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JUL 77 J C KERSHENSTEIN, F A HORRIGAN

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Mutual Interference of Optical Communication Links

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The problem of interference in optical communications systems caused by such communication systems is discussed together with suggestions to reduce this interference. The propagation of optical signals is studied to determine which propagation modes can contribute to interference. Twenty-four modes of possible interference are identified and analyzed.

Conclusions are drawn which indicate that in 21 of the 24 modes interference can be eliminated by simple geometric and modulation coordination restrictions. In the three remaining modes, which are

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20. Abstract (Continued)

scatter links, geometric coordination can resolve the conflicts, but it is definitely more restrictive and difficult to implement than for other modes.

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MUTUAL INTERFERENCE OF OPTICAL COMMUNICATION LINKS

I. INTRODUCTION

The promise of optical communication has been with us continuously since the discovery of the laser in the early sixties. Systems capable of simultaneously transmitting all the world's TV channels were envisioned, connecting satellites to satellites, or to ground stations along with extensive networks of terrestrial or ground-to-ground links. While the promise was real, the early technology could not support it immediately. Space applications, requiring great refinement of component technology were obviously for the more distant future. Terrestrial links, however, seemed possible and so were pursued from the start. The obvious problems that rain, fogs, and other meteorological phenomena offer to optical systems prompted some, Bell Labs in particular, to begin study of hollow pipe/periodically refocussed transmission links. Eventually it was realized that fiber optics offered a much more practical solution to this problem of establishing wide bandwidth all weather terrestrial links and this area of fiber optics wideband communications has become a rapidly expanding field.

Other workers, experimenting with unguided or free space optical communications began to appreciate more fully the subtle obstacles offered by the atmosphere in the form of turbulence, gaseous absorption and aerosol effects as well as the apparently less subtle effects of clouds, fogs, and rains. The technology, of course, continued its inevitable development until now we stand at the doorstep of a great mushrooming of practical laser applications, including the long awaited optical communication links.

Somewhat naively, this conjures up the image of laser beams, flying in all directions with the distant possibility that some of these systems will begin to interfere with the operation of others. This, in turn, suggests that sometime in the near future a real need for the regulation of optical communication links will arise. And if this indeed is the case, then we should begin to plan now so that this potential interference can be minimized while allowing the maximum exploitation of the benefits of optical communications.

Quite properly, in preparation for the 1979 general meeting of the World Administrative Radio Conference (WARC) this question has been formally addressed in question No. 53/1, approved and submitted in January 1976 as an addendum to the report of the XIIIth Plenary Assembly of the C.C.I.R., 1974. This document is incorporated in Appendix A. Question No. 53/1 suggests that to resolve these issues two specific questions should be addressed:

Note: Manuscript submitted June 28, 1977.

1) What kind of high frequency systems are practical and what are the technical problems associated with the realization of these systems? and

2) From a technical point of view, what is a reasonable upper limit frequency in the definition of "radio wave" (such that the Radio Regulations now in force can be logically and effectively extended upward)?

As stated the question is very broad for it addresses "the electro-magnetic spectrum above 40 GZ"; which includes the millimeter and submillimeter regions as well as the infrared, the visible, the ultraviolet spectral regions and on to Xrays and gamma rays presumably, if appropriate sources can be found. From another point of view, however, Question 53/1 is relatively narrow as it asks only how far should the Radio Regulations be extended continuously upward; not what form should the regulations take, if any, above this limit.

In the report we discuss Optical Communications Systems in the context of Question 53/1, restricting ourselves to those portions of the optical spectrum which propagate through the earth's atmosphere with relatively low losses -- that is from wavelengths of about 0.3 microns in the ultra-violet through the visible, the near infrared and the two nominal transmission "windows" of the infrared (i.e., 3-5 μm and 8-14μm). In terms of frequency this represents a range from about 2×10^4 GHz to 10^6 GHz -- quite far above the traditional radio and microwave bands.

The primary issue addressed is the question of the modes of mutual interference between optical communication links due to diffraction, refraction, and scattering effects. Some twenty-four distinct interference modes are identified and individually analyzed in the body of the text. Discussions of propagation phenomena and the state of the art of components are supplied in the appendices. Drawing upon available theoretical and experimental understanding of the relevant optical phenomena, worst-case interference estimates are established for most of the modes and used to establish "coordination" restrictions on transmitter powers and link geometries such that interferences are "eliminated" in the sense of being reduced to tolerable levels under practically all meteorological conditions.

Although some uncertain areas which could offer problems remain unresolved, in general it is concluded that because of the extremely narrow beamwidth characteristics of optical systems, few genuine conflicts are expected.

These few which do arise are most simply resolved by coordinating the parameters of all the optical links operating in the local geographical neighborhood. In most situations, this becomes a question of geometrical relationships -- that is, angles, fields of view, site separations, etc. The required angles and distances are so small as to put no great burden, technical or financial, on any of the systems involved. At worst, physically adjacent links may have to employ different modulations, or different wavelengths, polarizations and the like, which is definitely a local issue and easily resolved for fixed links.

Mobile systems definitely offer more opportunities for problems but may prove acceptably transient, where safety considerations do not prohibit their use altogether.

In view of the predicted effectiveness of local coordination in reducing mutual interferences, and the fundamental technological differences between the optical region and the radio region due to the extreme difference in wavelength, it is concluded that from the point of view of potential regulation, the optical region lies well above any logical choice for a continuous extension of the definitions of "radio wave" to higher frequencies. Global allocations of wavelengths (or frequencies), while capable of resolving many interference problems, as it does in the RF spectrum, is in all probability unnecessary and most certainly premature in view of our present uncertainty of the forms and applications the technology will ultimately assume. Strengthening this conclusion is the observation that, in contrast to RF oscillators, optical oscillators or lasers are severely limited such that only a few "good" lasers have the right combination of properties to be useful. It would be unwise to unnecessarily restrict today the future, flexible applications of these lasers on the basis of interference issues which can be resolved more practically in terms of locally imposed constraints.

II. OPTICAL COMMUNICATION SYSTEMS

Optical and microwave or radio frequency communication systems are closely related in concept for each transmits via modulated electromagnetic waves. The basic physical laws (i.e. Maxwell's equations) governing the propagation of these waves are the same as are the concepts of modulation, coding and information capacity. There are, however, many real practical differences between optical and microwave technologies, associated with the distinctly different scales of wavelength which characterize each. Optical wavelengths are measured in micrometers while microwaves are typically measured in centimeters, and RF in meters roughly four to six orders of magnitude larger. The result of this rather large characteristic difference in wavelength is a complete change in the nature of the physical processes which dominate each technology. The techniques which permit the efficient generation, modulation and detection of microwaves simply cannot be logically extrapolated to the optical region, and vice versa. Thus, the physical components of these technologies are strikingly different. There are also important differences in the manner and degree to which light and microwaves interact with the atmosphere, with optics considerably more affected by the meteorological events which characterize our environment.

A variety of optical communications links[1] have been proposed and/or implemented, differing in scenario, link geometry, mode of detection, type of modulation or coding, and information bandwidths. Each attempts to exploit one or more of the natural advantages of optical systems; gigahertz bandwidths, the covertness and low power requirements associated with the easily obtained milli- or microradian beamwidths, or perhaps simply a reduction in cost or complexity. On the other hand, the disadvantages of the very strong meteorological interactions, the accurate pointing and tracking performance required to effectively utilize such narrow beamwidths, and for some situations, the horizon or line-of-sight limitations must be faced.

For space-to-space and space-to-ground communications, optical systems are a natural for all of the positive reasons quoted above. The necessity for a fairly complex pointing and tracking capability, however, suggests that to be worth the effort, such links will probably also operate at very high data rates of several hundred megabits or more. The space-to-space links are free to choose any wavelength and any compatible forms of modulation and detection which are technologically suited for space operation and economically reasonable. Space-to-ground and ground-to-space links, on the other hand, have no such freedom as the propagation limitations of the atmosphere must be contended with. Redundant ground sites in meteorologically favorable locations can probably be selected to keep the overall link operating with high probability. However the wavelength of operation must lie in one of the good transmission regions of the atmosphere and be available from one of the good laser sources. At the present time there are only three lasers which can be considered seriously for this application -- the Nd:YAG laser (doubled $\lambda \simeq 0.53\ \mu m$ or undoubled $\lambda \simeq 1.06\ \mu m$) using direct detection, or the CO_2 laser ($\lambda \sim 10.6\ \mu m$) and the HeNe laser ($\lambda \sim 0.6328\ \mu m$, $1.15\ \mu m$ and $3.39\ \mu m$) with either heterodyne or direct detection. The Nd:YAG solid state laser is currently not suitable for coherent operation although this can be achieved with effort and cannot be eliminated from future considerations.

As aerosols (e.g., clouds, fogs, smoke, etc.) increasingly obscure a direct detection link -- whatever its form of modulation -- it rapidly loses its effectiveness for the beam is progressively attenuated and its useful information bandwidth quickly reduced to only a few megahertz through multipath, time dispersion effects. A coherent link, on the other hand, suffers only from attenuation, for recent theories and experiments[2] have shown that coherent detection responds significantly only to the unscattered portion of the original beam. The scattered photons are rendered incoherent and thus introduce no time dispersion, bandwidth limitations into the link. Technology and economies permitting, then, coherent systems offer the best meteorological immunity and will be preferred for all point-to-point high data rate optical communication links which pass through the atmosphere.

For links operating entirely within the atmosphere other considerations come into play. Both direct line-of-sight links and indirect scatter propagation links have been implemented. Since line-of-sight links are necessarily limited to distance of about 40 Km or less just as for microwaves, the power aperture sizes, pointing and tracking and data rate requirements are rather modest and thus more lasers are useable. The GaAs semiconductor lasers which are small and directly modulatable at rates of a few megahertz are particularly convenient and have been employed by the military for short distance covert voice links with direct detection and rather simple pulse code modulations.

Although both direct and heterodyne detection and practically any kind of modulation can be employed, experiments[3] at the Naval Electronics Laboratory Center with a reciprocal tracking heterodyne CO_2 two-way link have demonstrated the effective weather-penetration capabilities of this approach. The low scattering properties of the long wavelength 10.6 μm CO_2 radiation combined with the multi-scatter immunity of heterodyne detection suggests that this is probably the most attractive approach for fixed, reliable ground links, although the CO_2 could be supplanted in the future with a shorter wavelength system with less trying detector cooling requirements. Obviously other wavelengths are useable for the Russians have had a number of NeHe links in routine operation for quite a few years now. No doubt, in many other applications where link reliability and down time are not critical, the comparative simplicity and lower cost of the direct detection system may offer acceptable compensation for the increased susceptibility to meteorological interference.

In an effort to extend the limited range of the point-to-point links, the use of scatter propagation has been suggested, first apparently by King and Kainer[4] in 1965, and more recently by workers at NELC[5] and others[6]. Since effective use of coherent detection requires the use of the unscattered beam, it is not appropriate for scatter links. Direct detection must be employed. Because the objective of such a link is to make use of the scattering rather than suppress it, shorter wavelengths are to be preferred -- probably the visible or very-near ($\sim 1\mu$) infrared. Inherent in this approach is the fact that the light collected at the receiver be scattered one or more times thus requiring large collector fields of view and necessarily restricting the data rate to rather low values because of the inevitable path length, time of flight dispersion effects.

A detailed analysis of scatter propagation communication links has been carried out in reference 5. Figure 1 illustrates the scenario. For the calculation it has been assumed that for ranges beyond 100 Km only single scatter effects need be considered, although an analysis of multiple scattering effects suggests that the multiple scattered "aura" could provide as much as 10dB power transfer improvements at the shorter ranges.[5] Using reasonable system parameters, it has been estimated that for 20 Km clear visibility conditions useful signal-to-noise ratios (i.e. 15dB or larger) could be generated at ranges of 60 to 80 Km with a Nd:YAG 1.06 μ laser scatter link. If clouds are present, the link could deteriorate or improve depending upon the location.

The reasons for considering the potential of an optical scatter link with its inevitable low data rate and extreme meteorological sensitivity have to be rather special. Its relative covertness for the non-routine transmission of important messages in military applications perhaps, for the receiver's field of view still must encompass part of the transmitter direct beam path as in figure 2, or lie close enough to the "aura" point on the horizon. It is difficult to believe that such a low-bandwidth, unreliable scatter-link would be considered for a fixed point-to-point communication system in frequent, routine use, in spite of its range advantages.

A selection of various optical communication links which have been proposed and/or implemented are summarized in Table 1.

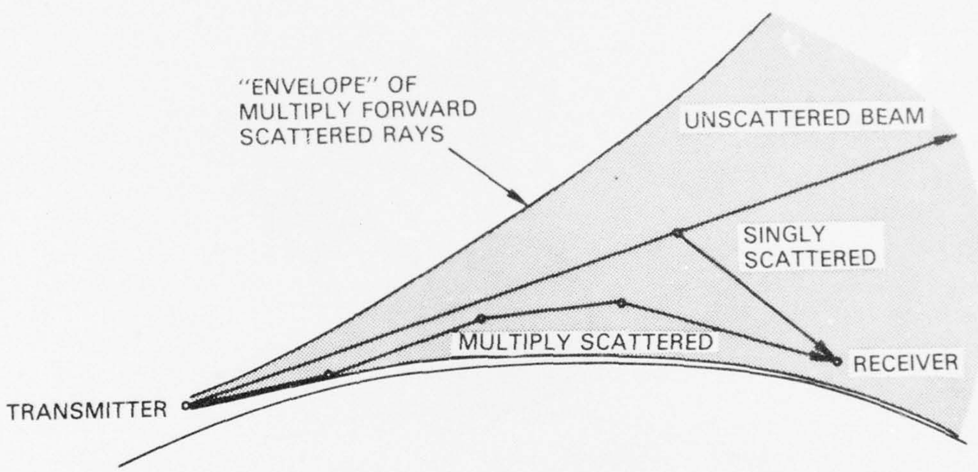

Fig. 1 — Beyond-the-horizon propagation mechanisms (cloud-free case)

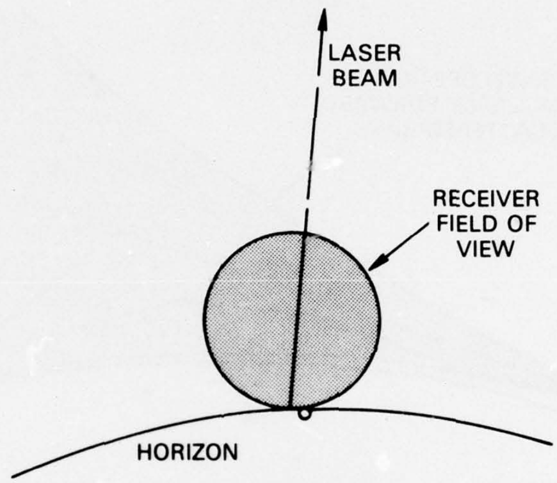

Fig. 2 — Field of view placement

TABLE 1

OPTICAL COMMUNICATIONS SYSTEMS

Demonstrated or Operational Systems

PCM/AM—Nippon Electric Direct Detection fixed, point-to-point terrestrial

3mW HeNe (0.6323μm) laser; mode-locked at 123.5 MHz bit rate, 45 MHz Bandwidth fully operational 14 mile, 2 way link between Yokohama and Tamagawa

PFM—Santa Barbara Research Center Direct Detection, mobile point-to-point terrestrial

GaAs (0.9μm) laser—3mW average power, 2W peak; 6 kbit/s, 2.3 kHz Bandwidth up to 6 miles range depending upon weather.

FM—NELC "OCCULT" Heterodyne Detection, mobile point-to-point terrestrial

CO_2 (10.6μm) laser—0.5 W; Information bandwidth > 5 MHz range > 20 miles; uses reciprocal pointing and tracking through common transmitter/receiver optics.

FM—Lockheed Direct Detection; experimental—intended for space/ground

Frequency doubled, CW, Nd:YAG (0.53μm); 2 G-bit/s laboratory demonstration.

PCM—McDonnell Douglas Direct Detection, Experimental—intended for space/ground

Frequency doubled, mode-locked Nd:YAG (0.53μm); > 200 M-bit/s laboratory demonstration.

Recently Proposed Systems

PCM, Scatter-Propagation Link—NELC/MEGATEK Direct Detection, terrestrial

Q-switched Nd:YAG (1.06μm); 25 to 200 Hz pulse rate; 75 to 2400 bits/s with 4° x 1° fan beams predicted ranges vary from 55 to 165 Km.

AM—NASA Heterodyne Detection with Doppler tracking; mobile satellite-to-satellite

CW CO_2 laser, 300 M-bit/s digital coding or 300 MHz AM modulation which would be equivalent to 3-Gbit/s digital

III. INTERFERENCE IN COMMUNICATION SYSTEMS -- PROCESSING GAINS

The performance of any communication link, RF, microwave or optical, is determined by the "quality" of the message which is measured numerically in different ways depending upon the nature of the information coding.[7] The quality of an analog message such as a telephone or television signal is usually measured by the signal-to-noise ratio (SNR) at the channel output with appropriate definitions of signal and noise. The output quality of digital messages, such as teletype or computer data is described by a probability of error (P_E). For both analog and digital coding, the output message quality of a communication link depends primarily on the ratio of wanted to unwanted signals or carrier-to-noise ratio (CNR) at the input to the receiver processor. The form of the mathematical relationship between SNR or P_E and CNR depends on the nature, analog or digital, of both the messages and the modulation or coding technique used for transmission.

When analog messages are transmitted using AM or FM modulation, the relationship between output message quality and the carrier-to-noise ratio is simple. At the terminal receiver where the messages are recovered, the output signal-to-noise ratio is directly proportional to the carrier-to-noise ratio, as long as this ratio exceeds a threshold value characteristic of the modulation/demodulation method; that is

$$SNR = R(CNR) \tag{1}$$

where the proportionality constant R is often known as the receiver transfer improvement (RTI) factor.

When analog messages are converted to digital form for transmission by such techniques as frequency-shift keying (FSK) or phase-shift keying (PSK), the relationship between SNR and CNR is no longer a simple proportionality. Nonetheless a receiver transfer improvement can still be defined via equation 1 although it will be necessary to indicate the particular value of SNR to which it applies.

For both analog and digital methods, the numerical values of the RTI depend upon a number of factors including the type of message, the types of signal processing to which the message is subject, the modulation index or bandwidth expansion ratio , the type of demodulation used and finally, on the nature of the unwanted signals. Of the several factors which affect RTI, regardless of the nature of the unwanted signals, one of the most important is the bandwidth expansion ratio W/B where W is the RF bandwidth of the wanted signal required to transmit the information bandwidth B. Figure 3 illustrates for representative modulation methods how the RTI for gaussian thermal noise varies with W/B. If the interfering signals are not gaussian noise but other message-carrying modulated signals it is found that the RTI varies rapidly with the frequency difference between the wanted and the unwanted carriers, as is illustrated in Figure 4. What these curves illustrate is that unless the interfering signal is extremely similar to the wanted signal, that is, similar modulation scheme, similar or smaller bandwidth expansion ratio and close to the same carrier frequency, the processing is capable of increasing the CNR by factors of 10 to 50 dB or more. Experimental investigation[7] for the worst case -- i.e., two TV signals on the same carrier -- have shown that if the interfering signal power is 30dB or more less than the desired signal, the interference effects are barely preceptible. These results are summarized in Table 2.

In most of the discussion which follows we will simply calculate the estimated magnitudes of the unwanted power received within the spectral and information bandwidths of interest, and assume that whatever the nature of the messages or the modulation, if this is equal to or less than the receiver's noise equivalent power NEP, the interference is acceptable. In a few cases when this condition is not sufficient it will be necessary to be more subtle and add processing gain margins.

IV. INTERFERENCE MODES IN OPTICAL COMMUNICATIONS SYSTEMS

The generic modes of interference which can arise in a general situation involving space and terrestrial systems can be classified systematically by considering the four types of links, that is, space-to-space, space-to-ground, ground-to-space and ground-to-ground. There are a total of twelve distinct interference modes arising from the fact that each of the three types of receiving stations (space, terrestrial* and earth station*) can experience interference from transmitters at other stations of the four types of links. Figure 5 illustrates these modes, which are summarized in Table 3, arbitrarily numbered for convenience.

For each of these modes there are two sources of interfering signals -- 1) direct illumination of the

* The terms "terrestrial" and "earth-station" are used to distinguish a ground-to-ground station from the earth-based portion of a space-ground link.

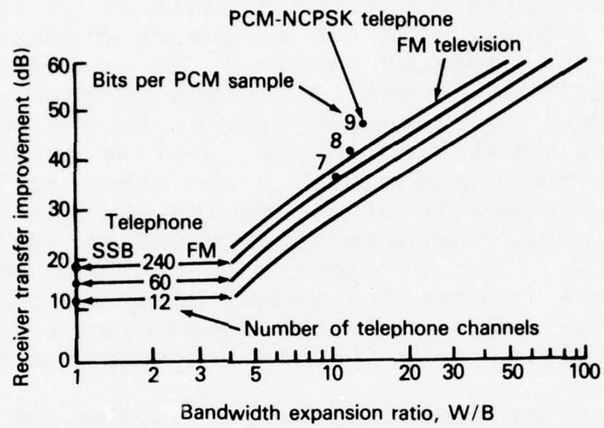

Fig. 3 — Receiver transfer improvement with white Gaussian noise (from Ref. 7)

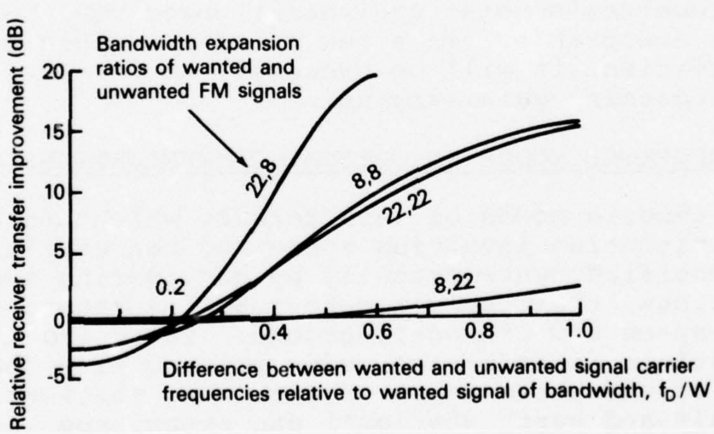

Fig. 4 — Receiver transfer improvement for interference between wide band FM telephone signals relative to that with white Gaussian noise (from Ref. 7)

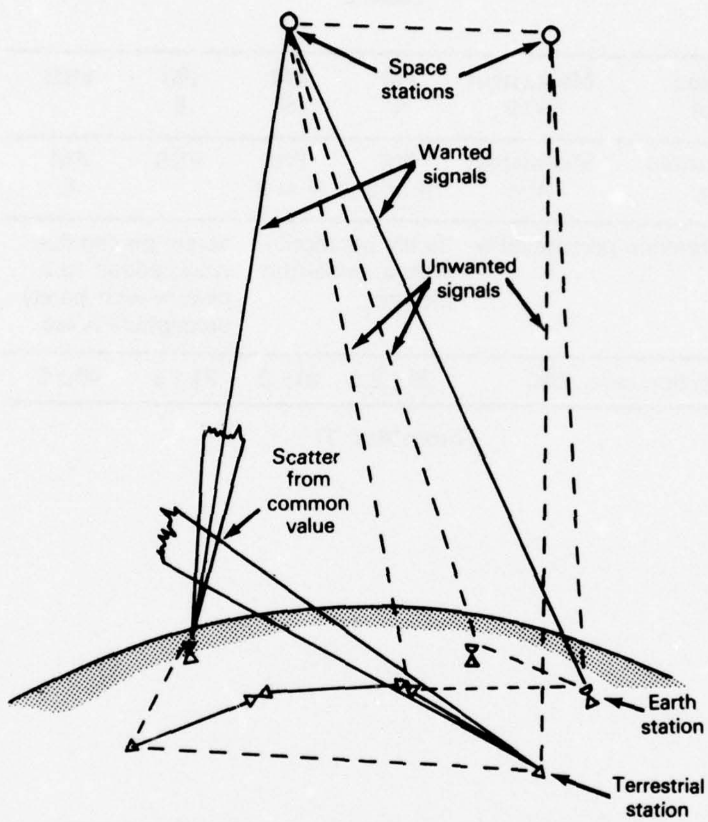

Fig. 5 — Interference modes with shared frequency operation of satellite and terrestrial systems

Table 2

Wanted Signal	Modulat[illegible] W/[illegible]	[illegible]	FM 8	FM 6	VSB
Unwanted Signal	Modulation W/B	FM 4 or 8	FM 4 or 8	VSB	FM 6
Interference perceptibility		barely perceptible with a noise-free picture		barely perceptible when added to a picture with barely perceptible noise	
Protection ratio (dB)		29 ± 2.5	20 ± 3	21 ± 5	43 ± 5

(from Ref. 7)

Table 3

The 12 Possible Modes of Interference

Receiver \ Transmitter Type	Space to Space	Earth to Space	Space to Earth	Terrestrial to Terrestrial
	Mode#			
SPACE	1	2	3	4
EARTH	5	6	7	8
TERRESTRIAL	9	10	11	12

receiver by the main beam or side lobes of the interfering beam, and 2) scattered radiations, -- giving a total of twenty-four situations to consider.

A. Direct Interference Modes

1. Fixed Systems

The direct modes are the easiest to treat and so they will be dealt with first. The most straightforward means for insuring the protection of optical communication links is to make sure that the receiver field of view contains no other optical transmitters than that associated with the intended link. Choosing a conservative 30dB safety margin we see from Figure B-1 of Appendix B that the antenna gain will be less than -30dB if

$$\frac{D}{\lambda} \cdot \frac{\theta}{100} \geqslant 3 \qquad (2)$$

where θ is the angle from the axis of the main lobe in degrees. For space-born receivers for which atmospheric turbulence has little importance, useful aperture sizes will be determined by practical considerations of size and weight. If we assume a conservatively small aperture size (D = 30 cm) we find that θ must exceed 10λ where λ is measured in cm and θ in degrees; hence

$$\theta \geqslant \begin{cases} 5 \times 10^{-4} \text{ deg for } \lambda = 0.5\mu \text{ (Visible)} \\ 0.01 \text{ deg for } \lambda = 10.6\mu \text{ (}CO_2\text{ Laser)} \end{cases} \qquad (3)$$

(a) Space-to-Ground

For a satellite at synchronous altitude (35,000 Km), these translate into circular fields of view on the ground of about 300 meters in radius for the visible ($\lambda \simeq 0.5$ µm) and 6.5 kilometers in radius for the CO_2 laser wavelength ($\lambda \simeq 10.6$ µm). Thus if earth stations were placed more than 7 Km apart, even if adjacent earth-space links operated on the same wavelength with precisely the same modulation scheme, etc. direct interference between links would not be a problem. Actually since we have completely neglected the transmitter antenna gain patterns which would be equally narrow at these distances the protection ratio would be 60dB or better depending on the wavelength and so the distance could be reduced even further with safety.

If one wished to crowd them together even more closely, and it is difficult to imagine that our demands for communication could push us this far, it would be a simple task to assign adjacent links to different optical frequencies. For example, the CO_2 laser operates well on a number of so-called P-transitions which differ by frequencies on the order of 30 GHz, and it is not difficult to implement heterodyne receivers which respond only to one P-transition. Adjacent links could be assigned to different P-transitions, thereby cutting the minimum separation further and so on. It is important to note here that only local coordination is required.

(b) Earth-to-Space

From the earth-to-space point of view, turbulence will influence the useable aperture dimensions. However, since serious turbulence phenomena in the atmosphere is limited largely to the lower few hundred meters, the total effective path lengths are small and the effects are easily encompassed by our worst case estimate given above. That is, if the angle between satellites is greater than 0.01 degrees, direct interference will not be a problem for any optical wavelength. Again it is extremely difficult to imagine a rationale to justify even this degree of orbit crowding, which exceeds even the most ambitious of today's plans by several orders of magnitude.

(c) Terrestrial

For terrestrial links, turbulence limitations become a much more serious problem; but then, the distances are much shorter (i.e., $\leq$ 40 Km) and the earth's surface is curved making it quite difficult to line up two ground-to-ground optical links. For strong turbulence conditions, and 40 Km of pathlength, the useable coherence diameter at 1 μm is only 0.5 cm while at 10 μm it has increased to 18 cm or so as can be seen from Figure B-6 of Appendix B. Actually the angular spreading associated with the turbulence varies only slowly with wavelength as $\theta \sim \lambda / r_o \sim \lambda^{-1/5}$. Therefore choosing a visible wavelength (λ = 0.5 μm) and a turbulence-limited aperture of 0.2 cm as a worst case it can be estimated that the angular separation of the interfering optical system must exceed 0.75 degrees for 30dB or more of protection from direct interference. At the maximum range of 40 Km, this gives rise to a field-of-view spot of 525 meters in radius.

These extremely conservative restrictions can be reduced orders of magnitude when the antenna patterns of both transmitters and receivers are properly taken into account, and even further if processing gains are available. For point-to-point direct links, which will typically make use of very narrow beam patterns in order to maximize signal-to-noise, the conditions can be met with easily implemented geometric coordinations of site placement and relative angles. Scatter links, with their necessarily larger antenna patterns -- i.e., beamwidth of a degree or so -- are not really much more difficult to handle from this point of view as the transmitted beams will be angled upward to maximize atmospheric scatter effects and minimize loss of beam power through illumination of ground objects. The scatter-propagation receivers may "look" closer to the horizon and thus be susceptible to direct interference from a non-scatter terrestrial transmitter; however, the geometric coordination requirements for this situation can be handled in terms of the narrow antenna pattern of the transmitter.

(d) Space/Terrestrial

There remains the possibility of direct interference between a space-based transmitter or receiver and a terrestrial link. Obviously for this to occur, the space system must be operating such that it grazes the earth tangentially. However, this appears to be an unlikely scenario for fixed links because of the relative inefficiency, from the space system's point of view, of traversing long atmospheric slant paths; more probably, space-to-ground links will operate close to vertical to minimize these effects. Space-to-space links most certainly would not choose to deal with meteorological interference unnecessarily.

2. Mobile Systems

The above discussion of direct interference modes has tacitly assumed that the optical communication links are all fixed -- that is, the ground stations are not mobile and the satellites are in geosynchronous orbit. Obviously optical links to and from moveable platforms such as aircraft or non-synchronous satellites are possible and will have to be considered. Such a mobile system runs a much greater risk of wandering into the antenna pattern of another fixed or mobile system. Under those conditions serious interference could result and some restrictions on the use of mobile optical communication links would seem appropriate. If the optical powers involved are not large enough to cause physical destruction the transient interference would probably be deemed acceptable if these occurrences were less frequent than the naturally occurring link interruptions associated with adverse meteorological conditions.

From another point of view, however, the increasingly severe safety regulations governing the usage of laser sources in the United States, already legislate strongly against such cavalier applications. It is entirely possible that the safety aspect of the questions will completely dominate the situation greatly reducing the likelihood of such transient interference. Whatever the point of view, restrictions on the usage and the operating optical power levels of mobile systems seem necessary and reasonable, and these alone may reduce the occurrence of direct interference between optical communications to acceptable levels.

B. Scatter Interference Modes

While the treatment of the direct interference modes is relatively straightforward, even with the meteorological uncertainties of turbulence-induced beam spreading, reliable quantitative estimates for the scatter modes are much more difficult to establish. Each of the twelve scatter interference modes are discussed separately below.

The four modes of interference which can affect a space receiver are the easiest to handle.

1. Space Receiver from Space-to-Space Transmitter (Mode #1)

Obviously atmospheric scattering is irrelevant to this scenario and the only way in which the space receiver can receive scattered radiations from an exoatmospheric optical communication link is for the interfering beam to illuminate some object (the receiving satellite, for example) which lies within the field of view of the receiver. For fixed position links involving geosynchronous satellites the geometric coordination restrictions which resolve the direct interference modes also automatically resolve this particular scatter mode. The space-born antenna pattern (i.e., with the 30dB definition) need only be smaller than the minimum angular separation of synchronous satellites as is illustrated in Figure 6 for the most difficult situation involving adjacent satellites. If either of the links involved are not fixed -- that is, utilize satellites not in geosynchronous orbit -- then, although transient interferences are possible, they will necessarily be of short duration and as such are probably tolerable.

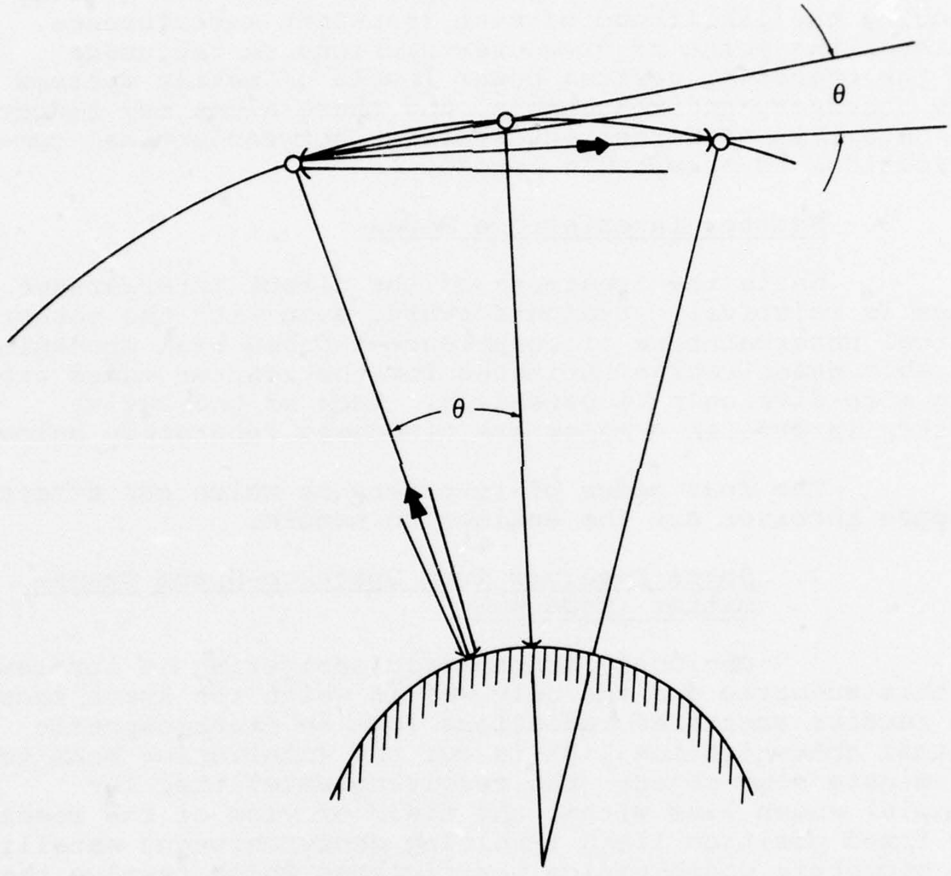

Fig. 6 — Space-to-space: scatter interference

2. Space Receiver from Earth-to-Space Transmitter (Mode #2)

This scenario is illustrated in Figure 7 in its two possible variations -- that is, the offending beam passes through the field of view of the space receiver of interest; or it doesn't.

The worst case is the one in which the interfering beam passes through the field of view of the receiver. This situation is related to the cases investigated in detail in Appendix D. Assuming the dominance of single scattering events, the unwanted power P_{UW} scattered into the receiver can be estimated in terms of such scenario parameters as beam angles, distances, angles, aperture sizes and power levels. If this unwanted power is less than the noise equivalent power (NEP) of the receiver, a combination of processing gains and the normal system signal-to-noise ratio required to minimize errors will generally insure that the interference is acceptably small.

In order to apply the results of Appendix D we note that this situation corresponds to the case in which the receiver beam dimensions are larger than those of the interfering transmitter's beam, and hence is described by equation D-10. Assuming typical conservative values for the various parameters; that is

$\Omega_R \simeq \Omega_T \simeq 10\lambda^2$ Steradians	(Antenna Solid Angles)
$A_R \simeq$ 1 sq. meter	(Area of receiver aperture)
$Z_R \simeq$ 35,000 KM	(Geosynchronous orbit)
$\ell \simeq Z_T$	(Distance received light travels within scattering medium)
NEP $\simeq 10^{-13}$ watts	(Noise Equivalent Power of receiver)
$f(\Theta) \simeq 10$	(Modest forward scatter)

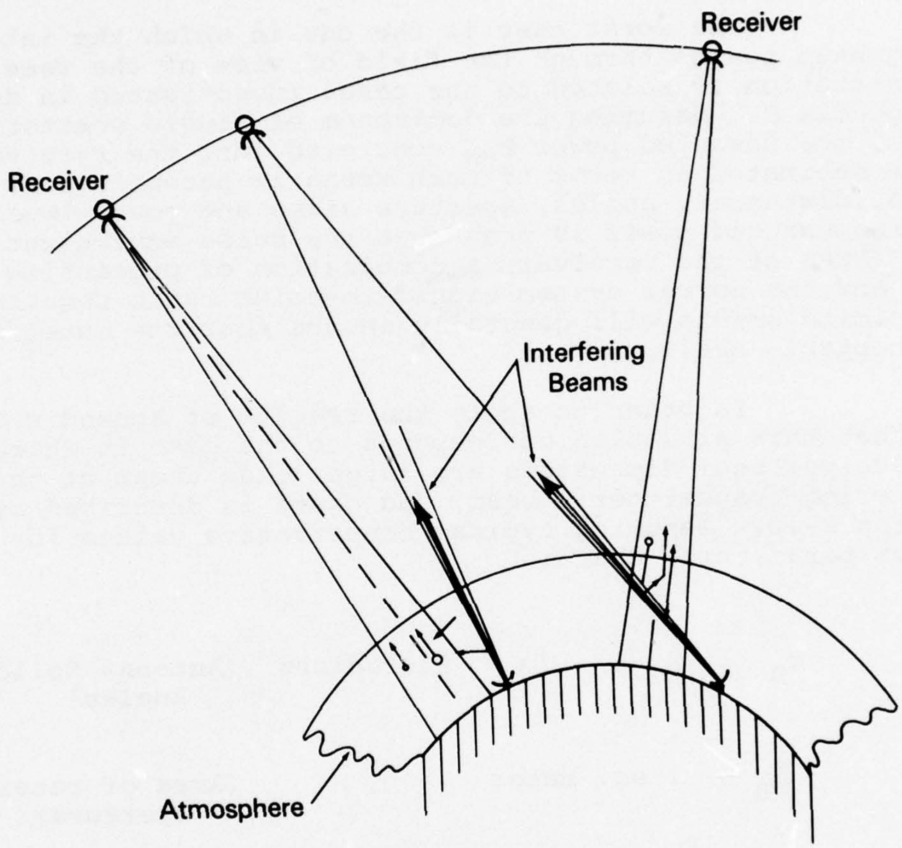

Fig. 7 — Space receiver — scatter interference

we find the following restriction on transmitter power P_T and distance Z_T from the transmitter to the intersection region:

$$\frac{P_T(\text{watts})}{Z_T(\text{Km})} \leqslant \frac{3780}{\lambda\,(\text{microns})} \qquad (4)$$

Assuming a minimum separation between earth stations, we must have $Z_T \geq 7\text{Km}$ and hence

$$P_T(\text{watts}) \leqslant \frac{26500}{\lambda\,(\text{microns})} \qquad (5)$$

Evidently, even with a CO_2 laser system (i.e., $\lambda = 10.6\ \mu$), kilowatts of transmitter power are required before serious interference problems can be anticipated in this scenario.

Actually for many cases of interest the immunity of a space receiver to ground transmitter scatter interference will be much larger than the above estimate suggests. If the link of interest uses heterodyne detection it will not respond significantly to any kind of scattered radiation -- from its own beam or another transmitter. The system will become useless because of the attenuation of unscattered main beam, long before it suffers from scatter interference.

If the system uses direct detection the above argument doesn't hold and one must use more care. As we have just seen for uniformly scattering atmospheres, single worst case power consideration suggests that scatter problems are less limiting than direct interference. But what if the scattering medium is something like a cloud layer with both the transmitter and interfering beams interacting in the clouds in the middle of the field of view of the receiver. If the cloud's scatter optical thickness is 5 or more, very little of the direct beam emerges and so the top of the cloud would be illuminated by multiple scatter from both beams to roughly the same extent. In this case we could expect a real interference.

Whether or not this is serious depends upon a variety of factors, the most important of which is the bandwidth limitations on direct detection system imposed by multiple scattering. As illustrated in Appendix B the multipath time dispersion grows more or less linearly with optical thickness, such that for a τ of 5 we find for the mean pulse width Δt and expression of the form

$$\Delta t \sim 0.62 \frac{T}{c} (5)^{0.94} \sim 2.8 \frac{T}{c} \qquad (6)$$

where T is the thickness of the cloud and c the velocity of light. Thus the useful information bandwidth W of the system will be limited to frequencies less than roughly Δt^{-1}, that is

$$W \leq 0.36 \frac{c}{T} \qquad (7)$$

For a cloud thickness T of only 100 meters, the system's useful bandwidth would have dropped to 1 MHz or so. Under these circumstances, such a low bandwidth space-to-ground link hardly seems useful, and the system would no doubt have shifted to an alternate cloud free earth station, carefully selected for just these occasions.

Again it seems although admittedly less firmly established, interference effects under worst case conditions will be less restrictive than direct interference effects. Both coherent and incoherent space-to-ground links will become useless, because of basic system losses, before the presence of an interfering link becomes noticeable.

Key to the so-called worst case conditions assumed in the above discussion has been the assumption that the links both pass through some common volume of space. With fixed links (i.e., geosynchronous satellites) and the very narrow antenna patterns typical of the optical systems, simple geometric coordination to insure such crossover poses no particular hardships and the interference issues are no longer relevant. For operation to non-synchronous satellites transient crossover could occur now and then, but should be of brief duration and even then the links are more likely to be "put out of business" completely by the clouds, than suffer interference.

3. Space Receiver from Space-to-Earth Transmitter (Mode #3)

Although considerations of direct interference probably eliminates this scenario, let us consider the unlikely situation illustrated in Figure 8, in which the field of view of the space receiver coincides with the interfering transmitted beam spot on the earth. Assuming that all the incident

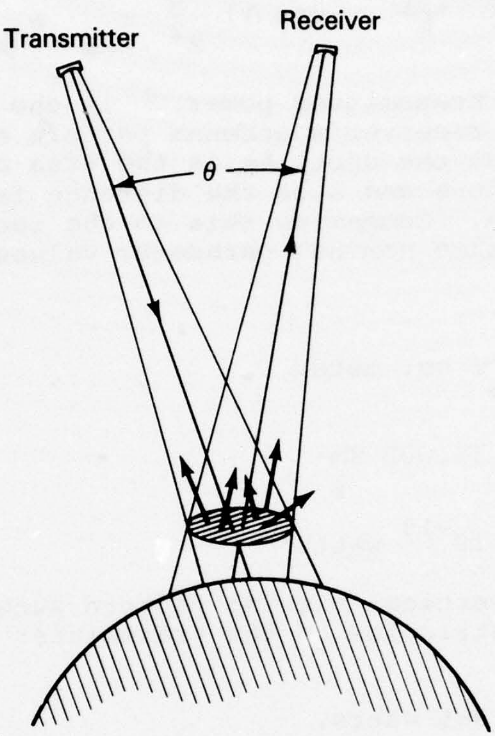

Fig. 8 — Space-to-ground/space-to-ground scatter interferences

power is diffusely reflected from the earth in a Lambertian distribution we can estimate a reasonable conservative upper limit for the unwanted power P_{UW} scattered into the space receiver; that is

$$P_{UW} \gtrsim \left(\frac{P_T}{\pi} \cos\theta\right) \frac{A_R}{Z^2} \qquad (8)$$

where P_T is the transmitter power, θ is the angle between the axis of the receiver's antenna pattern and the local earth vertical at the spot, A_R is the area of the space receiver's aperture and Z is the distance from the ground to the satellite. Comparing this to the receiver's NEP and taking the same nominal parameter values as before, that is

$A_R \simeq$ 1 sq. meter

$Z \simeq$ 35,000 Km

$NEP \simeq 10^{-13}$ watts

and assuming a vertical viewing pattern such that $\theta \simeq 0$ we find for the restriction on the transmitter power P_T,

$$P_T < 385 \text{ watts.} \qquad (9)$$

Since useful space-to-ground links can be designed within this rather crude, conservative limit, it appears that in this case, too, no serious scatter interference problems are anticipated. There is, of course, no reason why the antenna patterns on the ground should overlap at all.

4. Space Receiver from Terrestrial Transmitters (Mode #4)

This situation is essentially the same as case #2. Even with beam crossovers no interference problems are anticipated.

5. Earth Station Receiver from Space-to-Space Transmitter (Mode #5)

This case is identical to the corresponding case of a space receiver and offers no particular problems.

6. Earth Station Receiver from Ground-to-Space Transmitter (Mode #6)

This scenario is almost identical to the next mode, #7, with the important distinction that in this case the scatter is primarily the result of backscatter rather than forward scatter effects. Thus the multiple interference problem should be reduced by the ratio of back to forward-scattering cross sections. As can be seen from Figures B-9a and 9b in Appendix B this ratio can be expected to vary anywhere from 5 to 1000 or so, hence resolving scatter mode #7, which is discussed in more detail below, automatically resolves #6.

7. Earth Station Receiver from Space-to-Ground Transmitter (Mode #7)

Many of the space receiver considerations apply to this case also, with the important exception that the earth station receiver is located quite near the scattering regions and hence does not benefit as much from the $1/R^2$ free space propagation losses as does the space receiver. Again, if the earth receiver is using heterodyne detection, scatter is irrelevant. Direct detection systems however will have potential interference problems.

If the interfering beam crosses through the field of view of the earth station receiver somewhere within the earth's atmosphere then there obviously exists a possibility of scatter interference. However, since it is a simple matter to coordinate site placements such that no such intersections occur for links to geosynchronous satellites and other satellite-links interruptions must necessarily be temporary,* this scenario is not going to offer serious limitations and so will not be analyzed further.

There remains the possibility that a neighboring ground-to-space link with its ground station situated 7 or more Km away from the receiver of interest to avoid direct interferences, can deliver unwanted power to the receiver via multiple scatter effects. Some idea of the worst case

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*The maximum fraction of time such an interruption can occur is on the order of the ratio of ground station receiver beam width to 2π, which for reasonable assumptions is generally less than 10^{-4}.

possibilities can be gained by using the multiple scattering results of Appendix B. If we consider a vertical beam of light propagating vertically downward through the atmosphere, multiple scatter will cause it to increase its spread by something like the parameter $\langle r \rangle$ or r_c defined in reference 22. As Figure B-12 shows, there is a predicted maximum in the spread as the optical thickness varies such that in the worst case multiple scatter spreads the beam a radial distance on the order of the physical thickness of the scattering layer. Evidently if the separation between adjacent sites was increased by this amount, in addition to the distance required by our 30dB direct interference criteria, neither link would experience mutual interference via any direct or scatter mechanism. If we choose the unlikely situation of a giant cloud or fog which completely filled the space from the to an altitude of 40,000 ft (i.e. 12 Km), with a worst case total optical thickness of 2 or 3, then we would have to add a distance of 12 Km to our previously determined upper limit of 7 Km for minimum safe separation distance. Actually for most conditions the scattering will be confined to cloud layers or close to the ground under clear conditions such that the thickness of the scattering layers would be more like 2 Km or less, making a 19 Km separation very safe indeed.

8. Earth Station Receiver from Terrestrial Transmitter (Mode #8)

In this case the interference threat is associated with a terrestrial link which operates directly over the earth station's, more or less vertically oriented, receiver. If the terrestrial link is a direct one, (i.e., line of sight), its antenna patterns will be appropriately small (i.e., milliradian or less), and thus intersections with the FOV of the earth station receiver (also $\leq$ milliradian) are readily avoided by geometric coordination of sites. If the terrestrial link is a scatter propagation one, then some multiple scattered interference could be received by the earth station. But again, keeping the main beam of the scatter link out of the FOV of the earth-space link resolves most of the problem. The high bandwidth of the space-to-ground link and the necessarily low band width of the scatter link, make serious mutual interference doubtful as the information processing gains which we have neglected to this point could easily produce 20 to 50dB of additional protection.

9. Terrestrial Receiver from Space-to-Space Transmitter (Mode #9)

There is no possibility of interference here, if grazing is excluded.

10. Terrestrial Receiver from Earth-to-Space Transmitters (Mode #10)

If the terrestrial link is direct, that is line-of-sight, the considerations of interference from a second transmitter of a ground-to-space link are precisely the same as for the case of the earth station receiver and the direct terrestrial link -- that is, the beams are narrow and the geometric coordination required to prevent their intersections are easily implemented. If either case is resolved, so is the other. If the terrestrial link is a scatter link, the analysis of Mode 8 applies with the roles of transmitter and receiver reversed.

11. Terrestrial Receiver from Space-to-Earth Transmitters (Mode #11)

The interference of a space transmitter with a terrestrial link is a bit different as the space-to-ground beam, although angularly narrow, may still be several kilometers across as it penetrates the earth's atmosphere. Thus geometric coordination to eliminate potential interferences, while still feasible, is not as easily implemented as is the previous case where beam separation of meters rather than kilometers are probably sufficient. Let us suppose then, that the terrestrial receiver's FOV is looking through the several kilometers of atmosphere which is being illuminated by the space transmitter. Figure 9 illustrates the scenario.

This situation corresponds to case #1 discussed in Appendix D, in which the transmitted beam is much larger than the receiver's beam pattern in the intersection region. The unwanted power P_{UW} scattered from the space-to-ground beam into the terrestrial receiver will therefore be limited by an expression of the form (see equation D-9 in Appendix D)

$$P_{UW} \leq \frac{f(\theta)}{4\pi e} P_T \frac{\Omega_R A_R}{\sqrt{\Omega_T} Z_T \ell} \qquad (10)$$

where the terms are defined in the Appendix. In order to apply this to the scenario illustrated in Figure 7, we note that

$$f(\theta) \stackrel{c}{=} f(\pi/2) \lesssim 0.1 \text{(Figure B-9a and B-9b)}$$

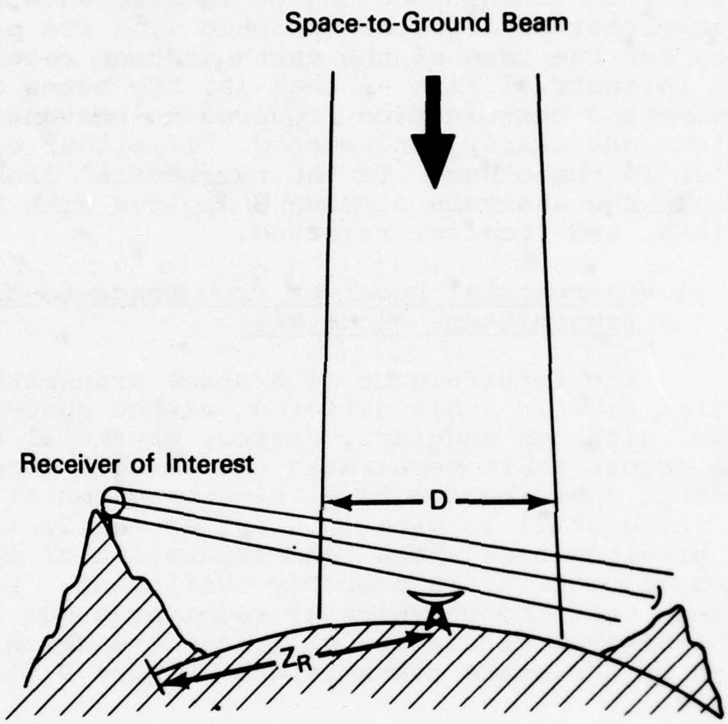

Fig. 9 — Terrestrial receiver — space-to-ground scatter interference

$$\Omega_R \simeq \begin{cases} 10\lambda^2 \text{ steradians (point-to-point receiver)} & [\lambda] \equiv \text{meters} \\ 1.2 \times 10^{-3} \text{ steradians (scatter-propagation receiver)} \end{cases}$$

$A_R \simeq$ 1 sq. meter (arbitarily chosen)

$\Omega_T \simeq$ $10\lambda^2$ steradians (space-to-earth transmitter)

$Z_T \simeq$ 35,000 Km (geosynchronous altitute)

$\ell \simeq$ $2 + Z_R$ (total path of light through scatter media)

where 2 Km has been chosen as an estimate of the effective vertical thickness of the atmosphere.

If the unwanted scattered power is required to be less than the receiver's NEP (i.e., $\sim 10^{-13}$ watts) we find the following coordination restrictions on the transmitter power P_T and the site separation Z_R;

$$\frac{P_T(\text{watts})}{Z_R(\text{Km}) + 2} \leq \frac{4 \times 10^4}{\lambda \text{ (microns)}} \quad \text{(Point-to-point receiver)} \qquad (11)$$

$$\frac{P_T(\text{watts})}{Z_R(\text{Km}) + 2} \leq 3 \times 10^{-4} \lambda(\text{microns}) \quad \text{(Scatter propagation receiver)} \qquad (12)$$

Evidently the direct or point-to-point terrestrial system can expect little interference from space-to-ground transmitters. Unfortunately the same cannot be said for the scatter propagation links--at least, not in terms of the simple power considerations used in the above discussion. The physical reasons for the above striking difference between direct and scatter links are easily understood in terms of the beamwidth or antenna patterns characteristic of the two systems. The scatter link necessarily operates with much larger fields of view. Comparing a typical scatter link FOV (i.e., $4°$ by $1°$) with a close-to-diffraction-limited direct link FOV (i.e., $\Omega \simeq 10\lambda^2$) as discussed in Appendix D, we find that as the unwanted power varies directly as the receiver solid angle. Thus the two systems should differ by a factor of about $8 \times 10^{-9} \left[\lambda(\text{microns})\right]^2$, that is, the ratio of the two solid angles.

Obviously, in practice the situation will not be as pessimistic as equation 12 suggests because of the large processing gains to be anticipated between such disparate systems as a scatter-propagation and a space-to-ground link. Assuming a 50dB processing gain, the coordination restriction for the scatter link case becomes

$$\frac{P_T(\text{watts})}{Z_R(\text{Km}) + 2} \leqslant 30\ \lambda\ (\text{microns}) \qquad (13)$$

which suggests that if the space-to-ground link is CW, that is, does not use a pulsed coding, there is probably little chance of it interfering with any kind of terrestrial link. If, on the other hand, the space-to-ground link is a pulsed system, with power levels of megawatts, interference problems cannot be ruled out by the simplistic arguments employed in this discussion.

12. Terrestrial Receiver from other Terrestrial Transmitters (Mode #12)

Again for this scenario it is possible to immediately eliminate coherent or heterodyne receivers for they are insensitive to everything except the unscattered portion of their own intended transmitter beam. Direct detection receivers on the other hand will be influenced by scattered radiation.

(a) Multiple Scatter Effects

As before, if the field of view of the receiver and the unscattered antenna patterns of the interfering transmitters do not intersect the problem reduces to a discussion of multiple scattering. This scenario is illustrated in figure 10.

To include the effect of the receiver's field of view we note that the multiple scattered radiation from the interfering transmitter at the receiver site can be assumed to be distributed more or less uniformly over the forward hemisphere and hence the receiver will accept approximately the fraction $\Omega_R/2\pi$, where Ω_R is the solid angle FOV of the receiver. Using the geometry defined in figure 10, and the results of the multiple scattering calculations discussed in Appendix B, we can estimate the unwanted power received P_{UW} as

$$P_{UW} \leqslant T_{SCAT} \cdot \frac{2P_T}{\pi \langle r \rangle^2} \cdot \frac{\Omega_R}{2\pi} \cdot A_R \qquad (14)$$

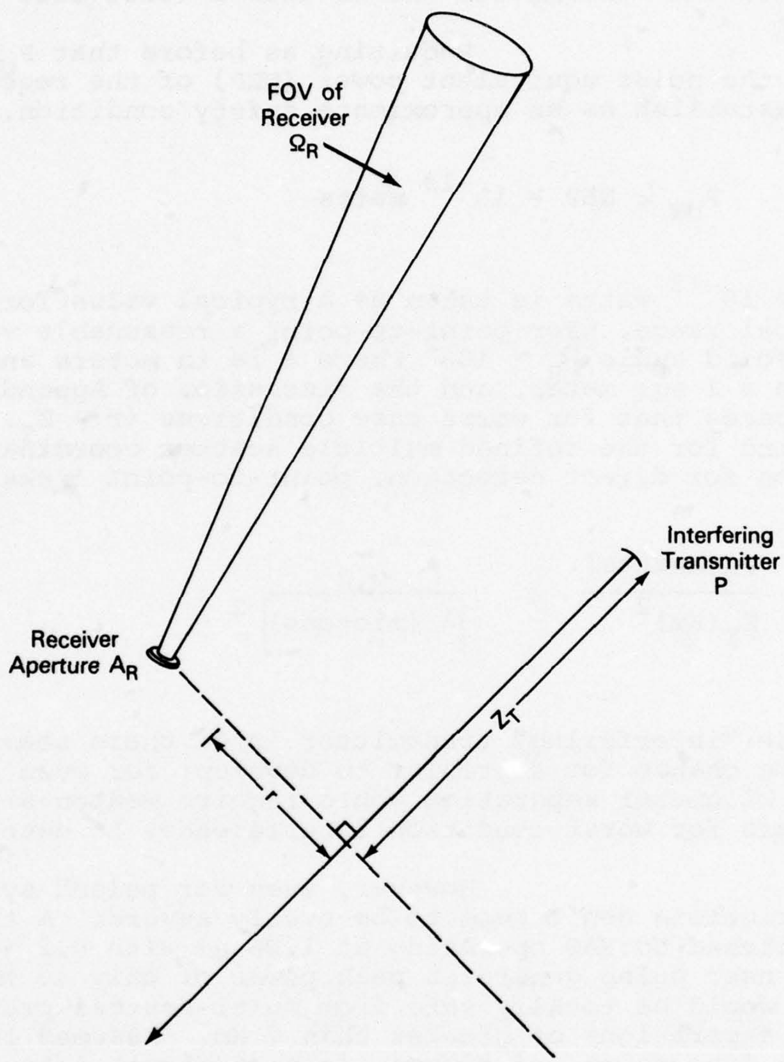

Fig. 10 — Terrestrial links — multiple scatter

where A_R is the area of the receiving antenna, $\langle r \rangle$ is a rough measure of the size of the scattered beam as defined in reference 22 and T_{SCAT} represents the total amount of radiation transmitted through the scattering medium to the plan which contains the receiver. The expression $T_{SCAT} \cdot 2P/\pi\langle r \rangle^2$ is approximately the peak irradiance on axis of the transmitter and is thus a worst case estimate.

Requiring as before that P_{UW} be less that the noise equivalent power (NEP) of the receiver we can establish as an approximate safety condition.

$$P_{UW} \leqslant NEP \simeq 10^{-13} \text{ watts} \tag{15}$$

where 10^{-13} watts is taken as a typical value for the whole optical range. For point-to-point a reasonable value for the solid angle $\Omega_R \sim 10\lambda^2$ where λ is in meters and A_R is taken a 1 sq. meter, and the discussion of Appendix B indicates that for worst case conditions $\langle r \rangle \simeq Z_T$. Thus we find for the refined multiple scatter coordination condition for direct detection, point-to-point links

$$\frac{P_T(\text{Mwatts})}{Z_T(\text{Km})^2} \leqslant \frac{0.2}{\left[\lambda \text{ (microns)}\right]^2} \tag{16}$$

If the "interfering" transmitter is CW there seems to be little chance for a problem to develop; for even a fraction of a kilometer separation would require weapon-sized transmitters for worst condition interferences to develop.

However, even for pulsed systems these restrictions don't seem to be overly severe. A typical Q-switched Nd:YAG operating at 1.06 μm with 0.2 joules in a 20 nsec pulse generates peak power of only 10 MW and thus would be totally safe from multi-scatter problems at site separations of greater than 7 Km. Assumed in the above discussion, of course, is that direct interferences have been eliminated by appropriate geometric coordination of the links.

If the receiver of interest is part of a scatter-propagation link the above analysis does not apply directly as the receiver is not generally operated with a diffraction-limited field of view. More probably Ω_R would correspond to something like the 4° by 1° FOV discussed in Appendix D so that $\Omega_R \simeq 1.2 \times 10^{-3}$ would be more appropriate. Taking a reasonable receiver aperture size of $A_R \simeq 1.0m^2$ we find for the multiple scatter coordination condition

$$\frac{P(Mw)}{Z(Km)^2} \leq 1.6 \times 10^{-9} \qquad (17)$$

clearing an extremely restrictive condition. In fact, if these estimates were realistic it would be a rather simple task to build a scatter propagation link with only a few watts of pulsed power. The more careful analysis of reference 5 indicates that this is not really the case, suggesting that our "worst case" estimates are actually extremely conservative.

However, it is probably fair to conclude that a scatter-propagation receiver could, in fact, receive significant amounts of multiple-scattered unwanted radiations from other optical links, particularly those operating close by.

There remains the potential for mutual interference between two scatter-propagation links via multiple scattering effects. This is real, but the analysis of all the possibilities and ramifications is too complex and too uncertain to be addressed here. This subject deserves much more experimental and theoretical attention.

(b) Single Scatter Effects

Finally, we come to the last set of scenarios of interest; that is, cases in which the transmitter beam of an interfering terrestrial link passes directly through the field of view of the receiver of a direct detection terrestrial link. Since for each type of receiver (point-to-point or scatter), there are two possible interfering transmitters, there are four possibilities to consider, as illustrated in figure 11.

Appendix D, which has been referred to several times in the discussion to this point, addresses these four situations. Although the expressions in the appendix are more general, let us only consider here simpler situations for which the intersecting beams cross at right angles (i.e., $f(\theta) \simeq f(\pi/2) \leq 0.1$) and for which the

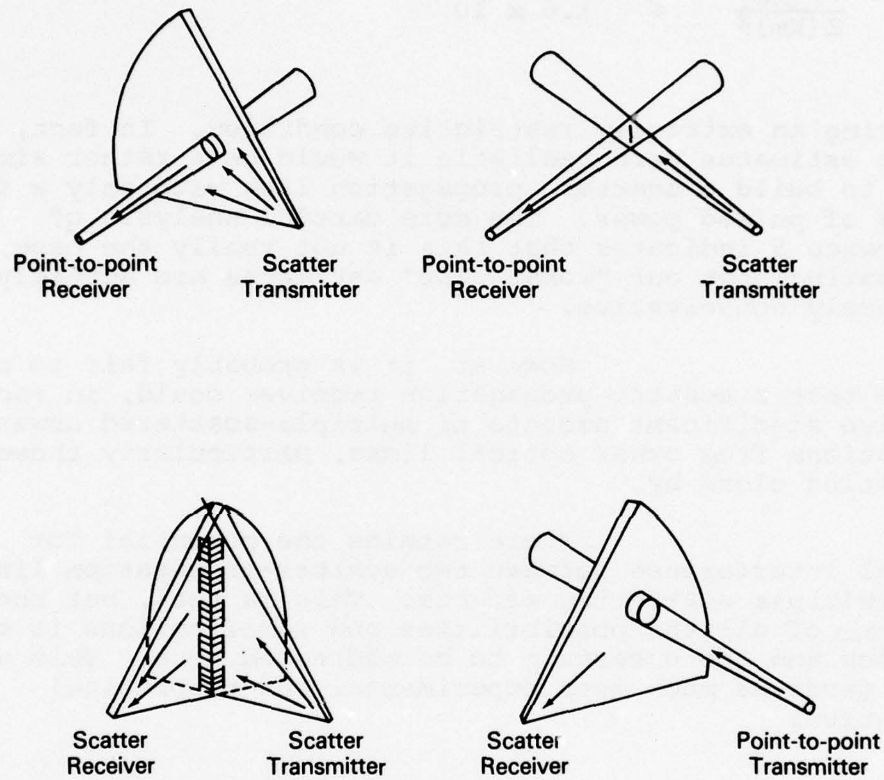

Fig. 11 — Terrestrial links — single scatter effects

receiver and transmitter of interest are equidistant from the intersection (i.e., $Z_T = Z_R \equiv Z$ and hence $\ell = 2Z$). Assuming typical system parameters, (i.e., $A_R = 1$ sq. meter, NEP $=10^{-13}$) watts and so on, we find for the coordination restrictions the following expressions

- Point-to-Point Receiver

$$\frac{P_T(\text{watts})}{Z(\text{Km})^2} \le \begin{cases} \dfrac{2.4 \times 10^5}{\left[\lambda\ (\text{microns})\right]^2} & \text{Scatter propagation Transmitter} \quad (18a) \\[2ex] \dfrac{22}{\lambda(\text{microns})} & \text{Point-to-point transmitter} \quad (18b) \end{cases}$$

- Scatter Propagation Receiver

$$\frac{P_T(\text{watts})}{Z(\text{Km})^2} \begin{cases} 2 \times 10^{-3} & \text{Scatter propagation transmitter} \quad (19a) \\ 2 \times 10^{-3} & \text{Point-to-Point transmitter} \quad (19b) \end{cases}$$

Again we see a common pattern emerge: the point-to-point receiver is reasonably immune to interference effects, while the scatter propagation receiver appears vulnerable. In fact, it seems quite clear that scatter propagation links will interfere with each other if antenna pattern overlaps occur.

V. CONCLUDING REMARKS

As has become increasingly obvious throughout the analysis of the mutual interference of fixed optical communications links, most conflicts are easily resolved through the coordination of all such sites in the local geographic neighborhood. In fact, our extremely conservative estimates indicate that 21 of the 24 possible interference modes can be eliminated or controlled by the application of relatively simple geometric and modulation coordination restrictions without any reference at all to questions of wavelength or frequency band limitations. Since laser-produced light beams are so narrow it is generally easy to select transmitter/receiver sites for fixed optical communication links such that the antenna patterns from each do not intersect those from any others with sufficient margin--measured in milliradians to a few degrees at most--to insure that under all weather conditions all interference effects both direct and scatter will be negligible.

The three remaining modes of interference involve scatter-interference from space-to-earth, earth-to-space and terrestrial transmitters into the receiver of a terrestrial, scatter-propagation link. Even in these three cases, geometric coordination can resolve the conflicts but it is definitely more restrictive and difficult to implement than for other modes. Scatter links necessarily use much larger field of view than point-to-point systems and thus make much larger volumes of space unavailable to other optical links. When beam intersections do occur, serious interference problems can be expected, particularly for the case of two terrestrial scatter propagation links which do not benefit from the large processing gains which characterize the other two scenarios. However, the seriousness of these potential interferences is extremely difficult to assess at the present time, for in addition to a technology which has not yet been field tested, the rationale for selecting such a low bandwidth, weather-sensitive scatter propagation link for non-military applications can validly be questioned. It may be that this approach to optical communications may never see widespread usage and hence its international regulation is a moot point.

Optical communications to and from mobile platforms also present interference possibilities which may or may not be serious, depending upon the degree to which safety considerations limit their application, and the degree to which transient interruptions can be tolerated. Direct illumination of a sensitive receiver by a carelessly aimed mobile transmitter operating in the wavelength band of the receiver could be physically disastrous--burning out detector elements, etc. Certainly human safety requirements will legislate against most such incidents as receiver sites, fixed or mobile, will generally be manned. At the very least, if permitted at all, mobile transmitters should be severely limited in power. Whether or not they should also be restricted in wavelength to insure against such "accidents" is definitely a question for the future and depends heavily upon the degree to which such safety-restricted links can be economically useful.

Although our discussion has been limited to optical communication links and their mutual interferences, it is clear that there are two other generic possibilities which should be considered; that is other active electro-optic equipment interfering with communications and the reverse, an optical communication link interfering with some other type of passive optical sensor such as an astronomical telescope. For both cases the arguments are little different from those that have been given in the body of the text--fixed installations such as an airport visibility measurement system or a cloud ceilometer can be coordinated with the communication system in the locality and mobile applications like a laser radar for clear air turbulence detection will be severely restricted by safety considerations. Conflicts are possible but difficult to define at the present time. Serious problems seem unlikely in most cases.

The astronomical telescope would seem to be particularly vulnerable to such interference, particularly when a laser beam passes through its field of view within the atmosphere. The resulting scatter into the telescope could seriously affect its ability to "see" weak stars. Obviously the resolution of this problem reduces again to the questions of local coordination -- e.g., restrictions on placing laser sources too close to major astronomical sites, time coordination with the lasers off while the telescope is on or perhaps appropriate filtering in the optical train of the telescope to reject the wavelengths of the laser systems known to be operating in the neighborhood, etc.

In conclusion then, with respect to question 53/1 of Addendum No. 1 to Vol. 1, XIIIth, P.A. of the CCIR, Geneva, 1974, we observe that:

1) Free space communication systems operating at optical frequencies (i.e., from approximately 10^4 to 10^6 GHz) are practical with only modest improvements in today's technology and will probably see widespread usage. The potential of such systems for

very high data rates (i.e., Gigabit or better) will definitely contribute to alleviating some of the present congestion in the use of radio waves in specific applications.

2) From a technical point of view, optical technology is completely distinct from radio technology. There exists a large gap in frequencies (of several orders of magnitude) between the optical portion of the electromagnetic spectrum and the radio or microwave portions due to the extreme attenuation of the earth's atmosphere for wavelengths in this forbidden region. Because of these many orders of magnitude difference in wavelength, the two regions are forced to utilize entirely different physical principles, materials, and components to achieve oscillation, modulation and detection. In addition, the propagation characteristics are quite different; optics being characterized by conveniently generated very narrow beam width and fairly strong absorptive and scattering interactions with the atmosphere while radio waves cannot be constrained to directional beams without heroic efforts and are relatively insensitive to meterological phenomena.*

Our analysis of mutual interference modes of optical communication systems strongly suggests that since most such conflicts are readily resolvable by coordination within the local geographical neighborhood of the systems' parameters such as angles, site separation, modulation schemes and wavelengths, -- a technique unsuited to the radio wave spectrum where spatial isolation of systems is largely impractical -- it would be naive and unnecessarily restrictive to automatically extend the radio regulations now in force into the optical region.

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*"Microwaves" are closer to optics in propagation characteristics but remain a continuous outgrowth of the radio spectrum and as such offer more subtle problems with respect to the establishment of an upper frequency limit to the definition of radio waves -- fortunately, not the subject of this work!

It is recommended that such regulation of optical systems as is deemed necessary, take the form of locally-coordinated restrictions on the characteristics of neighboring optical systems, rather than on global assignments of wavelengths or frequency bands. The paucity of good laser oscillators, in contrast to the complete tunability available to the radio range, further emphasizes the desirability of retaining the flexible application of the few "good" lasers currently available to us to a wide variety of tasks within the bounds of reasonable, practical local constraints.

APPENDIX A

QUESTION 53/1

SYSTEMS FOR TELECOMMUNICATION, DETERMINATION AND OTHER PURPOSES, OPERATING IN THE ELECTROMAGNETIC SPECTRUM ABOVE 40GHz, PARTICULARLY THE HIGHEST FREQUENCY REGION OF RADIO WAVES, AS WELL AS IN THE INFRA-RED AND VISIBLE LIGHT REGIONS

The C.C.I.R., (1975)

Considering

(a) that systems for telecommunication and determination operating in the highest frequency region of radio waves, as well as in the infrared and visible light regions, will make it possible to use a wider frequency band than conventional systems operating in the radio-frequency region, and that realization of these systems will contribute to alleviating the present congestion in the use of radio waves;

(b) that, if such systems are used for communications relating to mobile objects, in particular, in space or in the atmosphere, it will be a matter of great importance whether international technical standards to keep the operation of these systems in good order will be necessary or not;

(c) that the Radio Regulations which are now in force regulate systems of communication and determination operating in the electromagnetic spectrum below 3000 GHz and only a very small portion of the electromagnetic spectrum of lasers is subject to these Regulations. It is considered reasonable that these Regulations should also apply to systems which operate in the infrared and visible light regions, with principles similar to those of systems operating in the radio-frequency region;

Decides that the following question should be studied:

1. what are the practical kinds of systems for communication, determination and other purposes, that operate in the electromagnetic spectrum above 40 GHz, particularly in the highest frequency region of radio waves, as well as in the infrared and visible light

regions, and what are the technical problems for the realization of these systems? How can these systems contribute to alleviating the present congestion in the use of radio waves;

2. what will be the reasonable upper limit frequency in the definition of radio waves from the technical point of view, taking recent technical progress into consideration?

APPENDIX B

OPTICAL PROPAGATION PHENOMENA

The propagation of light is characterized by four major classes of phenomena:

- Diffraction
- Absorption by atmospheric constituents
- Refraction by atmospheric turbulence and density gradients, and
- Scattering by aerosols, fogs, clouds, etc.

The first, diffraction, is a characteristic of the free space propagation of all electromagnetic waves and is independent of the properties of our atmosphere, while the remaining three effects, absorption, refraction, and scattering, are explicitly dependent upon the atmosphere and its meteorology.

- Diffraction

The far field pattern of an illuminated aperture, be it an optical telescope or a microwave antenna, is expressible via the Huygens-Fresnel principle as a Fourier transform of the illumination pattern in the aperture. The details of the resulting beam patterns or antenna gain vary with the details of the aperture -- i.e., uniformity of illumination, blockage, etc. -- and as such may be quite complex with side-lobe structure. However, the general properties of such a diffracted beam are well known and expressible in terms of the familiar equations,

$$\theta_{DIFF} \simeq (\lambda/D) \qquad \text{(B-1)}$$

where λ is the average wavelength of the radiation and D, the diameter of the aperture. Squaring this expression and rearranging terms leads to Siegman's form of the fundamental antenna theorem[29], which he has shown applies equally well to coherent RF and optical systems; that is, if an antenna has a single main lobe which subtends a solid angular field of view of Ω (θ^2_{DIFF}) steradians, with an effective aperture A(D^2) for sources inside this field of view, then

$$A\Omega \simeq \lambda^2 \qquad \text{(B-2)}$$

Expressions 1 and 2 indicate quite clearly one of the outstanding differences between optical and microwave systems. Given the same size aperture, A, the solid angle Ω addressed by an optical system, is on the average about $(10^{-4})^2 = 10^{-8}$ times smaller than the solid angle into which a typical microwave beam would be spread from an antenna of area A. Correspondingly, the same size solid angle beam can be generated by the optical system with an output aperture A which is 10^{-8} times smaller in area than the microwave antenna. Optical beams with divergence in the milliradian to microradian range are extremely easy to produce from reasonably-sized (i.e., less than a meter diameter) apertures. This fact is key to the discussion of optical communication link interference modes and forms the basis for much of the coordination concepts recommended for consideration with respect to potential regulations. It should be noted that these simple diffraction considerations apply equally well to passive receiving antennas as to the transmitters; that is, the receiver's field of view (FOV) is also determined by λ/D.

In practice, particularly if quantitative estimates of interference are to be established, equations B-1 and B-2 are not sufficient. The variation of the antenna gain with angle off the axis of the optical system must be known in more detail. Given any particular system, this calculation is completely straightforward and would certainly be done as well as experimentally confirmed. For our purposes however it is sufficient to consider a few representative examples of typical antenna patterns. The example presented in figure B-1, taken from reference 7 was in fact prepared for microwave systems but as it is presented in terms of the ratio λ/D, applies equally well to optical systems. Note that the complications of the side lobe structure have been suppressed and only an average presented. For example, from the figure, we find that for all angles (in degrees) such that

$$\frac{D\theta}{\lambda\, 100} > 1.0 \qquad \text{(B-3)}$$

the antenna power gain is less than -20dB. For a typical optical system (i.e., $\lambda = 10\mu$, D = 20 cm), this 20dB point

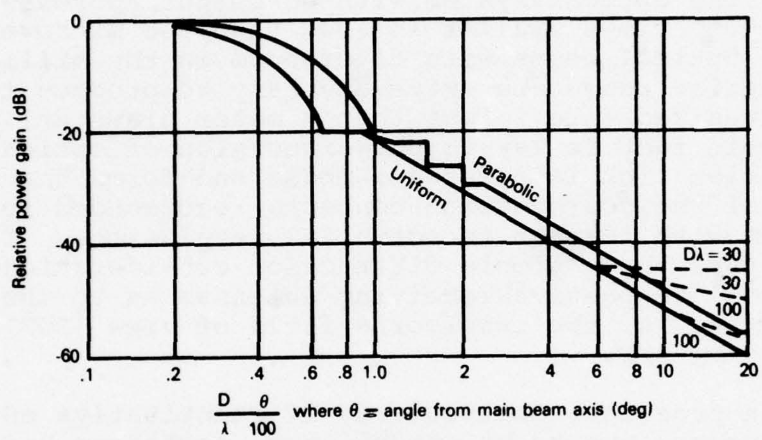

Fig. B-1 — Reference antenna patterns

corresponds to an angle of only 0.005 degrees, or 87 microradians. From these numbers it is easy to appreciate how narrow an optical beam can be. At a distance of 40 Km, which is about the limit for a line of sight ground-based system operating from hill top to hill top, the beam spot size would be only 3.5 meters in diameter.

- Absorption

The propagation of optical radiation through the atmosphere is heavily influenced by absorption processes associated with the gaseous and particulate constituents of the atmosphere. In the ultraviolet, ($\lambda < 0.3\mu m$) absorption by ozone combines with aerosol and Rayleigh scattering to induce very heavy propagation losses. For this reason, the optical region of the spectrum is generally considered to end near $0.3\mu m$. In the visible ($\sim 0.4\mu m$ to $0.7\mu m$) and near infrared ($0.75\ \mu m$ to about $1\mu m$), there are few absorption mechanisms of any consequence, in the absence of haze, dust, smog, etc... The propagation of these wavelengths is dominated by the particulate scattering effects to be discussed below. In the infrared, however, the major optical loss mechanism is absorption by various naturally occurring molecular gases including H_2O, CO_2, O_2, O_3, N_2O, CO, CH_6, HNO_3 and others. All of these gases with the exception of O_2, are minor constituents. Some, such as CO_2, are fairly uniformly mixed throughout the atmosphere. Others, such as water vapor (H_2O) and ozone (O_3) are distributed quite unevenly often changing rapidly with time and from place to place.

The great variety of possible combinations of transmission paths and atmospheric conditions makes it impossible to acquire adequate experimental data for all possibilities, and so a variety of computational methods have been evolved and refined over the years. For gaseous absorption, this calculation is easy in principle but difficult in practice because of the tens of thousands of vibrational-rotational lines in the infrared spectra of the gases involved. Each absorption line is extremely narrow, yet across a single such line, the transmittance can vary from nearly unity to near zero.

For our purposes here we do not need to go into great detail but merely to get an appreciation for the restrictions on optical communication systems associated with the absorption properties of the atmosphere. In figure B-2 we present a "low resolution" representation of the horizontal path transmission of light from $0.2\mu m$

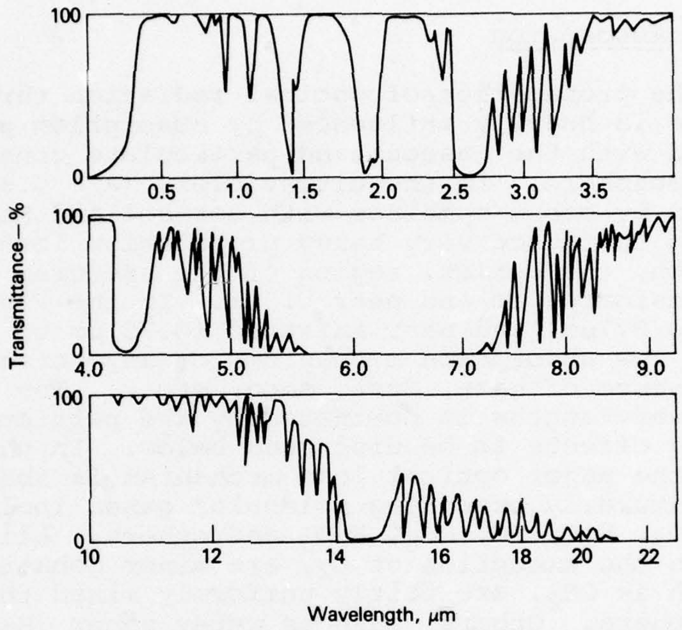

Fig. B-2 — Atmospheric transmission

(ultraviolet) to 25μ in the infrared. The complicated line structure associated with the molecular absorptions are suggested throughout the infrared, although the structure is much more complex than indicated when viewed on an expanded wavelength scale. The three classical optical transmission "windows" have also been indicated: the visible, the 3-5μm band and the 8-14μm band. Obviously this is a simplification as there are other regions of the spectrum outside the "windows" which show high transparency (e.g. near 1.65 and 2.3μm) as well as portions within the windows which have high absorptivity (e.g., near 4.3μ in the 3-5μm window, and 12.6μ etc. in the 8-14μm window).

Any optical communication link designed to operate within or through the atmosphere, such as a ground-to-ground or satellite-to-ground link must utilize wavelengths which lie in the few good transmission spectral regions. A possible exception to this might be a short-range link deliberately designed to operate in a high loss spectral region for reasons of covertness. And, of course, no such "window" restrictions apply to exoatmospheric applications such as satellite-to-satellite links.

While important to the designer of an optical communication link, these absorption considerations do not impact our interference considerations very much.

However, before we move on to the other propagation phenomena, turbulence and scatter, which do bear directly on the problem of interference, it is interesting to expand the above considerations a bit in the direction of longer wavelengths until we have passed smoothly from the optical portion of the spectrum into the microwave region. In figure B-3 we show a plot of the absorption of a typical clear (i.e., no clouds, fog, haze, etc.) atmosphere as a function of wavelength from 0.2μm (i.e., UV) through six orders of magnitude to 20 cm (i.e., L-band).[8] The pattern is interesting, for between the optical and microwave regions there lies a vast "mountain" -- a portion of the spectrum from 20μ to 1mm in which the average absorption on a 1 Km path exceeds 100dB or more. Evidently this intermediate portion of the spectrum will have little application to atmospheric communications. Somewhat coincidentally, and perhaps it is not really a coincidence, both optical and microwave technologies seem to give out in this same region. For example, available oscillator power goes down rapidly as the submillimeter region is approached from either side, for the wavelength dimensions are too small for easy implementation of microwave cavity concepts and still too large for molecular

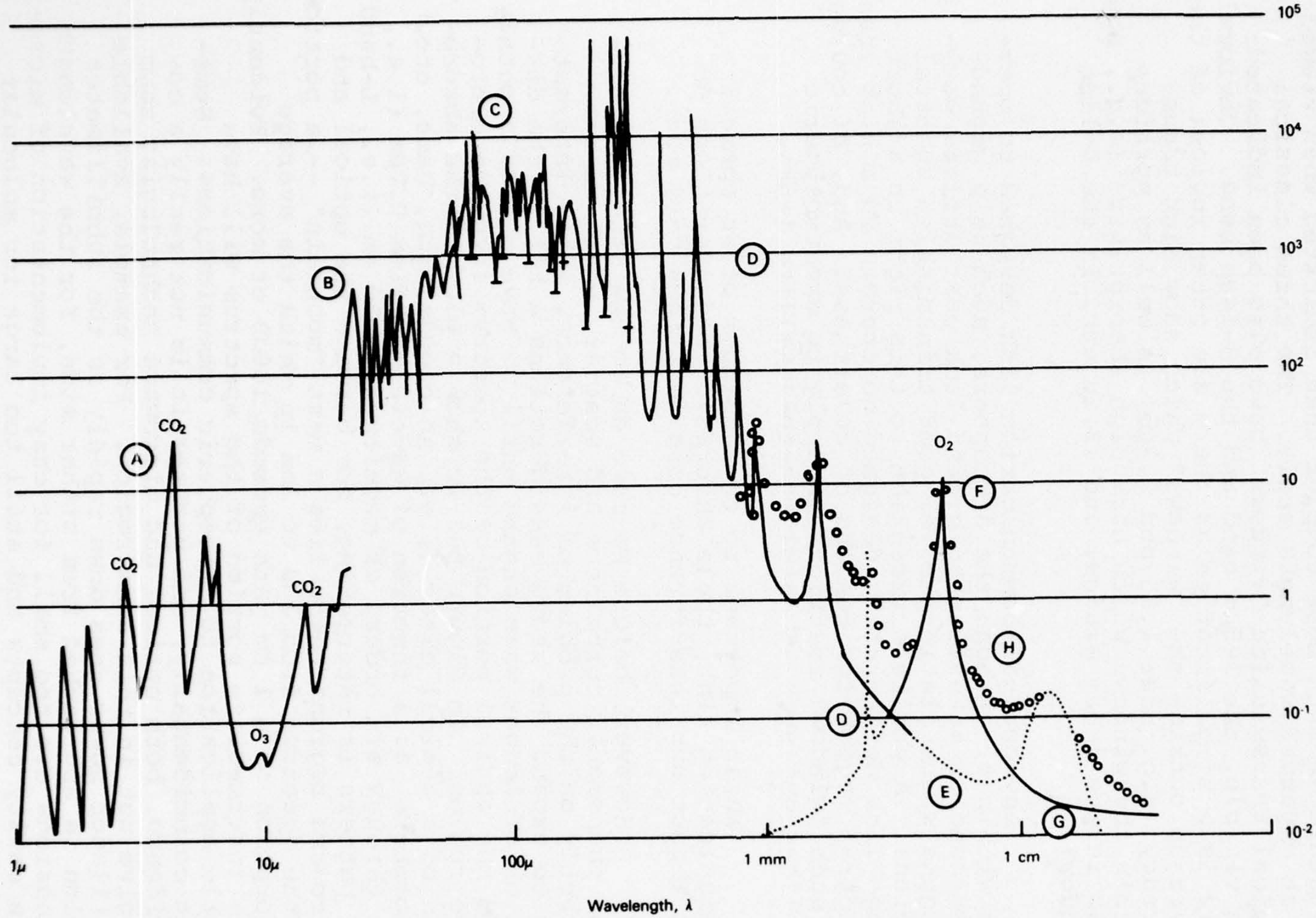

Fig. B-3 — Absorption coefficients due to atmospheric gases at sea level conditions for the spectral range 0.3 μ to 3.2 cm energy level laser concepts. Of course, another reason for the paucity of technology is the fact that very little effort has been devoted to it just because of the high atmospheric attenuation.

The end result is that the optical and microwave spectral regions are clearly separated by a rather substantial wavelength gap of about two orders of magnitude. Thus although they form parts of a continuum, they are by no means adjacent, neither in wavelength nor in component technologies. This important distinction is another key concept which has heavily influenced our view as to the most efficient and effective coordination techniques which might be employed to minimize the mutual interference of optical communication links.

- Refraction

The atmosphere, through spatial and temporal variations in gas composition and density, presents related variations in the optical index of refraction of the medium to light beams propagating through it. The light beams are thus refracted in both systematic and random fashions causing them to deviate from their original, free space, diffraction-limited paths.

The systematic effects are associated primarily with the vertical density and compositional gradients in the atmosphere. As a result light rays in the atmosphere are curved downward toward the surface of the earth by a small amount. As these vertical gradients change only slowly with time and vary on a scale which is much larger than the typical dimensions of an optical communication system light beam, the associated beam deflections are easily estimated and taken into account. In particular, they do not cause rapid, unpredictable deflections of the beams as is the case for the effects of turbulence and thus produce no adverse effects upon an optical communication link propagating through the atmosphere.

Superimposed upon these well-behaved vertical gradients, are the rapid, randomly varying fluctuations associated with atmospheric turbulence. Because of their statistical, time varying nature these turbulent fluctuations can seriously affect the performance of an optical link.

Figure B-4 illustrates the fluctuations in the received signal of a CW HeNe laser beam ($\lambda = 0.6328\mu m$) propagating along a horizontal path.[9] Large amplitude fluctuations or "fades" are observed at frequencies of a few to a few hundred Hz. For weak turbulence levels these intensity fluctuations are found to be distributed in a log-normal fashion such that the rms σ fluctuations in the logarithm of the intensity varies as

$$\sigma^2 \sim \frac{1}{\lambda^{7/6}} \; C_n^2 \; Z^{11/6} \qquad \text{(B-4)}$$

where λ is the wavelength of light, Z the total length of the path length in the turbulence and C_n^2 is the so-called "index of refraction structure constant", and provides a measure of the strength of the turbulence; $C_n^2 = 10^{-14}$ meter$^{-2/3}$ representing rather strong turbulence and 10^{-16} meters $^{-2/3}$, moderate to weak turbulence. The peculiar non-integer powers which appear throughout are a consequence of the Kolmogorov spectrum which is usually assumed to adequately describe atmospheric turbulence. For a very large level of turbulence, the rms log-intensity fluctuations reach a maximum value (i.e., "saturate") and then decrease slowly with further increases in turbulence strength.

Obviously, the signal "fades", described above must be carefully accounted for in designing an optical communication system, whether it relies on coherent or incoherent detection. If the system relies on coherent detection, however, additional problems arise for the phase front distortions induced by the turbulence not only cause the beam to deflect and spread but at the same time, through "beam scrambling" adversely affect the coherence properties of the beam. These coherence loss problems have been studied in great detail by a number of authors, both theoretically and experimentally. It has been found that if no attempt to compensate for these phase distortions is attempted, then the useful aperture of an optical heterodyne system is limited to a diameter r_o, known as the coherence diameter, where

$$r_o \sim \lambda^{6/5} \Big/ \left[C_n^2 \, Z\right]^{3/5} \qquad \text{(B-5)}$$

A physical aperture larger than this will not increase the heterodyne signal-to-noise. However, by measuring and tracking the average tilt in the received wave front,

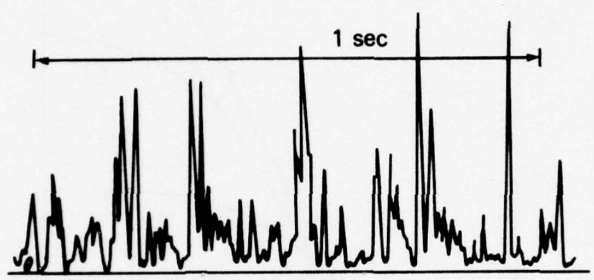

Fig. B-4 — Example of a recording of fluctuations in a signal propagating through the atmosphere /751/

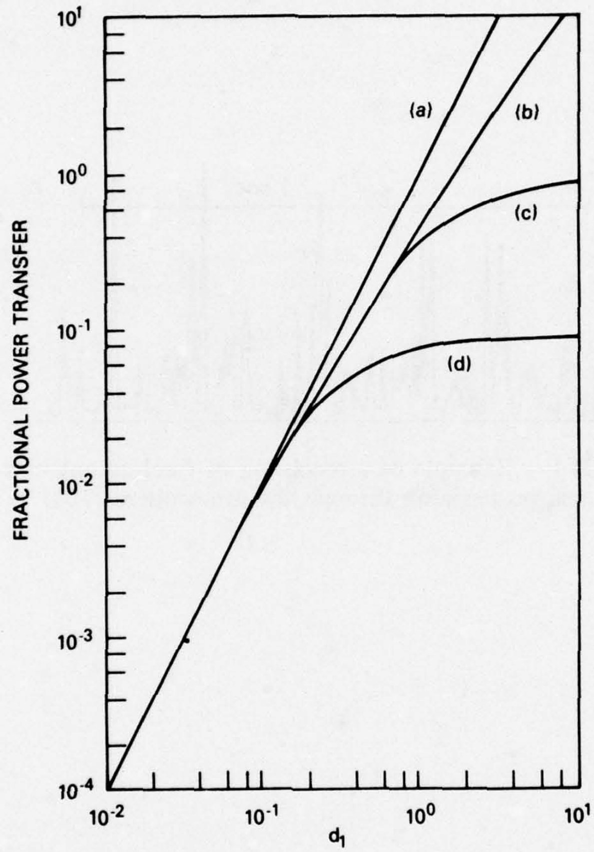

Fig. B-5 — The effect of tracking on average power transfer through a turbulent atmosphere. The ordinate is the ratio of power received (through a turbulent atmosphere by an optical heterodyne system) to power transmitted, in arbitrary units. The abscissa is the diameter of the receiving optics, also in arbitrary units. Curve (a) is for a diffraction-limited system in free space. Curve (b) is for a reciprocal pointing and tracking system. Curve (c) is for a system with only angle-of-arrival tracking at the receiver. Curve (d) is for a system without tracking.

this useable aperture diameter can be increased to $3.4r_o$, for a gain of about 10 log $(3.4)^2 \sim$ 10dB. Recently, a further refinement has been successfully introduced and experimentally verified in the form of reciprocal pointing and tracking.[2] If both ends of the communication link simultaneously transmit and track the received wave front tilt it can be shown through reciprocity arguments that the power transfer between the two terminals will be optimized. Figure B-5 shows the results achievable with reciprocal pointing and tracking. In addition Figure B-6 illustrates how r_o is related to wavelength, path length and the "strength" of the turbulence (C_n^2).

The coherence diameter r_o not only expresses the loss of heterodyne performance upon reception but also describes the turbulence-induced spreading of the beam propagating from a transmitter. Loosely speaking, if the physical aperture of the transmitter is smaller than the coherence diameter, then the spreading of the beam will be dominated by the diffraction-spread associated with the physical aperture (Figure B-1). On the other hand, if the turbulence is strong enough that r_o is smaller than the physical diameter of the aperture, then the average beam spread can be described as if it emanated from a physical aperture of diameter r_o. Thus through the use of figures B-1 and B-6, the average antenna gain in the presence of atmospheric turbulence can readily be estimated.

• Scatter

The most important propagation phenomenon relevant to the question of the mutual interference of optical communication links is the scattering of light by the molecular density fluctuations and the aerosol particles in the atmosphere.

Molecular Scatter

The attenuation and scatter of visible and infrared radiation by molecular density fluctuations in the atmosphere have been studied extensively.[11] A large number of tables of coefficients of molecular or Rayleigh scattering are available and cover a wide range of wavelengths in the ultraviolet visible and infrared. Because of the well-known λ^{-4} dependence of the Rayleigh scattering cross section this particular phenomenon is of impor-

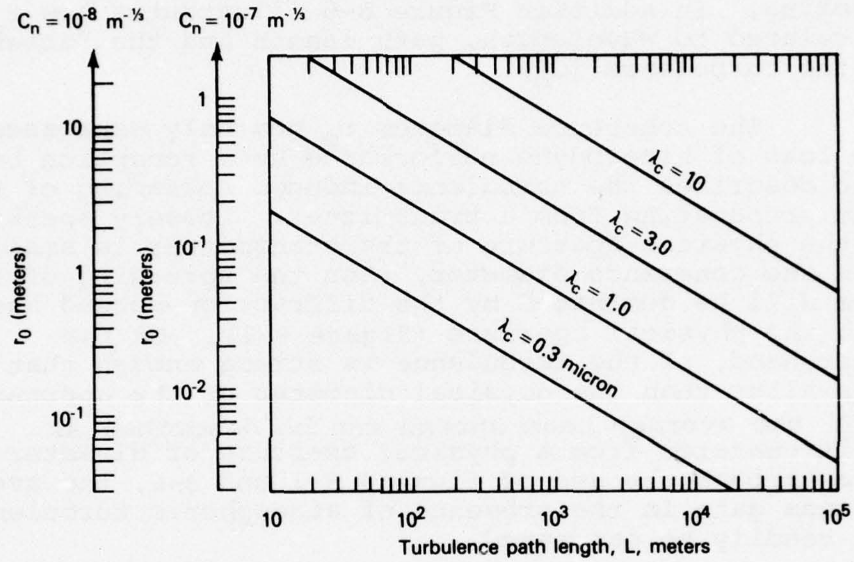

Fig. B-6 — The dependence of r_o on transmission wavelength, turbulence pathlength, and turbulence structure constant (from reference 2)

tance only for the ultraviolet and blue end of the visible wavelengths. For the remaining portion of the optical regions, aerosol scatter generally dominates.

Aerosol Scatter

Rayleigh scattering is readily accounted for in any particular light propagating scenario, as the molecular fluctuation properties of the atmosphere are spatially distributed in a known and relatively constant manner. Aerosol scattering coefficients, however, depend markedly on the dimensions, chemical composition and concentration of aerosol particles, which are highly variable in both time and space. Quantitative estimates of the effects of aerosol scattering thus becomes extremely difficult to establish for any given scenario. The best one can hope to achieve is a statistical description of the range of variations to be expected in terms of a theoretical and experimental understanding of scattering physics and the correlation of microscopic aerosol properties with such macroscopic variables as time, altitude, cloud conditions, etc.

Atmospheric aerosols divide naturally into two general classes:

- Water-related meteorological phenomena -- clouds, fogs, rain and snow; and
- Other particulates -- which are always present even under nominally "clear" conditions, including natural and man-made dust, carbon particles, salt precipitates of various kinds, and the like.

Clouds, fogs and precipitation

These forms of aerosols are characterized by single-peaked size distributions of more-or-less spherical droplets of water. As such, the optical properties of the individual particles are rather well defined and the scattering of light by these spherical water drops is well described by classical Mie scattering theory.[12] The observed size distributions are generally expressed as a so-called gamma distribution of the form

$$\frac{dn}{dr} = Ar^M e^{-\mu(\frac{r}{r_o})} \qquad \text{(B-6)}$$

where dn/dr is the number of particles per unit volume with a radius r in the range r to r+dr and A, μ and r_o are constants which characterize the distributions. In particular A is directly proportional to the total density of H_2O(i.e., gms/m^3) present and the peak of the distribution occurs at $r_{peak} = r_o$. Table B-1 presents a summary of some Russian studies[9] giving the most probable values of the parameters μ, r_o and the water content of different commonly encountered clouds and fogs. The peaks of the size distributions fall near 5 or 6 microns with most μ in the range of 2 or 3.

It is also possible to characterize precipitations, (i.e., rain and snow), as single peak gamma distributions with a μ of about 2 and peak sizes in the millimeter range. The microstructural parameters vary as a function of rain (or snow) intensity and distance from the base of the cloud which generated it. However, from the scattering of light point of view, the large particles dominate and knowledge of the rain fall intensity or overall water content is more significant than the details of the distribution. Table B-2 summarizes some typical rain characteristics in terms of the rate I(mm/hr), the water content (gm/m^3), the total particulate density (number/m^3), and the associated attenuation coefficient α (Km^{-1}).[9] The attenuation coefficient α is relatively independent of optical wavelength because of the large (as compared with optical dimensions) size of the particles which characterize precipitation. Infrared wavelength which are selectively absorbed by H_2O may exhibit much higher values of α but good experimental data of this sort are rare.

Natural Aerosols

Under meteorological conditions which are free from the more obvious obstacles of clouds, fogs and precipitation, the atmosphere is found to contain a significant background level of particulates which contribute to the scattering of optical beams. It has proven to be extremely difficult to adequately characterize the aerosols as they come in a great variety of sizes, shapes, composition, and spatial distribution. The state of our current knowledge of these atmospheric aerosols and

Table B-1

Most probable values of the gamma distribution parameters μ and r and of the water content of different droplet clouds and fogs

Cloud form	r, microns	μ	q,g/m^3
Heavy cumulus *Cu cong*	6	3	1.2
Cumulus *Cu*	6	3	0.2
Cumulonimbus *Cb*	6	1	
Stratocumulus *Sc*	5	2	0.1
Stratiformis *St*	5	2	0.1
Nimbostratus *Ns*	5	2	0.2
Altostratus *As*	5	2	0.2
Altocumulus *Ac*	5	2	0.1
Radiation fogs	5	6	0.1
Advection fogs	5	3	0.1

Table B-2

Maximum and minimum values of rain characteristics/451-453/

Amount of rain	r,mm/hr	ω,g/m^3	n,m^{-3}	a greatest,mm	a max,mm	α,km^{-1}
Minimum	0.3	0.02	80	0.7	0.025	0.10
Maximum	57	1.98	19,750	3.2	0.3	3.34

their optical properties has been reviewed recently.[13] They have developed a variety of models of typical aerosol distributions for each of four different altitude regimes, including systematic variations in environmental (i.e., rural, urban, and maritime), and seasonal (i.e., spring and summer vs fall and winter) parameters as well as such important accidentals as volcanic activity. Figure B-7 summarizes these altitude variations in terms of the attenuation coefficient for visible (i.e., $\lambda = 0.55\mu$ meters) light calculated from the model particle distributions by means of Mie scattering theory. Figure B-8 illustrates the maritime model which consists of two distributions of particle size superimposed, one characteristic of unpolluted continental air with a peak near 0.005 microns and one associated with sea spray droplets and salt particles with a peak near 0.3 microns. Note that these characteristic sizes are an order of magnitude or more smaller than those typical of clouds and fogs, and are comparable or smaller than the optical wavelengths of interest. Strong wavelength dependencies of scattering from these particulate distributions can be expected.

Light Scattering From Aerosols

Even if we assume that the distribution of aerosols is known in terms of size, shapes, composition, indices of refraction, spatial variations in density and kind, and whatever else is required to completely characterize the scatterers, the estimation of the effects of these scatterers on an optical communication link operating in this environment is still a formidable task. In practice, of course, we never have this degree of knowledge and must therefore be satisfied with relatively crude, order of magnitude, estimates.

The scattering of a uniform plane electromagnetic wave from a transparent, partially absorbing or conducting sphere has been described completely by a number of workers beginning with Mie, and experimentally confirmed.[12] It is found that the scattering efficiency (defined as the ratio of the cross section for scatter divided by the physical area $\frac{\pi}{4} D^2$ of the particle) are functions only of the state of polarization, the scattering angle θ and the dimensionless ratio $\pi \frac{D}{\lambda}$, where D is the diameter of the particle and λ the wavelength of the incident radiation. Extensive tables of Mie scattering results and convenient

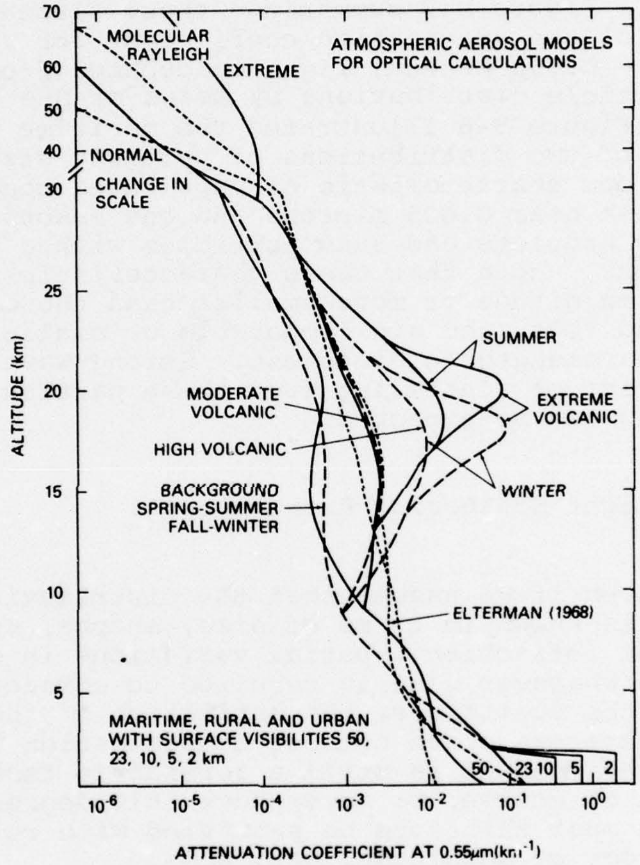
ATMOSPHERIC AEROSOL MODELS FOR OPTICAL CALCULATIONS
MOLECULAR RAYLEIGH
EXTREME
NORMAL
CHANGE IN SCALE
SUMMER
MODERATE VOLCANIC
EXTREME VOLCANIC
HIGH VOLCANIC
BACKGROUND
SPRING-SUMMER
FALL-WINTER
WINTER
ELTERMAN (1968)
MARITIME, RURAL AND URBAN WITH SURFACE VISIBILITIES 50, 23, 10, 5, 2 km
50
23
10
5
2
ALTITUDE (km)
70
60
50
40
30
25
20
15
10
5
10-6
10-5
10-4
10-3
10-2
10-1
100
ATTENUATION COEFFICIENT AT 0.55μm(km-1)

Figure B-7

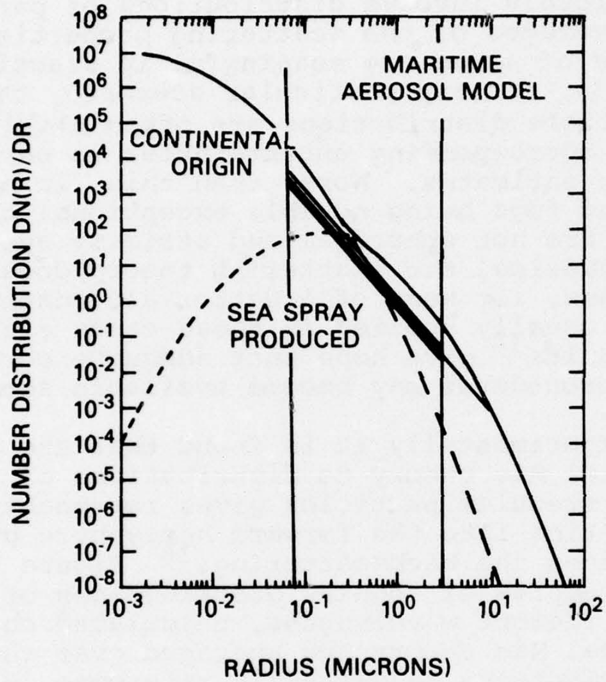
MARITIME
AEROSOL MODEL
CONTINENTAL
ORIGIN
SEA SPRAY
PRODUCED
NUMBER DISTRIBUTION DN(R)/DR
RADIUS (MICRONS)

Figure B-8

computer codes are available[14] for a wide range of complex indices of refraction, making it a simple task to calculate the effect of a single spherical particle on a uniform plane light wave.

However, this simple Mie scattering calculation can only be of limited usefulness. All natural atmospheric aerosols involve distributions of particle sizes, so only averages of the scattering properties over the variations of sizes are meaningful in practice. Unfortunately, for any particular scenario, the details of these particle distributions are often highly uncertain producing corresponding uncertainties in our light scattering estimates. Worse than this, in many cases (clouds and fogs being notable exceptions) the aerosol particles are not spherical and strictly speaking, averaged or not, classical Mie scattering theory does not apply. Nevertheless, for want of a better alternative, Mie theory is usually applied in these cases although some recent results[15] give hope that adequate correct calculational procedures may become available soon.

Experimentally it is found that the application of spherical Mie theory to distributions of randomly oriented irregular particles gives reasonably good results for scattering into the forward hemisphere but generally overestimates the backscattering.[16] Figure B-9 gives several examples of angular distributions of scattering for two different wavelengths, calculated on the basis of spherical Mie theory and averaged over the particle size distributions suggested in reference 13. The general shapes of these curves are characteristic of all atmospheric scattering, exhibiting a strong forward scatter peak, a weak back-scatter peak and a relatively smooth variation in between. They agree in shape with the scattering functions suggested earlier by Dermenjian[17] for the characterization of aerosol and cloud scattering on the basis of experimental measurements.

With some kind of estimate of the averaged scattering functions available, it is possible then to construct a complete discussion of the propagation of a beam of light through this scattering medium.

For the limit of weak scattering, which is appropriate for many cases of propagation through cloud- fog- and precipitation-free paths (i.e., clear atmospheres), an adequate description can be given in terms of single scattering events only. Under these conditions the unscattered light is simply attenuated exponentially with an extinction coefficient α which is directly related to the total scattering cross section and the total density of scatterers; the scattered light represents the missing intensity and is describable directly in terms of the angular distributions illustrated in figure B-9a and B-9b.

Shettle and Fenn[13] in their discussion of such aerosol models have calculated the wavelength dependence of the single-scatter attenuation coefficients (α) using their assumed aerosol properties and conventional Mie scattering theory. In Figure B-10 one such example is shown. The general behavior is typical of all their clear atmosphere models -- that is scatter attenuation coefficients which start near a few tenth's per Km in the ultraviolet and decrease rapidly with wavelength (i.e., as λ^{-1} or faster) reaching values approaching 10^{-2} per Km in the 8 to 14 micron infrared window. The structure which is evident in the figure is the result of molecular absorptions specific to the assumed composition of aerosols. Also indicated is the attenuation due to the absorption of light by the aerosols in addition to what is scattered. The two attenuation coefficients simply add linearly to give a composite "extinction" coefficient which represents the total aerosol effect on the beam. Generally the scatter properties of the aerosols dominate.

As the scattering becomes stronger, either due to an increase in the number of aerosols or an increase in total path length of the light beam (conveniently measured by the optical thickness τ of the medium, where $\tau \equiv \alpha \cdot Z$ and Z is the physical path length),[18] multiple scattering effects increase in importance. For optical thicknesses greater than about 1/2 (i.e., $\tau \geqslant 0.5$) the single scatter approximation is no longer adequate and multiple scatters must be included. Although a completely general theory can be formulated in terms of radiation transport theory,[19] solutions to specific problems via this approach often encounter formidable mathematical obstacles.[20] On the other hand, since photons do not noticeably interact with each other a valid and more tractable approach to the problem of propagation in optically "thick" scattering media can be obtained through the use of the Monte Carlo method.[21]

In this computer simulation technique, a large number of randomly selected initial photons are traced through a series of scatterings until each emerges from the medium as a transmitted or reflected ray or is

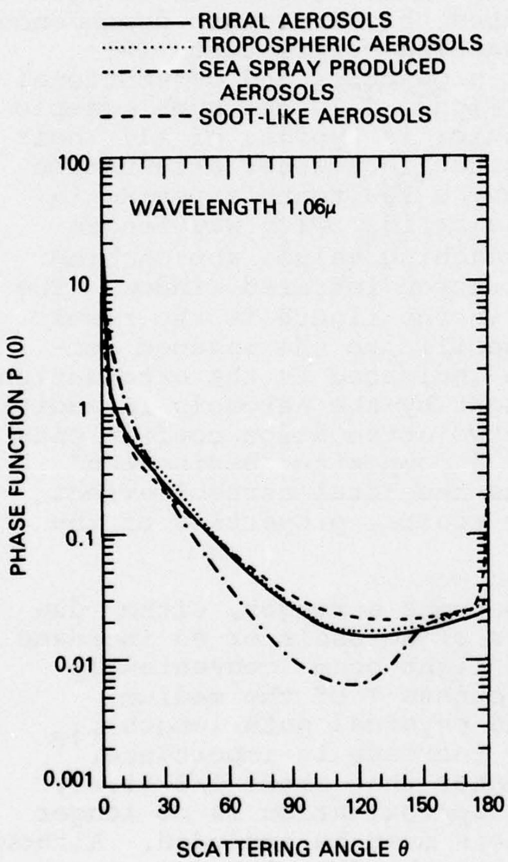

Figure B-9(a)

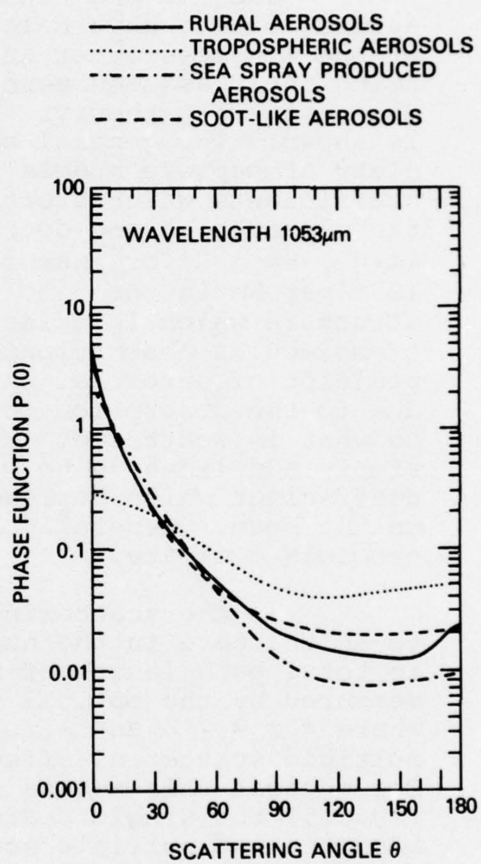

Figure B-9(b)

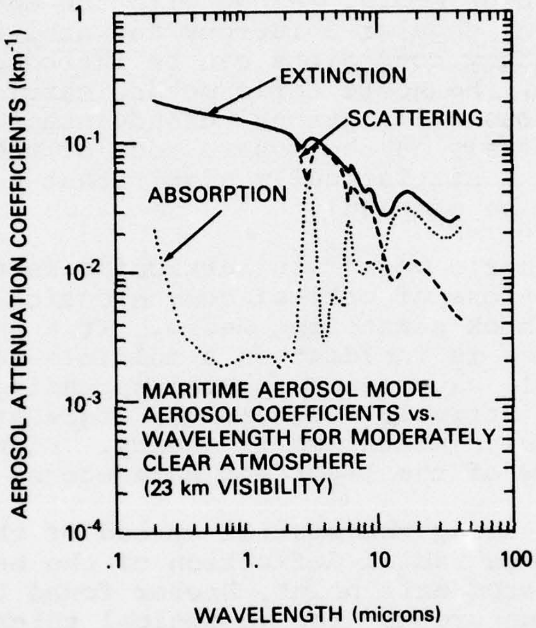
AEROSOL ATTENUATION COEFFICIENTS (km⁻¹)
1
10-1
10-2
10-3
10-4
EXTINCTION
SCATTERING
ABSORPTION
MARITIME AEROSOL MODEL
AEROSOL COEFFICIENTS vs.
WAVELENGTH FOR MODERATELY
CLEAR ATMOSPHERE
(23 km VISIBILITY)
.1
1.
10
100
WAVELENGTH (microns)

Figure B-10

absorbed by molecular or aerosol mechanisms. The probabilities of the individual scattering events are describable in terms of the single scatter differential cross section (Figure B-9). Many workers, notably Bucher[22] and Plass and Kathaway[23] have exploited this technique effectively to discuss the propagation of laser beams and sun irradiance through optically thick media. Along with the ease with which polarization, angular anistropy and arbitrary variation in the boundary conditions can be introduced into the calculation, the Monte Carlo method carries with it a rather obvious calculational disadvantage as the accuracy varies inversely as the square root of the computing time (i.e., a statistically significant number of trajectories must be sampled).

Bucher's work[22] in particular is of relevance to the questions of optical communication links through optically thick scattering media. If a collimated optical pulse is incident on a multiple-scattering region, the beam will experience spatial spreading, dispersion in angle of arrival, attenuation, degradation of spatial coherence pulse width and frequency. Figure B-11 illustrates a few of the important parameters.

Measuring the spatial spread of the beam in terms of the average radial deflection of the beam $\langle r \rangle$ from the unscattered exit point, Bucher found that the spatial spreading "saturates" for an optical thickness* of $\tau = 2$ or 3 and then decreases as the cloud becomes optically more dense (Figure B-12). In characterizing multipath time spreading, he found it necessary to introduce three statistical measures: the mean pulse width $\langle t \rangle$, its standard deviation σ_t, and the width of the most intense central portion of the time distribution or the multipath time spread L (defined as the shortest range of multipath times values which encompass 63% or the total transmitted rays). Actually all three measures give about the same result for optical thicknesses of 2 or greater so only one is illustrated in figure B-13; that is

$$\langle t \rangle = 0.62 \quad \Delta t(\tau)^{0.94} \qquad \text{(B-7)}$$

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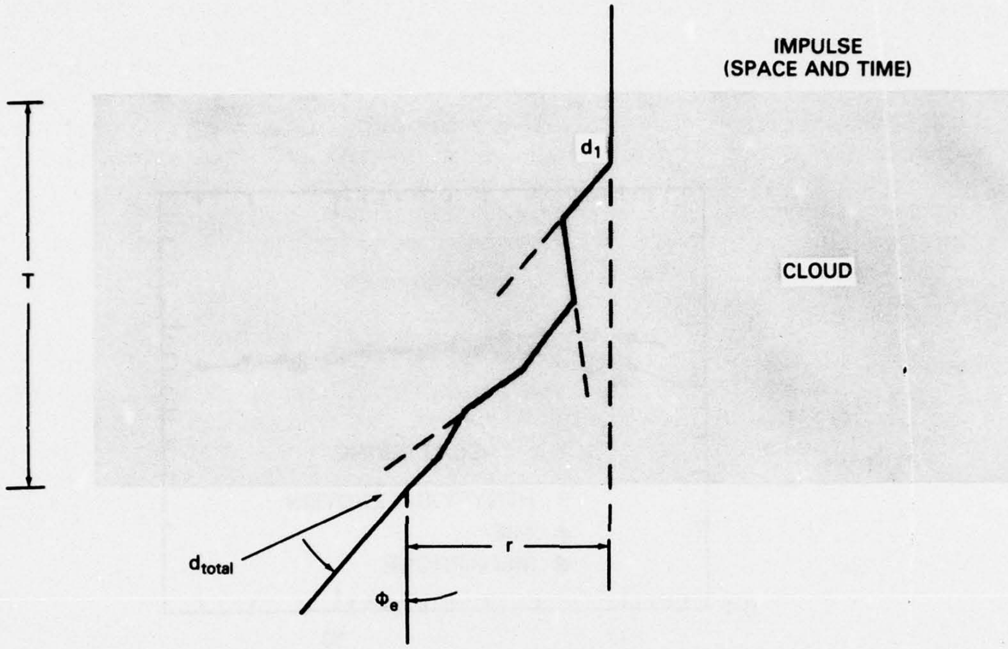
*Bucher actually deals with a weighted form of τ, a distinction of no practical importance to our crude considerations.



Simulation parameters and measures [10].

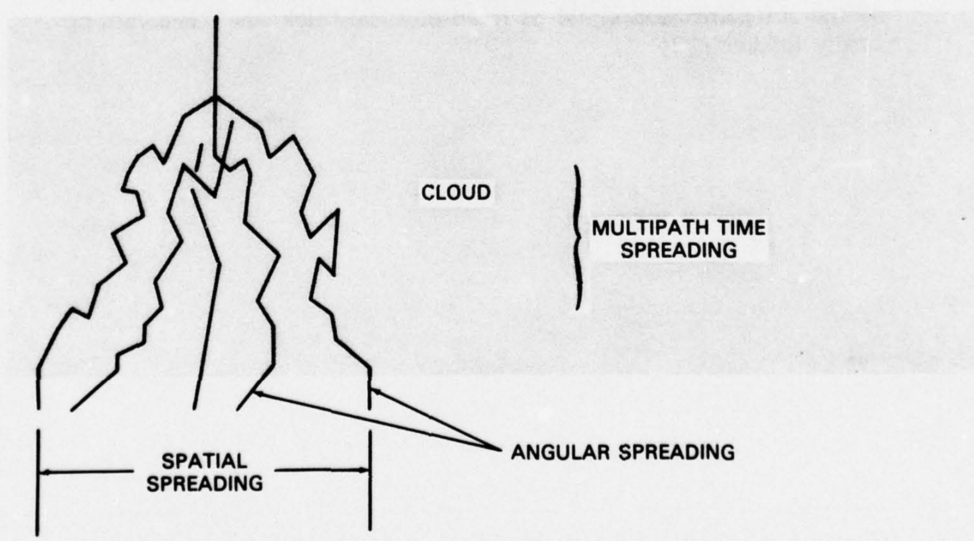


Fig. B-11 — Parameters of light propagation in clouds

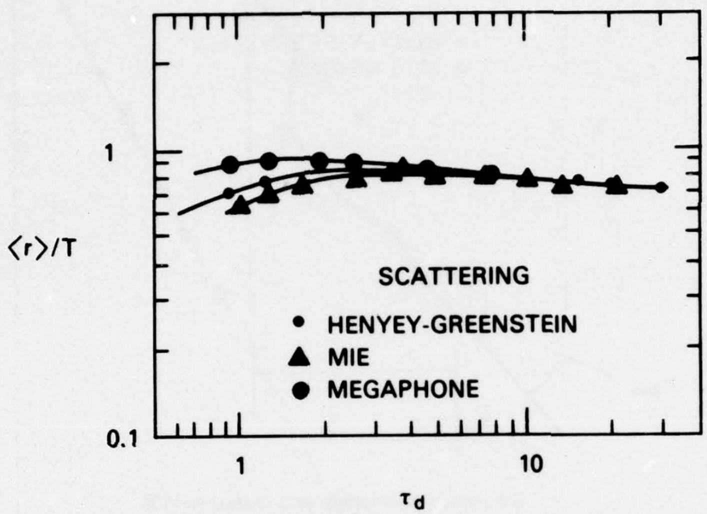


Fig. B-12 — Plot of ⟨r⟩/T as a function of τ_d showing the saturation in spatial spreading as a cloud of fixed physical thickness T becomes optically thicker [12]

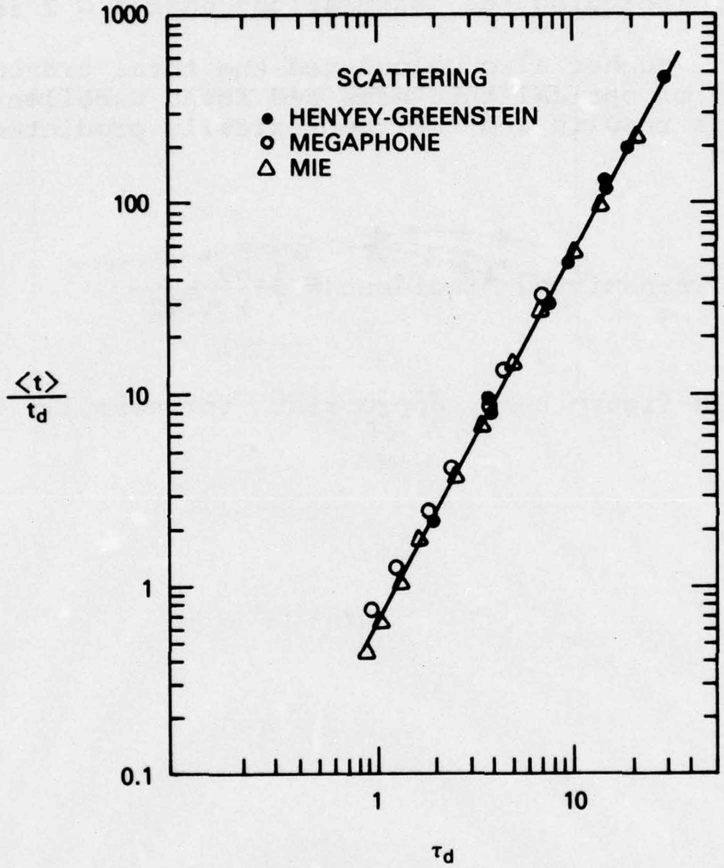


Fig. B-13 — $\langle t \rangle / t_d$ as a function of τ_d. The 90% confidence limits on all data points are ±2.5% or better [12] where Δ is the unscattered optical transit time through the cloud layer. The general validity of these Monte Carlo results are corroborated by some careful Russian experimental measurements of the propagation of HeNe laser beams through laboratory fogs and smokes reported in reference 9. Figure B-14 illustrates some of these results. The similarity of these experimental curves to the computer generated curves of Bucher, including the "saturation" near $\tau \simeq 2$ is evident.

Bucher also calculated the total transmission as a function of optical thickness and found excellent agreement between his results and the theoretically predicted analytic expression

$$I_{Transmitted}/I_{Incident} \equiv \frac{1.69}{\tau + 1.42} \qquad \text{(B-8)}$$

as shown in figure B-15, appropriate for normally incident light.

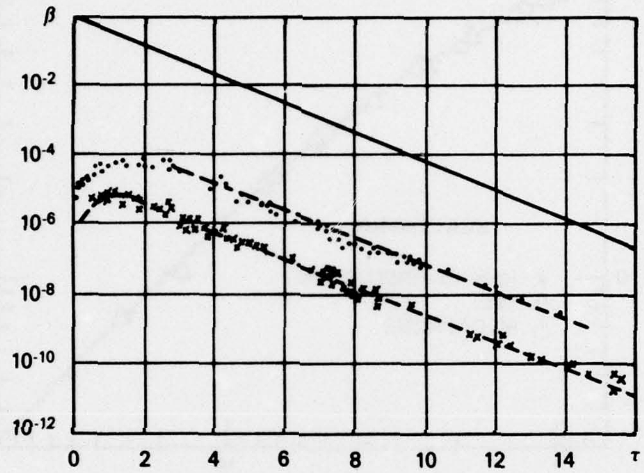


Fig. B-14 — Brightness of forward-scattered radiation as a function of optical thickness in fog (points) and smoke (crosses). Dashed curves were constructed from calculations of the theory of single scattering; the straight line describes the Bouguer extinction of direct radiation.

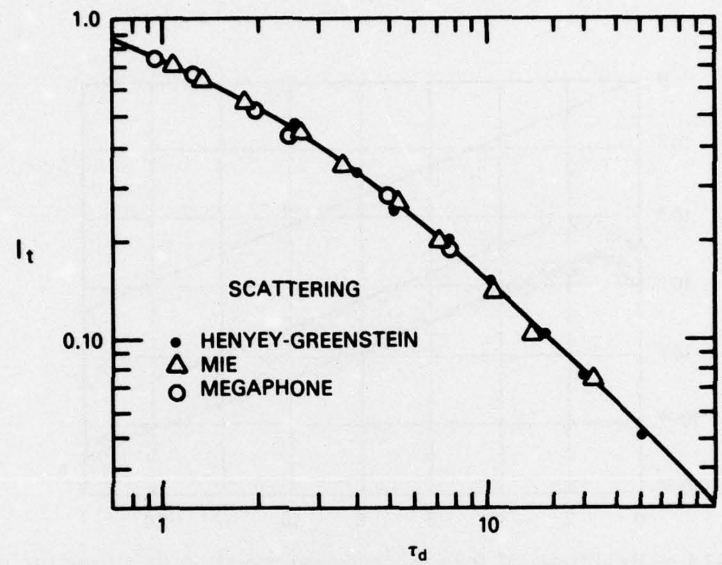


Fig. B-15 — Total transmission as a function of τ_d. The theoretical curve is from van de Hulst's work. The 90% confidence limits on all data points are ±5% or better [12]

APPENDIX C

COMPONENTS -- STATE-OF-THE-ART

The optical components appropriate for use in free space or unguided optical communication links include

- sources and amplifiers -- (i.e., laser primarily)
- modulators
- antennas -- (i.e., telescopes and lenses)
- optical filters, and miscellaneous optical components (e.g., polarizers, etc.)
- detectors

as well as standard electronics for power supplies, modulation/demodulation amplification, etc. It is not appropriate to discuss these subjects in great depth here as some aspects are quite standard (telescopes, for example) and others have been reviewed in detail in a comprehensive issue of the Proceedings of IEEE devoted entirely to the subject of optical communications.[1] In spite of the 1970 date of these reviews, they are representative of today's art to a large extent as only minor refinements have ensued in most areas.

A few salient points are worth noting however.

Optical oscillators or lasers are based on physical principals which are quite different from those used to generate microwave frequencies. Microwave oscillators make use of a gain mechanism -- generally the interaction of electromagnetic fields and plasmas in one form or another -- which are typically capable of amplifying an extremely wide range of frequencies. The specific frequency generated is then determined largely by the associated resonant cavity, an electrical/mechanical structure fabricated to mechanical dimensions on the order of the wavelength of the desired frequency of operation. For microwaves, with wavelengths in the millimeter to centimeter range, this is practical and permits the straightforward generation of any desired frequency in the microwave spectrum. As the frequencies are increased into the submillimeter range, the dimensional tolerances become increasingly severe until finally, well before the optical range of interest to communications, the technology of wavelength-sized resonant cavity structures is no longer useful.

To generate oscillators in the optical region, the characteristics of the gain medium and the associated resonant structures are generally reversed. Mechanically large broad based optical cavities with mirrors millimeters to meters apart, are used in combination with very narrow band gain media. By various excitation schemes, optical gain is established between specific energy levels of the atomic or molecular species being used. Such optical oscillators are then restricted to producing output in the immediate region of these sharp characteristic spectral lines. Laser sources then, in marked contrast to microwave oscillators, tend to be discretely distributed in wavelength or frequency as determined by the gain medium employed and not readily tunable over large frequency intervals to other portions of the spectrum. Actually some lasers are tunable to the extent that the spectral lines can be moved by electric or magnetic field -- Stark and Zeeman effects for example, or caused to broaden by collision effects as in gas lasers, and/or overlap neighboring lines as in dye lasers. However the tuning flexibility is always limited primarily by fundamental spectral characteristics rather than arbitrary variations in the optical cavity's resonant structure.

Literally thousands of laser transitions from the deep ultraviolet to the far infrared have been made to oscillate. However only a few have demonstrated the right combination of power, efficiency, coherency and good atmospheric transmission properties to warrant serious consideration for optical communication links. A summary of these lasers and their properties are given in reference 24 and the primary pulsed and CW laser candidates listed in Tables C-1 and C-2.

Electro-optical modulators are available throughout the optical range with different spectral regions requiring different materials. Although development continues, performance bandwidth in hundreds of megahertz range are available as off-the-shelf commerical items today and bandwidths considerably in excess of gigahertz have been available in the laboratory for many years. An excellent review of modulator technology is to be found in reference 25.

Telescopes and lenses etc. are so well established as to require no particular comment. Diffraction limited apertures of a meter or more in diameter are readily available, but expensive -- costs vary roughly as diameter cubed. And the development of deformable optical systems (i.e., "rubber mirrors") with the capability of correcting turbulence-induced phase front distortions in real time is well under way with experimental models already available from several sources.[26]

Optical filters and miscellaneous optical components also pose no particular problems and have been reviewed in the context of optical communication in reference 27. Filter bandwidths as narrow as 0.005μm and with good transmission properties can be generated via interference techniques and are useful for background suppression.

Detectors, adequate for communication purposes, are generally available at all optical frequencies of interest. Quantum efficiencies of 0.5 or greater are possible from the visible through the infrared 8 - 14 μmeter band and D sensitivities approaching theoretical limits are also becoming increasingly common. Infrared detectors unfortunately require cryogenic cooling, which presents complications, but no fundamental obstacles. An excellent review of optical detectors for optical communications is to be found in reference 28.

In short, the component technology for optical communications is presently available for exploitation. Applications will certainly come when the requirements and economics warrant them.

Table C-1

PULSE LASERS.

Wavelength	Type	Output		Pulse Width	Pulse Rate	Beam Divergence	Approximate Price Range (1976)
		Energy Joules	Peak Power MW				
(μm)				μs	(pps)	mrad	$k
0.337	Nitrogen	0.01	1	0.01	50	1	23
0.53	Neodymium Yag-	0.1	5	0.02	30	4	40-60
	frequency doubled	0.15	10	0.014	10	3.5	50
Selected within 0.45 to 0.69	Dye	0.1	2		30		
0.49	Dye	0.12	0.25	0.5	10		
1.06	Nd:YAG	0.05	5	0.01	2400	—	—
		0.1	6	0.015	50	3 to 5	15 to 30
		0.15	10	0.015	30	1.2	27
		0.45	30	0.015	20	3 to 5	30 to 40
		1	50	0.02	30	2	35 to 55
		1.2	80	0.015	30	0.8	75
2.8 to 3	Hydrogen Fluoride	0.7	1.4	0.5	1 to 2	0.5	15
3.5 to 4	Deuterium Fluoride	1	2	0.5	1 to 2	0.3	15
10.6	Carbon Dioxide	0.5	2.5	0.2	200	1.2	15
		3	30	0.1	300	0.6	30
		800	8000	0.1	0.1	0.5	90

Table C-2

CONTINUOUS-WAVE LASERS.

Wavelength µm	Type	Output (watts)		Beam Divergence	Commercial Units Approx Price Range (1976)
		Principal Mode	Multimode	mrad	$k
0.337	Nitrogen	0.1			
0.351 to 0.52	Argon	4		0.6	8
		5		0.5	10.5
		8		0.5	13
		16	20	0.6	16
0.53	Nd: YAG Frequency doubled	2			20
0.69 to 1	Ruby/Glass		to 20	5	6 to 12
1.06	Nd: YAG		15	6 to 8	8 to 15
			25	5 to 8	10 to 18 (20 to 26 MILSPEC)
			50	6 to 8	13 to 30
		15	200	5 to 15	20 to 40
			800-1000	16 to 20	100
2.6 to 3.5	Hydrogen Fluoride	4000			
10.6	Carbon Dioxide	3		4	4
		50		1 to 2	8 to 13
		250	300	1	30
		500		1.4	35
		1000		2.1	47

APPENDIX D

COMPUTATIONAL MODEL -- INTERSECTING BEAMS/ SINGLE SCATTER

Consider situations for which the transmitted beam of an interfering link passes directly through the field of view of the receiver of interest such that unwanted radiation can be redirected by a single scattering event into the receiver. A general scenario of this sort is illustrated in figure D-1. In order to simplify the calculations as much as possible, we assume a uniform scattering medium filling the common intersection volume of the beam and treat only single scattering events. For geometries in which the forward- or back-scatter peaks of $f(\theta)$ come into play, neglect of multiple scattering will lead to overestimates of the unwanted scattered power received -- a conservative assumption. For side-scattering angles for which $f(\theta)<1$, multiple scatterings can enhance the scattering -- but never produce an $f(\theta)$ larger than one (i.e., isotropic scattering). For these situations a conservative estimate follows if we set $f(\theta) \equiv 1$.

In order to avoid unimportant geometric refinements, we also will assume that the overlap or intersection volume is small as compared with the distance from the intersection to the receiver and transmitter and thus that the transmitted beam is more or less uniform throughout the common volume.

The total power P_S scattered (into all directions) from the intersection volume is given roughly by the expression

$$P_S \simeq \alpha \, \bar{I} \, \Delta V \qquad \text{(D-1)}$$

where α is the scatter extinction coefficient, $\bar{I}$ is the average incident transmitted irradiance (watts/unit area) appropriate to the intersection region and ΔV is the common volume. If we think of the volume ΔV as an area A perpendicular to the direction of the transmitted beam through a distance L which represents the thickness of the intersection region along the transmitted beam (i.e., $\Delta V = A \cdot L$) it is easy to see that the total transmitted power incident upon the common region is just $\bar{I} \cdot A \equiv P_{INC}$ and the total flux scattered from this beam as it travels through the volume a distance L is therefore $P_S \equiv \alpha \cdot P_{INC} \cdot L$. Hence $P_S \equiv \alpha \bar{I} AL = \alpha \bar{I} \Delta V$. If this flux was scattered isotropically, the amount of unwanted radiation P_{UW} collected by the receiver's aperture would be given approximately as

$$P_{UW} \simeq \frac{P_S}{4\pi} \cdot \frac{A_R}{Z_R^2} \cdot T_R = \frac{\alpha \bar{I} \Delta V A_R}{4\pi Z_R^{\ 2}} \cdot T_R \qquad \text{(D-2)}$$

where A_R is the area of the receiver's antenna, Z_R is the distance from the intersection volume to the receiver and T_R is the atmospheric transmission of the path along Z_R. For a uniform scattering medium filling all space along the path, $T_R \equiv \exp(-\alpha Z_R)$, neglecting all other loss factors. To account for nonisotropic scatter we simply introduce the factor $f(\theta)$ discussed previously.

In order to make this expression useful we must evaluate $\bar{I}$ and ΔV in terms of the parameters of the two communication links involved. Specifically for the averaged irradiance in the intersection volume we find

$$\bar{I} \simeq \frac{P_T}{\Omega_T Z_T^{\ 2}} \cdot T_T \qquad \text{(D-3)}$$

where P_T is the transmitter power, Ω_T is the solid angle characterizing the transmitted beam, Z_T is the distance from the transmitter to the intersection and T_T is the atmospheric transmission of the paths along Z_T. And for the volume ΔV we can write

$$\Delta V \simeq \left[\Omega_< Z_<^{\ 2}\right] \cdot \left[\sqrt{\Omega_> Z_>^{\ 2}}\right] \qquad \text{(D-4)}$$

where $\Omega_<$ and $Z_<$ are the parameters associated with the smaller of the two beams, and $\Omega_>$ and $Z_>$ correspond to the larger beam. Combining equations, we find for the two general scenarios possible

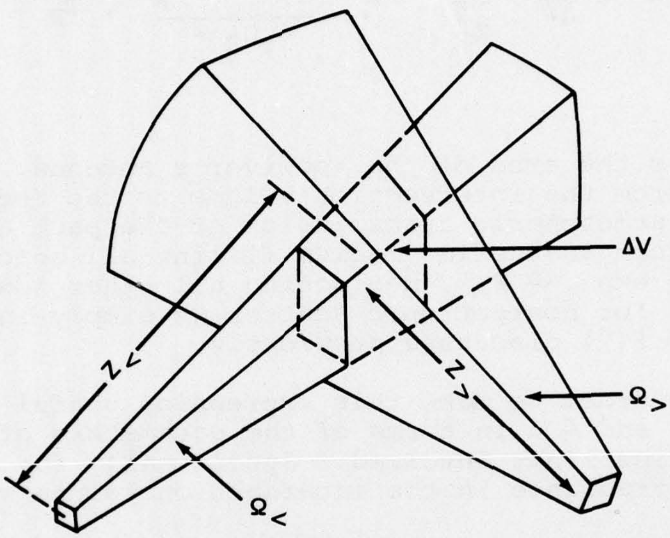


Fig. D-1 — General scenario assumed for calculational model for terrestrial, single scatter effects

Case 1

Receiver beam smaller than transmitted beam

$$P_{UW} \simeq \frac{f(\theta)}{4\pi} P \frac{\Omega_R A_R}{\sqrt{\Omega_T} Z_T} \left[\alpha T_R T_T\right] \tag{D-5}$$

since $\Omega_< = \Omega_R$, $Z_< = Z_R$, $\Omega_> \equiv \Omega_T$ and $Z_> \equiv Z_T$.

Case 2

Receiver beam larger than transmitter beam

$$P_{UW} \simeq \frac{f(\theta)}{4\pi} P \frac{\sqrt{\Omega_R} A_R}{Z_R} \left[\alpha T_R T_T\right] \tag{D-6}$$

since $\Omega_< = \Omega_T$, $Z_< = Z_T$, $\Omega_> = \Omega_R$ and $Z_> = Z_R$.

These upper limits can be further simplified by noting that generally the product $T_R T_T$ represents an expression of the form

$$T_R \cdot T_T = \exp(-\alpha \ell) \tag{D-7}$$

where $\ell = Z_R + Z_T$ if all space is filled with the uniform scattering medium. With this in mind we see that the expression in square brackets is a function of the scattering coefficient α with a maximum value, which occurs when $\alpha \ell = 1$; that is

$$\left[\alpha T_R T_T\right] \cong \alpha e^{-\alpha \ell} \leq \frac{1}{\ell} e^{-1} \tag{D-8}$$

Hence we estimate that the unwanted scattered power collected will be limited by

$$P_{UW} \leq \begin{cases} \dfrac{f(\theta)}{4\pi e} \; P \; \dfrac{\Omega_R \; A_R}{\sqrt{\Omega_T} \; Z_T \; \ell} & \text{Case 1 Receiver < Transmitter} \quad \text{(D-9)} \\[2ex] \dfrac{f(\theta)}{4\pi e} \; P \; \dfrac{\sqrt{\Omega_R} \; A_R}{Z_R \; \ell} & \text{Case 2 Receiver > transmitter} \quad \text{(D-10)} \end{cases}$$

For numerical purposes, we shall assume a standard collector area of reasonable size; i.e., $A_R = 1$ meter^2. For a scatter-propagation system we will assume the parameters suggested in reference 5, that is a fan beam field of view for both the transmitter and receiver of 4° and 1° giving

$$\Omega_{SCATTER} \approx \left(\frac{4}{57.3}\right)\left(\frac{1}{57.3}\right) = 1.2 \times 10^{-3} \text{ steradians} \quad \text{(D-11)}$$

For a point-to-point link we assume three time diffraction limited optics and apply Siegman's Antenna Theorem[29] to express the beam solid angle in terms of the wavelength; that is

$$\Omega_{point\text{-}to\text{-}point} \simeq \frac{(3\lambda)^2}{A_R} \doteq 10\lambda^2; \; [\lambda] \equiv \text{meters} \quad \text{(D-12)}$$

since we have already taken $A_R \simeq 1$ sq. meter.

Further, let us compare these estimates of unwanted scattered powers with the noise equivalent power (NEP) of the receiver by requiring that

$$P_{UW} \leq NEP \simeq 10^{-13} \text{ watts} \quad \text{(D-13)}$$

where we have chosen a reasonable, representative value of NEP. This condition can be translated via equations D-9 and D-10 into restrictions on P_T, θ and the distances Z_R, Z_T and ℓ such that the scattered interferences be no worse than the system noise. Even if $P_{UW} \simeq$ NEP in some situations, if processing gains are available because of modulation differences, this plus the system's normal signal to noise ratio will usually be enough to insure the desired 30dB margin between wanted and unwanted signal.

Summarizing the results of these calculations for the cases of interest we find the following four coordination conditions

<u>Point-to-Point Receiver</u>

$$\frac{f(\theta)P_T(\text{watts})}{Z_T(\text{Km})\,\ell(\text{Km})} \le \begin{cases} \dfrac{1.2 \times 10^4}{\left[\lambda \text{ (microns)}\right]^2} & \text{Scatter Transmitter} \quad \text{(D-14)} \\[2ex] \dfrac{1.1}{\lambda \text{ (microns)}} & \text{Point-to-point Transmitters} \quad \text{(D-15)} \end{cases}$$

<u>Scatter Receiver</u>

$$\frac{f(\theta)\ P_T(\text{watts})}{Z_T(\text{Km})\,\ell(\text{Km})} \le \begin{cases} 10^{-4} & \text{Scatter Transmitter} \quad \text{(D-16)} \\[2ex] 10^{-4} & \text{Point-to-point Transmitter} \quad \text{(D-17)} \end{cases}$$

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