OPTICAL ANTENNAS

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Optical communication systems have the capability to transmit very high data rates (1-Gbps) over long distances. One primary reason is the narrow beamwidths achievable with optical antennas having diameters of less than 30 cm. This paper discusses how the Gaussian beam patterns of the laser sources are modified as they are transmitted through physically realizable optical antennas. Measurements taken on an optical antenna developed for spaceborne operation are presented and compared with theoretical predictions. Optical receiver antennas are also discussed stressing the differences between direct and heterodyne detection. Finally, consideration is given to the privacy and jamming resistance of optical communication systems using these small optical antennas.

INTRODUCTION

Communications in the optical portion of the spectrum have become a reality with the development of the laser as a source of coherent radiation. However, to fully utilize lasers in open-beam communication systems (as opposed to fiber-optic systems), it has been necessary to develop optical systems to shape, direct, and collect the laser radiation. These "optical antennas" function in a manner similar to rf antennas, but there are some basic differences, primarily due to the Gaussian amplitude distribution of laser sources and the much shorter optical wavelengths involved. It is the purpose of this paper to discuss the theoretical and practical design of both transmitting and receiving optical antennas, present some actual performance data, and finally to point out the system privacy and anti-jamming characteristics provided by optical antennas.

TRANSMITTERS

The primary function of the transmitter antenna is to shape and direct the optical radiation from the laser source. The measure of the effectiveness of the antenna is the intensity of radiation available in the center of the far-field radiation pattern. Quantitatively the effectiveness can be expressed by the antenna gain given in generalized format by

$$G = \frac{4\pi}{\Omega} \tag{1}$$

where:

- G = antenna gain
- Ω = solid angle of the radiation pattern.

A high gain indicates that the radiation pattern is a small fraction of the full spherical solid angle of 4π steradians. The more familiar gain representation is given by

$$G = \frac{4\ A}{\lambda^2} \tag{2}$$

where

- A = area of the antenna
- λ = wavelength

Since the optical wavelengths are typically a factor of 10^{-4} smaller than the millimeter wavelengths, the gain of an optical antenna will be approximately 80 dB higher than the gain of a millimeter wave antenna with the same area.

The laser source in its normal operating mode emits a highly directional, narrow beam of optical radiation, and for some applications an optical antenna is not even required. However, the beam diameters emitted by lasers suitable for optical communications are on the order of a few millimeters resulting in radiation patterns having angular beam widths on the order of a few milliradians. Therefore, to realize the full communication potential of the optical wavelengths, the laser beam size must be expanded and the radiation pattern narrowed with the use of an optical antenna. In accomplishing this beam expansion, there are trade-offs to be made and optimizations to be performed. Some of these trade-offs and optimizations will be discussed in the following paragraphs to provide a basis for evaluating the real performance of an actual transmitting optical antenna.

The radial intensity distribution of the optical radiation pattern as it leaves the laser is circularly symmetric and is given by

$$I(r) = \frac{2P}{\pi r_o^2} e^{-\frac{2r^2}{r_o^2}} \tag{3}$$

where

- I(r) = intensity as a function of radial coordinate
- P = total power emitted
- r_o = the point where the intensity is l/e 2 of the intensity at the center of the beam.

Equation (3) is the Gaussian distribution generated by the TEM_{oo} mode, the lowest order mode of the laser. As the laser beam propagates to the far field, the angular beam width is given by

$$\alpha = \frac{2\lambda}{\pi r_o} \tag{4}$$

where

α = full angular beamwidth to the $1/e^2$ intensity points

λ = wavelength.

Since the far-field angular distribution of radiation is the Fourier transform of the amplitude distribution at the source, the far-field angular distribution of the radiation pattern emitted directly from the laser is also Gaussian and is given by

$$I(\theta) = \frac{2\pi r_o^2 P}{R^2\lambda^2} \quad e - \tfrac{1}{2}(k\theta)^2 r_o^2 \tag{5}$$

where

$$k = \frac{2\pi}{\lambda}$$

R = range from the source.

This expression normalized for unity intensity at $\theta = 0$ is plotted in Figure 1. Note that there are so sidelobes, and the intensity falls off monotonically. The angular beamwidth as defined by width at the $1/e^2$ points is given by equation 4, where the values for wavelength and the laser beam radius, r_o, have been chosen as 532 nm (green light) and 1 mm respectively, resulting in a full angular beamwidth of 0.34 milliradians.

This angular beamwidth can be significantly reduced by expanding the 2-mm diameter with an optical antenna. However, when this is done, the far-field intensity distribution of the laser beam itself will be modified by the diffraction effects due to the finite size of the optical antenna. The diffraction effects could be made negligible if the diameter of the optical antenna were made at least three times larger than the desired laser beam size. Since the size and weight of the optical antenna is an important consideration in any system design, there exists a trade-off between minimizing the diffraction effects while also minimizing the size of the optical antenna.

To make this trade-off, we first consider the expression for the intensity of the far-field pattern of a Gaussian beam passing through a circular aperture such as a finite sized lens given by

$$I(\theta) = \frac{8\pi P}{R^2\lambda^2 r_a^2}\left| \int_0^a e^{-\frac{r^2}{r_a^2}} J_o(k\theta r)\, r\, dr \right|^2 \tag{6}$$

where

k = $2\pi/\lambda$
a = radius of the circular aperture,
$J_o(\ )$ = Bessel function of zero order
r_a = $1/e^2$ point of the Gaussian beam in the plane of the aperture

and the integration is taken in the plane of the circular aperture. This expression is plotted in Figure 2 for values of a = 9.5 cm and r_a equal to 8.7 cm. The intensity values have been normalized to unity for the case where a is infinitely large.* Note the presence of sidelobes or diffraction rings. The width of the center portion of the pattern is not appreciably different from the width of the undiffracted pattern having an $1/e^2$ diameter of 17.4 cm. However, the intensity at the center of far-field pattern is significantly less than that for the undiffracted case because some of the power has been diffracted into the sidelobes.

In most practical applications the size of the circular aperture or optical antenna is limited by the system considerations. To minimize the effects of diffraction, the intensity of the center of the far field pattern should be maximized for a fixed value of a. The parameter to vary is r_a, the radius of the laser beam at the surface of the optical antenna. This is accomplished by differentiating equation 6 with respect to r_a for a value of $\theta = 0$ and setting the resulting expression equal to zero. Solving the equation gives the following expression
for r_a as function of "a"

$$\frac{r_a^2}{2a^2 + r_a^2} = e^{-\frac{a^2}{r_a^2}} \tag{7}$$

The solution to the transcendental equation 7 is given by a value of r_a = .892a. Thus to maximize the intensity at the center of the far-field pattern, the $1/e^2$ diameter of the laser source should be expanded to a value of .892 of the diameter of the optical antenna. The value of the intensity in this case is 51 percent of (or approximately 3 dB less than) the intensity of the same size laser beam passing through a very much larger aperture. If it were possible to use a larger antenna (approximately 3 times larger), the 3 dB loss could

* Equation 6 will reduce to the form of Equation 5 if the upper limit in the integration is infinity through the use of the Hankel transform.

be recovered for the same sized laser beam. However, if the antenna were three times larger, the intensity could be increased by a factor of nine or 9.5 dB by expanding the size of the laser beam to .892 of the larger antenna diameter. In that case the angular beam width would be narrower by a factor of three. The inevitable conclusion is that the use of an optical antenna will result in a diffraction loss of at least 3 dB compared to an undiffracted laser source approximately the same size as the optical antenna.

The expansion of a Gaussian laser beam requires an equivalent focal length for the optical antenna given by

$$f = \frac{\pi r_a r_o}{\lambda} \tag{8}$$

where

r_a = radius of the $1/e^2$ point of the expanded beam
r_o = radius of the $1/e^2$ point of the waist of the laser source.

For r_o equal to 1 mm, r_a equal to 8.0 cm and a wavelength of 532 nm, the required equivalent focal length is 4.7 x 10^4 cm. A simple lens having this focal length would be impractical because the extremely large focal length would require the laser source to be positioned too far away from the optical antenna. However, an effective focal length of this magnitude can be achieved by using two techniques. The first is illustrated in Figure 3, and relies on the principle of optical magnification. The effective focal length for this case is given by

$$f_{eff} = \frac{\pi r_o^2 f_2}{\lambda f_1} \tag{9}$$

where the magnification given by $\frac{f_2}{f_1} = \frac{r_a}{r_o} = 80$. In choosing the actual values of f_2 and f_1, the major consideration is to keep the cone angle of radiation as small as practical to minimize the effect of optical aberrations. In optical terms, the F# , given by the ratio of the focal length to the diameter, should be at least 10 for each optical element. A practical choice for the case being considered is to make f_2 equal to 200 cm ad f_1 equal to 2.5 cm. This results in an effective focal length of 4.7 x 10^4 cm being realized in a physical length of approximately 203 cm. The second technique, which reduces the 200 cm dimension, is to use a Cassegrain type system illustrated in Figure 4. Here the large refractive element is replaced by two reflective elements, but the 200 cm focal length can be achieved in a physical length on the order of 15 to 20 cm depending on the curvatures of the two reflective elements.

However achieving the small physical length does result in a penalty in the intensity of the far-field radiation pattern. The far-field radiation pattern for a Cassegrain type system is given by

$$I(\theta) = \frac{8\pi P}{R^2\lambda^2 r_a^2}\left|\int_b^a e^{-\frac{r^2}{r_a^2}} J_0(k\theta r)\,r\,dr\right|^2 \qquad (10)$$

where

a = radius of the large primary mirror
b = radius of the small secondary mirror

This expression is very similar to equation 6 with the lower integration limit of b instead of 0. The secondary mirror has the effect of blocking the center of the transmitted beam. Figure 5 is a plot of the resulting Cassegrain far-field intensity pattern normalized to the case where the primary aperture radius, a, is infinite and the secondary radius, b, is zero. Note that the intensity at the center of the pattern is lower than that of Figure 2 and that the first sidelobe starts at a smaller angle. In this case more of the total radiated power has been diffracted into the sidelobes.

The optimization procedure for finding a value of r_a, the expanded laser beam radius, is similar to that for the unobstructed aperture. The resulting transcendental equation is

$$e^{\frac{a^2 - b^2}{r_a^2}} = \frac{2a^2 + r_a^2}{2b^2 + r_a^2} \qquad (11)$$

which is solved for a value of r_a = .95a for a representative case of a/b = 4. The value of the intensity at the center of the optimized Cassegrain far-field pattern is 0.80 times that for the optimized unobstructed aperture having the same radius. Therefore, in a typical case the penalty paid for significantly reducing the physical distance between the optical antenna and the laser source is only 1 dB.

Up to this point, the optical quality of the optical antenna has been assumed to be perfect. This means that the path difference between any two portions of the beam passing through the optical antenna is zero or at least a negligble fraction of the wavelength. Since the optical wavelengths are on the order of 1 µm or less, assuming a negligible path difference is not realistic. however, optical antennas can be manufactured such that an rms path difference over the entire surface is less than $\lambda/10$. For rms path differences of this order, the reduction in far-field intensity due to the wavefront error can be expressed by

$$\frac{I(\varepsilon)}{I(\varepsilon=0)} = e^{-\frac{4\pi^2\varepsilon^2}{\lambda^2}} \tag{12}$$

where

ϵ is the rms wavefront error expressed infractions of a wavelength.

For $\epsilon = \lambda/10$, the far-field intensity is reduced by a factor of 0.67 or 1 .7dB.

To summarize this discussion of transmitting optical antennas, equation 1 can now be modified to account for the actual radiation pattern emitted by a representative optical antenna. For the Cassegrain type optical antenna, with a primary of a and a secondary radius of b, the antenna gain is given by

$$G = \frac{8\pi^2 r_a^2}{\lambda^2}\left[e^{-b^2/r_a^2} - e^{-a^2/r_a^2}\right]^2 \tag{13}$$

For antenna diameters on the order of 20 cm, theoretical antenna gains of 115 to 120 dB can be achieved. When wavefront errors are considered, the actual antenna gains differ by only about 2 dB from theoretical. Thus, optical antennas are able to provide extremely high gains, or narrow radiation patterns, with relatively small antenna sizes.

HARDWARE IMPLEMENTATION OF OPTICAL ANTENNAS

The most sophisticated hardware implementation of optical antennas for laser communications has occurred within the Air Force 405B space laser communication hardware development program over the past six years.

The engineering feasibility phase of this program produced a compact package of optics, laser, and modulator which demonstrated the ability to transmit encoded data over an optical link at a rate of one gigabit per second.

The prime transmitting antenna for this equipment was a state-of-the-art 19 cm diameter, all beryllium, Cassegrain telescope which interfaced with the high precision pointing and tracking optical unit of the equipment.

The telescope was designed to provide scaling (i.e., passive focus stability over a limited temperature range of ± 5°C. The optics, produced by the Applied Optics Division of the Perkin Elmer Corporation, tested to a value of $\lambda/16$ rms over the full aperture at 633 nm. The total telescope, shown in the photo in Figure 6 weighed approximately 2 Kg, and survived environmental testing with no measurable degradation.

With further definition of the ultimate space system requirements it was determined that the telescope could not be fully protected from direct solar illumination at all times. Therefore, asymmetrical scaling of both the barrel and the mirrors would occur, to the significant detriment of the quality of the transmitted wavefront.

After extensive trade studies were performed, a decision was made to construct, for the then space flight test system, a fully insulated lightweight telescope from Invar with CER-VIT mirrors. This unit, through the extremely low coefficient of expansion properties of the selected materials, will maintain the required focus stability by reducing thermally induced mechanical changes to negligible levels.

The telescope, also of 19 cm aperture, is shown in outline form in Figure 7, and will be delivered in the Fall of 1978. This unit, which has been designed to extremely stringent environmental specifications, is expected to perform at $\lambda/40$ rms or better, and despite being constructed from high density materials, will weigh only approximately 8 kg. The mirrors which have already been fabricated perform together with a total wavefront deviation of $\lambda/20$ peak to peak ($\sim\lambda/60$ rms).

Both of these units are designed in an optically compact Cassegrain configuration with a 216 cm focal length, 19 cm primary diameter and a secondary to primary diameter ratio of 0.22. This, combined with spider support blockage, results in a total area observation of only 5%. The theoretical antenna gain for an obscured Gaussian beam of this blockage ratio has been described previously, and the practical implementation of precision optical antennas through careful design and construction has been shown to very closely approximate this theoretical goal.

RECEIVERS

Receiving optical antennas serve to collect the radiation reaching the antenna surface and focus it onto an optical detector. The requirements for receiving optical antennas can be significantly different depending on whether the communication system employs direct detection or heterodyne detection techniques. Direct detection can be used in optical communications systems operating in the visible or near infrared portion of the spectrum because the available detectors such as photomultiplier tubes provide almost noiseless gain. The resulting electronic signal is sufficiently above the thermal noise of the detector itself so that the system sensitivity can approach the quantum noise limit. Heterodyne detection is required for communication systems operating in the mid and far infrared such as those using CO_2 lasers. Here the available detectors do not provide noiseless gain, and the system sensitivity would be limited by the detector noise unless heterodyne techniques are used.

The requirements for the receiving antenna in a direct detection system are far less stringent than for a heterodyne detection system. The antenna only has to focus the collected radiation onto the detector surface. It does not have to maintain any coherence properties of the radiation, and the size of the focussed spot needs only be small enough to fit within the sensitive area of the detector. This permits the use of a receiver antenna having far less optical quality than that required for a transmitter antenna. There is no requirement to maintain a small path difference between any two portions of the beam. Therefore, the thickness and consequently the weight and cost of the receiving antenna can be significantly lower than for a transmitter antenna of the same diameter.
The field of view of a direct detection system is given by

$$\theta = \frac{d}{f} \tag{14}$$

where

θ = full angular field of view
d = diameter of the sensitive portion of the detector
f = effective focal length of the receiving antenna.

The field of view is not limited by the radiation pattern and can thus be as large as the system sensitivity to background radiation allows. The larger the field of view, the less accurately the receiver antenna must be pointed toward the transmitter. The angular pointing error between the receiving antenna and the transmitter must be almost as large as $\theta/2$ before the gain of the receiving antenna drops below that given by equation 2.

In an optical heterodyne detection system, the heterodyning takes place at the detector surface. The local oscillator is a laser whose wavelength is shifted slightly from that of the transmitting laser. To obtain an IF beat signal, the wavefront of the received radiation pattern must be parallel to the wavefront of the local oscillator within an angle such that the path difference between the two wavefronts is a small fraction of a wavelength. This places two restrictions on the receiving antenna. First, the receiving antenna must be of sufficient optical quality to preserve the spatial coherence of the received radiation. This requires the optical quality of the receiving antenna in a heterodyne detection system to be every bit as good as that of the transmitting antenna. Second, the receiving antenna must be accurately pointed toward the transmitter. Figure 8 shows the normalized heterodyne signal level for an optimized system as a function of the normalized angular pointing error of the receiving antenna. A normalized angular pointing error of 1 is equal to λ/D where D is the diameter of the receiving antenna. For an optimized heterodyne system, a normalized pointing error of 1 also corresponds to the center of the focussed point being at the edge of the detector. Note that the heterodyne signal level, or the effective antenna gain, drops with any pointing error and is 10 dB lower for an angular pointing error of λ/D. In a direct detection system the antenna gain remains at its full value until just before the angular pointing error causes the center of the focussed spot to move to the edge of the detector.

When the receiver for an optical communication system is located within the atmosphere, there is a limitation on the maximum size of the antenna diameter for a heterodyne receiver and a limitation on the minimum size of the antenna diameter for a direct detection receiver. Atmospheric turbulence causes the laser radiation pattern to break up into hot spots and holes, and the full spatial coherence properties of the beam are lost. The size of the portions of the beam that retain spatial coherence is a function of wavelength, path length through the atmosphere, the strength of the turbulence, and the angle of the transmission path with respect to the horizontal plane. For a link from a synchronous satellite to a receiver in the southern United States the typical coherence diameters are approximately 30 cm for the 10.6-µm wavelength of the CO_2 laser and less than 5 cm for the visible wavelengths. Since heterodyne detection is dependent on the coherence properties of the received beam, the diameter of a 10.6- µm heterodyne receiver antenna is limited to approximately 30 cm. A larger diameter antenna would not give a higher effective gain. Since direct detection is not dependent on the coherence properties of the received beam, the diameter of a 0.53- µm direct detection receiver must be several times larger than 5 cm so that the higher energies contained in the hot spots and lower energies contained in the holes are averaged out. However, the antenna gain will continue to increase as the antenna diameter is increased.

SECURITY CONSIDERATIONS

The very narrow angular beamwidths of the transmitted optical radiation patterns make interception of signal exceedingly difficult. Consider the far field pattern of the Cassegrain transmitting antenna of Figure 5. The full angular beamwidth of the center of the pattern is 7.2 microradians. For a transmitter in a synchronous satellite and the receiver on earth as shown in Figure 9, the center of the pattern has a diameter of .16 miles on the earth. The third sidelobe is down by almost 10^{-4} or 40 dB. The fourth sidelobe (not shown) is down by 60 dB. At 18 microradians from the center of the pattern (or at a distance of 0.4 miles from the receiver), an antenna diameter more than 1000 times larger would be required to intercept the signal. Since a 4-foot diameter antenna can adequately be used to detect a 0.53 µm beam carrying a 1-Gbps data rate, intercepting this signal with another receiver a mile away from the main receiver would be virtually impossible.

The very narrow angular fields of view of the optical receiving antennas make jamming the receiver very difficult. Consider the scenario shown in Figure 10. The transmitter is on earth and the receiver with a 100-microradian field of view in a synchronous satellite 40,000 km away. The plot shows the ratio of the required power for a jamming source having the same transmitted beamwidth as the communication source. If the jamming source is also on earth and 10 km away, the required jamming power would exceed 10^4 times the communication power. Since about 200 mW of average power is required from a Nd:YAG laser, operating at 0.53-µm, to complete a 1-Gbps communication link over this distance, a jammer located 10 km away would require more than 2000 W of average power. No Nd:YAG laser with this average power capability exists. If the jammer were located in a satellite at a range of only 400 km away from the receiver, but was positioned such that its distance from the line of sight between the communication transmitter and receiver was more than 1 km, the required average jamming power would still be 10^4 times that of the communication laser having the same beamwidth. Therefore, jamming an optical communication system is also a very difficult task.

CONCLUSION

Optical antennas are able to realize very much higher gains than rf antennas of similar size because the optical wavelengths are many orders of magnitude shorter. The resulting narrow angular beamwidths of the transmitted radiation patterns and narrow angular fields of view of the receivers do require that optical antennas be pointed very accurately, but also allow optical communication systems to be highly resistant to being intercepted or jammed.

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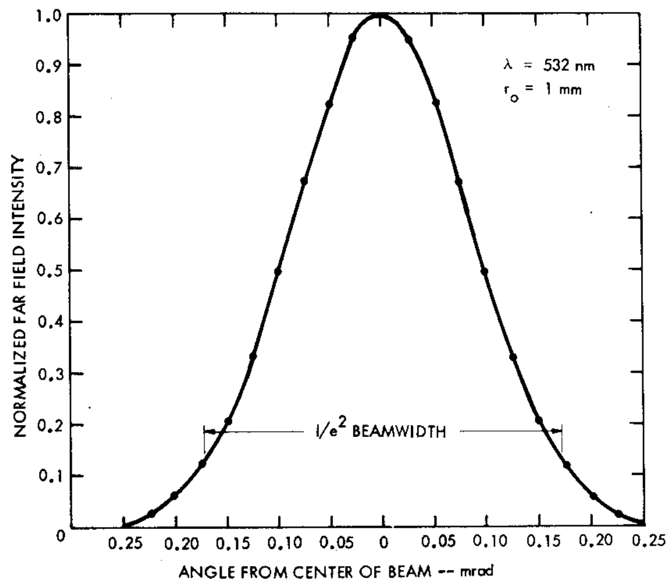

Figure 1. Gaussian For Field Angular Distribution

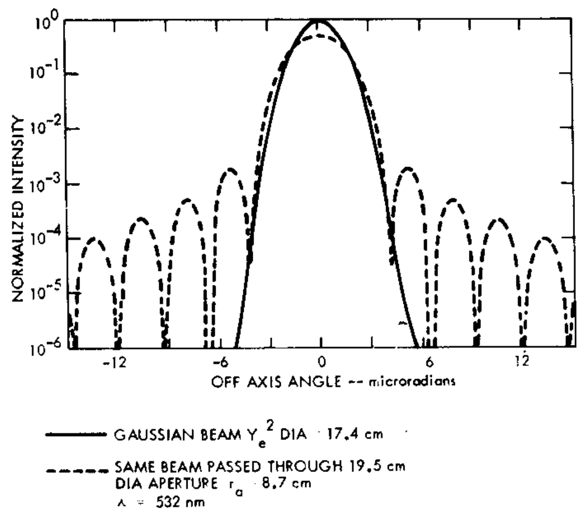

Figure 2. Far-field Intensity Distribution For Circular Aperture Normalized To An Infinite Aperture

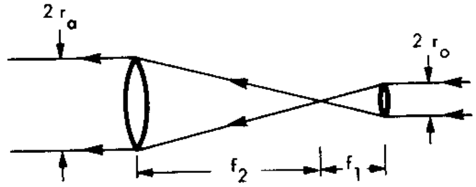

Figure 3. Optical Magnification

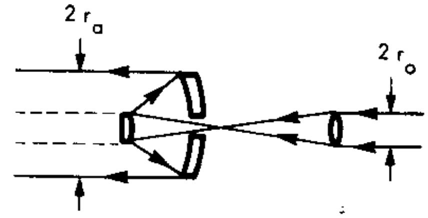

Figure 4. Cassegrain Configuration

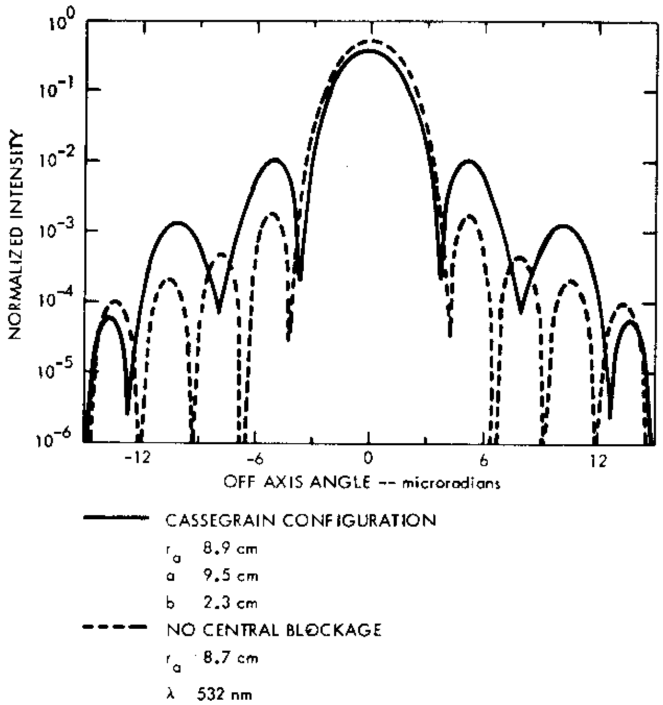

Figure 5. Far-field Intensity Distribution For Cassegrain Normalized To An Infinite Aperature With Zero Secondary Blockage

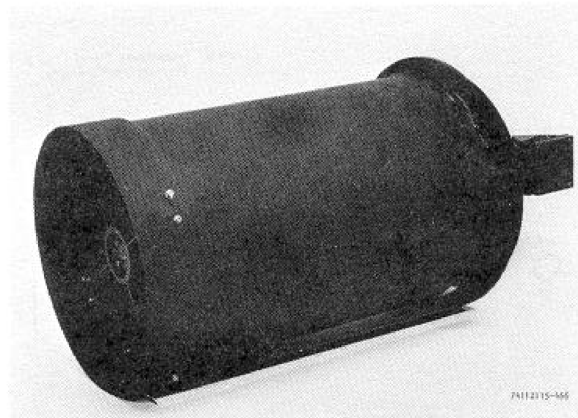

Figure 6. Beryllium Transmitter Antenna

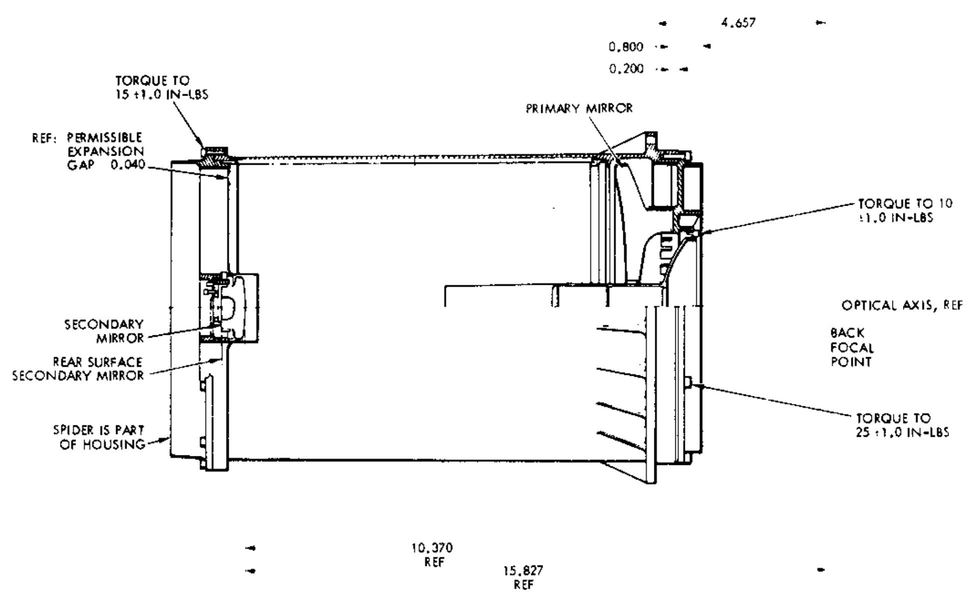

Figure 7. Invar/Cervit Transmitter Antenna

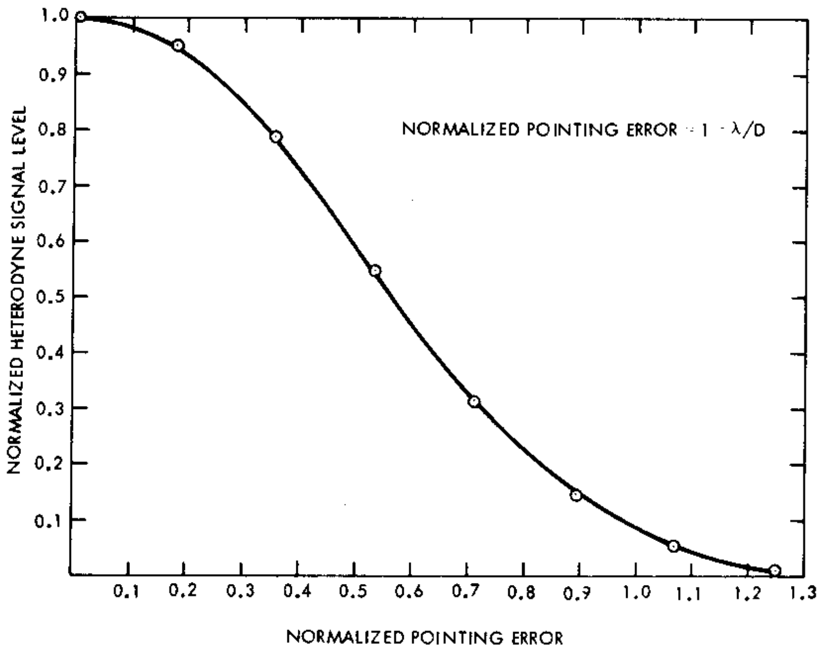

Figure 8. Heterodyne Signal Drop As A Function Of Receiver Pointing Error

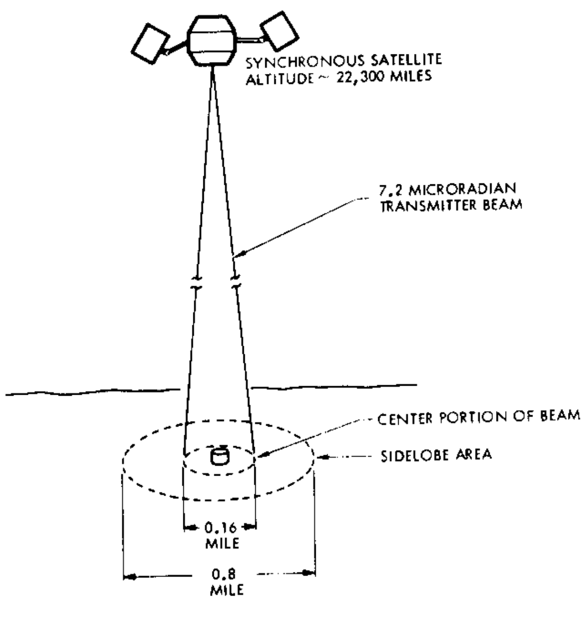

Figure 9. Optical Transmitter Security Considerations

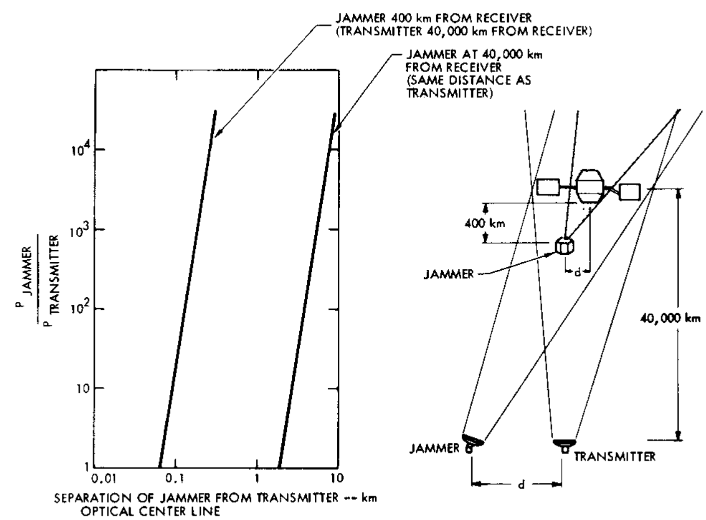

Figure 10. Optical Receiver Jamming Considerations