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Technical note

Multidirectional retroreflector assembly with a common virtual reflection point using four-mirror retroreflectors

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Abstract

A brief survey of retroreflector designs and applications is presented. A novel multidirectional (as opposed to omnidirectional) retroreflector concept is proposed by the author. A practical four-mirror retroreflector subassembly with a common virtual reflection point (thus eliminating the Abbe error), is described. Applications include: multilateration with interferometers, laser trackers, and electronic distance measurement surveying instruments; hidden point measurements to inaccessible locations; an extension of the concept to include optical targets for theodolite work; and an extension to other radiation sources, e.g., microwaves and acoustics. Example configurations are given.

Keywords: Retroreflector; Multilateration; Laser tracker; Surveying; Large-scale metrology; Coordinate measurement machine calibration; Four-mirror retroreflector; Electronic distance measurement; Hidden point target; Optical target

1. Introduction

A number of laser interferometer and electronic distance measurement (EDM) applications desire wide angle of acceptance, or multiple retroreflectors [1–14]. The primary problem with using multiple retroreflectors is due to the measurement axes not passing through the measurement point, thus making the measurements sensitive to rotations of the object and/or angle between the instrument and object, i.e., Abbe error [15,16].

Surveying equipment manufacturers have assembled solid glass retroreflectors, such as the Leica [17] GRZ4 360° prism, but the glass offset is a function of the incident angle [2,18,19], and coverage overlaps between adjacent retroreflectors, so there is a significant error (several mm for the GRZ4).

Goldman designed a “triplet” assembly consisting of a cat’s-eye retroreflector midway between two solid glass corner cubes directed to the rear of the cat’s-eye [20]. The center of the cat’s-eye and the optimal “optical center” of the corner cubes are colinearly mounted on a rigid beam assembly. One group of EDM instruments ranging on the cat’s-eye and another group of EDMs ranging on the pair of corner cubes can be tied together through the triplet benchmark. In order to avoid crosstalk between the two corner cubes, it is necessary to physically space them apart by several beam diameters. While the angle to the cat’s-eye can, in general, be anywhere in the field of view, the angle to the corner cubes must be limited to minimize the Abbe error.

Laser interferometers are typically calibrated in a back-to-back retroreflector configuration, where the rotation of the retroreflectors is constrained. For example, the National Institute of Standards and Technology (NIST) has built a Laser Rail Calibration System (Larcs) for calibrating laser trackers [21,22] against an interferometer on a linear rail [23]. Larcs uses two spherically mounted retroreflectors (SMRs) (described in more detail further), in a back-to-back configuration on a carriage, to build a bidirectional retroreflector assembly, i.e., one direction fixed for the reference interferometer parallel to the rail, and the other free to rotate in a nest to accommodate the laser tracker under test.

The Abbe error is minimized by mounting the two retroreflectors as close as practical and constraining the carriage to a rail system to minimize rotations of the assembly. However,

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for portable rails, the uncertainty due to the Abbe error is estimated to be a significant part of the total error budget. We have also used a similar technique at the National Radio Astronomy Observatory (NRAO)[1] [24], but used an additional mirror on the carriage for an autocollimator target and adjust the carriage mechanical alignment before taking readings.

NASA has built custom hollow retroreflector assemblies with a common physical reflection point [25,26], and thus eliminated the Abbe error. These solve the Abbe error problem for some classes of measurements. However, since these retroreflectors share a common physical point, they sacrifice part of the center aperture, are difficult to build, are difficult to reference to an outside mechanical point, are expensive for routine applications, and the directions are not adjustable.

Gelbart and Laberge describe an “omnidirectional retroreflector” pair combined with a fixed probe [9,10]. By multilaterating on the pair of retroreflectors, the probe coordinate is calculated. The omnidirectional retroreflector, described in one of their patents [9], “consists of two concentric spheres made of transparent material and having the refractive index of the inner sphere higher than the refractive index of the outer sphere, the outside sphere coated with a partially reflective coating.” Gelbart suggested that an improved design could be achieved by using three concentric spheres [27].

Recently, ideal omnidirectional spherical retroreflectors have been built from high index of refraction $N = 2$ glass [13,14,28]. Unfortunately, the glass is difficult to work, expensive, and the return power is low—due to the spherical aberration and small working aperture, as well as the low reflection coefficient of the glass/air interface on the backside of the sphere, i.e., most of the power is transmitted through the sphere. While these problems will hopefully be overcome by advances in materials and manufacturing techniques, only a few of these retroreflectors have been built since being introduced in 1994.

1.1. Multidirectional applications

Laser trackers incorporate a laser interferometer with an automated mirror system to track a retroreflector [21]. The interferometer measures differential range, with the fundamental environmental limitation being the uncertainty of the index of refraction of air—which is typically in the 1 ppm range.

The angle measurements are somewhat less accurate. The fundamental environmental limitation is atmospheric turbulence and temperature gradients bending the beam. There are also practical limitations with the encoders, mechanical system, beam quality, gravitational reference, etc. Nakamura et al. [13] points out that for a distance measurement uncertainty of δr, in an ideal orthogonal trilateration measurement, the uncertainty volume is $(\delta r)^3$. For two angles and a distance measurement, the uncertainty volume is $(r\delta\theta)^2\delta r$. For example, for a typical distance measurement uncertainty of 1 ppm ($\delta r/r = 10^{-6}$) and an angle uncertainty of one arc second ($\approx 5 \times 10^{-6}$ rad), the trilateration uncertainty volume would be

$$\delta v = r^3 \times 10^{-18}, \quad (1)$$

whereas the uncertainty volume for two angles and a distance would be

$$\delta v = 25r^3 \times 10^{-18}, \quad (2)$$

or 25 times greater than the trilateration uncertainty volume—hence, the inherent potential improvement in accuracy by using multiple distance measurements. In practice, there are two primary obstacles to achieving this huge improvement. Conventional retroreflectors do not support simultaneous measurements in the three orthogonal directions, and in actual field conditions it can be hard to mount an instrument on a stable tower or structure.

Laser trackers typically use spherically mounted retroreflector targets. These are typically hollow or cat’s-eye type [29–31] retroreflectors, with the optical centers carefully located in the center of the spherical mounting—thus allowing the optical measurements to be related to the physical center of the sphere. Hollow SMRs are more economical than cat’s-eye SMRs, but have a reduced angle of acceptance and thus are more susceptible to lose contact with the laser interferometer beam while tracking (requiring repeat measurements).

An obvious improvement in the accuracy of the laser tracker (or EDM) is to use multiple instruments and/or augment with additional information, e.g., known artifacts, stable bench marks, hydrostatic leveling, or other constraints. For three or more instruments, oriented in the proper baselines, the less accurate angle measurements can be neglected or weighted less in a least squares, or more sophisticated, reduction. While crosstalk is not a problem using multiple laser trackers on a common SMR, the relatively small angle limitation of even the cat’s-eyes makes the instrument baselines unfavorable for high accuracy multilateration measurements, and of course the Abbe error is the limitation for conventional assemblies of SMRs.

The Robert C. Byrd Green Bank Telescope (GBT) large-scale metrology system was designed to operate as a multilateration system employing 18 laser ranging instruments measuring ranges to cardinal points on the moving telescope [5]. While some paths are physically blocked by the structure, it behooves the designers to use multidirectional retroreflectors in order to maximize the number of independent measurements, and thus strengthen the calculation of cardinal point coordinates.

The increasing interest in multilateration, using laser trackers or other EDMs, has created a need for less expensive and more practical multidirectional retroreflectors with zero Abbe error.

[1] The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.