. One approach is to mechanically locate a cylinder in its V without an optical element, to secure the cylinder, and then to cement on the element. A front surface mirror can be located axially by at least two mechanical methods best understood pictorially, Fig. 31. Both use a ball the diameter of the cylinders, a cylinder of specific length, and two cylinders whose lengths are not critical. Both involve point contact between the ball and the mirror at a point far from the axis.



### Beam splitters

A cube beamsplitter has the advantage over a plate beamsplitter of not laterally offsetting the transmitted beam. If a cube beam splitter is mounted on a cylinder whose axis lies along the transmitted beam, Fig. 32, then the transmitted beam is unaffected by the cylinder's axial position and azimuth, so these two degrees of freedom can be used freely to control the reflected beam. If the cube is attached to the cylinder off center in the V

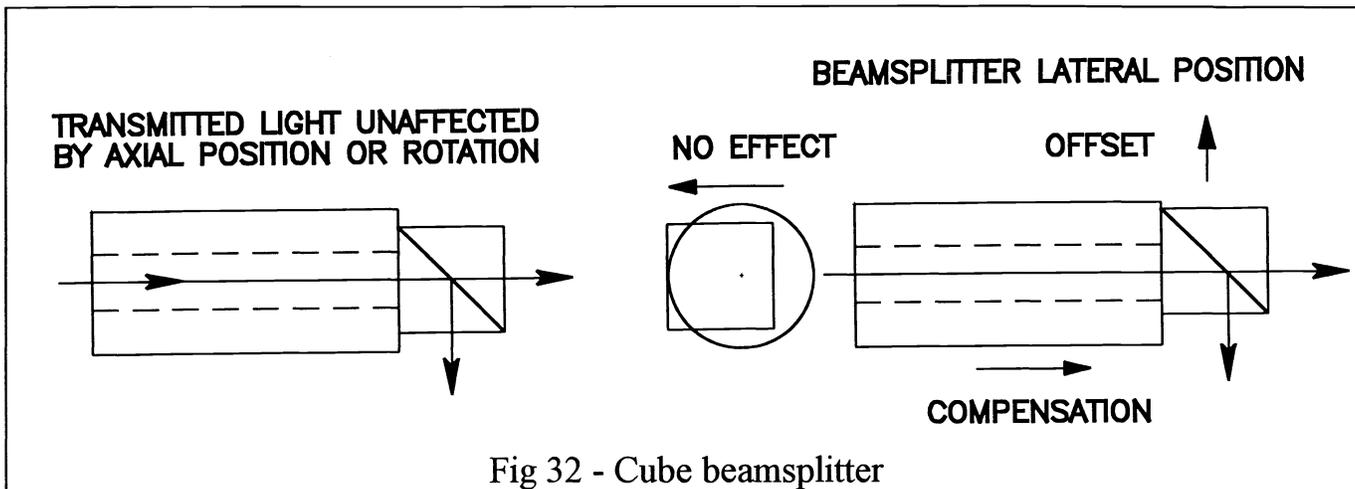


Fig 32 - Cube beamsplitter

plane, an axial translation of the cylinder compensates. The cube location in the direction vertical to the plate is not critical. A beamsplitters may require a light trap, which can be built in a cylinder located in a fourth section of V. A mechanical method to locate cube beamsplitters is shown in Fig. 33.

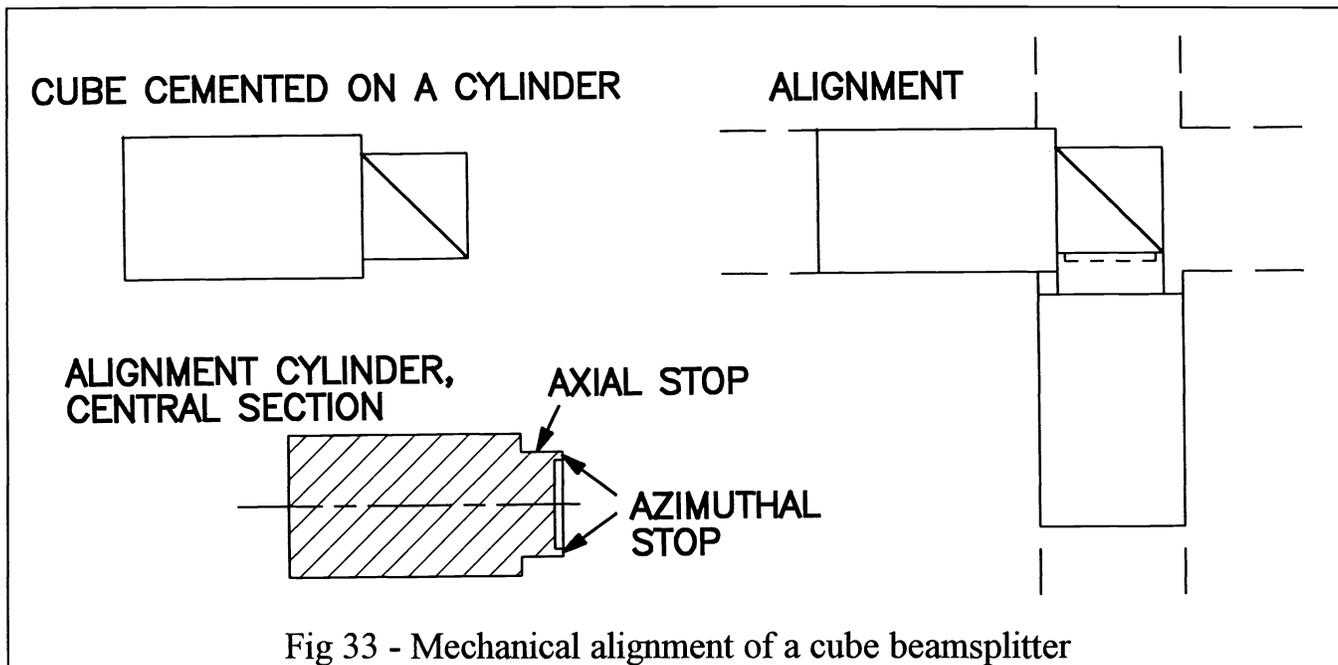
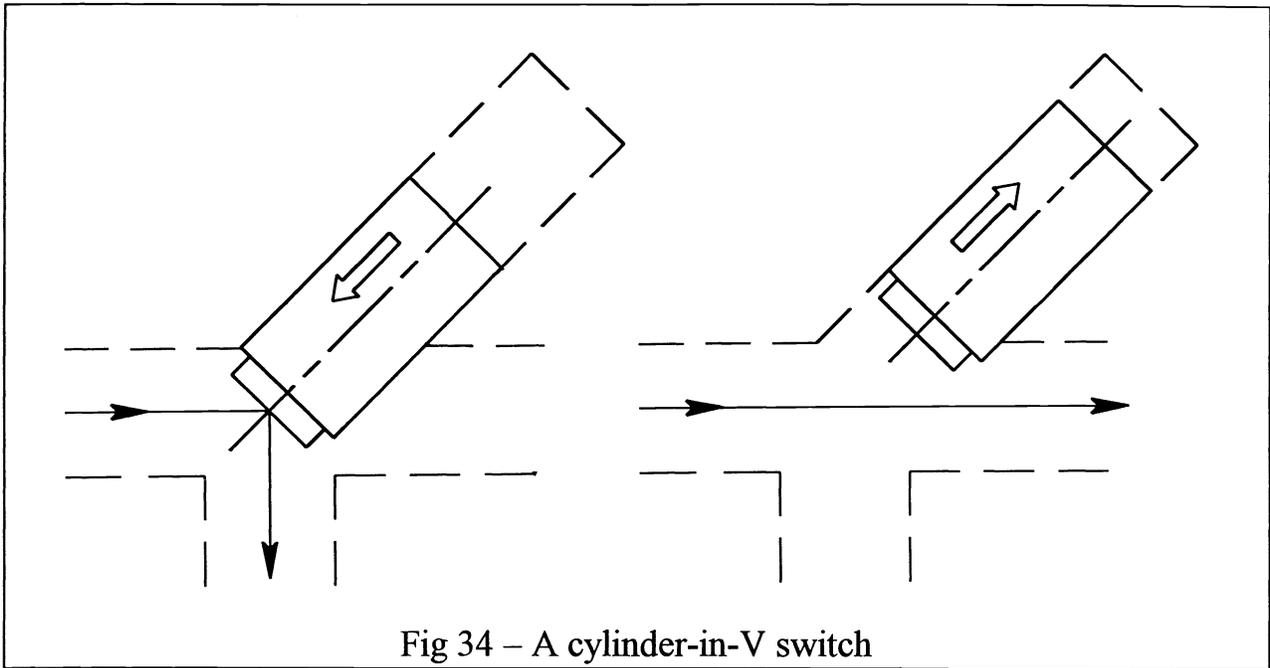


Fig 33 - Mechanical alignment of a cube beamsplitter

### Intermittent apparatus

In order to change beam paths optical elements can be moved into and out of a beam in a variety of ways. One method is with a cylinder in a V at an angle to that of the incident beam, Fig. 34. In general, this requires both axial and azimuthal control. Round cylinders can be fitted with azimuth stops and flat-sided cylinders can be used. Only axial control is needed with a mirror whose surface is perpendicular to the cylinder's axis, as is the case in Fig.34.



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