# Monolithic Hollow Corner Cube Retroreflectors for Precision Metrology

David Cook

Spectrum Scientific, Inc.

## Retroreflectors

Retroreflectors can be found in all aspects of our daily life from bicycle reflectors, traffic signs and reflective tape through to 'cat's eyes' on roads and reflectors on airport runways. In science and industry they are found in a number of metrology applications such as surveying and open path gas detection as well as in Michaelson type interferometers and laser based tracking systems.

You can even find retroreflectors on the moon as part of the Lunar Laser Ranging Experiment, where they are used to measure the distance between the earth and the moon.

## Types of Retroreflectors

Unlike a flat mirror where reflection is dependent on incident angle, retroreflectors reflect light back to their source along a parallel path with minimum deviation and scattering.

Common methods for producing this effect are achieved by the cats-eye method or using a trihedral corner reflector where three perpendicular planar surfaces meet at an apex point.

For the cat's-eye type method, the index of refraction, diameter and sphericity are important factors for proper function.

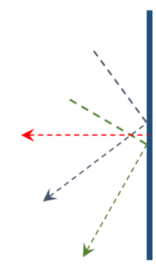
Cats-eye reflectors can be made from glass or plastic and higher grade versions are used for applications such as airport runways and safety related equipment.

Whilst precision cats-eye reflectors can be made by cementing two hemispheres with different radii, small glass spheres are more common and used as a low-cost solution.

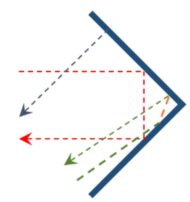
Another type of retroreflector is the corner cube retroreflector, which consist of three mutually perpendicular faces that intersect at a common vertex and come in three different types; prismatic, solid or hollow.

Prismatic corner reflectors are produced by plastic injection molding or embossing onto a flexible plastic sheet whilst solid corner cube retroreflectors are manufactured by conventional grinding and polishing methods and hollow retroreflectors are usually made using optical replication.

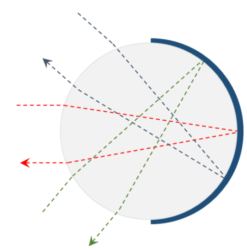
With metrology, imaging and other precision applications, minimum beam deviation and/or wavefront distortion are extremely important and as a result solid glass or hollow corner cube retroreflectors are used.



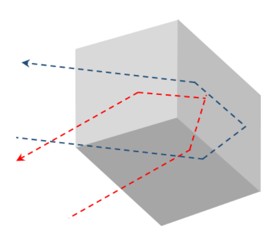
*Flat Mirror*



*Prismatic Reflector*



*Cat's-eye Retroreflector*



*Corner Cube Retroreflector*

# Monolithic Hollow Corner Cube Retroreflectors for Precision Metrology

Spectrum Scientific, Inc.

## Corner Cube Retroreflectors

Corner Cube Retroreflectors operate on the principle of total internal reflection (TIR). A beam entering the effective aperture is reflected by the three roof surfaces and emerges from the entrance / exit surface parallel to itself.

With metrology, imaging and other precision applications, minimum beam deviation and/or wavefront distortion are extremely important.

Thus for high precision applications, the choice is generally between solid glass retroreflectors or hollow retroreflectors.

One of the main drawbacks of using a solid glass retroreflector is the chromatic aberration that occurs when using broadband or multiple frequency light sources. Since glass is a dispersive medium, waves of different frequencies will propagate with different phase velocities ($\nu$), for a single wavelength this is given by:

$$\nu = dx/dt = \omega/k$$

Where $\omega$ is the frequency and $k = 2\pi/\lambda$.

In practice, a group of frequencies, or wave packet, is given by:

$$\nu_{group} = (\omega_2 - \omega_1) / (k_2 - k_1) = \Delta\omega/\Delta k \Rightarrow d\omega/dk$$

Thus, the original wave packet will change its shape based upon the time delay of each frequency and be different after retroreflection.

Hollow corner cube retroreflectors, such as those manufactured by Spectrum Scientific, do not suffer from chromatic aberration, making them ideal when the application requires a broadband or multiple frequency light source.

Hollow retroreflectors are created using the optical replication process which can achieve a return beam accuracy of better than 2 arc seconds. Made from a solid block of aluminum they are also thermally stable, insensitive to vibration, position and movement and can incorporate mounting features and fiducials onto the retroreflector itself for easy alignment, giving additional design and cost benefits.

*Figure 1. Hollow retroreflector with integrated mounting features*

Advantages of Monolithic Hollow Retroreflectors

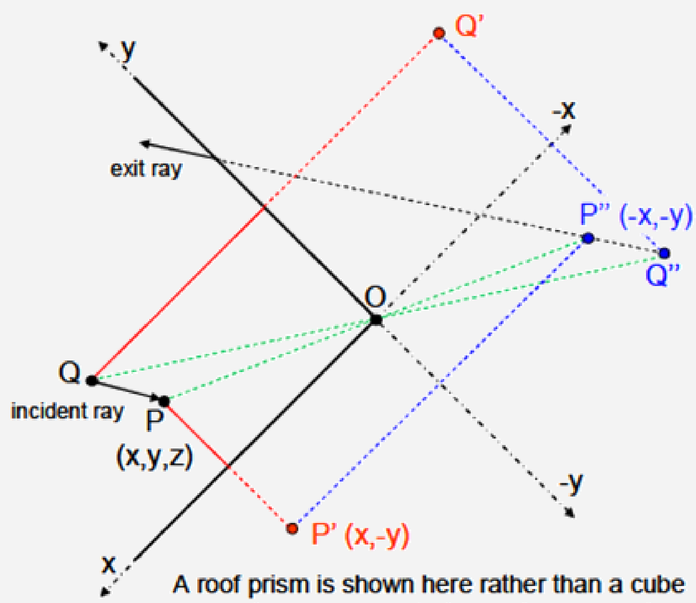
| | Solid Glass | Bonded Glass Hollow | Monolithic Hollow |
|---|---|---|---|
| No Chromatic Aberration | | ✓ | ✓ |
| Break Resistant | | | ✓ |
| Deep UV to IR | | ✓ | ✓ |
| Athermal | ✓ | | ✓ |
| No Fresnel Losses | | ✓ | ✓ |
| Integrated Mounting Features | | | ✓ |
| Larger Physical Dimensions | ✓ | ✓ | |

## Corner Cube Retroreflectors; A Simple Proof

Most of us know that a cube corner prism (hollow or solid) reflects back a ray of light exactly in the reverse direction (180°). Here I present a very simple proof of this without recourse to any ray tracing effort. The only property I use is that the virtual image of a point in a plane mirror is exactly at the same distance on the opposite side.

First let us consider a hollow cube corner. This can be defined by the mutually perpendicular axes X, Y and Z with the origin at O. (Note that in the illustration to the right, a simple roof prism is used to simplify the drawing; the same principles apply for a cube corner).

Thus we have three plane mirrors XOY, YOZ and ZOX. Let us consider a point P(x,y,z) any where inside the hollow cube corner. The virtual image of this point is P’(x,y,-z) after reflection at XOY. The virtual image of this in YOZ is P”(-x,y,-z) and finally the virtual image of this in ZOX is P’”(-x,-y,-z). This means that the point P(x,y,z) and its virtual image P’”(-x,-y,-z) form a straight line POP’”.




A roof prism is shown here rather than a cube corner to simplify illustration of the concept.

Let us consider another point Q. (Note that P and Q should be chosen so that the line joining them represents a ray incident on one cube corner surface that will also undergo reflections on the other surfaces.) By the same argument, we have its virtual image Q’” such that QOQ’” is a straight line. Now if we consider PQ as the incident ray direction, P’”Q’” is the emerging ray direction. It is easily seen that the triangles OPQ and OP’”Q’” (or OP”Q” in the illustration) are identical, and hence PQ and P’”Q’” are exactly parallel to each other. Since we have chosen P and Q arbitrarily, the property is valid for any ray of any direction.

Now consider a cube corner made of glass. We can assume that the hollow cube corner is filled with an infinite number of thin parallel plates of glass. Since a parallel plate of glass does not change the direction of a ray of light, the retroreflective property is true for a solid cube corner also.

*Semantic note: Cube corners are frequently called “corner cubes”. The proper term “cube corner” refers to being a “corner of a cube”, that is, a corner “sliced” off of a cube.*

*Figure 2. Used with permission from the authors, Dr. Murty V. Mantravadi and Susan Rico*

# Monolithic Hollow Corner Cube Retroreflectors for Precision Metrology

Spectrum Scientific, Inc.

## Applications

It is clear that a hollow cube retroreflector (HCR) is required when the metrology technique requires a broadband or multiple frequency light source.

Common applications that require HCRs include:

- FTIR Spectroscopy
- Laser Tracking Systems
- Range-finding
- Long Range Chemical Detection
- Lateral transfer applications
- Continuous alignment of large telescopes
- Optical Delay Lines

FTIR Spectroscopy is one of the many applications that use a hollow corner cube retroreflector since it requires a Michelson-type arrangement with a movable mirror.

The frequency spectrum of the helium neon laser is combined with the sample to produce a complex spectrum of amplitude as a function of time.

The spectrum is converted to frequency domain by applying fast Fourier transform (FFT). A smooth linear movement is necessary so that the signal is continuous and uninterrupted. By using a hollow retroreflector, any wobble or angular misalignment in the linear stage becomes irrelevant, thus alleviating the need for a precision stage.

This technique is also applied to environmental monitoring of atmospheric pollutants, with large arrays of retroreflectors deployed in oil processing facilities and other industrial settings.

Another application is Laser Tracking Systems which send out an encoded stream of pulses that are returned to the tracking head by a sphere-mounted retroreflector (SMR) and are able to measure distances many meters away with accuracies of 25 microns.

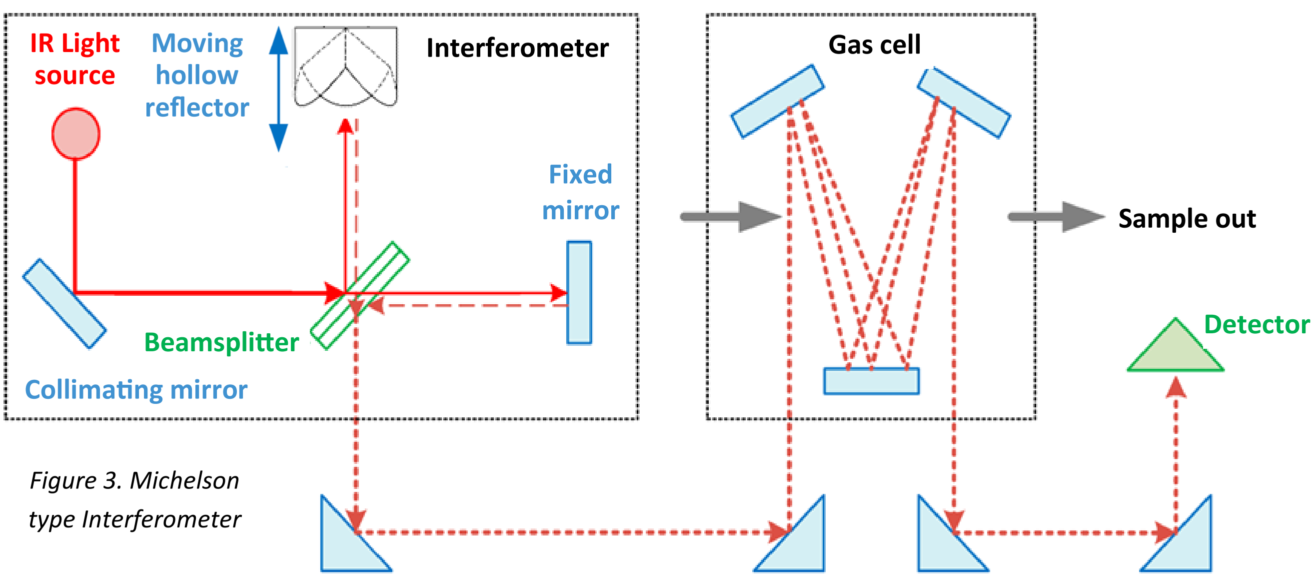



*Figure 3. Michelson type Interferometer*

## Applications cont...

These devices often use multiple wavelengths in order to obtain the accuracies needed and therefore, require hollow retroreflectors.

For this application, dihedral angle errors in each pair of plane segments is a critical parameter.

Sometimes referred to as adjacent angle error, there are three combinations to consider (see figure below).

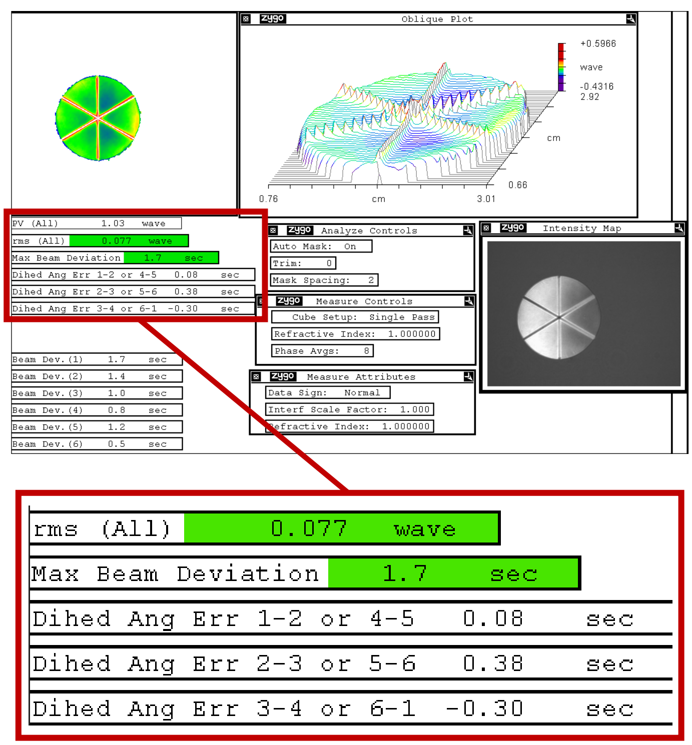



*Figure 4. Single Pass Interferometer scan of a Hollow Retroreflector with < 2 arc seconds beam deviation*

Dihedral angle error will cause the optical center of the beam to be offset with respect to the mechanical center of the SMR. This type of error will create a position offset in the system that must be reported so that the instrument can be properly calibrated to maintain accuracy.

Hollow retroreflectors are also used in Optical Delay Lines which can be used for path length adjustments in low coherence interferometer set ups, time resolved spectroscopy, bore sighting, range finding and beam delivery.

These applications will typically use a lateral transfer mirror arrangement. In addition to requiring a good quality linear stage, the set-up often uses several optical mirrors and mounts.

By replacing the mirrors with a hollow retroreflector or dihedral reflector, the opto-mechanics become much simpler and as in the FTIR example, will reduce linear stage errors.

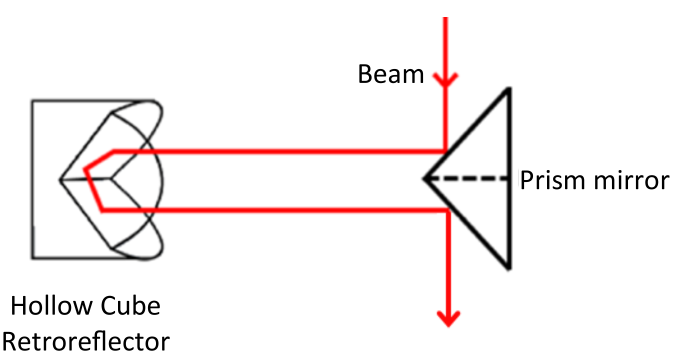



*Figure 5. Optical Delay Line*

# Monolithic Hollow Corner Cube Retroreflectors for Precision Metrology

Spectrum Scientific, Inc.

## Beam Deviation or Reflected Wavefront?

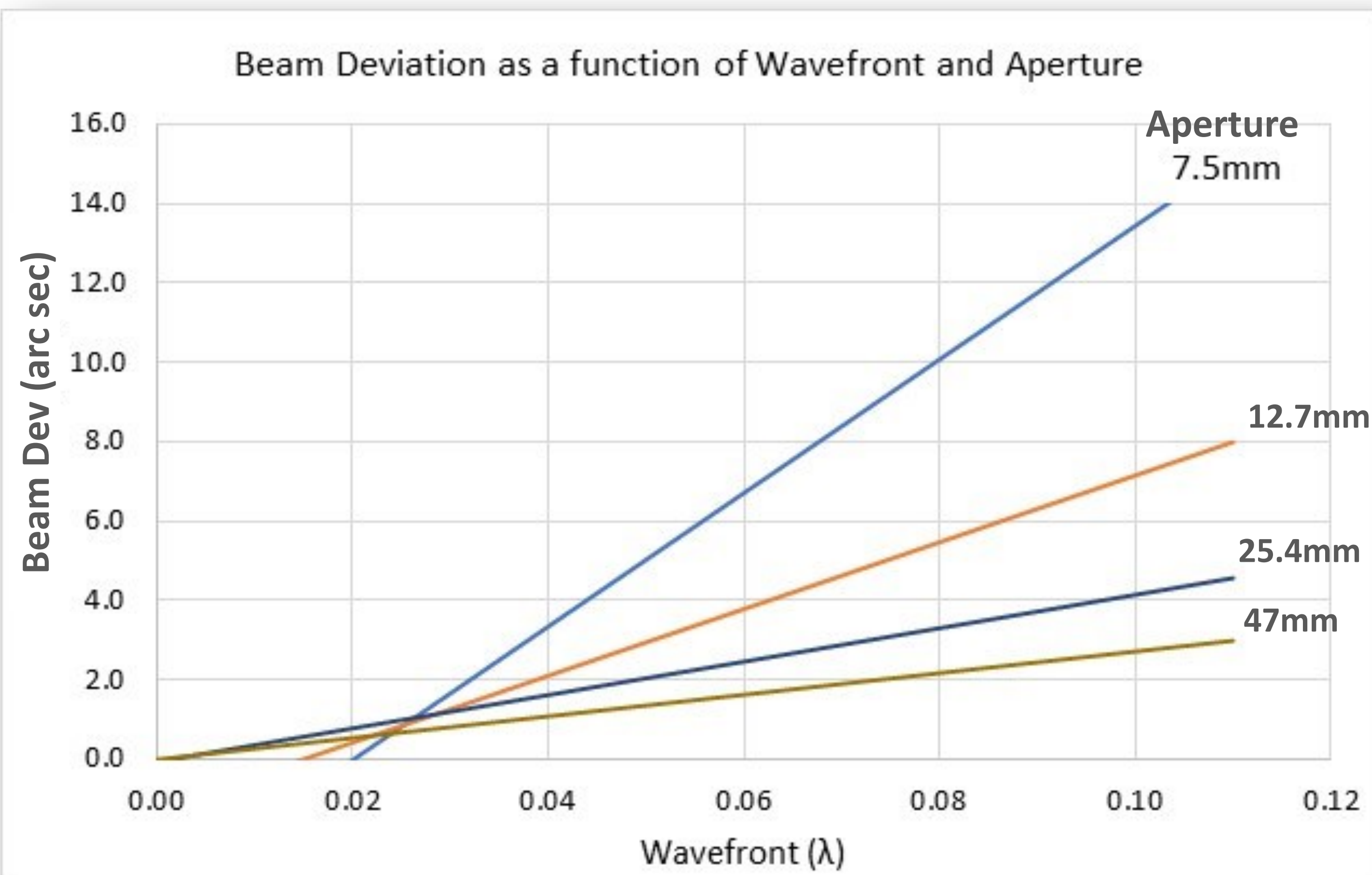
Theoretically speaking, the relationship between peak-to-valley (PV) wavefront distortion and beam deviation is given by:

$$\sin \alpha = E\lambda/r$$

Where:
E = PV wavefront distortion,
λ = interferometer wavelength (typically 632.8nm)
r = retroreflector aperture radius
α = angular deviation in radians.

In this relationship, the beam deviation is inversely proportional to the radius of the aperture, in other words, larger parts will more easily achieve better beam deviation.

Below is a chart derived from real production data of hundreds of parts which essentially supports the linear relationship.



## Beam Deviation or Reflected Wavefront cont...

However, upon closer inspection, it is apparent that as beam deviation approaches 1 arc second, the theoretical relationship diminishes, especially for smaller apertures.

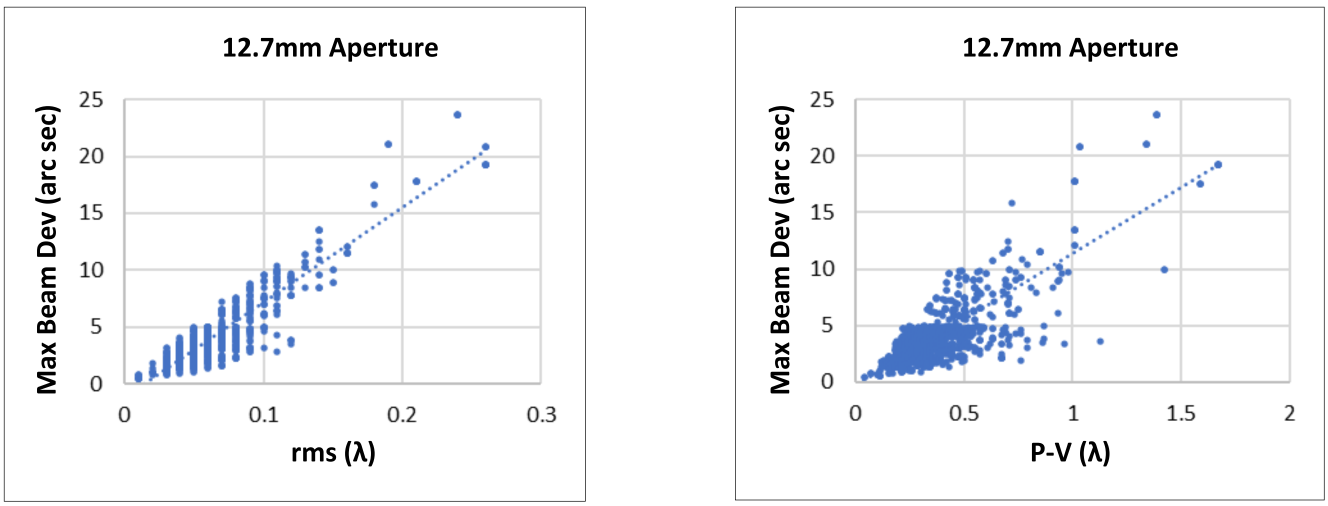
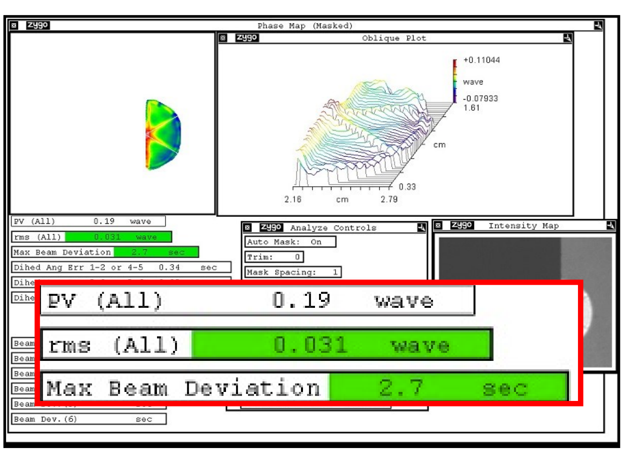
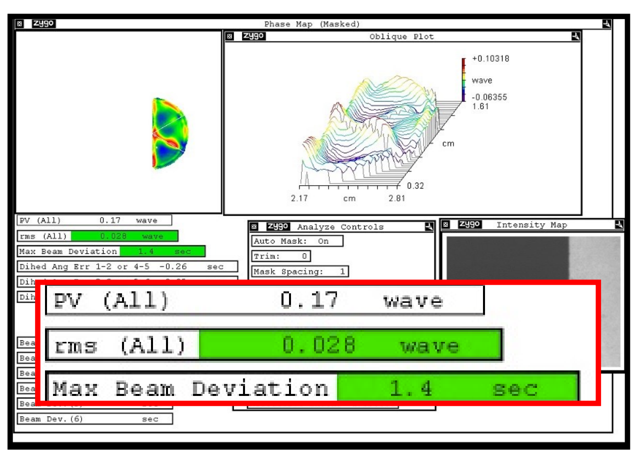



*Figure 6. Chart showing that on smaller parts with smaller beam deviations, retroreflectors can depart from theoretical linearity*

Parts with similar wavefront values, whether it's PV or RMS, are shown to have a variety of beam deviations present. While the magnitude of the PV values is similar, the varying shapes of surface perturbations cause different amounts of beam deviations.




In the double-pass set up the PV values are very close, yet the resulting beam deviation is different by nearly a factor of two.

## Specify RWE not SFE

For optical mirrors used in metrology applications, surface figure error (SFE) or reflected wavefront error (RWE) is often specified.

For retroreflectors it is not practical to use SFE because the light beam always strikes three mirror surfaces, and it is impractical to measure each mirror facet individually.

It is also possible for one mirror's surface figure to cancel out errors from an adjacent mirror. Therefore, we always specify RWE, beam deviation or dihedral angle error.

Another measurement distinction is single-pass versus double-pass measurements.

One of the strengths of the Fizeau interferometer design is that with their common path design, errors in the beam delivery optics are cancelled out.

Double pass measurements retain the common path method, however, single pass measurements do not.

Single pass measurements have the potential of being less accurate because a ray entering the hollow retroreflector will be shifted laterally and not come back through the same section of the reference flat as well as the collimating optics.

These errors may be slight, but it is often the reason that single pass and double pass results do not match.

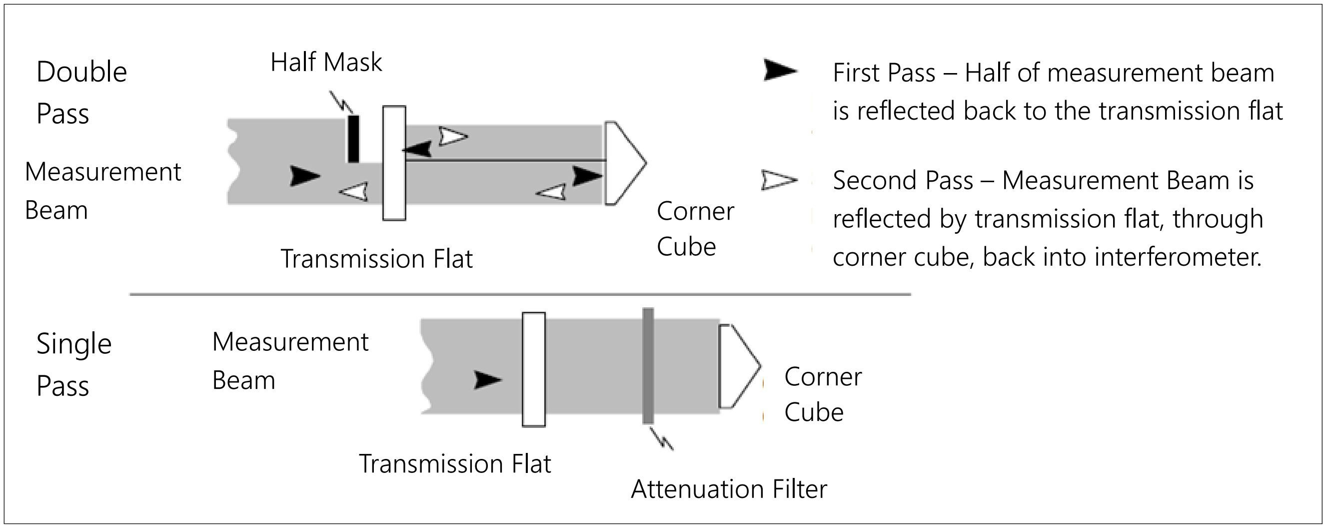



*Figure 7. Fizeau Interferometer Layout. Image courtesy of Zygo® Corporation*

## Conclusion

Monolithic, hollow retroreflectors are becoming increasingly important in precision metrology and other applications where high accuracy and repeatability are essential. They offer a number of advantages over traditional retroreflectors, including their ability to maintain a constant angle of reflection and their lack of joints or seams. As new manufacturing techniques are developed, we can expect to see even more innovative uses for these versatile optical components.

## About Spectrum Scientific

Spectrum Scientific, Inc (SSI) has been manufacturing high volume flat, aspheric and freeform reflective optics, hollow retroreflectors and holographic diffraction gratings since 2004.

We primarily use the optical replication process allowing us to supply high fidelity, high specification precision optics at a lower cost compared to traditional volume manufacturing.

One of our key capabilities is the manufacture of freeform optics, off-axis paraboloids and ellipsoid mirrors with surface figures down to λ/10 or better. We also manufacture plane, concave and convex holographic diffraction gratings, which can be supplied as blazed gratings using our proprietary blazing technique, which not only offers high efficiency in the UV, but lower stray light compared to conventional ion etched gratings.

Spectrum Scientific is ISO 9001:2015 certified and RoHS compliant and our production and test areas are space qualified offering a silicone free production environment where we can replicate reflective optics for space borne telescopes and optical interconnect systems.

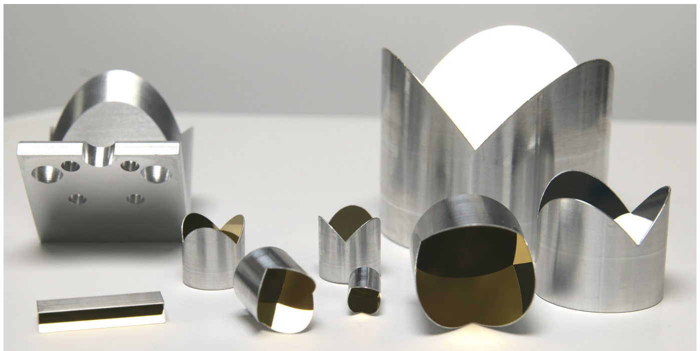


*Figure 8. A range of Spectrum Scientific's Monolithic Hollow Retroreflectors*

We have supplied a number of ultra-low stray light gratings for a number of high profile projects, including the Orbiting Carbon Observatory (OCO) and Ozone Mapping Profiler Suite (OMPS).



**Spectrum Scientific, Inc**
**16692 Hale Avenue**
**Irvine, CA 92606, USA**

**+(800) 774 0334**
**+1 949 260 9900**

**sales@ssioptics.com**
**ssioptics.com**