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Non-image-forming optical components

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Abstract

In this paper we review the geometrical characteristics of optical components such as plane-parallel plates, flat mirrors, and prisms that serve extremely useful purposes in optical instruments, but nominally do not contribute optical power and, hence, cannot form images by themselves. The principal uses of such components as windows; filters; reticles; beam-folding optics; beamsplitters/combiners; image erectors, rotators and scanners; etc. are addressed. Representative configurations for these components and typical designs for mounting them into common types of instruments also are described.

Introduction

Many optical components serve extremely useful purposes in optical instruments other than forming images. Nominally, they do not have optical power since their surfaces are all flat. Typical categories of these non-image-forming components are listed in Table 1. We will describe representative examples of each category, explain their functions, and consider some of the important opto-mechanical principles underlying their design.

Table 1. Typical Categories of Non-Imaging Optical Components.

- Windows
- Filters
- Reticles
- Beam folding components
  - flat mirrors
  - prisms
- Beamsplitters and beamcombiners
- Image erectors
- Image rotators and derotators
- Scanning devices

Windows

A window is commonly used in an optical instrument as a transparent interface between the internal components (optics) and the outside environment. It may also constrain the internal environment such as that within a gas laser tube, a spectrometer sample cell, or the observation channel of a wind tunnel. In its simplest form, the window is a plane parallel plate of optical glass, fused silica, plastic, or crystalline material that allows the desired radiation to pass through with minimum effect upon intensity and beam quality while excluding dirt, moisture and other contaminants. In some cases, the window must mechanically support a positive or negative pressure differential between the internal and external atmospheres.

The location of the window is important to its design. If at or near a pupil, a prime consideration is deformation of the transmitted wavefront. Cosmetic defects such as scratches and digs are of little significance. The opposite is true for a window at or near a focal plane. Defects or dirt on a window then may appear in the image produced by subsequent optics. Since thin plane parallel plates have essentially no effect upon collimated light beams or ones with very slight convergence or divergence they may be considered relatively benign elements of the optical system in such applications. If thick planeparallel windows are located in beams with large convergence or divergence they may contribute aberrations in the same manner as prisms (discussed below). Usually windows inside an optical system are thin enough for this not to be a serious problem.

Windows that are wedged to control spurious surface reflections or to deviate the beam in a specific direction may require special mounting arrangements to ensure proper orientation of the wedge apex. They may also cause spectral dispersion if the wedge angle is significant.

Table 2 is a list of important parameters to be considered in the design of optical windows. Only rarely would all these factors need be considered in a given design. Rather than to review these item by item, let us consider a few representative window configurations from the optical and mechanical viewpoints. This will help us understand some of the interrelationships between different types of applications and technical requirements. We intentionally omit consideration of high energy laser system windows since space limitations do not allow that complex topic to be adequately treated.

Table 2. Parameters of Importance in Optical Window Design

- o Transmission throughout applicable spectral range
- o Dimensions
  - Optical aperture (instantaneous and total)
  - Diameter or width and height
  - Thickness
  - Wedge angle (incl. orientation)
  - Special shape and/or bevel requirements
- o Optical properties
  - Transmitted wavefront quality requirements (or surface flatness/irregularity and index homogeneity)
  - Transmitted wavefront relative aperture (f/no)
  - Surface and bulk scatter characteristics
  - Coating requirements (reflectance, thermal emissivity, electrical)
  - Bubbles, inclusions and striae
  - Polarization characteristics
- o Environment
  - Temperature extremes and exposure profiles (storage and operational)
  - Pressure (incl. ram air and turbulence effects)
  - Pressure differential to be supported (magnitude and sign)
  - Exposure to humidity, rain erosion and particular matter
  - Radiation (thermal, cosmic, nuclear)
  - Vibration (amplitude and frequency power spectral density)
  - Shock (amplitude and duration)
- o Mounting configuration
  - Orientation relative to optical beam and windstream
  - Mechanical stresses induced (operation and storage)
  - Thermal properties of materials
  - Heat transfer mechanisms and paths
  - Mechanical interface (i.e., hole pattern, sealing)

Catalog window components

A large variety of types of plane parallel plates are available from optical component vendors to meet the needs of their customers for individual piece parts to be used in OEM optical instruments, laboratory experiments and other purposes. They can be purchased in standard sizes and uncoated or antireflection coated.

Needs for components not available as catalog items can frequently be met by special order if the specifications of the desired part do not deviate strongly from some vendor's nearest standard version. If this approach is unsuccessful, the need can usually be met by custom fabrication to print.

Laser tube windows

Figure 1 shows schematically the construction of a typical 632.8 nm helium neon continuous wave gas discharge laser tube with external resonator mirrors. The ends of the tube are sealed with thin windows made typically of uncoated glass fused in place. They are oriented at Brewster's angle (about 55^{o} incidence) to preferentially transmit collimated beams of P - polarized light about 2 mm in diameter.

These windows are usually rectangular or elliptical in shape, have thickness sufficient to maintain optical figure while supporting a modest pressure differential between the ambient exterior and low pressure gas interior atmospheres, and are considerably larger than the transmitted beam diameter. The window surfaces must be parallel to a few arc-seconds and flat to at least 0.01 wave over the used aperture.

Military telescope entrance window

Figure 2 shows a window subassembly typical of what might be used as an environmental seal at the entrance aperture of a high magnification military telescope. In this example, the optical part is a disc of borosilicate crown glass nominally 52 mm in diameter and 8.8 mm thick. Since the light beam transmitted through this window is collimated and nearly fills the clear aperture at all times, the critical specifications for the window are transmitted wavefront error ($\pm$0.5 wave power and 0.05 wave peak to valley irregularity for green light over the clear aperture) and wedge angle (30 arc-sec maximum). By choosing high quality optical material (Schott BK7), the designer is confident of a high degree of refractive index homogeneity, freedom from striae, bubbles and inclusions, adequate climatic resistance, and ease of fabrication. This window is antireflection coated with magnesium fluoride on both sides to maximize mechanical durability and environmental resistance while providing high transmission (over 98 percent per surface) at visual wavelengths.

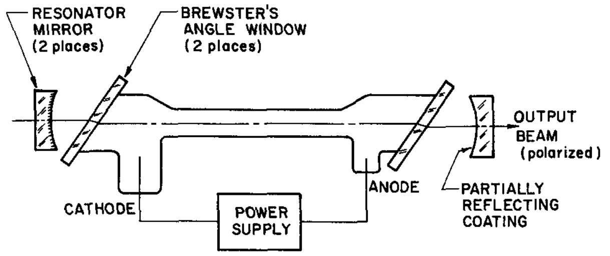


Figure 1 - A gas discharge laser with external resonator mirrors employs Brewster's angle windows to seal the low pressure gasfilled tube.

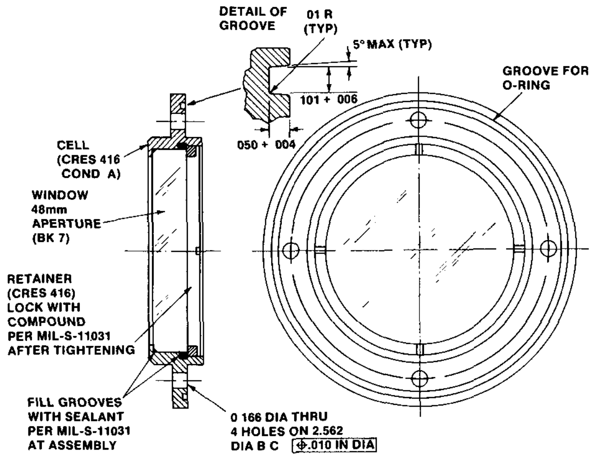


Figure 2 - Example of a circular aperture window subassembly for a military telescope. The optic is held in place with a threaded retainer and sealed with an elastomer.

Mechanically, the window is secured into a stainless steel cell with a torqued threaded retaining ring (also made of stainless) and sealed with a MIL-spec elastomeric sealant. The cell is provided with a mounting flange that is grooved to accept an O-ring as indicated in the detail view. When bolted to the telescope housing, the seal is adequate to hold a positive pressure differential of 5 lb/in^2 relative to the external ambient pressure for an indefinite (but long) period. The bowing of the window due to this pressure differential is insignificant.

Window for an airborne electro-optical sensor

The multi-aperture window assembly shown in Figure 3 is designed for use in a military aircraft application involving a forward looking infrared (FLIR) sensor operating in the 8,000 to 12,000 nm spectral region and a laser rangefinder/target designator system operating at 1,060 nm. The larger window is used by the FLIR system and is made of a single pane of chemical vapor deposited (CVD) zinc sulfide (ZnS) approximately 1.6 cm thick. Its aperture is 30 x 43 cm. The smaller windows are similar and have elliptical apertures of 9 x 17 cm. They are used by the laser system and are made of BK7 glass 1.6 cm thick.

All surfaces are appropriately antireflection coated for high transmission at the specified wavelengths and at $47^{\circ} \pm 5^{\circ}$ angle of incidence. The coating also provides rain erosion resistance. The specifications for transmitted wavefront quality are 0.1 wave peak to valley at 10,600 nm over any 25.4 cm instantaneous aperture for the FLIR window and 0.2 wave peak to valley power plus 0.1 wave irregularity at 632.8 nm over the full aperture for the laser windows.

The CVD ZnS used in this design is not the easiest material to work with. It transmits adequately in the visible for the optician to select the region in each raw slab most free of inclusions and bubbles for location of the finished window.

Mechanical strength of the infrared and laser windows is enhanced by controlled thickness removal with progressively finer grits during grinding to ensure that all subsurface damage caused by the previous operations has been removed. Wedge also is brought within specified limits (66 arc-sec maximum for the ZnS window and 30 arc-sec maximum for the BK7 windows) during the grinding process. The edges of all windows are control ground and polished primarily for strength reasons.

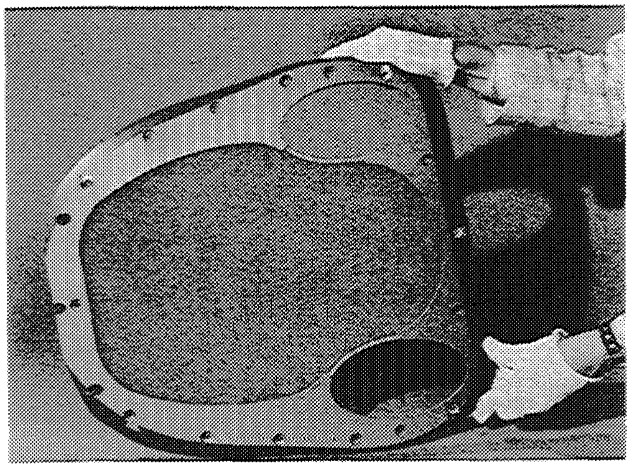


Figure 3 - A multi-aperture, multi-spectral window subassembly used in an airborne electro-optical sensor system. The large window is infrared transmitting while the two smaller ones are optical glass.

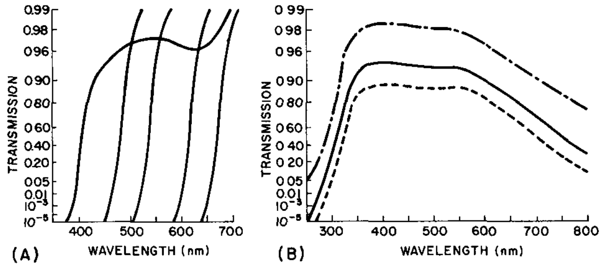


Figure 4 - Representative transmission curves for sharp-cut filters effective in the visible spectrum; (A) long-wave pass filters; (B) short-wave pass filters. Data from Schott Glass Technologies, Inc.

Because of inherent localized material refractive index inhomogeneities, as large as 5×10^{-4}, a ZnS window polished with flat surfaces usually fails the transmitted wavefront quality test. Fortunately, the bad regions have higher index so the required quality can be achieved by localized hand or computer controlled polishing of one side.[1]

All three window panes are bonded with an elastomeric adhesive into a lightweighted frame made of aluminum plate anodized after machining to the complex contours shown in Figure 3. The bonded assembly attaches to the aircraft structure by screws passing through the several recessed holes around the edge of the frame. The mating surfaces of the frame and structure must match closely in contour in order not to deform the window.

Optical filters

An optical filter may be thought of as a special kind of window; one that has the capability of attenuating particular wavelengths of radiation while passing other wavelengths with little or no change. The attenuation process may involve ionic absorption or selective scattering within the substrate material or within an applied thin film coating. It may also result from selective reflection or interference effects. The substrate may be glass, plastic, gelatin, liquid, or crystalline material as suits the application.

It is most convenient to describe a filter in terms of its spectral properties. In fact, this is the only generic way in which they differ from windows. A plot of transmittance vs wavelength is the best means of defining a filter's spectrophotometric characteristics.

The fraction of the incident light transmitted at normal incidence through an absorbing filter of thickness x at a given wavelength (called its transmission factor T_{lambda}) can be computed to a level of approximation adequate for most engineering purposes from the internal transmittance Tt provided by the filter manufacturer for a specific thickness t of the material at the wavelength in question. The pertinent equation[2] is then:

$$T_{lambda} = \frac{2N}{N^2 + 1} T_t^{\,x/t} \qquad (1)$$

In this expression, the first term, involving the material's refractive index N, approximates the Fresnel losses including multiple reflections, but neglecting absorption for the internally reflected beams.

If the beam is incident obliquely at an angle I, the absorbing path x through the filter is increased by a factor $N/(N^2 - \sin^2 I)^{1/2}$. The Fresnel equation also changes to more complex forms involving the light beam's state of polarization.[3] Since the loss of intensity due to surface reflections is generally a small fraction of the absorption achieved, the normal incidence value is frequently used at all but the most extreme incident angles.

All optical filters fall into one or more of five general categories which identify them by their spectral properties.[4]

Sharp-cut filters

These have a more or less abrupt division between spectral regions of high and low transmission. Figure 4(A) illustrates typical filters for which the cut occurs at various colors in the visible. These are long-wave pass filters. Filters with short-wave pass characteristics are shown in Figure 4(B). The ones shown have heat absorbing properties. Sharp-cut filters are sometimes identified by the wavelength at which the transmittance equals 37 percent and the slope of the "cut" which is defined as the wavelength difference between the 5 and 70 percent transmittance points.

Band-pass filters

These filters transmit within a specific spectral region and reject out-of-band radiation. The spectral region of interest in a given application is called the "pass band" and may be represented in terms of the wavelength interval in which the transmitted intensity is at least 50 percent of the peak value. Figure 5 shows the transmission curve for a typical filter with pass-band in the green region of the visible spectrum.

Compensating filters

These filters have more gradual changes in transmission. One prime application is in photography where they are used to modify the spectral characteristics of the illumination to more closely match the sensitivity curve of the film. Most of the Wratten series of gelatine filters supplied by Eastman Kodak Company fall into this category.

Neutral density filters

Filters with nearly uniform transmission characteristics over extended spectral ranges (usually including the visible region) are called "neutral". The transmission property for this type of filter is commonly expressed as optical density D, defined as (-log T) where T is the transmission factor. For example, for $T = 0.01$, $D = 2$. A typical transmission curve for a ND 1 filter is included in Figure 5.

Some neutral filters function by absorption while others rely upon reflection from coatings such as evaporated metal (typically Inconel). Obscuring mesh screens or grids serve this purpose in some applications where diffraction is not a problem or in spectral regions where normal optical substrates do not transmit.

Counter-rotating Polaroid films or polarizing prisms (such as the Nicol variety) serve as adjustable neutral filters. Filters with continuously or stepwise variable reflecting metallic film thickness along a line or around a disc also make variable transmission devices. Still another type of variable neutral filter functions by changing the Fresnel reflection losses at uncoated surfaces of a set of four tilted fused silica wedge prisms arranged so as to counterrotate about an axis perpendicular to the plane of refraction.[5]

Interference filters

Members of this general category of filters function by virtue of multiple-beam interference of light within stacks of low and high refractive index thin film layers deposited on an optical substrate. They include (1) single films such as the quarter-wave magnesium fluoride layer commonly used as an antireflection coating on optics--as well as multi-layer coatings for the same purpose, (2) beamsplitters/combiners in which dielectric layers transmit and reflect either neutrally or selectively (i.e. as a dichroic), (3) narrow band-pass (spike) filters, (4) reflection enhancing coatings for metallic mirrors and (5) polarizers.[6]

The wavelength at which an interference filter peaks depends strongly on the inclination of the incident beam since this affects the optical path through the coatings. The magnitude of the peak shift with angle change depends upon the refractive indices used in the filter design. In practice, filters with half band-width larger than 30 angstroms have inconsequential shifts in convergent or divergent beams up to 5° total cone angle (f/11).

As a rule, interference filters are temperature sensitive in two ways. The central wavelength shifts linearly with temperature at a rate (typically) of 0.1 to 0.3 angstroms per degree C. The operating temperature range of these filters is generally from $-60^{\circ}C$ to $70^{\circ}C$ if the rate of change is less than $10^{\circ}C$/minute. Permanent damage may result from faster changes or exposure to temperatures outside the safe operating range. Some interference filters also are susceptible to humidity damage.[7]

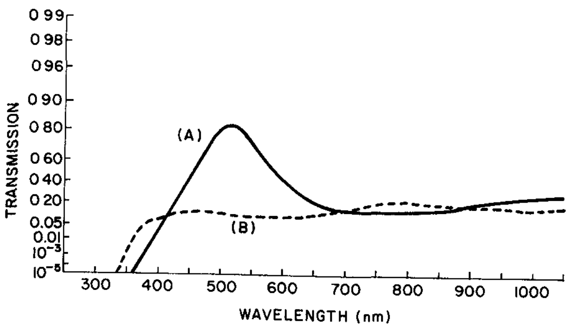


Figure 5 - (A) Representative transmission curve for a green transmitting band-pass filter. (B) Transmission curve for a ND 1 neutral filter.

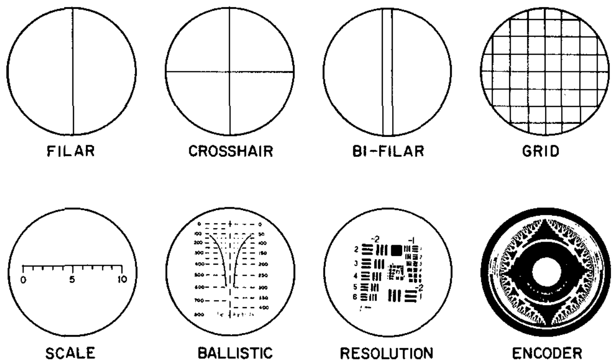


Figure 6 - Some reticle patterns commonly used for various purposes in optical instruments.

Reticles

A reticle (or graticule as is is called by the British) is a device which causes a geometric pattern to appear superimposed upon the field of view of an optical system such as a visual telescope or camera. This forms a pointing reference or a means for measurement. Several typical patterns are shown in Figure 6. The thicknesses of the lines are exaggerated here for visibility. Resolution targets for collimators, binary disks used in optical encoders and reseau plates used in metrological cameras are really special forms of reticles.

The most common way of introducing a reticle pattern is by means of a thin glass window bearing the desired markings located at a system image plane. Fine spider web (typically 2 to 3 micrometers in diameter) stretched across an open frame is the traditional way of making a simple cross hair. Deve described in great detail a procedure for "harvesting" the best web threads and securing them to the frame.[8] Fine platinum wire can also be used for this purpose.

Glass reticles can be made by diamond scribing the pattern into the glass, usually with a pantograph, etching through a scribed resist and filling the grooved pattern, by photo lithography, by the glue silver process, by the black print process or by direct photography on a fine grain emulsion. Deve also detailed the engraving and acid etching processes.[8] Smith described each of these processes briefly and compared the line widths that typically are produced thereby.[9]

The appearance of the pattern depends strongly upon the reticle line widths, the illumination conditions, the background, and the magnification. In a visual telescope with the reticle at the eyepiece focus (see Figure 7), the angular subtense of the line in milliradians at the eye is given by (1000 line width)/eyepiece EFL. For example, a line 12.5 micrometers wide will subtend 0.5 mrad if observed with a 25 mm EFL eyepiece. This is typical of the nominal apparent widths of etched and filled reticle lines used in U. S. military fire control instruments. Alphanumerics are designed to appear typically 6 to 10 mrad high in these applications.

An advantage of the etched and filled reticle is that it can be edge illuminated when natural lighting is dim so the pattern appears bright against a darker target background. Small "grain of wheat" light bulbs powered by batteries were developed during World War II for this purpose.

In some applications it is necessary for the reticle pattern to be projected into the optical path rather than to lie directly in the beam. As an example, an aircraft pilot's heads-up gunsight such as that shown schematically in Figure 8 requires that a bright-line reticle pattern be reflected as a collimated beam from a beamcombining plate into the eyes. A back-illuminated opaque reticle with transparent lines located at the focus of a collimating lens can provide the needed image.

Generally the opto-mechanical design problems associated with reticles involve the mechanization of alignment adjustments and the stability of location of the element once adjusted. In simple fire control instruments, it is common practice to hard mount all the optics, including a glass reticle, into the instrument housing then to focus the objective and the eyepiece to the reticle. The line of sight of the device is then aligned angularly in an adjustable mount relative to the associated weapon. In other applications, the instrument is hard mounted and lockable lateral adjustments are provided internally to permit the reticle pattern to be adjusted to some external alignment reference.

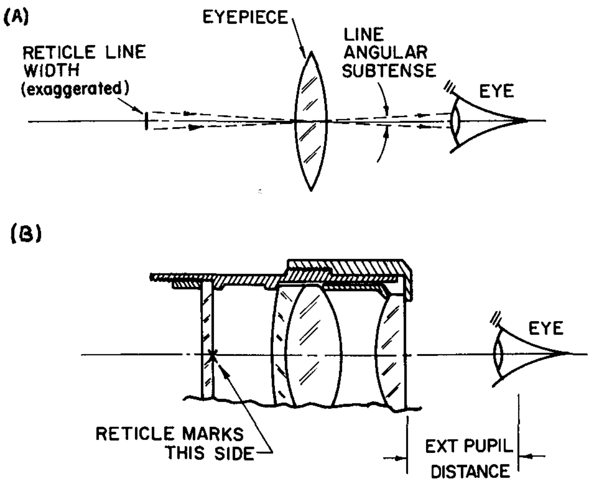


Figure 7 - (A) Schematic of a reticle at an eyepiece focal plane illustrating the angular subtense of a typical line. (B) Optomechanical subassembly of a typical telescope eyepiece with a reticle.

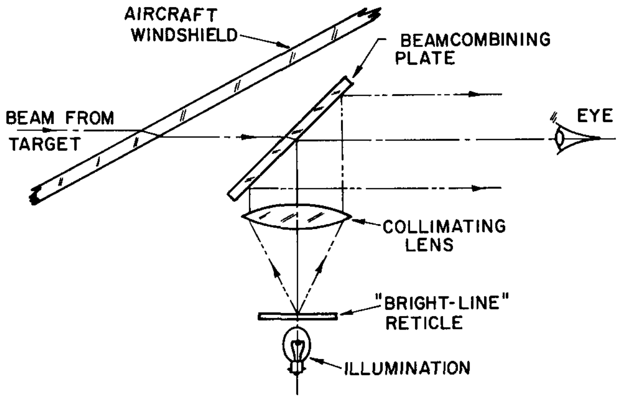


Figure 8 - Simplified schematic of a typical "heads-up gunsight for an aircraft application. The reticle pattern is projected as if at infinity superimposed upon the view of the distant target area.

Flat fold mirrors

The principal uses of flat mirrors in optical systems are listed in Table 3.

Most mirrors used today in optical instruments are of the first surface type and have thin metallic film reflecting coatings such as aluminum or silver overcoated with a protective dielectric coating such as magnesium fluoride or silicon monoxide. Substrates are typically crown glass, fused silica, one of the low expansion materials (such as ULE or Zerodur), or metal (such as aluminum, beryllium, copper, or molybdenum).

The physical size of the mirror is, of course, determined primarily by the size and shape of the "beam print" of the light beam to be reflected plus any allowance considered appropriate for mounting provisions, misalignment, and/or beam motion during use. The "beam print" can be determined from a scaled layout of the system showing the extreme rays of the light beam. This method is rather time-consuming and often inaccurate due to compounded minor drafting errors. A preferred method is to have the lens designer raytrace the beam through the mathematical representation of the mirror surface. One ray in the tangential meridian and one in the sagittal meridian should suffice for an axisymmetric system. The thickness of the substrate is traditionally chosen as 1/5th to 1/10th the largest face dimension. Thinner or thicker substrates are used as the application allows or demands.

The appropriateness of the design of a mechanical mounting for a flat mirror depends upon a variety of factors including the inherent rigidity of the optic; the tolerable movement and distortion of the reflecting surface; the magnitudes, locations and orientations of the steady-state forces driving the optic against its mount during operation; the transient forces driving the optic against or away from the reference surfaces during exposure to extreme shock and vibration; thermal effects; the flatness of the mounting surface on the optic; the size, flatness, and coplanarity of the mounting surfaces (pads) on the mount; and the rigidity and long-term stability of the structure supporting the mount. In addition, the design must be compatible with assembly, adjustment, maintenance, package size, weight, and configuration constraints and, of course, must be affordable in the context of the cost of the entire instrument.

Figure 9 shows a relatively simple means for attaching a glass mirror to a metal surface. The reflecting surface is pressed against three coplanar machined (lapped) pads by three spring clips. The spring contacts are directly opposite the pads so as to minimize bending moments. This design constrains one translation and two tilts. The spacers that position the clips are machined to the proper thickness for the clips to exert clamping forces (preload) of controlled magnitude normal to the mirror. The spring clips

Table 3. Principal Uses of Flat Mirrors in Optical Systems

o To bend (or deviate) light beams around corners
o To fold an optical system into a given shape
o To provide proper image orientation
o To displace the optic axis transversely
o To provide optical path adjustment
o To split or combine beams by intensity sharing

must be strong enough to restrain the mirror against the shock and vibration to which it may be subjected.

Lateral motions of the mirror on the pads and rotation about its normal are not constrained other than by friction in the design represented in Figure 9. This is allowable (within limits) because performance of a flat mirror is insensitive to these motions. Excessive lateral movement of the optic can be prevented by adding stops or, if the mirror is round, by sizing the spacers so as to provide a minimal clearance to the mirror. Thermal expansion differences must be taken into consideration if the mirror touches these stops.

One easily overlooked problem in designing clamped mountings is the direct path from metal to glass that could cause damage under severe mechanical shock conditions during the rebound after shock compression of the clamps. This effect is worthy of consideration in larger assemblies where the mass of the mirror supported is significant.

A technique that is highly favored by opto-mechanical engineers for mounting small to medium sized mirrors and prisms involves glass-to-metal bonds using adhesives. This design technique generally results in reduced interface complexity and compact packaging while providing mechanical strength adequate for withstanding the severe shock, vibration, and temperature changes characteristic of military and aerospace applications. The technique is also frequently used in less rigorous applications because of its inherent simplicity and reliablity.

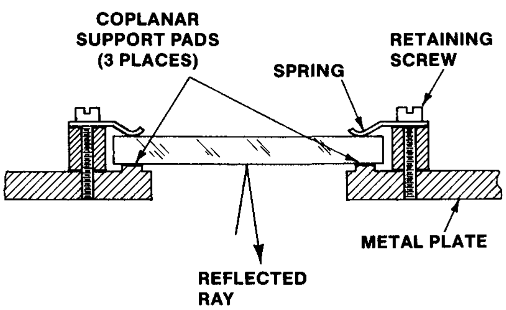


Figure 9 - Typical construction for a clip-mounted flat mirror subassembly.

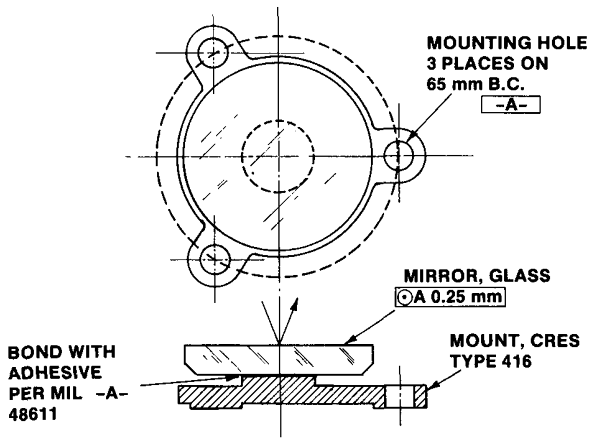


Figure 10 - Typical construction for a bonded flat mirror subassembly.

It is quite feasible to bond first surface mirrors of aperture 15 cm or less directly to a mechanical support. The ratio of largest face dimension to thickness should be less than 10:1 in order not to distort the mirror surface. Figure 10 illustrates such a design. The mirror is made of Schott BK7 glass, is 5 cm in diameter and is 0.84 cm thick (6:1 ratio). The mounting base is stainless steel. The bonding land is circular and has an area of 3.2 cm^2. Epoxy adhesive is appropriate for use in this design. Care should be exercised during its application to ensure that only a very minute fillet remains around the glass-to-metal interface to prevent stressing the glass during curing.

The critical aspects of a glass-to-metal bond are the characterics of the chosen adhesive, the thickness of the adhesive layer, the cleanliness of the surfaces to be bonded, the dissimilarity of coefficients of thermal expansion for the materials bonded, the weight-to-bond area ratio, and the care with which the bonding operation is performed.

For maximum bond strength, the adhesive layer should have a specific thickness. For a typical epoxy, this is 0.075 to 0.125 mm. A simple method for assuring the right layer thickness is to temporarily place plastic shims of the specified thickness locally at three places symmetrically located on one bonding surface before applying the adhesive. Care must be exercised to register the glass part against these shims during assembly and curing. The adhesive should not extend between the shims and either part to be bonded since this could markedly affect the adhesive layer thickness.

Figure 11 shows a concept for a flexure mounting in which a mirror of rectangular shape is supported in a cell attached to three wide flexure blades. The dashed lines indicate the directions of freedom (approximated as straight lines). The intersection of these lines does not coincide with the geometric center of this particular mirror nor with the center of gravity of the mirror/cell combination. By changing the angles of the corner bevels and relocating the flexures, the intersection point could be centralized and the design improved from a dynamic viewpoint. In either case, thermal expansion of the mounting can occur without stressing the mirror. Since the flexures are stiff in the direction perpendicular to the mirror face, motion in that direction is resisted.

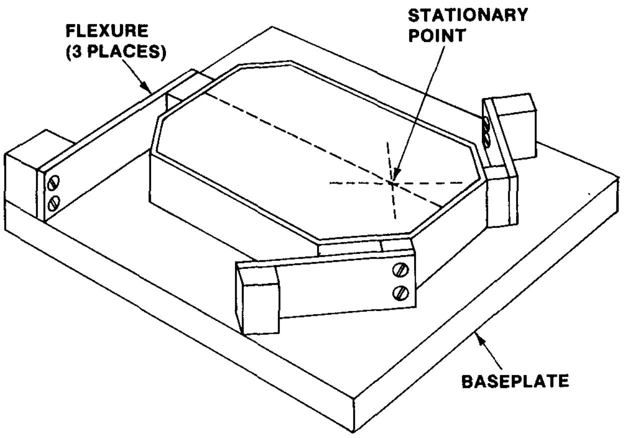


Figure 11 - Conceptual sketch of a flexure-mounted rectangular flat mirror subassembly.

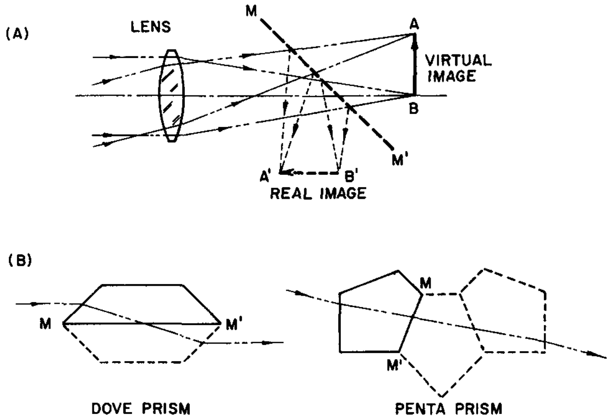


Figure 12 - (A) Reflection of a light beam at a 45° mirror or prism surface folds the path 90° about the line MM'. (B) Tunnel diagrams for two typical internally-reflecting prisms.

Prisms

Prisms are almost always made of good quality optical glass and serve the same purposes in optical instruments as mirrors (Table 3) plus the following:

- To disperse light spectrally
- To modify the aberration balance of the system.
- The design considerations of Table 2 apply also to prisms.

Internally reflecting prisms are generally designed so that the entering and exit faces are both perpendicular to the optical axis of the transmitted beam. If the beam is collimated and enters the prism normal to the entrance face, no aberrations are introduced. Aberrations are introduced if the beam is divergent or convergent and become asymmetrical if the beam enters at an angle to the axis. In a converging beam, a prism overcorrects the three longitudinal aberrations (spherical, chromatic aberration, and astigmatism) while it undercorrects the transverse aberrations (coma, distortion, and lateral color). Smith provided convenient equations for computing the aberration contributions of a prism by defining it as a thick plane parallel plate.[9]

Reflection at a mirror or within a prism constitutes "folding" of the ray paths. In Figure 12(A) the lens images an arrow at AB. If a reflecting surface is inserted as indicated by the dashed line MM', the reflected image is formed at A'B'. Notice that if the page were folded along the line MM', the virtual image AB and the solid line rays would exactly coincide with the real image A'B' and the reflected (dashed-line) rays. It is frequently convenient to represent such a folded diagram by its simpler in-line or unfolded counterpart as indicated by the dashed lines in the figure. With internally reflecting prisms, an unfolded diagram is called a "tunnel diagram". Figure 12(B) shows tunnel diagrams for two typical prisms. Such diagrams are particularly helpful when designing an optical instrument using prisms, since they simplify the determination of required apertures and, hence, prism size. MIL-HDBK-141[10] is an excellent source of tunnel diagrams for the standard prisms.

We next consider two types of mounts that utilize springs to clamp prisms against mounting surfaces in semi- or non-kinematic fashion. If the prism is stiff this does not overly distort or strain the glass.

Our first example of prism mounting is one in which the prism is held by five springs and is most applicable to a cubeshaped prism as described by Lipshutz[11] and shown in Figure 13.

The prism (View A) is a beamsplitter made of two similar right angle prisms cemented together after the appropriate partially reflecting coating was applied to the hypotenuse of one element. It may be treated as a rigid body subject to six positional constraints plus surface distortions due to improperly applied forces or constraints and size variations due to temperature changes.

A beamsplitter of this type is frequently used to divide a beam converging toward an image plane into two parts each forming its own image as indicated in View (B). In order for these images to maintain a constant alignment relative to each other and to the structural reference of the optical instrument, the prism must not translate in the plane of the figure (XY) nor rotate about any of the orthogonal axes. Translation along the Z axis does not introduce error.

Once the optical train is aligned, the beamsplitter must always be pressed against its five mounting pads indicated by the symbol labeled K_∞ in View (A). These are raised areas on the instrument structure that are assumed to have spring rates approaching infinity. The combination of pads singly constrain translations in two directions, and rotations about the three axes. The five constraining elements (Ki in View A) have relatively low spring constants; they are illustrated as compression springs.

These elements are located opposite the mounting pads to put the glass in pure compression thereby minimizing glass distortion. Preload on the glass may be determined by application of standard rigid-body mechanics.

The dashed lines in Figure 13(B) show how increased temperature will expand the cube. The light path to each image (at X and Y detectors) is not deviated due to such changes with this mounting configuration.

Another example of a clamped design is the Porro prism erecting system used widely in military and commercial binoculars. Figure 14 illustrates the design used in a military binocular of World War II vintage. In this design, the prisms are light barium crown type optical glass, the shelf is aluminum, the straps are spring temper phosphor bronze, the light shields are aluminum alloy painted matte black, and the pads are cork.

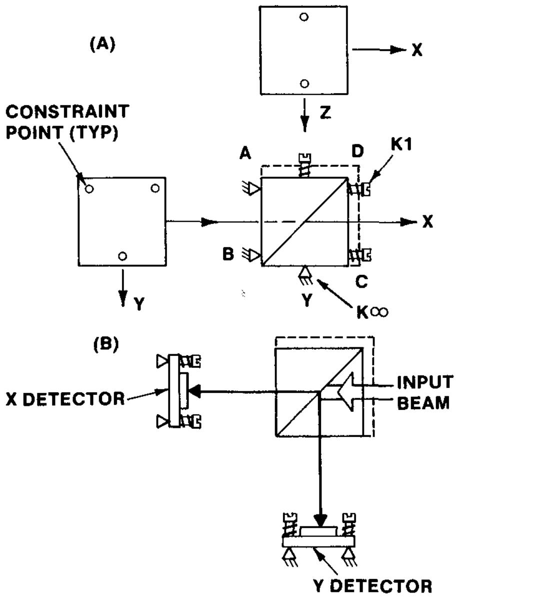
The index of refraction of the prism glass is high enough for total reflection to take place so the prisms are not silvered. The light shields reduce the level of stray light entering the optical path through the reflecting surfaces. They are slightly bent so as not to touch the glass within the reflecting apertures.

Figure 15 shows a simple bonded mounting design for a large Porro prism. The prism is cantilevered from a nominally vertical surface. The prism is Schott SK16 glass and the plate is stainless steel. The thermal expansion coefficients of the glass, metal and adhesive are 34, 8.9 and 102 ppm/^{o}F respectively. The missmatch of the adhesive coefficient is not a problem since its thickness is small and the adhesive remains slightly flexible.

Beamsplitters and beamcombiners

These components are generically the same except for the direction of light propagation and, hence, their function. They come in two varieties; the plate and the cube (see Figure 16).

Pellicles are very thin plates made of plastic film with the splitting/combining occuring at a coating on one side. They have a distinct advantage over thicker (glass) plates in that the ghost reflection from the "other" side is superimposed upon the main image. Unfortunately, pellicles are not so durable as their glass equivalents and tend to vibrate if acoustically driven.



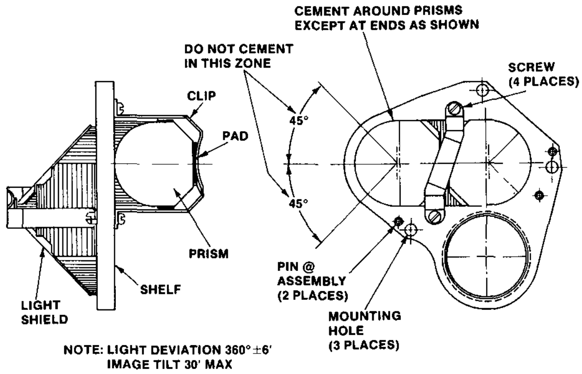


Figure 14 - A mechanically clamped Porro prism subassembly of the type commonly used to erect the image in binoculars and telescopes.

Figure 13 - (A) Simple semi-kinematic mount for a cube prism. (B) When used as a beamsplitter, the paths are as shown here. Thermal expansion problems are minimized in this mounting arrangement.

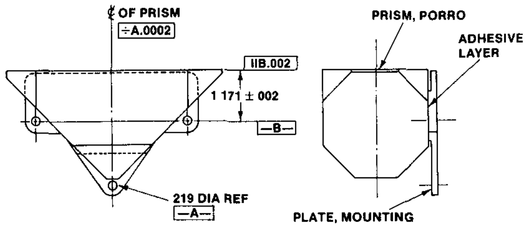


Figure 15 - Typical configuration for a large prism epoxy bonded in cantilever fashion from a nominally vertical plate. Dimensions are in inches.

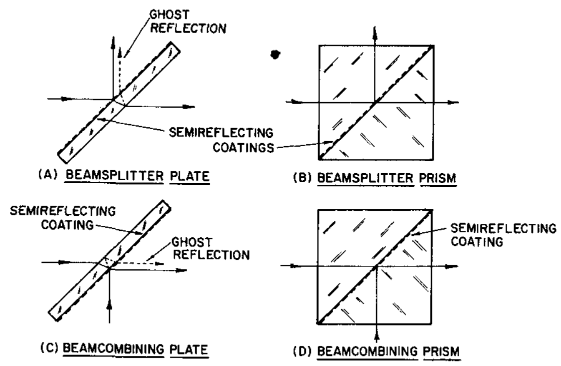


Figure 16 - Plate and prism varieties of beamsplitters and beamcombiners.

If the tilted plate beamsplitter has significant thickness and is located in a beam of significant convergence or divergence, aberrations (spherical, coma, astigmatism and lateral color) are introduced as mentioned above for prisms. Partial compensation can be achieved by adding an oppositely tilted plate identical to the first. Sometimes the plates are wedged slightly. Shafer[12] described a technique involving a tilted meniscus lens to achieve 3rd order correction for the single tilted plate over a finite field of view.

Image erectors, rotators and derotators

Systems of mirrors and/or prisms are commonly used to achieve proper orientation of the image produced in an optical system. The number of reflections in each of the principal meridians determines the orientation. Usually, a "left-handed" image is undesirable. We mean by this an image that cannot be read from left to right for any azimuthal rotation about the axis. Adding a reflection usually corrects this problem. This is why some prisms (such as the Amici or roof-penta) have a roof.

The Porro prism arrangement of Figure 14 is an example of an erecting prism while the Dove prism of Figure 17(A) is typical of an "inverting" type since it erects in only one direction. The Dove prism is most commonly used as a dynamic device to maintain a fixed image orientation in an instrument such as a panoramic telescope as the line of sight is scanned in object space. It must be used in collimated light since it functions as a tilted plane parallel plate. The Pechan prism (see Figure 17(B)), which also is commonly used to derotate images, can be used in convergent light since its entrance and exit faces are normal to the axis.

Space limitations do not allow further consideration of the design and applications of prisms, beamsplitters, beamcombiners, and image erectors/rotators/derotators. The interested reader will find MIL-HDBK-141[10], Hopkins[13], Smith[9] and DeVany[14] to be excellent sources of detailed information on this subject.

Scanning devices

Non-image-forming optical components are commonly used to scan (i.e., geometrically deviate or displace) optical beams by reflection, refraction, or diffraction. In a review of scanning devices which forms the basis for much of the following, Marshall[15] identified two types of scanning systems as illustrated in Figure 18. These are reading systems that interrogate an object field of view and receive data as a modulated signal and reproducing systems that transmit data as a modulated light signal to form temporary or permanent recordings. The functions of the scanning devices of concern here are basically the same in both types.

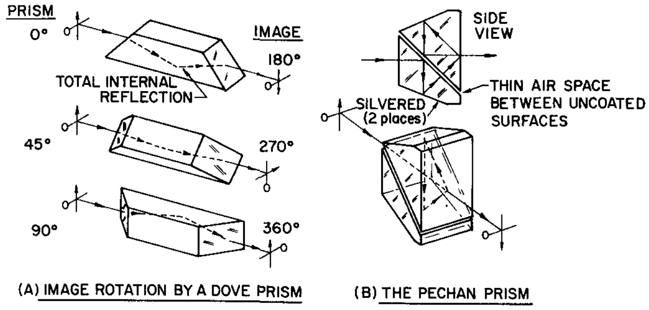


Figure 17 - Two types of image rotating prisms. The images rotate twice as fast as the prisms in each case.

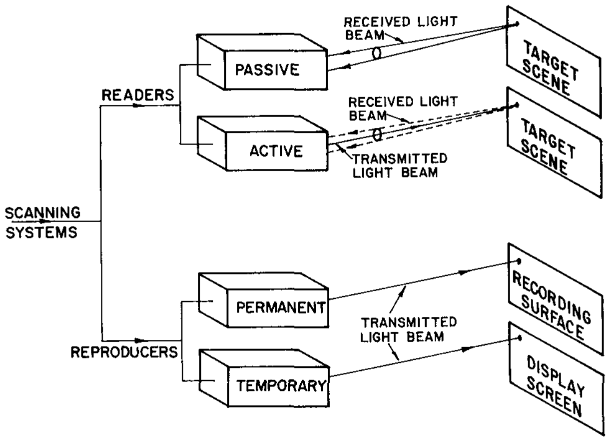


Figure 18 - A classification af scanning systems into receiving systems (readers) and transmitting systems (reproducers). From Marshall[15].

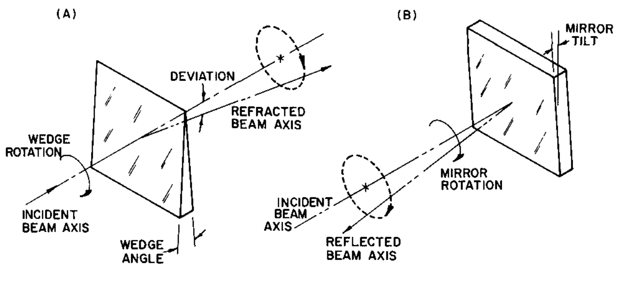


Figure 19 - Examples of ratational (conical) scan motions achieved (A) from a rotating wedge and (B) from a nutating mirror.

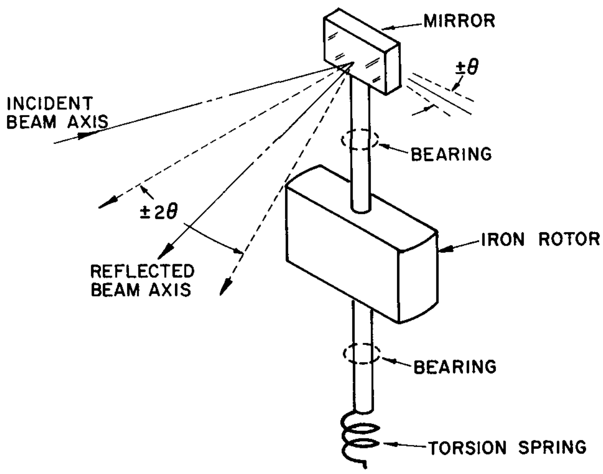


Figure 20 - The resonant nodding mirror scanner (optical galvanometer) mechanism produces a simple harmonic oscillatory motion of the reflected beam.

Scanning motions may be rotational, oscillatory, or unidirectional. Rotational (or conical scan) motion results when a beam passes through an optical wedge or reflects from a slightly tilted mirror while either of these rotates about the optical axis as indicated in Figure 19. Oscillatory motions result from nodding mirrors such as the resonant one illustrated in Figure 20. Relatively slow uni-directional linear motions can be produced by translating a prism as shown in Figure 21(A). Faster but relatively small motions can be produced by refraction through a plane parallel plate that rotates about an axis perpendicular to the optical axis (see Figure 21(B)). The latter device is commonly used in high speed photographic cameras.[16] Tilting plates were used in a similar, but static way, in optical coincidence rangefinders as a field adjustment to bring the two images adjacent to each other vertically so they could easily be compared.

A variety of motions are produced by combinations of two of scanning devices operating at the same or different frequencies. For example, synchronized rotation of two thin optical wedges (Figure 22(A)) can produce a linear or spiral scan while two mirrors nodding in simple harmonic motion at right angles to each other (Figure 22(B)) can produce various Lissajous scan patterns. A TV-style raster scan with flyback and frame interlace can be achieved with two orthogonal nodding mirrors operated at constant but different rates in response to sawtooth drive signals. Similarly, two polygon mirrors rotating about mutually perpendicular axes at different constant rates (Figure 22(C)) can produce a raster scan without flyback. If successive facets on the vertical scan polygon are at slightly different angles, interlace can be introduced. Precision diamond machining techniques are employed today to manufacture such components.[17]

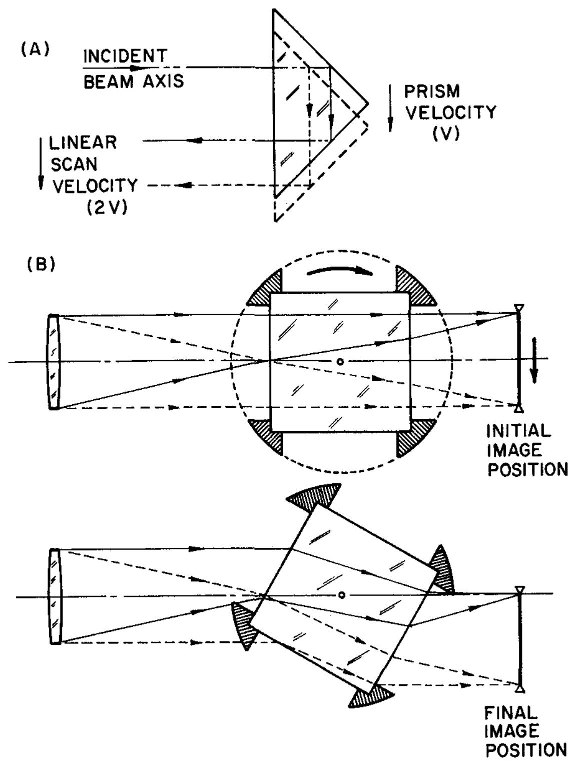


Figure 21 - Two constant path length optical mechanisms for producing a linear scan motion. (A) Translating a Porro prism, from Marshall[15]. (B) Rotating a four-sided polygon (dual plane parallel plate), from Kingslake[16].

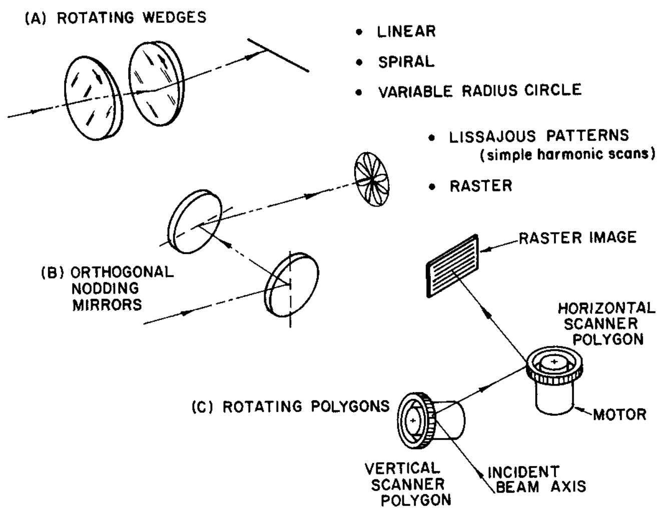


Figure 22 - Mechanical scanning system concepts using (A) rotating wedges, (B) nodding mirrors, and (C) orthogonal polygon mirrors to produce various scanned image formats.

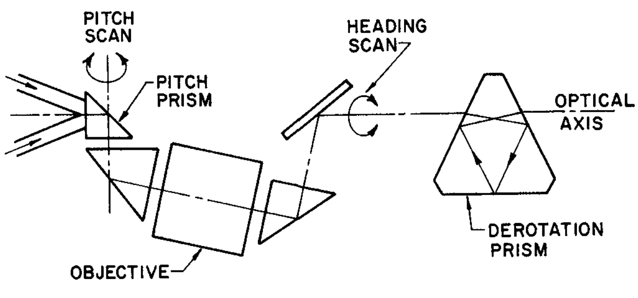


Figure 23 - Arrangement of prisms and mirrors typically used as a two-axis scanning head assembly in visual simulator systems employing scale models of the real world.

High speed operation of opto-mechanical components in rotational or linear motions is inevitably limited by the resulting reversible (i.e., elastic) optical surface deformations. Materials with high stiffness, such as beryllium, serve well. Catastrophic failure may result if the yield point of the scanner material is exceeded. As two examples of the latter condition, the limiting peripheral velocity of a stainless steel scanner is 570 m/sec while that of a fused silica scanner is only 200 m/sec.[15] Air and liquid bearings are good for rotational mechanisms while flexures are commonly used to support oscillating components.

Scanning mechanisms are frequently used in electro-optical systems for beam steering, to track targets and to stabilize the line of sight against vibration and/or limited vehicle motions. Flat mirrors in 2-axis gimbal mounts are typical. Coelostat and heliostat tracking systems are frequently used in astronomical applications.[16,18]

The popularity and capability of diffractive optics as scanning devices are increasing. Today's most common example is the holographic scanner used in point of sale product/price readers. Ultrasonic acousto-optical deflectors also are viable in optical signal processing applications.

Another interesting type of optical scanner is that used in optical probes for flight training devices using scale models as visual simulator targets. Figure 23 illustrates one form of scanning head for such a device.[19] It uses prisms and mirrors to point the line of sight in two directions while maintaining an erect image at the eye. A "delta prism" is shown as the derotator in this instrument.

Conclusion

In this paper, we have explored many but not all key forms of non-image-forming optical components and their typical embodiments in common applications. It is hoped that this will clarify some of the unique ways that these components function in the optical instruments we design and use.

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