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Laser Communication Range

You can estimate the range of a laser communications system using Fig 1. The graph is based on:

$$\text{range} = \sqrt{\frac{P_\ell \times A \times T_a \times T_o \times 4}{D_s \times \pi \times \Theta^2}} \quad \text{(Eq 1)}$$

where

range is in kilometers
P_ℓ = laser power
A = area of receiving optics (lens or mirror)
T_a = transmissivity of the atmosphere
T_o = transmissivity of the receiving optics
D_s = detector sensitivity (minimum detectable signal)
Θ = beam divergence (in radians)

The graph shows the theoretical maximum communications range for a 1-mW HeNe laser operating at 6328 angstroms (Å) with a 1-mR beam divergence (0.001 radians), assuming minimal atmospheric absorption and scattering (visual range = 100 km—a *very* clear day) and average optics (T_o = 0.85).

The value of T_a is determined by a number of factors. First is the absorbance of the atmosphere. For these calculations, T_a was assumed to be negligible at a wavelength of 6328 Å. Second is scattering loss from two sources: the molecules in the atmosphere (Rayleigh scattering) and dust and moisture droplets in the atmosphere (Mie scattering). Both of these forms of scattering are wavelength dependent. The third factor that determines T_a is the path length over which the light travels. The transmissivity due to scattering loss is given by:

$$T_a = e^{-sd} \quad \text{(Eq 2)}$$

where

e = 2.71828 (the base of natural logarithms)
s = the combined Rayleigh and Mie scattering coefficients (calculated to be 0.0327 km^{-1} for the stated conditions)
d = distance

In order to determine the range the transmissivity of the atmosphere is needed, and in order to determine the transmissivity, the range is needed! This conflict can be dealt with by a mathematical method of successive approximations; this technique was used to obtain the values shown in Fig 1. The effects of atmospheric turbulence have been omitted from these calculations. When present, turbulence can cause a reduction in received signal through a number of mechanisms, including beam steering, spreading and scintillation. These effects all reduce the potential range, and are minimized by the use of large-area receiving optics. Other effects are present in coherent-detection systems (homodyne or heterodyne detectors), but they will not be dealt with here, as all amateur work to date has used direct detection.

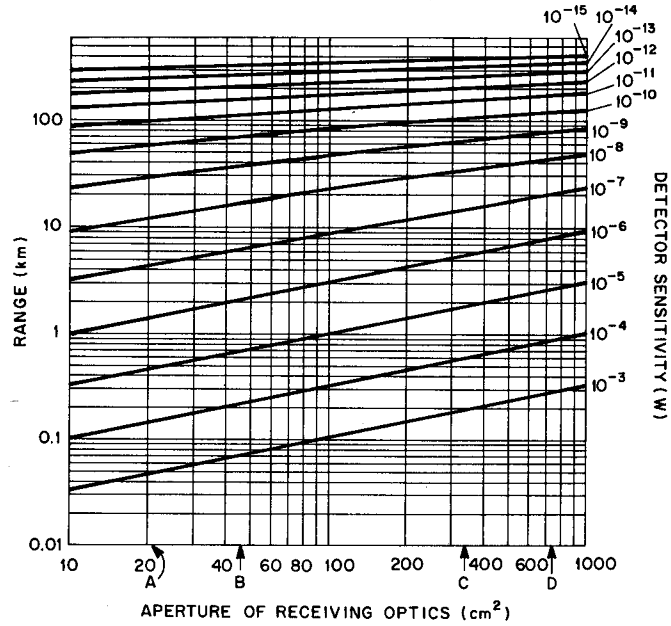

Fig 1—This graph can be used to calculate communications distances for HeNe lasers and combinations of optics and detector sensitivities. These range estimates are based on a 1-mH HeNe laser with a 1-milliradian beam divergence. Along the Aperture of Receiving Optics scale, A represents a 2-inch lens, B represents a 3-inch lens, C represents an 8-inch mirror and D represents a 12-inch mirror or a 10.5-inch-square Fresnel lens. See text.

Range is given for various detector sensitivities from 1 mW (10^{-3} W) to 10^{-15} W. To obtain the range for higher laser powers, read from a proportionally higher sensitivity curve, ie, for a 10-mW laser and a 10^{-6} W detector, use the range for a 10^{-7} W detector. For a different beam divergence, use the same technique. For example, for a system using a 10× beam expander, a 10× decrease in beam divergence is obtained. In this case read from a sensitivity curve which is the square of the relative beam divergence (10 × 10 = 100) times more sensitive (this comes from the Θ^2 term in Eq 1) than the actual detector sensitivity in use; ie, for a 1-mW laser with a 10× beam expander (and consequently 10× less beam divergence) used with a detector of 10^{-6} W sensitivity, read the range from the 10^{-8} W detector-sensitivity curve. For visible-light lasers other than HeNe (red), range will be less, because higher-frequency light (ie, more blue) will suffer more scattering loss.

The best detector systems (such as photomultipliers), operating under ideal conditions (no background light), can reach a detector sensitivity of 10^{-12} W. A typical photoDarlington transistor detector should be easily capable of a sensitivity of 10^{-7} W in an amateur system, and can probably do much better. The atmospheric transmissivity depends on atmospheric conditions and path length. For short (several-km) paths, T_a approximates to 1 under clear conditions. The transmissivity of the optical system depends on the quality of the optics. A typical value is around 0.85.

As you can see, using the very best detector, a 1-mW laser is capable of working the longest line-of-sight paths available. Even with a simple solid-state detector and small-aperture receiving optics (such as a 3-inch diameter lens, A = 43 cm^2) a range in the tens of kilometers is possible. It can also be seen from the graph that the best practical way to achieve maximum range is to develop the most sensitive detector system, because receiving-optics apertures of more than 1000 cm^2 are unwieldy (and expensive), and surplus lasers of more than 10 mW are hard to find, and potentially quite dangerous.

Anyone interested in the rather complex details involved in calculating scattering losses, please drop me a line at the address at the top of this column.