

Retroreflectors using a birefringent wedge for efficient velocity aberration compensation

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With introduction of optically anisotropic components, it is possible to deflect the return laser beam from a retroreflector relative to the incoming beam by any predetermined value, thus providing compensation for velocity aberration without considerable loss of return signal intensity caused by division of the reflected beam into separate lobes which normally occurs when dihedral angle offset is used.

Various practical solutions for this approach are presented, and experimental verification is provided.

Currently, for satellite and lunar laser ranging (SLR and LLR) on board of various spacecraft optical retroreflectors and retroreflector arrays are mounted, most of them using cube corner retroreflectors (CCR). A measure of their efficiency is their cross-section value having an upper limit [1]:

$$\sigma_{\max} = 4\pi A^2 \eta / \lambda^2$$

where A is the retroreflector aperture area, λ is the wavelength of incoming laser radiation, and η is a factor taking into account the total loss of optical energy in the retroreflector.

When the spacecraft (SC) carrying the retroreflector (RR) or RRA moves relative to the laser station, the reflected laser beam deviates from the direction towards the laser station by a certain angle called velocity aberration angle

$$\alpha = 2v_t/c$$

where v_t is the SC orbital velocity tangential component, and c is velocity of light.

If, due to the SC velocity and the RR aperture dimensions, the α value cannot be counted as small in comparison to the RR far-field diffraction pattern (FFDP) angular width θ , which is

$$\theta \approx \lambda/D$$

where D is the RR aperture dimension, then the σ value is reduced relative to the σ_{\max} value.

In real SLR conditions, the θ value for typical CCR dimensions is 3...4 arcsec, while the α value is 3,5...5 arcsec for high-orbit SC used in current satellite geodesy and navigation satellite systems (GNSS), and may reach 10 arcsec for low-orbit SC.

To minimize the optical power loss caused by the velocity aberration, usually angular offsets are made between the CCR reflecting surfaces (dihedral offsets) [2]. Thereby, in the simplest case the FFDP is divided in two lobes, and if the angle between the lobe axes is nearly 2α , Then with the lobe axes lying in the plane where the SC velocity vector is lying, the σ value may approach

$$\frac{1}{2} \sigma_{\max} = 2\pi A^2 \eta / \lambda^2$$

However, it is possible to avoid the two-fold σ reduction by forming a single-lobe FFDP of the reflected radiation, with the lobe axis deviation value equal to α relative to the incoming radiation direction. To achieve this, one may use the properties of birefringent

optical materials having different refraction indices for orthogonal polarization components of the incoming radiation.

The operation principle of such an RR is shown in Figure 1

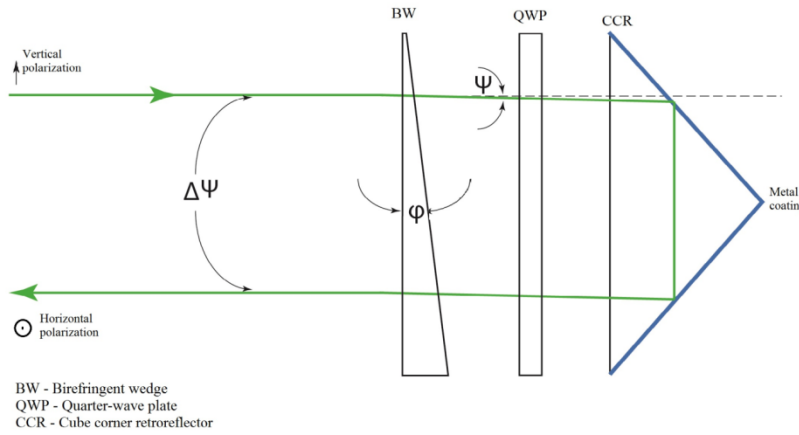


Figure 1 Retroreflector with velocity aberration compensation

Here BW (Birefringent Wedge) is a wedge-formed plate made of a birefringent material (e.g. quartz), QWP (quarter-wave plate) is a quarter-wave phase plate converting the incoming radiation having a linear polarization into a radiation having a circular polarization, while CCR is a cube-corner retroreflector with metal-coated reflecting surfaces which does not introduce any considerable distortion in the reflected radiation polarization.

If the crystal axis of the BW lies in the same plane as the wedge angle φ (i.e. in the Figure 1 drawing plane), and the incoming laser radiation polarization vector lies in the same plane, then with the small φ value (several arcmin) the direction of radiation passed through the BW will be deflected within the φ angle plane by

$$\psi \approx \varphi(n_o - 1),$$

where n_o is the ordinary-ray refraction index of the BW material.

After passing through the QWP, the laser radiation polarization will be circular, and after the reflection from the CCR and the second passing through the BW it will return to a linear state, but with a plane direction perpendicular to the incoming radiation polarization plane. As the BW material refraction index for this polarization state is n_e (i.e. is the material refraction index for the extraordinary ray), the direction of radiation passed through the BW will be deflected from the incoming radiation direction by a value of

$$\psi = \varphi \cdot \Delta n,$$

where $\Delta n = n_o - n_e$.

In a quartz crystal, the $\Delta n = n_o - n_e$ value at $\lambda = 532 \text{ nm}$ (operation wavelength typical for most of the current SLR stations) is ~ 0.0091 , so with $\varphi \approx 0.0026 \approx 9 \text{ arcmin}$ the outgoing beam axis deflection angle value (relative to the incoming radiation beam axis direction) will be

$$\Delta\psi = \varphi(n_o - n_e) = 0.0026 \cdot 0.0091 \approx 2.4 \cdot 10^{-5} = 24 \text{ } \mu\text{rad},$$

which is approximately equal to the velocity aberration value for GNSS satellites with an orbit height of 20...24 Mm (GPS, GLONASS, GALILEO).

By a practical implementation of such a retroreflector, instead of a BW made of solid quartz, a wedge-formed anisotropic coating may be used [3], deposited directly on the CCR face or on a glass plate placed in front of the CCR face (in the last case, QWP made of quartz or also fabricated as birefringent coating [3] may be installed on the opposite side of the glass plate (Figure 2), which may be rotated to follow the SC velocity vector direction, while the CCR will remain fastened to the SC); as an option, instead of a QWP, a multilayer dielectric coating on the CCR reflecting surfaces may be used creating the necessary phase shift between the orthogonal components of polarization (p and s) (Figure 3). With this option, the retroreflector will look as an ordinary CCR.

It should be noted that using of such a retroreflector on board of any SC will need a control of the SLR station laser beam polarization plane to provide its direction parallel to the SC velocity vector.

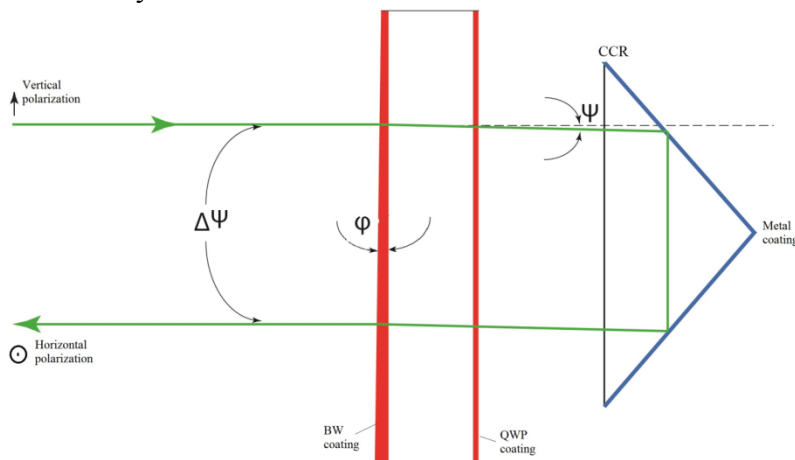


Figure 2 Modification of the device shown in Figure 1: BW and QWP are implemented as birefringent coatings.

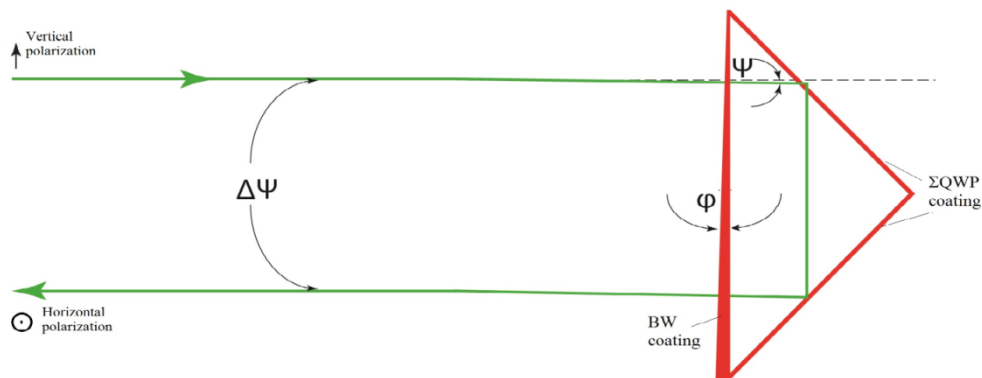


Figure 3 Modification of the device shown in Figure 1: BW and QWP are implemented as reflective multilayer dielectric coatings on the CCR providing total 90-deg phase shift after 3 reflections (Σ QWP coating).

Such a control may be avoided if the SLR station laser beam has a circular polarization, while the RR device is equipped with an extra QWP in front of the device providing conversion of the incoming circular-polarization radiation into a linear-polarization radiation with the necessary polarization plane direction (the QWP axes should be therefore

parallel to the axes of the QWP on the opposite side of the BW (Figure 4). The reflected radiation from this device will also have a circular polarization.

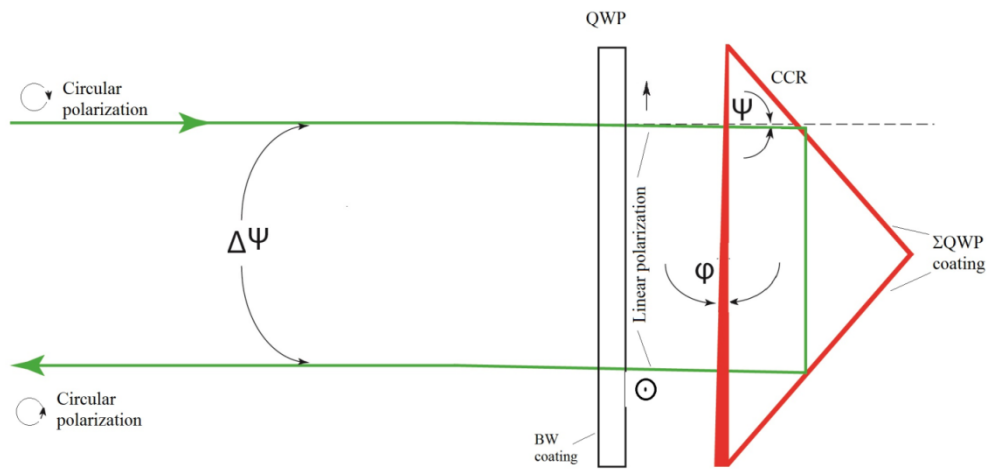


Figure 4 Modification of the device shown in Figure 3: for circular polarization of SLR station signal.

For demonstration and experimental testing of the proposed approach, a breadboard have been made in accordance with Figure 1, and placed into a measurement system used for regular RRA FFDP measurements with a radiation wavelength $\lambda = 532 \text{ nm}$ (Figure 5). The quartz BW had a wedge angle $\varphi \approx 26 \text{ arcmin}$, which corresponds to a calculated reflected beam axis deflection angle of 14.3 arcsec .

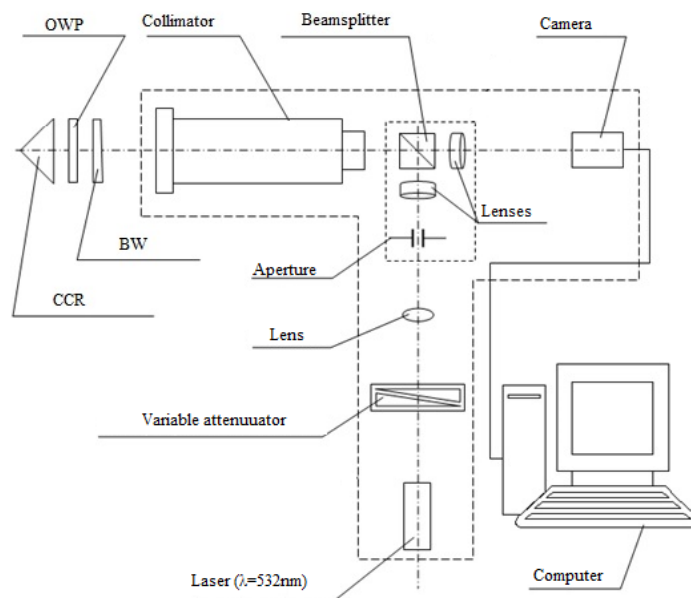


Figure 5

In Figure 6, the measurement results are presented. The reflected FFDP axis deflection corresponds to the calculated value within the measurement system accuracy (± 0.3 arcsec).

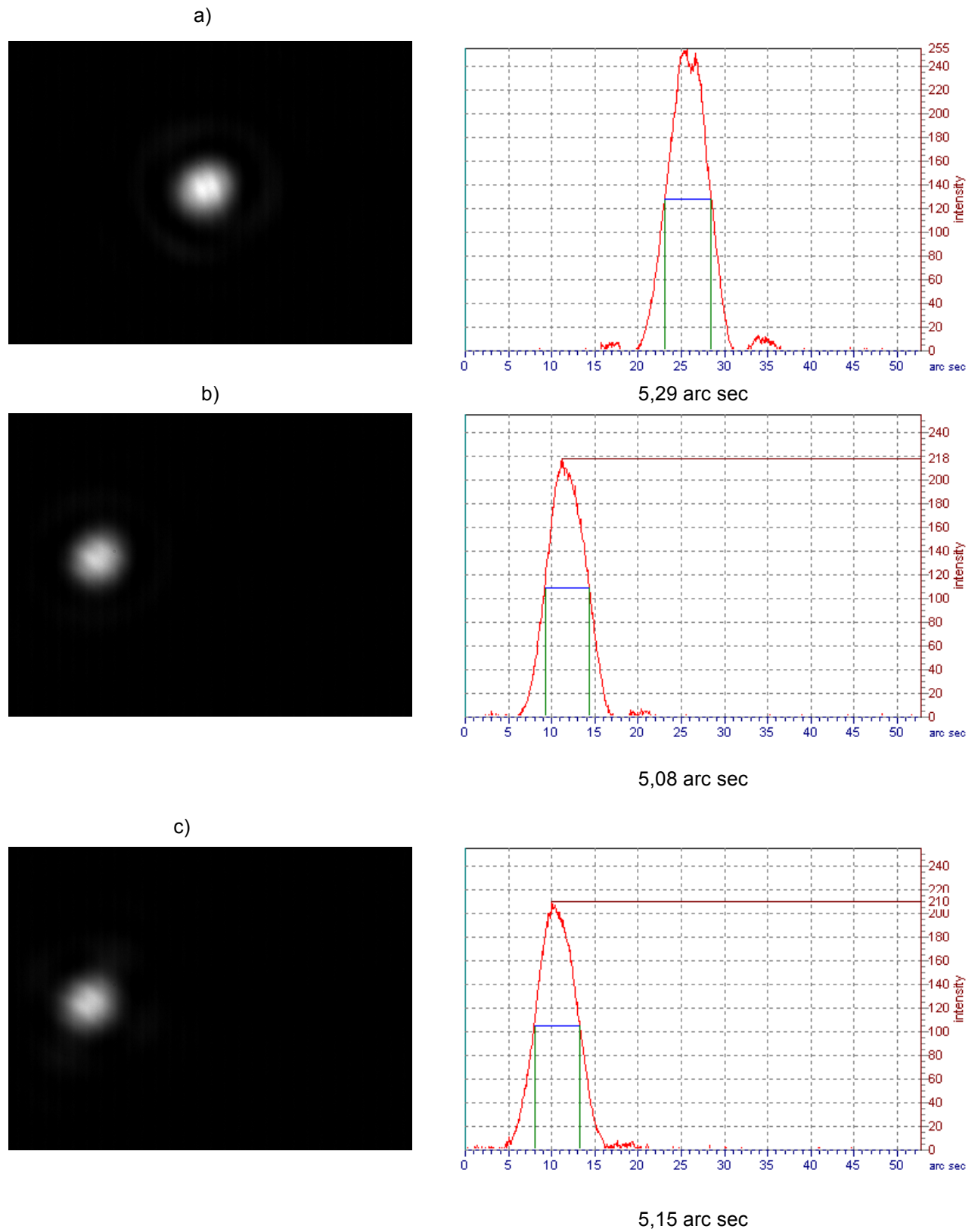


Figure 6
Retroreflector FFDP measured as shown in Figure 5.

- a) Without birefringent wedge;
- b) With birefringent wedge No 1 (two birefringent wedges were fabricated, each with a wedge angle of 26 arcmin);
- c) With birefringent wedge No 2.

The FFDP axis shift is ~ 14 arcsec (the shift direction depends on the BW orientation).

The QWP axes are at 45° to the BW crystal axis lying in the wedge plane.

The FFDP width ($\theta \approx 5$ arcsec instead of 4 arcsec for the 28-mm CCR aperture) was caused by the QWP aperture diameter (23mm).

A retroreflector of this type with a CCR aperture diameter of 48 mm equipped with a sun shade to prevent distortion caused by thermal gradients in the solid CCR body may provide a cross-section value of $\sigma \geq 100$ millions of square meters, corresponding to the requirements of the International Laser Ranging Service (ILRS) for GNSS retroreflector arrays, while having a zero signature necessary to provide highest ranging accuracy. As seen from Figure 6, the reflected beam intensity is only slightly less than the intensity of a beam reflected by a CCR without a velocity aberration compensation in a stationary state; some reduction is caused only by Fresnel reflections from the BW surfaced having no antireflection coatings.

A retroreflector of this type could be tested on board of a geostationary satellite which typically has a stable 3-axis orientation, thus avoiding the need for azimuthal rotation of the RR or some of its components relative to satellite body.

If necessary, the above approach may be used with other types of RRs (“cat’s-eye”, etc.)

References

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