A NEW LOOK AT RISLEY PRISMS

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Introduction
With laser beams finding more and more applications that require aiming them at distant targets (line-of-sight communications, aircraft-to-satellite secure communications, laser weapons and countermeasures, etc.) there are increasing demands for compact, robust, and economical devices for beam-steering. Gimbaled mirrors are the most commonly used beam-steering systems, but recently more and more beam-steering requirements are being met by Risley prisms. The advantages of a Risley prism beam-steering system include:

- compactness
- relative insensitivity to vibration
- low moment of inertia
- independent rotational axes (no carried axes, no need for slip rings)
- robustness
- speed

Risley prisms were originally used by ophthalmologists to measure binocular accommodation, and thus had a relatively small angular range. More recently, Risley prisms have been designed to cover a wide range of angles and have been achromatized to minimize chromatic variations in steering direction.

The operation of Risley prisms is most easily understood with reference to figure 1. Two prisms are shown (a) oriented such that they both refract light in the same direction and act as a single prism with twice the prism angle of either. In figure 1(b) each prism has been rotated about the optical axis by the same angle, but in opposite directions. In this case the beam remains close to the plane defined by the optic axis and the refracted beam shown in figure 1(a). Finally, in figure 1(c) each prism has been rotated by 90º and they combine to act as a parallel plate – with no net angular deviation. We will refer to the angle of the beam relative to the optic axis as the beam altitude. The beam azimuth, shown in Figure 2, refers to the angle around the optic axis relative to a reference direction perpendicular to the optic axis. As the prisms are rotated together in opposite directions, they continuously deviate the beam from the maximum angle off-axis, to zero, with little or no change in azimuth. It order to steer the beam to any specified altitude and azimuth, think of starting with the prisms as shown in figure 1(b), then rotating them in opposite directions until the desired altitude is achieved, and finally rotating them together about the optic axis until the desire azimuth is reached.

Figure 3 illustrates another way to view the action of a pair of Risley prisms. The red vector represents the deviation of the beam due to the first prism, and the blue vector – which rotates
about the end of the red vector – represents the action of the second prism. The end of the blue vector represents the net deviation produced by both prisms.

Extension to Larger Beam-Steering Angles
For small prism angles, as the second prism is rotated 360° about the optic axis the steered beam travels in a circle about the direction in which the beam would have been steered by the first prism acting alone. Basically, each of the two prisms acts independently to steer the beam by a fixed amount in a direction determined by the rotation of the prism about the optic axis. This neat picture becomes less accurate as the prism angles are increased; the locus of the beam steered by the second prism is no longer a circle, but becomes somewhat flattened in the vicinity of the maximum beam deflection. Moreover, as the beam deflection angle increases, the cross-section of the beam becomes elliptical, with the diameter being reduced in the direction in which the beam is steered. This means that the diffraction spread is increased in this direction. Standard optical design programs such as Zemax and Oslo allow rays to be easily traced through pairs of Risley prisms in various configurations, and also allow the distortion of transmitted images to be readily assessed.

Achromatization
An obvious disadvantage of Risley prisms is their inherent chromatic aberration; prisms are, after all, widely used to disperse spectra. However, Risley prisms can be corrected for chromatic aberration in the same way that lenses can be corrected – namely by combining materials having different indices and differing dispersion characteristics. Optical design programs can be used to design achromatic and apochromatic Risley prisms (using 2 or 3 different materials) that minimize wavelength-dependent variations of beam-steering direction over relatively large spectral ranges. For narrow spectral bands, where the chromatic beam-steering errors are very nearly linear with wavelength, we have also designed diffractive optical elements that do an excellent job of achromatization.

The Nadir Problem
The Nadir problem has to do with difficulties steering beams in the immediate vicinity of the optical axis. The first problem is that if the two Risley prisms are not precisely matched, it may not be possible to steer the beam along the optical axis (i.e. without deviation); in figure 3, this situation is equivalent to the red and blue vectors being of unequal length. The second problem is that even if the two prisms are precisely matched, it may require large prism rotations (like 180°) to make very small changes in the beam steering direction in the vicinity of zero beam deviation. This latter problem is particularly troublesome in tracking applications close to the axis. A simple way to cope with this problem is to insert a weak prism in the optical train when the steered beam approaches the nadir (zero deviation).

Design
The optical design of a pair of Risley prisms is fairly straightforward. The second prism generally has to be somewhat larger than the first prism in order to accommodate the full beam diameter at maximum deviation. We generally like to keep the adjacent faces of the two prisms parallel and normal to the common rotation axis of the two prisms; this tends to minimize the

overall size of the Risley prism pair. From a mechanical point of view it is extremely convenient that both prisms have a common rotation axis.

Figure 4 illustrates the mechanical design of a Risley Beam-Steering system. The key elements are the two Risley prisms, the two hollow-core brushless motors, the two sets of bearings, the two rotary encoders, and the housing that defines a mechanical frame of reference. Figure 5 shows two such Risley Beam-Steering (RBS) systems: Figure 5(a) shows a small RBS that can steer a 3mm diameter laser beam over a full 120° cone angle, and is achromatized for the 2µm to 5µm spectral band, and figure 5(b) shows a larger RBS that has a 4-inch aperture and can steer a diffraction-limited beam over the same angular range – with an aiming repeatability of better than 50 microradians (10 arcsec). The table below gives the specifications for these two Risley Beam-steering systems.

<table>
<thead>
<tr>
<th>Specification</th>
<th>3mm beam model</th>
<th>4” beam model</th>
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<tbody>
<tr>
<td>Max. beam diameter</td>
<td>3mm</td>
<td>4” (100mm)</td>
</tr>
<tr>
<td>Angular range</td>
<td>±60°</td>
<td>±60°</td>
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<tr>
<td>Pointing accuracy</td>
<td>1 milliradian</td>
<td>0.7 milliradian</td>
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<tr>
<td>Response time (full move)</td>
<td>100 msec</td>
<td>500 msec</td>
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<tr>
<td>Closed loop bandwidth</td>
<td>50 Hz</td>
<td>50 Hz</td>
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<tr>
<td>Update rate</td>
<td>500 Hz</td>
<td>500 Hz</td>
</tr>
<tr>
<td>Approximate size</td>
<td>3.5” long x 3.2” diam.</td>
<td>8.7” long x 10.75” diam.</td>
</tr>
<tr>
<td>Power requirement</td>
<td>28 watt</td>
<td>86 watt</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-40°C to +70°C</td>
<td>-40°C to +70°C</td>
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Figure 1  Risley Prism orientations

Figure 2  ALT & AZ definitions

Figure 3  Vector Model of Risley Prisms
Figure 4  Risley System Layout

Figure 5  Operating Risley Systems
(a) System designed for 3mm beam; 2µm to 5µm;
(b) System designed for 4” beam, 1.55µm, with 30µrad beam-steering repeatability