

Feasibility of Free-Space Optical Communication Using Retroreflectors with Very Wide Field of View

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Abstract

This paper presents power budget predictions for retroreflective, free-space optical communication systems and examines options for producing retroreflectors with very wide field of view. Power budgets containing data representative of practical conditions show that operational ranges of many kilometres can be expected. Novel graded-index (GRIN) spherical retroreflectors have been examined in comparison with other types of retroreflector, and it is shown that they can offer technical advantages if they can be fabricated with suitable sizes and focal lengths. It is also shown that realisable high-index corner cube reflectors may be technically acceptable for this application.

Keywords: Retroreflectors, free-space optical communication, Graded-index, sphere lenses, corner-cubes

Introduction

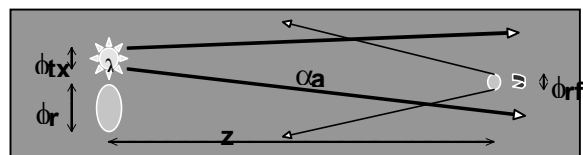
This paper examines the feasibility of developing enabling technology for optical interrogation and upload of data using a retroreflective, coherent optical communication system. Applications include covert surveillance and asset tracking in friendly and denied areas using small, low signature, low cost, remote sensor or tagging nodes. When used as optical tags, on friendly vehicles or personnel, asset tracking and IFF capabilities will also be possible.

The practical feasibility and theoretical performance limits of possible systems can be established by considering the optical power budgets and technical features of the major system components. It will be particularly important for the retroreflectors to have a very wide field of view to make such systems practicable and affordable.

Power budget analysis

A schematic diagram of a retroreflective optical communication system is shown in

the figure below. Light of wavelength λ from an optical aperture of diameter ϕ_{tx} strikes a retroreflector of diameter ϕ_{rf} and is collected by a receiving aperture of diameter ϕ_{rx} . The retroreflector is located a distance z from the source and receiver. During its journey, the light will be attenuated by the atmosphere, with attenuation α_a dB/km and will suffer diffraction which will ultimately be limited by the sizes of the apertures of the transmitter and reflector. The light is finally collected with an efficiency which is determined by the diameter of the receiving aperture.



Schematic diagram of retroreflective optical system

The equation below predicts the major influences on the reflected power captured

by a receiver for a long-range system, based on fundamental limits. Both the transmitter and the retroreflector are assumed to be diffraction limited for the purpose of calculating beam divergence. Losses due to atmospheric absorption and the mean scattering level are lumped into a single attenuation parameter.

$$P_{rx} \propto \frac{\phi_{rf}^4 \phi_{tx}^2 \phi_{rx}^2 e^{-2\alpha_a z}}{\lambda^4 z^4}$$

Additional parameters must be added into the power budget calculation in order to account for other important considerations. Amongst others, these may include:

- Fade margin

This is the dynamic component of atmospheric scattering and can be treated as a statistical variation of the received power. The magnitude of this variation can vary widely, and depends strongly on a combination of atmospheric conditions and range.

- System margin

This is an allowance which is normally made in order to account for component ageing and other imperfections which may accumulate during the life of a system.

- Receiver sensitivity

This is normally expressed as the required received power at a specific wavelength in order to achieve a given maximum bit-error rate (BER) at a given data rate.

- Background noise

For free-space systems, extraneous light can enter the detection system and lead to additional noise components in the receiver. This can be physically modelled, given assumptions about the nature of the extraneous light, or a fixed margin can be allocated.

- Modulation efficiency

For a retroreflective system, the modulator which is integrated with the retroreflector may be imperfect and its efficiency may also vary with the angle of arrival of

incident light.

- Mis-pointing loss

In a free-space, retroreflective system, additional loss will arise if the transceiver is not accurately pointed at the reflector.

- Receiver imperfection loss

In practice, receivers will include losses through a combination of the inevitable imperfections of practical components and designed-in factors such as beam sampling for pointing or other control systems.

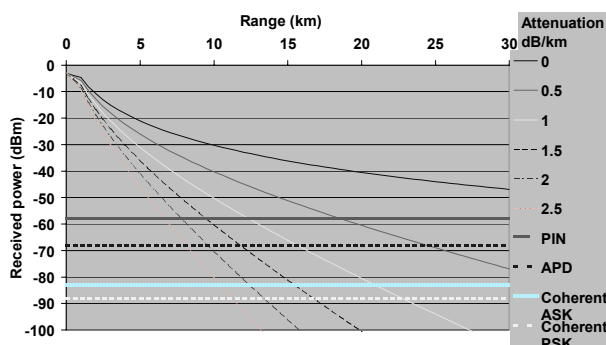
The table below shows choices of fixed parameters for a possible case. Mis-pointing loss is ignored due to lack of reliable data. Background noise has also been ignored for the present, as this tends to be very dependent on the overall system design. The reflector efficiency is assumed to be unity, since a well-made corner cube reflector with anti-reflection coating should be capable of less than 1dB reflection loss. A standard allowance of 10dB is typically introduced as a system margin. Two published demonstrations [1,2] of retroreflective systems have been used to help to estimate likely values of modulation efficiency and receiver loss, and also to choose a value for the fade margin.

Base parameters	Value	Unit	Notes
Source wavelength	1.5	µm	Practical option
Source power	5	W	Practical option
Tx aperture diameter	10	cm	Maximum practicable value?
Mis-pointing loss	0	dB	Ideal case
System margin	10	dB	Standard allowance
Reflection efficiency	0	dB	Ideal case; Corner cube on-axis
Modulation efficiency	-6	dB	Published results [1,2]
Reflector aperture diameter	5	cm	Maximum practicable value?
Fade margin	10	dB	published results [1,2]
Rx optical loss	-2	dB	published results [1,2]
Receiver aperture	10	cm	Maximum practicable value?

Fixed parameters for power budget example

The remaining parameters for the power budget example given here include the receiver sensitivity and the atmospheric attenuation. The sensitivity depends on the design of the receiver. In order to show the range of choice available, and to illustrate the effect on system range, four examples of different receiver types are shown in the results plotted in the figure below. A range of values was also chosen for the atmospheric attenuation, in order to show the effect this parameter has on the achievable distance for reliable communication. Zero attenuation represents the ideal case, while values ranging from 0.5dB/km up to 2.5dB/km represent typical conditions at different latitudes and seasons, from sub-arctic winter to tropical conditions [2].

The figure below displays the results for received power obtained from the power budget calculations, together with the powers required for reliable communication using different types of receiver. The received powers are plotted for the end-of-life condition, that is, with the 10dB allowance for the system margin having been deducted. Corrections were added to model special conditions encountered at very short range, leading to the sudden change of slope of the curves near to 1 km.



Variation of received power with range

The figure clearly shows that the most simple type of receiver, the PIN-

transimpedance variety, is able to offer almost 25 km range for atmospheric attenuation up to 0.5dB/km for the assumed example. Above approximately 1 dB/km, however, coherent detection techniques are required in order to achieve as much as 20 km range. When the attenuation is as high as 2.5 dB/km, the PIN based receiver can still provide approximately 6.5 km range, while the best coherent detection technique can increase the possible range to about 11 km. These results provide encouragement that useful communication range should be achievable with retroreflective systems. The system experiments reported by Olson et al. [2] achieved successful communication using coherent detection over a distance of 24 km near to the ground. Swenson et al. [1] were successful in communicating across distances up to 41.8 km along slant paths from the ground to an airborne reflector, using a detector based on a photomultiplier tube. Both of these reports appear to be reasonably in line with the predictions of the analysis presented here.

Comparison of retroreflector types

A number of generic retroreflector designs have been compared in the work done to date. These are:

- Conventional corner cube
- Uniform sphere with refractive index ~ 2 in air with integrated reflector
- Uniform-index sphere lens in air or refractive index immersion medium with separate reflector
- Graded-index (GRIN)-sphere lens in refractive index immersion medium with separate reflector
- Catadioptric lens

A fair comparison of reflector performance can be made by considering equal cross-sectional diameter of the package, not equal diameter of the optical aperture. This distinction is expected to be important from the user's point of view, since it is anticipated that there will be constraints on

the available package size in real applications, and there can be a large advantage in choosing designs which offer the largest aperture for a given package size.

The on-axis reflection performance in the far field of a given reflector is dominated by diffraction effects. For an ideal, diffraction limited retroreflector, such as a perfect corner cube used on axis, the reflected intensity I_{\max} at range z depends on the following relationship:

$$I_{\max} \propto \frac{r^4}{z^2 \lambda^2}$$

The corner cube and catadioptric lens reflectors are assumed to be diffraction limited for the purposes of this paper. Thus, used on-axis, they can be expected to deliver equal reflection efficiency at equal aperture. However, the uniform index sphere lens is badly limited by spherical aberration, and so is unsuitable for long-range applications. This problem may be avoidable by grading the refractive index distribution of the sphere [3].

The off-axis performance of retroreflectors can be analysed by calculating the reduction in effective aperture area due to geometrical effects as the source moves away from the axis of the reflector. The total reflected power will reduce in direct proportion to the area reduction factor. Also, the reduction in the effective linear dimensions of the aperture will increase the diffractive loss, once again in proportion to the area reduction factor of the aperture. It is very desirable to find designs which maximise the angular field of view in order to reduce the number of reflectors required to fulfil likely practical requirements. Of the various types of retroreflector considered here, the catadioptric lens is least likely to be able to fulfil this requirement. Furthermore, it requires the precise manufacture and assembly of a number of elements, and this

is unattractive for cost-sensitive applications.

For a corner cube, the geometrical argument leads to the following expression for the variation of reflected power $P_s(\theta)$ with angle of incidence θ :

$$\frac{P(\theta)}{P(0)} = (1 - \sqrt{2} \tan \phi)^2 \left(1 - \frac{\sqrt{2}}{3} \tan \phi\right)^2 \cos^2 \theta$$

where $P(0)$ is the on-axis reflected power, ϕ is given by $\phi = \sin^{-1}\left(\frac{\sin \theta}{n}\right)$ and n is the

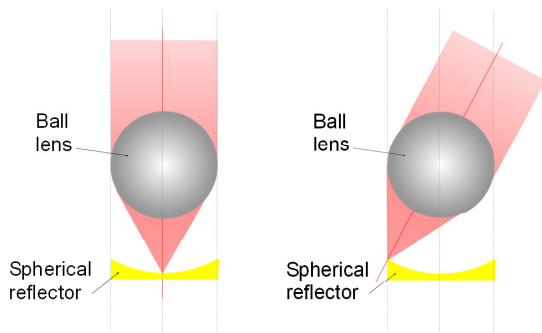
refractive index of the material filling the corner-cube. Examples of the off-axis reflection performance of corner cubes made with materials of different refractive indices are given at the end of this paper.

The normalised reflection efficiency of sphere-lens based retroreflectors depends on their design. The main factors which influence the efficiency are the focal length of the lens, and the angular field of view which must be covered by the reflector. The radius of curvature of the reflector, R , must be equal to the effective focal length of the lens. The ratio F of the reflector's radius of curvature to the radius of the sphere lens r_s , $F = \frac{R}{r_s}$, can be regarded as

the normalised focal length of the sphere lens, and is useful for comparing different cases.

An example of a retroreflector having a package radius equal to the radius of the sphere lens itself, is shown in the figure below. If this were a perfect GRIN-sphere, then the normalised reflection efficiency would be unity, (i.e. the reflection efficiency would be equal to that of a corner cube having the same aperture). As the angle of incidence is increased from zero, there will be no change in the reflection

efficiency because the aperture of the sphere lens is not obstructed and all of the incident light is accurately focussed on the reflecting surface. This situation will persist until a limiting case where $\theta = \theta_{\max}$, which is encountered when the extreme ray becomes parallel to the axis. For greater angles of incidence, the light will miss the reflector, so the efficiency will then be zero.



Sphere lens reflector with limited field of view

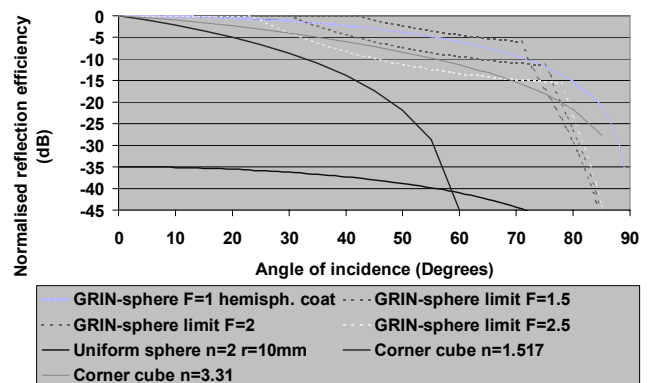
The limiting angle of incidence for this design is defined by the expression

$$\theta_{\max} = \sin^{-1} \left(\frac{1}{F} \right).$$

The useful angular field of view of the retroreflector can obviously be increased by extending the reflecting surface further over the imaginary sphere of radius R . This will obviously increase the cross-sectional radius of the package r_p , but the useful optical aperture remains fixed with radius equal to r_s . Though the reflection efficiency will be independent of the angle of incidence up to some new maximum angle, the normalised reflection efficiency will now be uniformly reduced by an aperture factor given by $(r_s / r_p)^4$. For very large angles of incidence, the incident light can also be obstructed by the reflector, producing a sharp decrease in the reflection efficiency.

The figure below shows a comparison of reflection efficiency and field of view of the most attractive types of retroreflectors which might be made, and also a uniform index spherical reflector. Since GRIN-sphere reflectors are not currently available, performance envelopes are given instead of specific examples, except for one highly

idealised case where the normalised focal length is taken as unity, and a hemispherical reflective coating has been assumed. For most other cases, the GRIN-sphere will deliver a rectangular reflection characteristic bounded by the performance envelope for the relevant normalised focal length. Uniform index spheres are easily available at low cost, but suffer from a serious disadvantage in reflection efficiency across most angles of incidence. Standard, commercial corner cubes ($n = 1.517$) are unacceptable for use beyond angles of incidence approaching 60° , but higher-index corner cubes may be adequate if they can be made with sufficiently high index for acceptable cost. GRIN-sphere reflectors with normalised focal lengths up to $F = \sim 1.5$ can in principle produce better reflection than the $n = 3.31$ (GaP) corner cube at 60° angle of incidence. However, for equal package size, a penalty in reflection efficiency must be accepted at low angles of incidence compared to the performance of corner cubes. Finally, if large GRIN-spheres could be made with a normalised focal length of $F = 1.5$ or below, very worthwhile gains in reflected power can be expected, amounting to 10dB or more near to 60° angle of incidence with negligible penalties at lower angles of incidence.



Comparison of normalised reflection efficiency for various retroreflectors

Conclusions

This paper predicts that retroreflective, free-space optical communication systems using retroreflectors with very wide field of view can operate over ranges of many kilometres.

References

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