Image rotation devices - a comparative survey

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Optical systems which, when rotated, produce a rotation of an image about the optical axis have been known and used for a long time. Information on such systems is sparse, however, and widely scattered. This paper discusses image rotation devices in general terms, and then attempts to collect together the more commonly used devices and to present comparative information on them, in order to provide a convenient reference source for optical designers. In addition a number of lesser known and novel arrangements are described.

1 Introduction

An image rotation device is an optical system which produces a rotation of the transmitted scene about the optical axis when it is itself rotated about the axis. Such devices are frequently necessary in optical and electro-optical systems for reasons which will be examined briefly in Section 3. Although image rotation devices have long been known and used, no collected reference source exists which includes more than a small number of the available systems or gives much information on the systems included.[1,2]

Information is therefore difficult to find, and the situation is made worse by the fact that most of the better known arrangements were described originally in very early papers. This paper attempts to improve the situation by providing a convenient reference source, and at the same time by contributing one or two new ideas. It does not set out to trace the history of image rotation devices, and early references are therefore not given in general. This raises a problem of nomenclature. Where a commonly used name is available, that name has been used. Where this is not the case a name has been provided for convenience of reference. As well as 'image rotation systems' – a descriptive but clumsy phrase – devices of the type under consideration are also known as derotation systems, roll prisms, and half-speed prisms. For simplicity and economy of words, 'rotator' will normally be used in this paper.

In Section 2 below, the operation of a rotator is considered in general terms. In Section 3, rotator applications are briefly examined. Section 4 considers individual rotators and their characteristics, and Section 5 presents a comparison of these.

2 Rotator operation

Rotators can conveniently be considered under three headings, according to whether the axis of the transmitted light is co-linear with and in the same direction as the incident light (transmission rotators), co-linear but in the opposite direction (reflection rotators) or at an angle. This paper is primarily concerned with the first of these, because it is by far the most useful, although the other cases will be dealt with briefly later. Systems in which the axis of the transmitted light emerges parallel to, but displaced from, the incident axis have not been considered.

2.1 Transmission rotators

The essential function of a rotator is to provide an effective reflection in a plane containing the optical axis of the system. The rotator itself does not have a uniquely defined optical axis, but an optical plane (the effective reflecting plane) and an axis of mechanical symmetry can be defined in this. Mechanical rotation should occur about the axis so defined. The consequences if it does not are considered in Section 5.4.

The effective reflecting plane is fixed with respect to the rotator itself and rotates with it. An image of a stationary object in this plane therefore rotates in the same direction but at twice the angular velocity: or, alternatively stated, if the image is required to rotate at a given angular velocity the rotator must turn at half the angular velocity (Fig. 1). It is this which gives rise to the name 'half-speed prism' for image rotation devices. If the rotator is stationary and the object rotates, of course, the image will rotate with an angular velocity which is equal in magnitude but opposite in direction.

It follows from this mode of operation that the use of a transmission rotator necessarily results in a unidimension-

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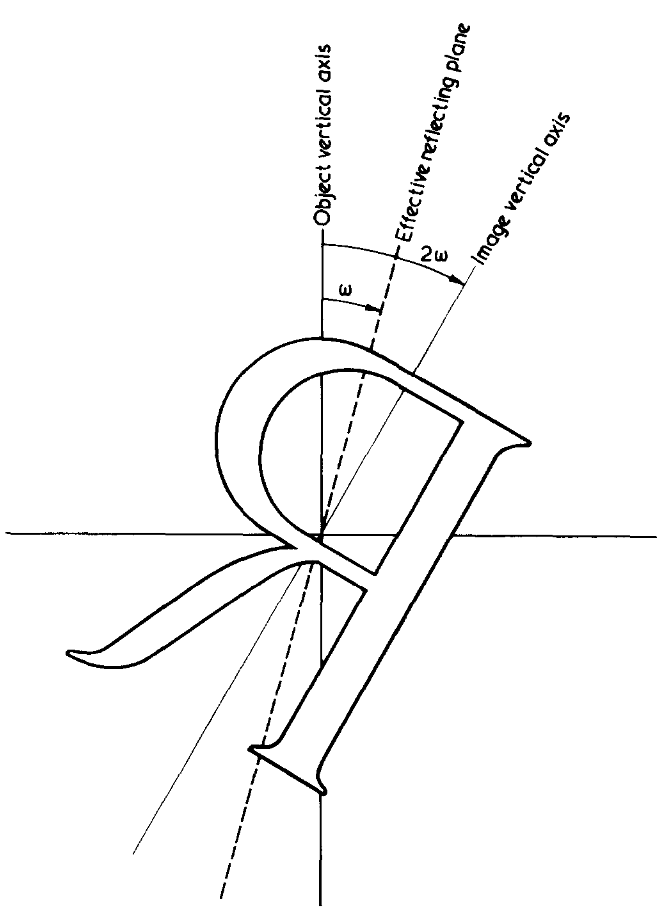


Fig. 1 The action of a rotator

ally reversed image – i.e. an image reflected about a line in its own plane. The word 'reversed' has been used in this sense in this paper, but is not intended to imply any particular axis. There seems to be a lack of agreement about terminology here, and other terms also used with the same or similar meanings include 'transposed', 'reverted', 'inverted', and even 'perverted'.[3] If a 'right-way-round' image is required, as is usually the case, it is necessary to ensure that the remaining optical system introduces a further reversion. The axis about which this is effected is immaterial since any residual rotation of the image can be removed by using the rotator itself, which makes systems including rotators particularly simple to check for correct image presentation. All that is necessary is to add the reflections in the system and ensure that the total number is even. The rotator itself must contribute an odd number, and therefore the remaining system must also contribute an odd number.

2.2 *Reflection rotators*

A rotator to work in reflection is a less usual requirement, but is not without application. The operation is essentially identical to the transmission rotator, but an extra reflection is required to take into account the reversal of the light direction. Consequently, a reflection rotator must involve an even number of reflections instead of an odd number. However, the observation made at the end of the previous section that the overall optical system must involve an even number of reflections is unchanged, and therefore in this case the remaining system must also contribute an even number to obtain a 'right-way-round' image.

A second difference with respect to the transmission case is that the reflection rotator is not defined by a plane, but by a line. It can be thought of as the line of intersection of a transmission rotator effective reflecting plane and a normal plane mirror, which together constitute the reflection rotator. The mechanical rotation axis and axis of the further optical system should intersect this line orthogonally.

2.3 *Angled systems*

The previous two sections have dealt with the situation where the emergent beam is co-linear with the incident beam. Where this is not so, for example in a right-angle deviation of the axis, one still obtains image rotation. Indeed, the need for a rotator in an optical system often arises due to the necessity to remove unwanted image rotation introduced in just this way. However, the situation here is quite different, since the system axis itself is changed by the rotation. 'Image rotation' therefore has a different meaning in this case: in fact the image changes as the system turns and its orientation is judged from the local vertical. This orientation rotates at the same angular velocity and in the same direction as the system. The number of reflections in the system does not affect this, but does affect the phase i.e. the direction of the axis when the image is regarded as 'right-way-up' and whether the final image is reversed or not.

If the axis is deviated through an angle of other than 90°, the situation is more complex. It would not be worthwhile to give a detailed evaluation here, however.

3 Applications

This brief section is intended to indicate some of the applications of rotators, to provide a background against which the individual systems can be assessed. It is not intended to be exhaustive.

3.1 *Image rotation or derotation: variable*

The self-evident application of a rotator is to rotate a stationary image, or to hold stationary the image of a rotating object. Both requirements arise in practice. A typical example of the former occurs in a moving map display system for aircraft, where the map image on the screen must be appropriately orientated with respect to the flight direction. In common with most avionic equipment, small size is a major consideration, and this tends to require a rotator which is itself small and which permits a relatively wide angle beam to be transmitted.[4] Another example is the visual display of a flight simulator, where a rotator is used to provide roll.

Derotation is the same requirement as rotation in all but name. The most common derotation application occurs when a 45° mirror or prism is rotated to pan the direction of view of a system, which causes the scene to rotate as explained in Section 2.3. A rotator geared to the panning motion so as to rotate at half speed is required to correct this. Other applications include the correction of object misorientation, for example in an electro-optical document communication system or a microfilm or microfiche reader.

3.2 *Image rotation or derotation: constant*

Another group of applications is identical to that just considered except that the rotation required is constant. Such a requirement commonly occurs as a result of a sequence of reflections, especially when space constraints are severe. Normally the limitation which has been assumed here, that emergent and incident axes are co-linear, is not necessary in this case so that the choice of systems available is much greater. The special case of a 180° rotation is particularly important: it can be dealt with by using two orthogonal rotators in series, although this is rarely practicable due to system length. (An exception is the Porro prism system, consisting of two reflection rotators in series.) Alternatively, the judicious addition of an extra reflecting surface to a rotator by replacing a plane surface by a roof edge will serve the same purpose.

3.3 *Beam deflection*

A problem which sometimes arises in an optical system is to deflect the axis of a beam through a small angle, possibly a variable angle; and the use of a rotator is one way of doing this. It must be tilted about an axis lying in the effective reflecting plane and perpendicular to the optical axis of the system. This type of requirement occurs commonly in viewing systems operating in parallel light, and system dimensions are often important.

3.4 *Alignment*

Since a rotator is equivalent to a plane mirror, it can be used to define a plane – the effective rotating plane – and it is therefore potentially useful in an alignment device. Two rotators orthogonally mounted can define an axis. This can conveniently be arranged by separating an incident beam into two halves (with a polarization selective beam splitter for example), passing each half through a separate and orthogonally mounted rotator, and recombining the halves. This gives two similar superimposed beams, one of which is rotated 180° with respect to the other. The rotation axis (the unique common axis in the two superimposed beams) provides an axis of symmetry which can be used for alignment either by direct visual observation, or as an addition to a conventional alignment laser. Such an arrangement was in fact proposed by Burch and Gates of the National Physical Laboratory some years ago[5], and it has very attractive advantages in both modes of operation. As a zero power device it can be used in front of a telescope which then needs no graticule and has no requirement for precision focusing arrangements. The axis is defined wholly independently of the telescope. Used with an alignment laser and a quadrant photo-detector it results in a greater stability of the axis, as this is independent of temperature changes and other effects in the laser itself. It should therefore be possible to achieve equivalent results with a simpler, cheaper laser.

4 Rotators

Since any system which provides image reversion operates as a rotator, there are an infinity of possible rotators; but only a limited group of these are of practical interest. The devices included here have been selected either because they are in common use or because they are especially compact (in some cases both), but clearly the choice is arbitrary and there will undoubtedly be special applications which can profitably use a system which has not been included. The characteristics which may be important are the physical dimensions, including the length of the optical path; the off-axis transmission characteristics; the ease (and cost) of manufacture; the weight, and moment of inertia. It is necessary before considering individual systems to comment briefly on some of the measures adopted.

All dimensions given are expressed in terms of the diameter of the paraxial beam of circular cross-section which will just pass through the system. They are in each case the minimum dimensions of the active components, with no allowance for mountings, housings, etc.

Physical length is the actual overall length of the system. Optical length is the length of the optical path to traverse the complete system, and in the case of systems with non-normal entrance and exit faces, it is measured from the planes normal to the effective reflecting plane passing through the extremities of the system, and not from the faces. Since the path through many rotators is in glass throughout, it is convenient to give the actual path length in the glass or referred to the glass in all cases: where the effective path length in air is intended this is stated.

The diameter is the swept diameter when the system is rotated, i.e. twice the dimension from the axis to the extremity of the system.

Off-axis performance has been evaluated in two complementary ways. 'Parallel transmission' is the total energy transmission of a plane parallel beam at angle θ to the axis as a fraction of the axial transmission. 'Beam acceptance' is the maximum value of the reciprocal of the F-number of the beam which can reach a point on the exit face, and is a function of the distance y of the point from the effective reflecting plane. In both cases it is assumed that the entrance face is square and limiting, and only variations in a plane perpendicular to the effective reflecting plane are considered. Where the situation is not symmetrical with respect to the effective reflecting plane, the worst case (i.e. the limit when the system is rotated) is taken.

All these measures are intended solely to facilitate comparison between rotators and allow a ready assessment of suitability for specific applications. They are not intended to be applicable for detailed system design. This would not be practicable in a paper of this nature because of the large number of variables involved, not only with respect to the rotators themselves but also with respect to the systems in which they may be applied.

For each rotator a tunnel diagram – i.e. a prism diagram 'folded' along each reflection in turn to provide an apparently straight line path – is given. The nature of the surfaces traversed by the light is indicated in the diagrams by a simple convention which is explained in Fig. 3.

The rotation systems will now be considered individually.

4.1 *Dove*

The Dove (Fig. 2) is probably the best known and most used rotator. It has the merit of simplicity, being a single element, but the disadvantage of non-normal entrance and exit faces. In consequence it is only suitable for use in near-parallel light, the permissible deviations from parallelism being

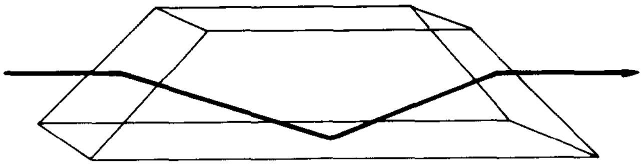


Fig. 2 Dove rotator

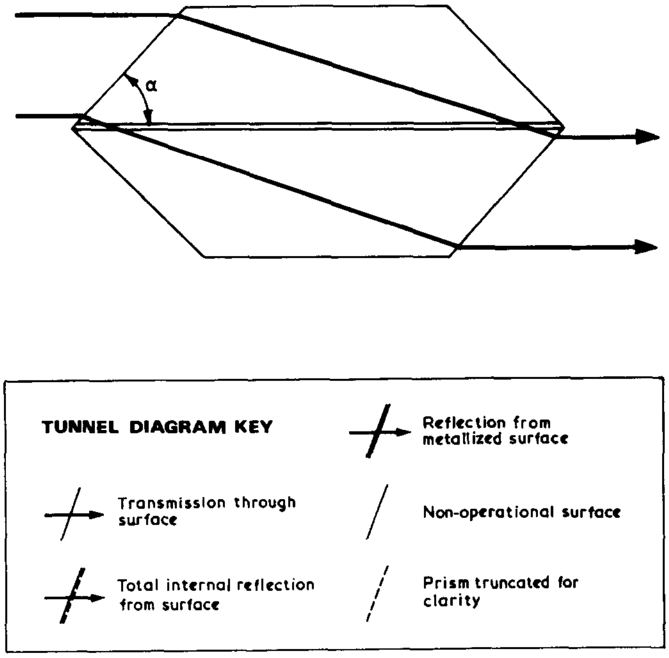


Fig. 3 Dove rotator tunnel diagram

determined by the tolerance of the particular application to lateral colour and astigmatism.

The faces of the Dove are usually taken to be at 45° to the axis, but this is not a necessary limitation. Figs 4 and 5 show the variation of length, diameter and optical path length with the angle between faces and axis, with refractive index as parameter. The discontinuity apparent in these curves occurs when the length of the short, inoperative side of the prism is reduced to zero. It is usually desirable to have either minimum length or minimum optical path length. In either case high refractive index is desirable, but note that for a given index there is an optimum prism angle, which is somewhat less for minimum physical length than for minimum optical path length, and which is in both cases rather less than 45°.

The Dove provides a good example of the confusion over nomenclature. The name 'Dove' is currently in general use in Britain, although 'Harting-Dove' is apparently used in the United States,[2] and other alternatives include names reserved here for quite different systems, such as 'Wollaston'[6] However, in 1921 it was described as an 'erecting rhomboid prism' and the name Dove was given to a *pair* of such prisms arranged in series at right angles to one another.[7] Such a pair was also alternatively called a 'Harting-Dove reversion prism'.[7] It (the pair) was in fact described by Dove in 1851,[8] but – presumably unknown to him – it had been patented in 1838 by Delaborne.[9] It will be clear that the unravelling of this type of situation is a task more suited to a historian than a physicist, and, whilst interesting, it has not been attempted in this paper.

4.2 Double-Dove

Two Dove prims can be cemented together along their reflecting faces to produce a double-Dove with only half the physical and optical path lengths for a given diameter[2] (Fig. 6). The effective reflecting planes of the two constituent Dove prisms are not coincident (although they must be parallel), so the system is usable only in parallel light; but this was already a characteristic of the Dove due to the non-normal entrance and exit faces. The double-Dove is in fact used, not as an image rotation prism, but as a deflection system in front of the objective of an infinite conjugate system, as described in Section 3.3.

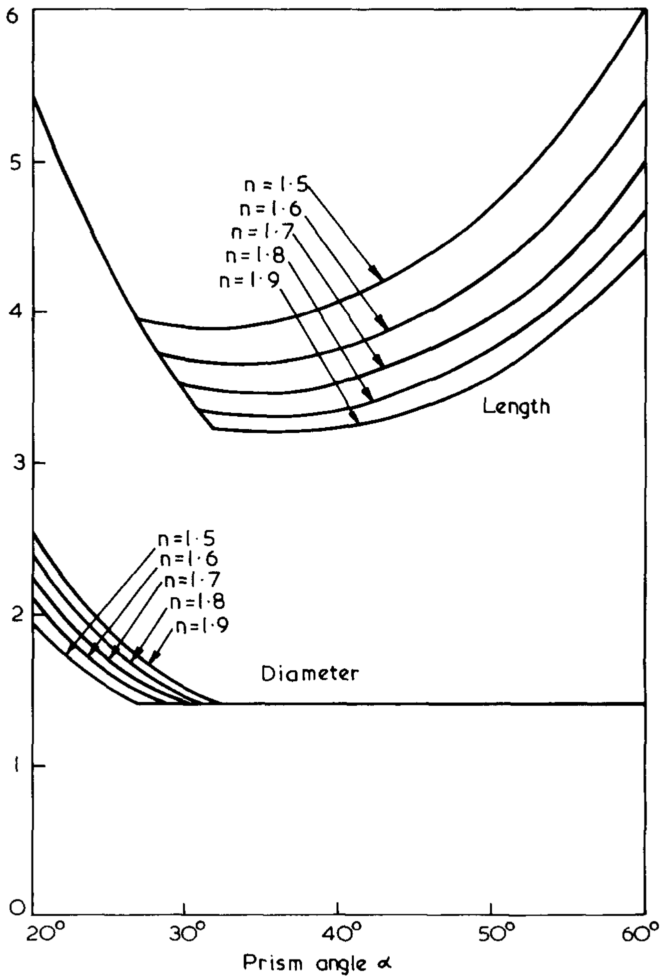


Fig. 4 Dove rotator: length and diameter. Ordinate in units of the diameter of the paraxial beam of circular cross-section which will just pass through the system

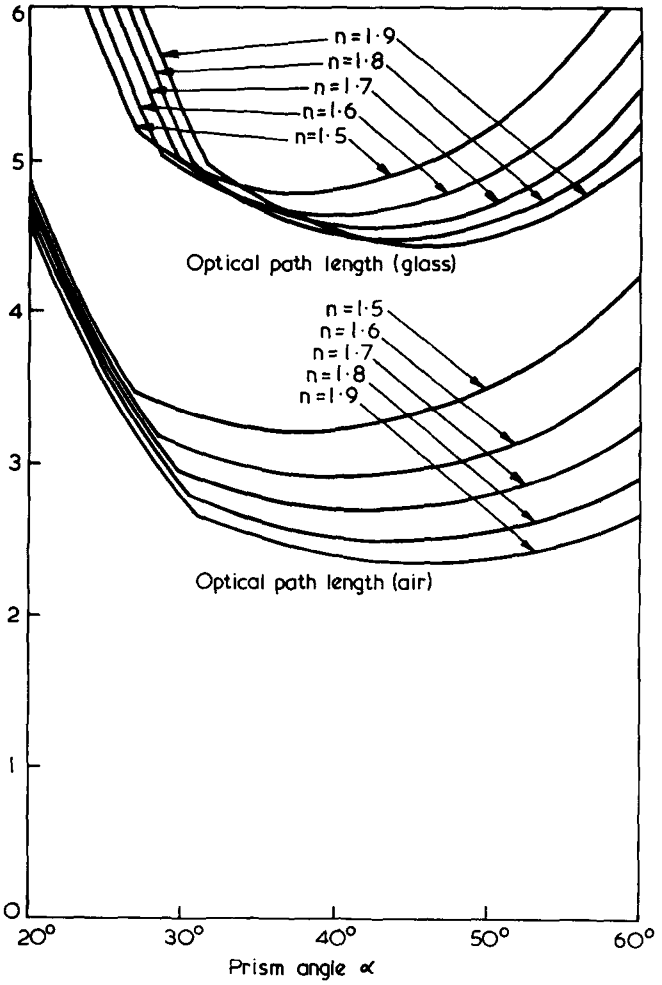


Fig. 5 Dove rotator: optical path length. Ordinate in units of the diameter of the paraxial beam of circular cross-section which will just pass through the system

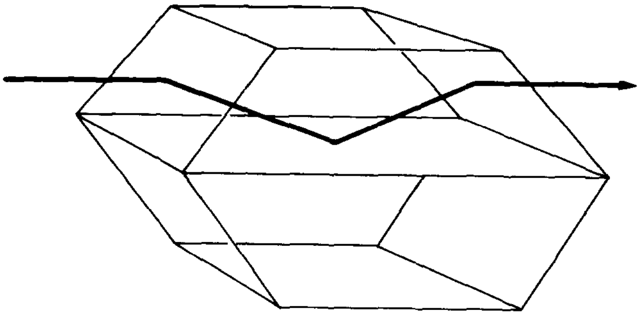


Fig. 6 Double-Dove rotator

4.3 Schmidt type

The prism shown in Fig. 7 uses total internal reflection at the entrance and exit faces to achieve compactness.[10] The range of angles over which this prism is useful is limited: as the base angle increases above 60° the angular acceptance for any reasonable refractive index falls rapidly to zero because of the total internal reflection requirement. If the angle decreases on the other hand the physical length of the prism increases rapidly compared with the beam width. Although the optimum will depend upon requirements in any given application it is likely to be close to the situation where the axial ray, after total internal reflection from the exit face, travels parallel to the entrance face. This occurs at the values of angle and refractive index shown in Fig. 9 as the 'Schmidt-Dove condition' and is associated with a physical length of approximately 1.2 and an optical path length of approximately 3.8. Angular acceptance of the prism is also indicated in Fig. 9. As in the case of the Dove, it is only suitable for use in parallel light due to the non-normal entrance and exit faces. The designation 'Schmidt type' is based on the relationship of this rotator to the Schmidt prism, which has a roof edge at the base, although it is recognised that this is not ideal.

4.4 Schmidt-Dove

It is interesting to note that the Schmidt type rotator and the Dove can be combined into a single unit – i.e. a single prism can operate in the Schmidt type mode near the apex and the Dove mode near the base. This is a special case of the Schmidt type rotator. As can be seen from the tunnel diagram (Fig. 10), it will operate over the entire entrance face if the prism angle and refractive index are chosen appropriately, which means according to the curve in Fig. 9. The effective reflecting planes are displaced in the two sections, and in addition the optical path lengths are different. Hence this arrangement is severely restricted to parallel light. A double system, analogous to the double-Dove, is naturally also possible, and is very compact.

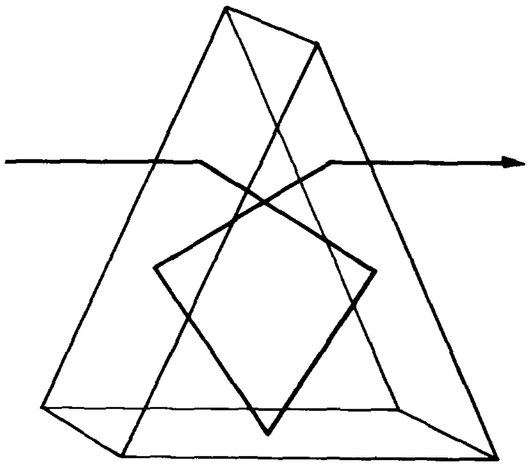


Fig. 7 Schmidt type rotator

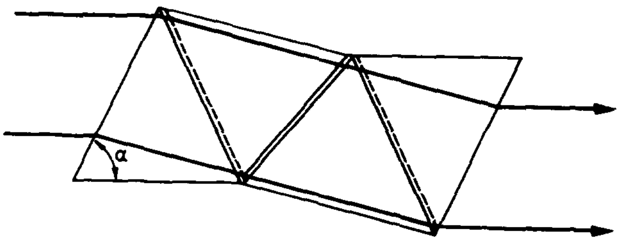


Fig. 8 Schmidt type rotator tunnel diagram

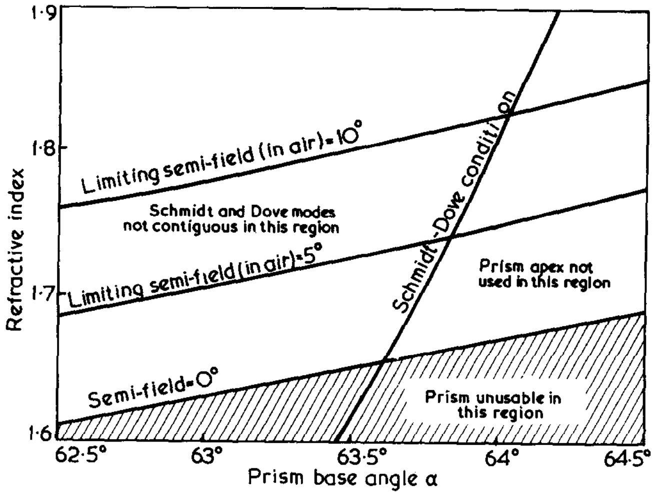


Fig. 9 Schmidt and Schmidt-Dove rotators: characteristics

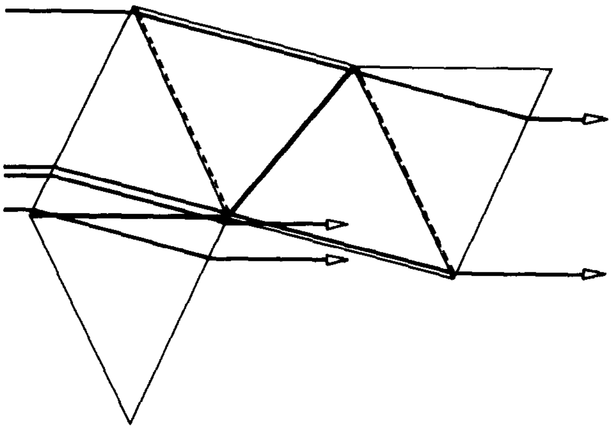


Fig. 10 Schmidt-Dove rotator tunnel diagram

4.5 *Array rotator*

In the double-Dove, the reflecting faces of the prisms are usually cemented together. In principle, the opposite sides could equally well be cemented. It is therefore possible to produce a relatively thin arrangement of contiguous Dove prisms, as shown in Fig. 11, which will operate as an image rotation system in parallel light. It will also operate as a beam deflector when tilted, as in the case of the double-Dove, but with a considerable size and weight advantage. The principal disadvantage is the practical one of production. The effective reflection plane of every individual roll prism must be parallel within the appropriate tolerances.

This type of arrangement is one member of a family known in Pilkington Perkin-Elmer as 'array optics', hence the designation 'array rotator'. The individual elements need not be Dove prisms but can be any roll prism in which the full cross section area is utilized. As an example, a modified folded-Abbe arrangement (see Section 4.7) is shown in Fig. 11c, but in practice difficulty and cost of production rule out these more complex arrays at the present time.

4.6 *Abbe type*

The Abbe type prism (Fig. 12) is normally made with $\alpha = 30^\circ$ [2], although once again this is not essential.[10,11] In fact it corresponds to the minimum optical path length. Increase of α decreases physical length but increases diameter, and vice-versa. These variations are shown in Fig. 14, although for comparison purposes (Section 5) the 30° case is considered. This prism, as all the following ones, has normal entrance and exit faces and thus does not suffer the parallel light limitation, but does have other disadvantages. It is long, wide, and mechanically markedly unbalanced. Notice that the effective air path is the same as the physical length for $\alpha = 30^\circ$ and for a refractive index of 1.5. For higher indices a match can be achieved by a suitable choice of angle. This characteristic is shared with one or two other systems which will be mentioned, including the next one. Although symmetry has been assumed in this paper, it may be advantageous to use a system which is not symmetrical[11]. In an actual system design the rotator must be optimized for the application.

4.7 *Folded Abbe type*

This prism (Fig. 15) operates in exactly the same way as the previous one, but the optical path is folded to make the arrangement more compact.[12] Both length and optical path length are identical to the Abbe type prism, but the diameter is reduced and the system is mechanically balanced. Over the normal refractive index range, angular acceptance is limited by vignetting and not by failure of the total internal reflection requirement. It is advantageous if the two end prisms are made together and subsequently sawn apart, since then errors will be largely compensated.

4.8 *Vee block*

A rotator which is related to the Abbe type in a similar manner to that in which the Schmidt type is related to the Dove, is shown in Fig. 17. The optimum case (minimum physical and optical path lengths) occurs when $\alpha = 60^\circ$, when physical length = 1.5, diameter = 3.16, and optical length (in glass) = 4.04. The principal advantage here is the short physical length. Disadvantages are the large diameter and mechanical unbalance. It is interesting to note that the angular acceptance on one side of the effective reflecting plane is unusually good, as may be seen from the tunnel diagram, Fig. 18.

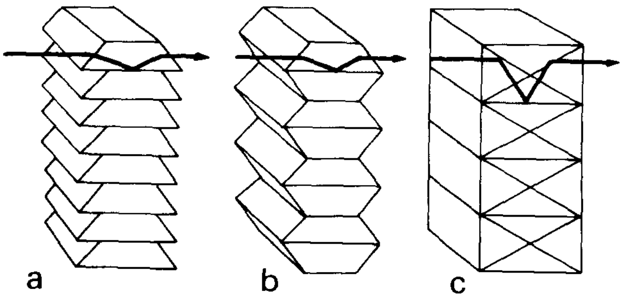


Fig. 11 Array rotators: 11a and 11b are based on the Dove rotator; 11c is based on the folded Abbe type

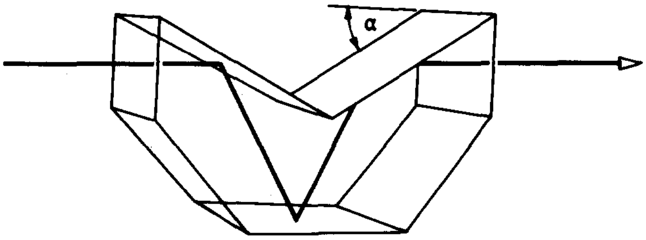


Fig. 12 Abbe type rotator

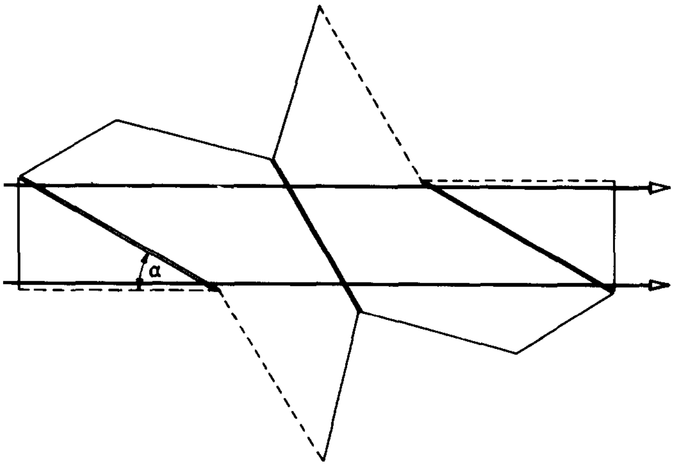


Fig. 13 Abbe type rotator tunnel diagram

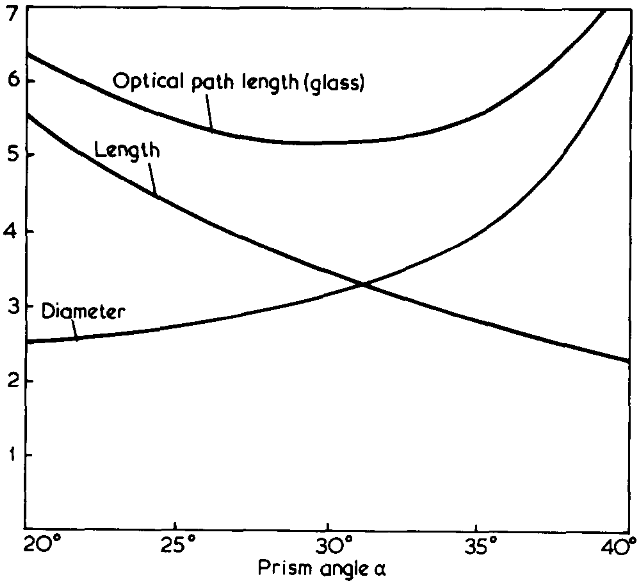


Fig. 14 Abbe type rotator: length, optical path length and diameter. Ordinate in units of the diameter of the paraxial beam of circular cross-section which will just pass through the system

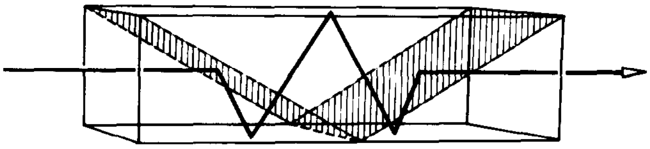


Fig. 15 Folded Abbe type rotator

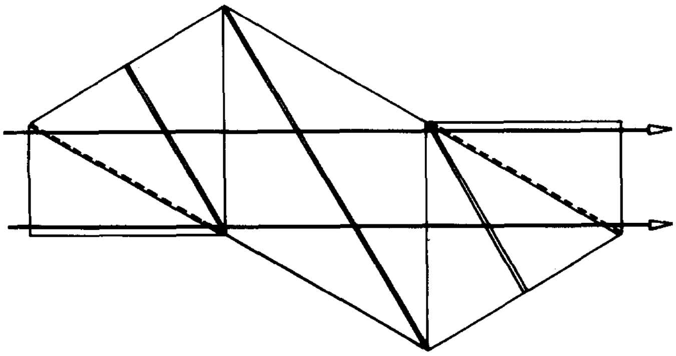


Fig. 16 Folded Abbe type rotator tunnel diagram

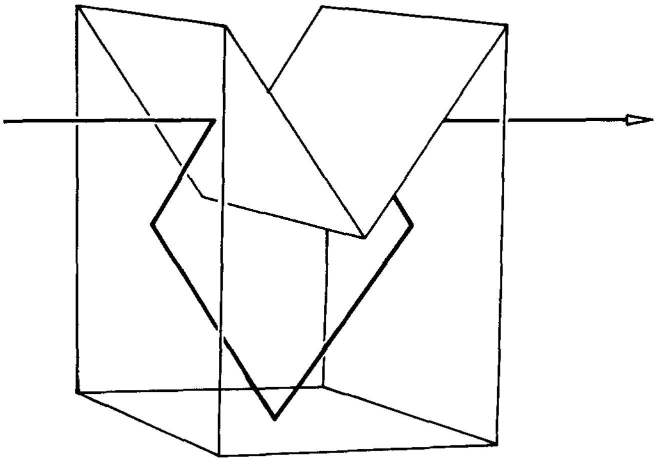


Fig. 17 Vee block rotator

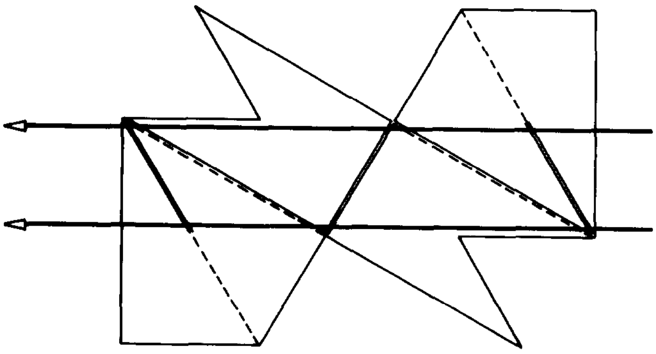


Fig. 18 Vee block rotator tunnel diagram

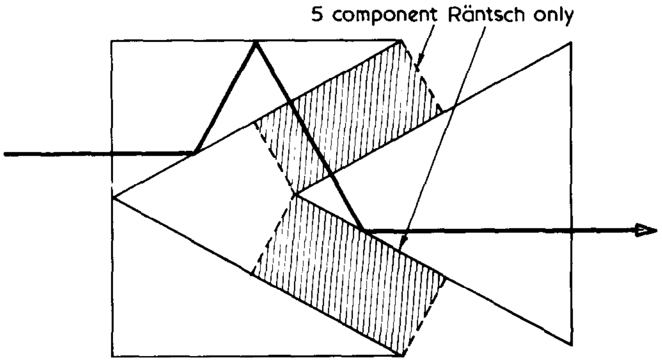


Fig. 19 Cross section of the Räntsch rotator: The five component Räntsch includes the two dashed blocks; the three component Räntsch does not

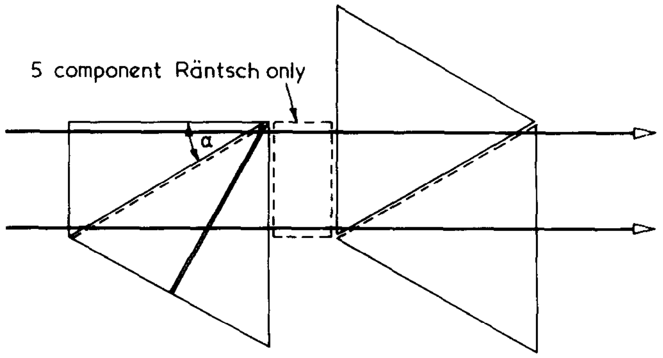


Fig. 20 Räntsch rotator tunnel diagram (half system)

4.9 Räntsch

There are two versions of the Räntsch prism, with three and five components respectively[11,13] (Fig. 19). It is a very attractive rotator due to the small size and short optical path length. Physical length is 1.44, diameter 1.414, and optical path length in glass (assuming the five component case, with the spaces filled with glass with an air space on each side) is 2.02. In practice the glass inserts are not normally used, to save cost in manufacture, and the optical path length is consequently somewhat greater. In principle it might be possible to incorporate an optical element (in two halves) within the air spaces, although there would of course be severe alignment problems. The principal disadvantages of the Räntsch arise due to the necessity to align the two halves, and the presence of the central line across the prism.

The central line is most conveniently dealt with by keeping it remote from an image plane, but it should be noted that this is not always practicable. In particular the vignetting characteristics of this prism are not symmetrical, as can be seen from the tunnel diagram in Fig. 20 and from Fig. 34. If the two halves of the Räntsch prism are to be aligned properly, the component prisms must be accurately made. (In practice for use at specific conjugates it will often be possible to compensate for small misalignments by longitudinal movement of the third prism.)

The dimensions given apply to a 30°/60° prism with entrance and exit faces of equal size. By choosing other angles they can be reduced even further but the air gap is then no longer normal: Figure 21 illustrates this for the five component Räntsch. In the same figure the maximum semi-field is also shown, i.e. the angle at which the parallel transmission falls to zero. The complexity of the curves arises due to different effects forming the limit: namely vignetting; the need for total internal reflection at two surfaces; and the need for transmission at one surface. Note that these curves apply only to the symmetrical case illustrated.

4.10 Pechan

The Pechan or Malmros prism is almost as familiar as the Dove as an image rotator (Fig. 22). It is principally valuable for the short physical length (1.21) but unfortunately suffers from a relatively long optical path (due to the considerable

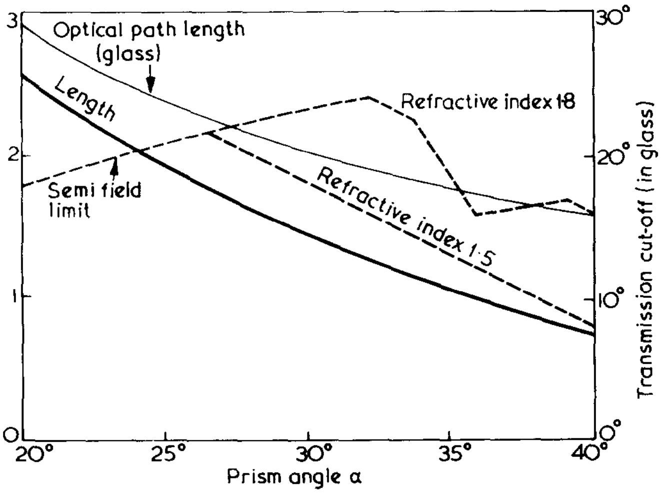


Fig. 21 Five component Räntsch: length, optical path length and parallel transmission cut-off. Ordinate in units of the diameter of the paraxial beam of circular cross-section which will just pass through system

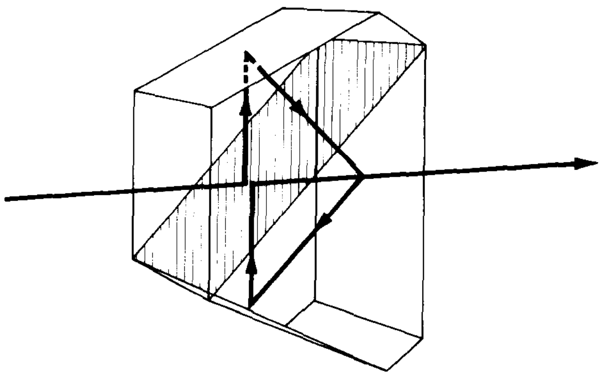


Fig. 22 Pechan rotator

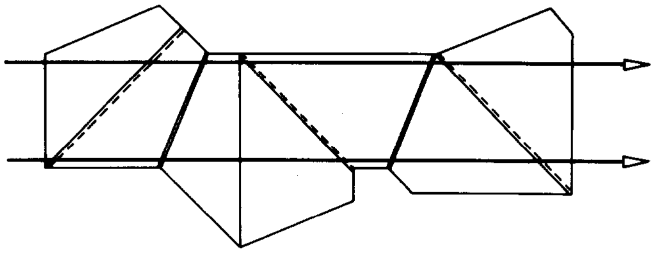


Fig. 23 Pechan rotator tunnel diagram

folding) which amounts to 4.62 in glass. The physical diameter is 1.85 if all unnecessary glass is removed, although as normally manufactured it is nearer 2.1. (Fig. 22 shows this latter configuration.) In addition to vignetting resulting from the long optical path, the total internal reflection face at 45° is also a constraint on off-axis transmission.

4.11 Polarization selective block

Fig. 24 shows a very compact roll prism based upon the use of polarization selective reflective coatings. Orthogonal polarization components of the incident beam follow different paths as will be clear from the Figure, and are subsequently recombined. There will be no problem due to interference betweeen the two separate beams (since they are orthogonally polarized), unless an analysing element occurs later in the system, but it would of course be necessary to ensure accurate registration of the beams. The central line is a problem as in the Räntsch. A further problem lies in the polarization selective beam splitter. Very efficient coatings of this type have been designed and produced for operation at a single wavelength and a specific incidence angle, but it is not easy to cover an appreciable wavelength and angular range with high efficiency. Where this merely produced losses the effect can be serious enough but in this case it produces a leakage path straight through the device. Manufacture would be difficult: the component prisms must be produced to tight tolerances.

4.12 Cylindrical lens system

Most of the arrangements mentioned have used only reflections, although the Dove and its derivatives use refracting surfaces in addition. It is also possible to use a pure refracting system consisting of cylindrical lenses only, shown schematically in Fig. 26. The characteristics of such a system cannot, of course, be defined since they would depend upon specific requirements, although for realistic assumptions it is unlikely to be particularly compact. In one respect it is potentially useful, however: the physical diameter is unity. Production presents difficulties: good quality cylindrical optics are not easy to make, and are therefore expensive.

4.13 Fibre-optics

It is possible in principle to make a fibre-optic rotator, after the fashion of Fig. 27. Consideration of the Figure will make it clear that the problem with the device is to pack the fibres in a satisfactory manner. It would also be an expensive device to manufacture. As in the case of the cylindrical lens

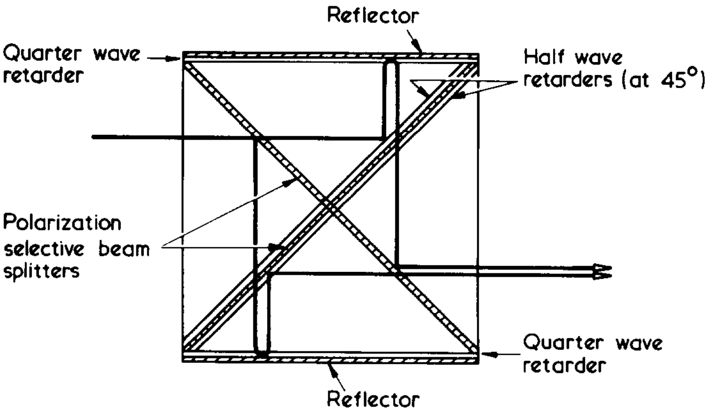


Fig. 24 Polarization selective block rotator

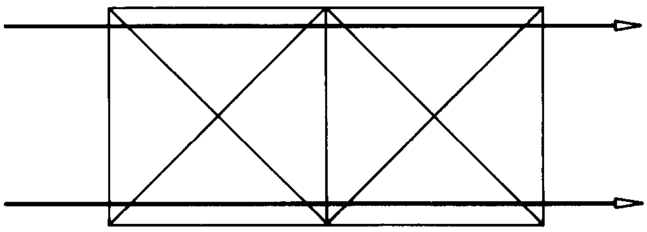


Fig. 25 Polarization selective block tunnel diagram

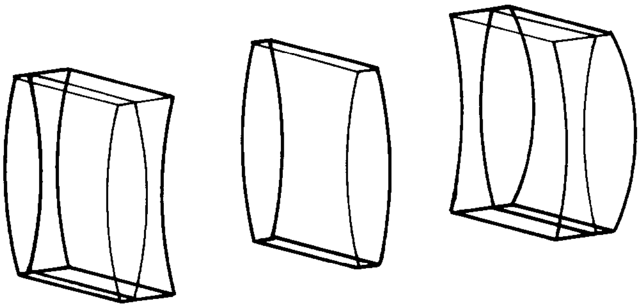


Fig. 26 Cylindrical lens rotator (schematic)

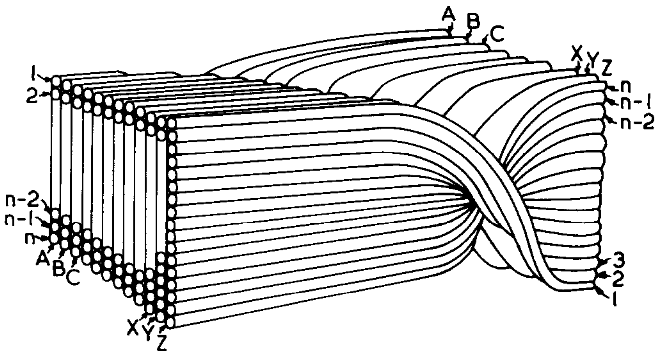


Fig. 27 Fibre-optic rotator (schematic)

Table 1. Comparison of image rotation devices

The figures in brackets refer to footnotes below

Rotator	Fig. number	No. of components	No. of reflections	Diameter	Length	Optical path length (glass)	(1) Parallel light use only	(2) Mechanical balance	(3) Difficulty of manufacture	(4) Suitable for array
Dove (5)	2	1	1	1.41	4.05–3.36 (6)	4.81–4.53 (6)	P	*	–	A
Double-Dove (5)	6	2	1	1.41 (7)	2.02–1.68 (6)	2.40–2.26 (6)	P	–	–	A
Schmidt (8)	7	1	3	1.77	1.20	3.76	P	**	–	–
Schmidt-Dove (8)	7,10	1	3/1	1.41 (7)	0.98	3.06/0.85 (9)	P	*	–	A
Double Schmidt-Dove (8)	–	2	3/1	1.41 (7)	0.49	1.53/0.42 (9)	P	–	–	A
Array	11	Many	(10)	1 (11)	0 (11)	0 (11)	P	–	**	
Abbe	12	2 or 3	3	3.16	3.46	5.20	–	**	–	–
Folded Abbe	15	3	5	1.41	3.46	5.20	–	–	–	A
Vee block	17	2	5	3.16	1.15	4.04	–	**	–	–
3 component Räntsch	19	3	3	1.41	1.44	2.16–2.25 (6)	–	–	*	A
5 component Räntsch	19	5	3	1.41	1.44	2.02	–	–	**	A
Pechan	22	2	5	1.85 (12)	1.21	4.62	–	–	–	–
Polarization block	24	4	3	1.41	1.00	2.00	–	–	**	A
Cylindrical lens	26	(13)	–	1.00	(13)	(13)	–	–	*	A
Fibre-optic	27	–	–	– (13)	(13)	0.00	I	–	**	–
Roof edge (14)	28	1	2	1.00	0.50	1.00	–	–	–	A
Right angle	29	4	3	–	–	3.00 (15)	–		*	–

Notes on Table 1

(1) P indicates suitable for use in parallel light only

I indicates suitable for use in image plane only

(2) Increasing imbalance indicated by more asterisks (no asterisks = balanced)

(3) Increasing manufacturing difficulty and cost indicated by more asterisks

(4) A indicates suitable in principle for array. (Not necessarily practicable)

(5) $\alpha = 40^\circ$

(6) Assumes refractive index 1.5–1.8

(7) Not strictly applicable, since circular incident beam emerges non-circular

(8) Assumes $\alpha = 64^\circ$, refractive index 1.8

(9) Two different optical path lengths

(10) Dependent upon constituent systems

(11) Ideal limit. Practical limit set by cost and production difficulties

(12) Assumes all unnecessary glass removed. Diameter for normal configuration = 2.08

(13) Dependent upon design

(14) Reflection rotator

(15) Excess length over 90° prism = 2.00.

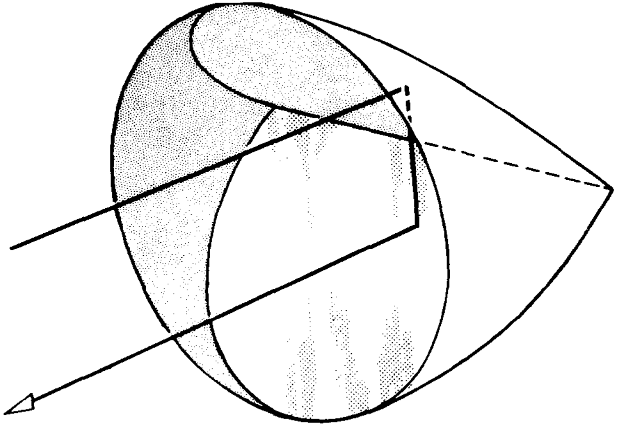


Fig. 28 Roof-edge rotator

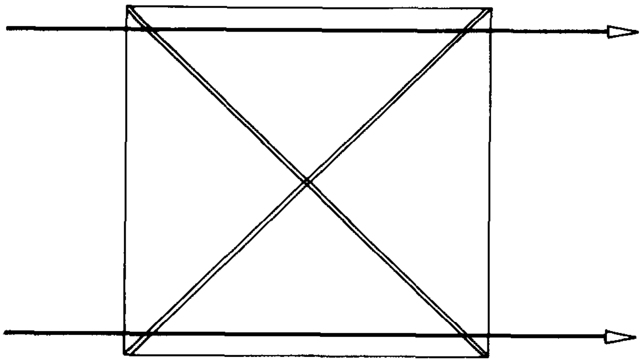


Fig. 29 Roof-edge tunnel diagram

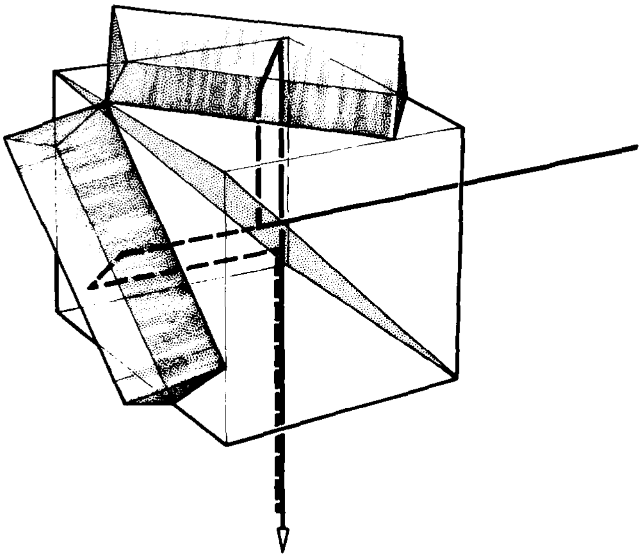


Fig. 30 Right angle rotation system

system it is not practicable to estimate dimensions, but it may be noted that the rotator is only suitable for use in an image plane since the fibres do not preserve phase information, and that the effective optical path length is zero.

4.14 Reflection systems: roof edge

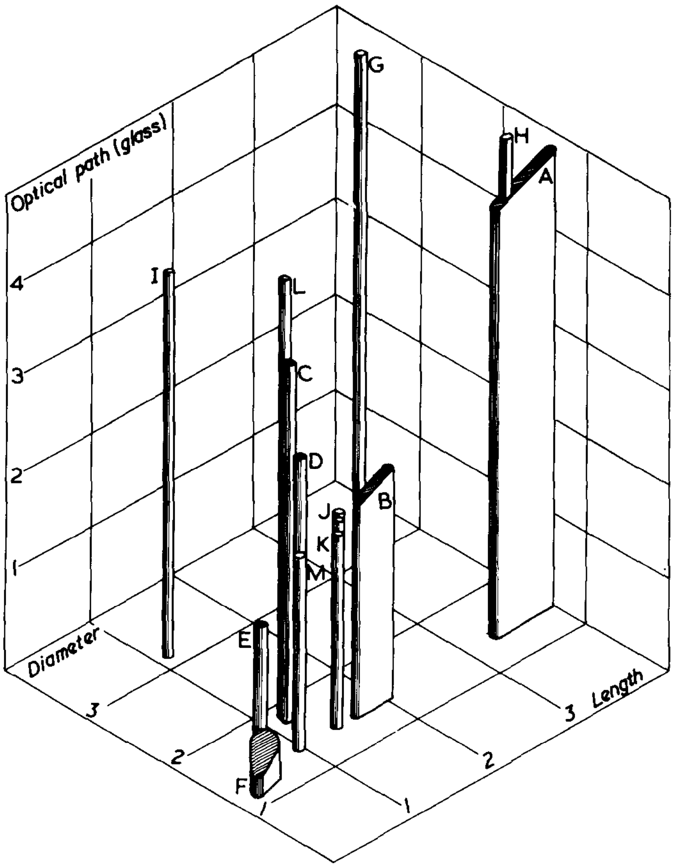
As already noted, reflection systems are less usual than transmission systems. The roof edge is such a compact and obvious solution that it is the only one which will be mentioned. Note that a roof edge array is possible, analogous to the transmission rotator array (Fig. 28).

4.15 Right angled systems

It was observed in Section 2.3 that unwanted image rotation often occurs as a result of rotation of a 90° 'bend' in an optical system. Fig. 30 shows an arrangement in which the image rotation can be removed 'at source' by the use of two roof edge rotators. Both of these must be coupled to the primary rotation through a 2:1 reduction gear, which can be accomplished in a direct and compact manner. To conserve light, a polarization selective beam splitter is used: suitable coatings must be used on the roof edges to ensure that there are no differential phase effects with different polarization directions. Notice that in this system, unlike that described in Section 4.11, the inevitable lack of perfection of the polarization selective beam splitter results in light loss but not light leakage.

5 Comparisons

In this section the rotators described in Section 4 are compared, to some extent after the style of a *Which?* report. Because dimensions, angles, and refractive indices are in most cases not uniquely determined, this is not, and cannot be, definitive, but should serve rather to focus attention on to the interesting possibilities. The principle characteristics are tabulated in Table 1.



A	Dove
B	Double-Dove
C	Schmidt
D	Schmidt-Dove (longer path)
E	Double Schmidt-Dove (longer path)
F	Array
G	Abbe
H	Folded Abbe
I	Vee block
J	3 component Räntsch
K	5 component Räntsch
L	Pechan
M	Polarization block

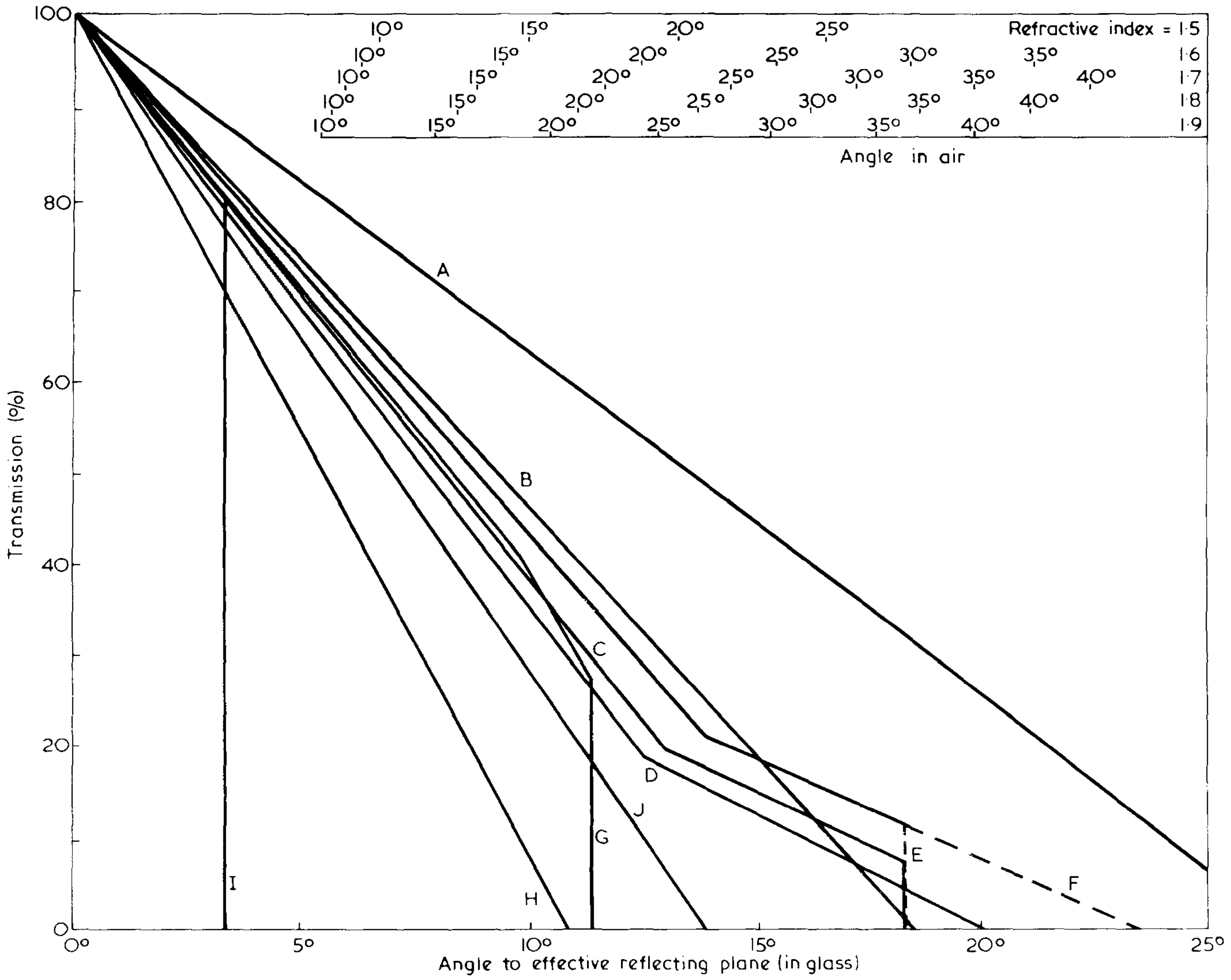
Fig. 31 Comparison of rotator dimensions. Units of the diameter of the paraxial beam of circular cross-section which will just pass through the system

5.1 Dimensions

The three most significant dimensions are length, diameter, and optical path length. Fig. 31, which is an isometric projection, compares these three for the rotators described. An ideal rotator would plot to 0, 1, 0, on this diagram, a point approached only by the array. It is not surprising to find that in general the rotators tend to become more difficult and costly to manufacture as they get closer to this point.

5.2 Off-axis characteristics

The parallel transmission (see Section 4) of the various rotators as a function of angle from the effective reflecting



A	Polarization selective block (vignetting only)
B	Right angle rotator
C	3 component Räntsch (n = 1.5)
D	3 component Räntsch (u = 1.8)
E	5 component Räntsch (n = 1.5)
F	5 component Räntsch (n - 1.8)
G	Pechan (n = 1.8)
H	Abbe and folded Abbe
I	Pechan (n = 1.5)

Fig. 32 Off-axis parallel transmission. The scales labelled 'angle in air' are to be used as abscissa scales to read off the angles outside the prisms. Each scale applies to glass of a different refractive index as indicated at the end of the scale

plane is compared in Fig. 32. The general decrease with increasing angle is due to geometrical vignetting, and the disappointing performance of the Räntsch in this respect is due to the fact that it consists of two separate halves. The discontinuity also results from this. Parts of transmission characteristics which are vertical, i.e. where a sharp cut-off occurs at a specific angle, result from total internal reflection requirements in the rotator. To keep Fig. 32 intelligible,

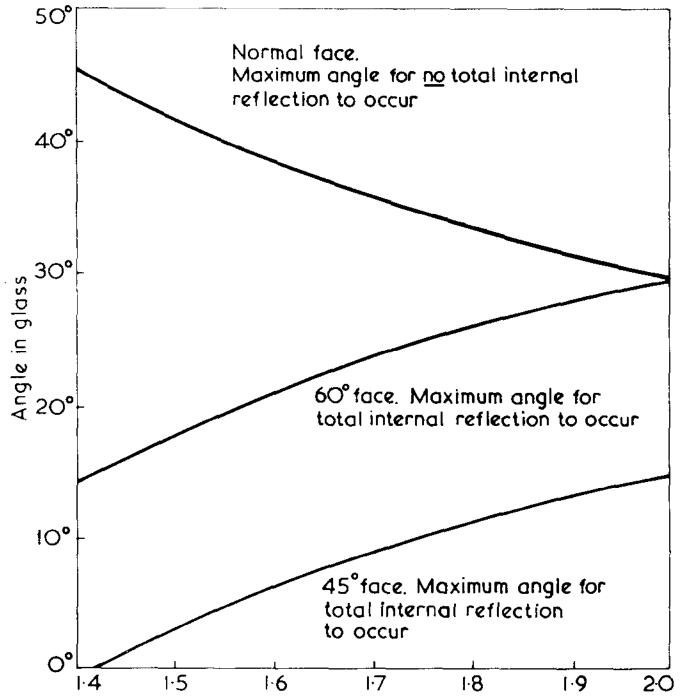
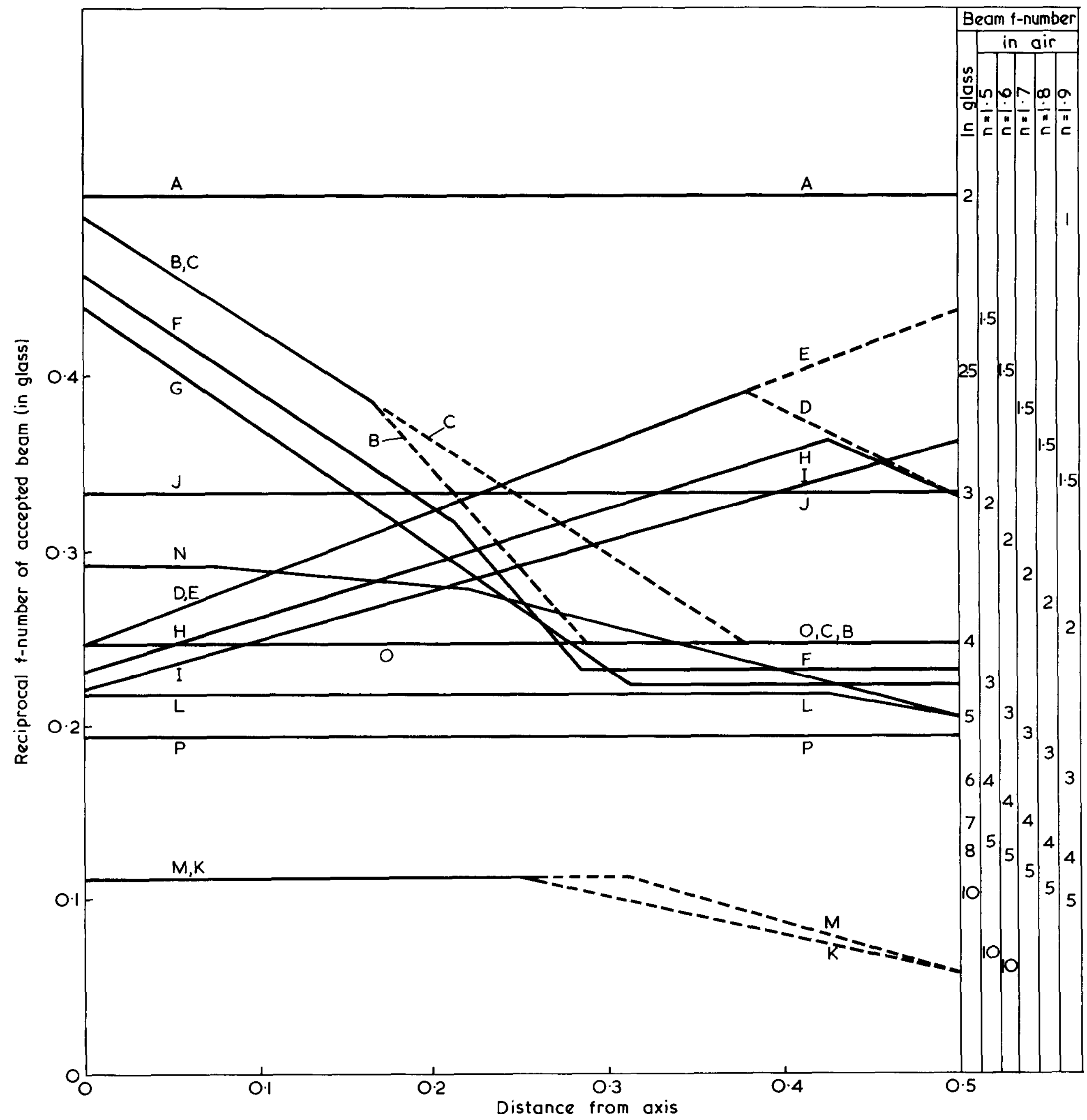


Fig. 33 Total internal reflection limitations



A	Polarization selective block (vignetting only)
B	5 Component Räntsch, orientation 1 (n = 1.5)
C	5 Component Räntsch, orientation 1 (n = 1.8)
D	5 Component Räntsch, orientation 2 (n = 1.5)
E	5 Component Räntsch, orientation 2 (n = 1.8)
F	3 Component Räntsch, orientation 1 (n = 1.5)
G	3 Component Räntsch, orientation 1 (n = 1.8)
H	3 Component Räntsch, orientation 2 (n = 1.5)
I	3 Component Räntsch, orientation 2 (n = 1.8)
J	Right angle rotator
K	Pechan orientation 1 (n = 1.5)
L	Pechan orientation 1 (n = 1.8)
M	Pechan, orientation 2 (n = 1.5)
N	Pechan, orientation 2 (n = 1.8)
O	Vee block
P	Abbe and folded Abbe

Fig. 34 Beam acceptance

results are shown for values of refractive index of 1.5 and 1.8 only. General curves showing total internal reflection limitations on semi-field are given for the convenience of the reader in Fig. 33. No allowance has been made in Fig. 32 for other losses, such as reflection or absorption. This is of significant importance only in the case of the polarization block, where vignetting only is included and not the efficiency of the beam splitting and polarization rotation layers.

Figure 34 shows the beam acceptance (see Section 4) as a function of distance from the axis. Notice that in the case of the Räntsch and Pechan the performance depends upon the orientation of the prism.

5.3 Ghosts

Light loss in the rotator may be serious, but often even more serious is unwanted light which is transmitted. This occurs in particular as a result of unwanted reflections, giving rise to so-called 'ghosts'. Potential problem areas of this type can often be identified in the tunnel diagram, but a complete examination of all possible stray light paths is most conveniently carried out by computer ray tracing. Many of the rotation systems described can suffer from ghosts unless care is taken to eliminate them at the design stage. Because of the dependence upon system requirements, no useful comparison is possible in this respect.

5.4 Production

As has already been observed, a rotator is equivalent to a plane mirror, which should lie in a plane including the rotation axis. If it does not, rotation will result in nutation of the image – i.e. the image will rotate about a point which itself rotates (at half speed) about the rotation axis. In a practical system it may be sufficient to ensure that the rotation axis intersects the effective reflecting plane in the image plane, provided that the angle between them is small.

Errors in prism angles perpendicular to the effective reflecting plane will tilt the effective reflecting plane and may result in aberrations – in particular chromatic aberration if the entrance and exit faces of the prism are not effectively parallel. The tilt of the effective reflecting plane may be corrected by a tilt of the rotator as a whole.

Errors in prism angles in the effective reflecting plane (due for example to pyramidal errors in components) are not amenable to correction in this way, and therefore if they occur in one-component prisms they will result in image nutation. In two or more component prisms such errors can be compensated by a twist between the components, providing that the errors are small. This will result in an error normal to the effective reflecting plane which must be corrected by tilting the complete system. Thus multi-component systems can in general be manufactured either by producing high precision components (the usual and more satisfactory situation) or by accepting only moderate precision and adjusting during assembly. Two path devices such as the Räntsch do not allow this choice and must be assembled from accurate components, with the additional requirement that registration between the two paths must be ensured. In fact even here some tolerances may be permissible since, as already remarked, it will generally be sufficient if the rotation axis intersects the effective reflecting plane – in this case both planes – in the image plane. Thus a small change in the axial position of the third component may compensate for small prism errors. Production difficulties have been crudely, qualitatively estimated in Table 1 using a simple classification.

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